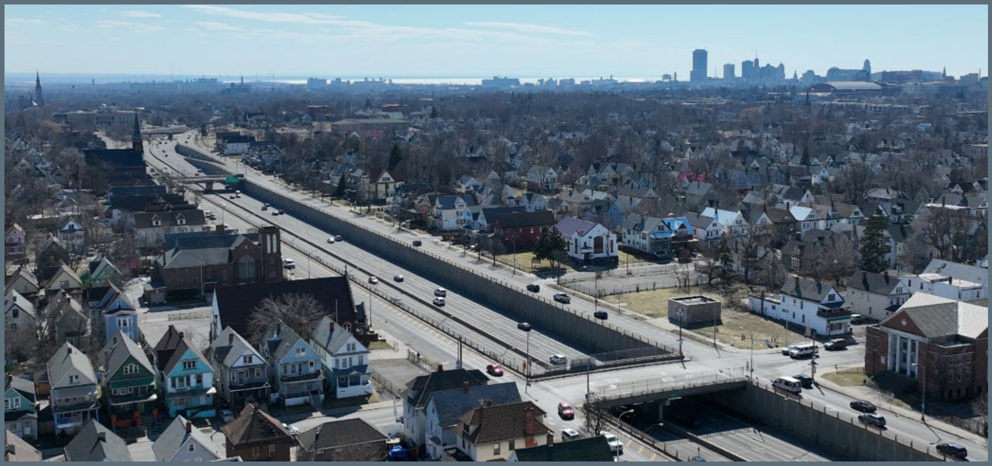
Appendix A15

Technical Memorandum:

Rock Removal



TECHNICAL MEMORANDUM: ROCK REMOVAL

KENSINGTON EXPRESSWAY PROJECT, PIN 5512.52

DRAFT

September 10, 2023

PREPARED FOR

NEW YORK STATE OF OPPORTUNITY. Department of Transportation

PREPARED BY

HNTB

LaBella

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1. Introduction

1.1. Project Location and Description

The Kensington Expressway Project is seeking to reconnect communities surrounding a stretch of the currently depressed NYS Rte. 33, Kensington Expressway corridor, Figure 1. The project includes the reconstruction of the Kensington Expressway with a cut and cover tunnel extending approximately 4,150 feet, with the southern portal at Dodge Street and the northern portal at Sidney Street, Figure 2.

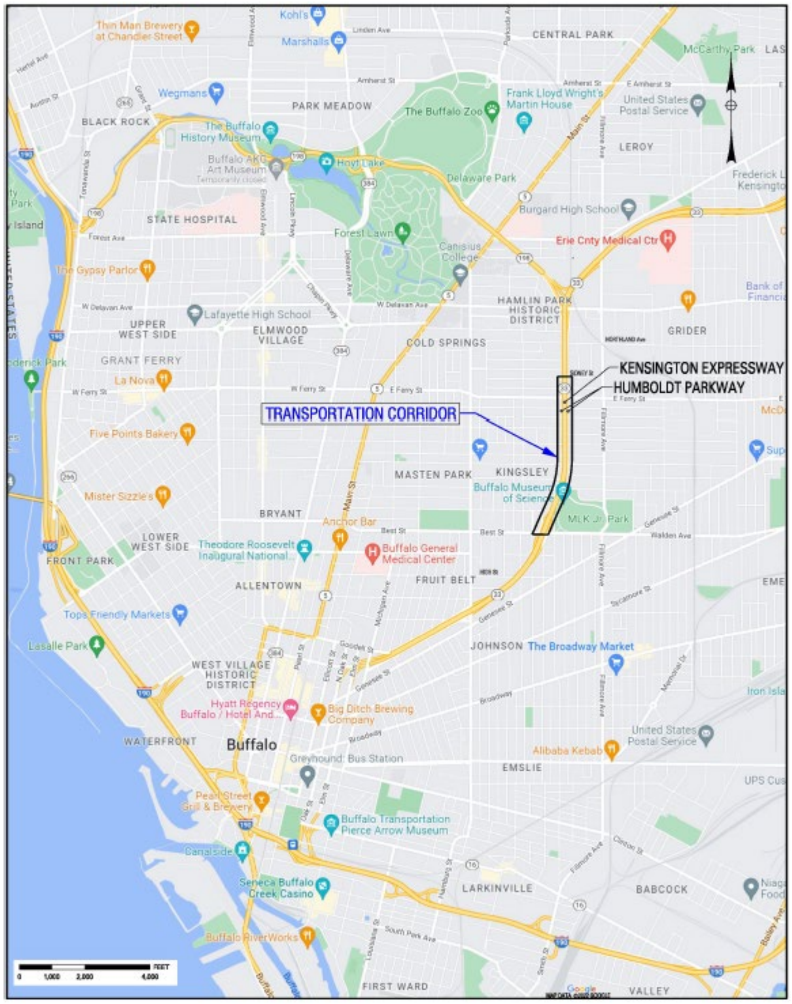


Figure 1 Project Location Map

Figure 2 Proposed Plan of Tunnel – Project Limits

1.2. Objectives

The Project involves the removal of bedrock to achieve the final lowered NYS Route 33 (Kensington Expressway) roadway profile through the proposed tunnel limits. This Technical Memorandum serves to approximate the limits where rock removal will be required, define methods of potential rock removal, review existing NYSDOT guidance for rock removal, and provide recommendations based on best industry practices while seeking to minimize impacts, such as noise and vibration, to properties, structures, and utilities in proximity to rock removal areas.

2. Existing Conditions

The most efficient means of hard rock removal is by blasting; however, there may be instances where mechanical removal methods are more appropriate. Since these non-blasting methods are not as efficient as blasting, they will be used where rock removal is near delicate structures or utilities or where the required rock removal depth is minimal and blasting not feasible. Where used, blasting will be conducted in a safe and efficient manner, with the application of controlled blasting techniques.

There is an approximately 1,600-foot length of the Project in which rock elevations are such that rock removal is not anticipated. This area extends from approximately 300 feet north of Dodge Street to approximately Landon Street. For the remainder of the proposed tunnel length, rock removal will be required as follows:

- At the southern limit of the proposed tunnel and to the southern roadway profile tie-in point, the rock elevation is generally below the proposed final tunnel roadway profile. Limited rock removal may be required at the southern limits of the Project, over a length of approximately 1,250 feet from approximately 300 feet south of the Best Street bridge to approximately 300 feet north of the Dodge Street bridge. It is anticipated that this removal would be by mechanical methods.

- From approximately Landon Street to approximately Woodlawn Avenue (an approximate length of 1,400 feet), the depth of rock removal is anticipated to be less than 5 feet, so mechanical removal methods will likely be employed in this area.
- From approximately Woodlawn Avenue to approximately 300 feet north of the northern portal (an approximate length of 1,250 feet), the rock elevations are more than 5 feet higher than the proposed tunnel profile. It is anticipated that rock removal will be by blasting methods in this area.

See Appendix A for Soil and Rock Excavation Plans and Profiles demonstrating the above noted removal limits.

3. *Review of NYSDOT Rock Excavation Guidance and Requirements*

Rock excavation is covered by NYSDOT Standard Specifications Section 203 – Excavation and Embankment (See Appendix B), and more specifically, Section 203-3.02.A, Rock Excavation, which covers requirements for blasting. Additionally, NYSDOT Geotechnical Engineering Manual GEM-22 (See Appendix C) defines procedures for blasting.

The NYSDOT Standard Specifications for rock excavation are primarily directed to removal from an existing slope, such as the widening of a highway or maintenance of such slopes. As such, the specifications are directed to presplit blast procedures, to ensure that the excavated profile has a smooth final face.

GEM-22 contains a detailed discussion of procedures for blasting within the New York State Department of Transportation Right of Way. GEM-22 was last revised in 2015. Since then, there have been significant advances in blasting technology. These changes have improved the safety and accuracy of blasting, and reduced potential for adverse impacts. These changes should be implemented for the Kensington Expressway project.

It is recommended that special specifications be created for this project, based upon updated revisions to the Standard Specifications and GEM-22. We will recommend that the special specifications use the recommendations in Appendix B of the US Bureau of Mines in Report of Investigations 8507 (USBM RI 8507) from 1980 (see Appendix D) for low frequency vibration limits, which are more stringent than the current NYSDOT guidance. These criteria are commonly applied by worldwide regulatory agencies to ensure blast vibrations are at levels low enough to avoid threshold damage to surrounding structures. The recommended special specifications for the Project will incorporate the latest advances to ensure the Kensington community experiences the least impacts possible.

4. Rock Removal Best Practices

4.1. Blasting

The design of controlled blasting starts with a review of the neighboring receptors and determination of the noise and vibration levels acceptable for these receptors. With the noise and vibration criteria established, a series of test blasts will be conducted to develop the site-specific relationship relating distance and explosive charge weights, which is an attenuation relationship. This relationship will take the form of maximum allowable charge weight, in pounds, per delay for a given standoff distance. With the use of electronic delays, the initiation of the blast in each hole can be timed to an accuracy of a few microseconds. During both test and production blasting, instrumentation will be used to measure noise and vibration near structures proximate to the blasting and these data will be used to verify and update the attenuation relationship.

Blasting procedures and protocols will be consistent with Federal, State, and local regulations, but also with recommendations for procedures and field seismograph operation provided by the International Society of Explosives Engineers (http://www.isee.org). Furthermore, recommendations by the Institute of Makers of Explosives (www.ime.org) Safety Library Publications, particularly the "Always and Nevers" document, SLP 4.

A Construction Vibration Mitigation Plan would be developed during final design that would:

- Implement a construction vibration monitoring program that includes a communication and public outreach plan throughout the construction period.
    - The construction vibration monitoring program would be prepared with input from the community and allow for modification of methodologies based on public input throughout construction.

  - The results of construction vibration monitoring would be available for the public to view on the project website.
  - NYSDOT would include a contract requirement for a public outreach liaison that would conduct proactive outreach ahead of blasting activities. Further, the community liaison would be able to accept complaints from the public which would then be assessed by NYSDOT for any appropriate action. If at any time it is determined that vibration levels are unacceptable, the problematic construction operations would be halted until a plan to mitigate the vibration issues has been approved by NYSDOT.
  - A blasting schedule would be published and made available for viewing at the Project public outreach office.
  - Local police and emergency services wound be informed of the blasting schedule.
  - Pre-blast audio alert procedures would be established, consisting of a well-defined sequence of airhorn blasts prior to a blast and a following all-clear.
- Prohibit nighttime use of impact and drilling equipment including jackhammers, hoe rams, core drills, direct push soil probes (e.g., Geoprobe), pavement breakers, pneumatic tools, and rock drills.
- Require contractor to develop and implement a blasting program designed to avoid the potential for damage to structures by modifying the weight of explosives per delay, the loading density, and the delay pattern consistent with GEM-22. Blast vibration would be kept within bounds as determined by USBM RI 8507 and adjusted on an as-needed basis during construction.
- Require test blasts, prior to construction blasting, to assess appropriate explosive charge weights, and if deemed appropriate, industry-standard signature hole analysis.
- Require vibration and airblast monitoring per the blasting program.
- Although no threshold damage is expected, any unanticipated damage to buildings or utilities found by the NYSDOT to be attributable to the construction would be repaired by the contractor. Pre- and post-construction surveys of building conditions would be conducted within a survey area of up to approximately 300 feet (this estimated distance for the surveys would be refined during final design, as appropriate).

4.2. Mechanical Rock Removal Methods

Mechanical splitting methods will be used where predicted blast induced vibrations cannot be reduced to below acceptable levels or in areas of limited (less than approximately 5 feet) rock removal, where removal by blasting is not feasible. With these methods, a pattern of closely spaced holes is drilled. The rock may be split using a hoe ram or mechanical wedges. With the exception of the hoe ram, the noise and vibration generated is governed by the drilling of the holes. Although hoe ram excavation will not generate substantial vibration, repetitive hoe ramming may generate annoying vibration, and should be monitored. Hoe ram excavation will also generate noise, which will be monitored and may require potential shielding to meet noise criteria.

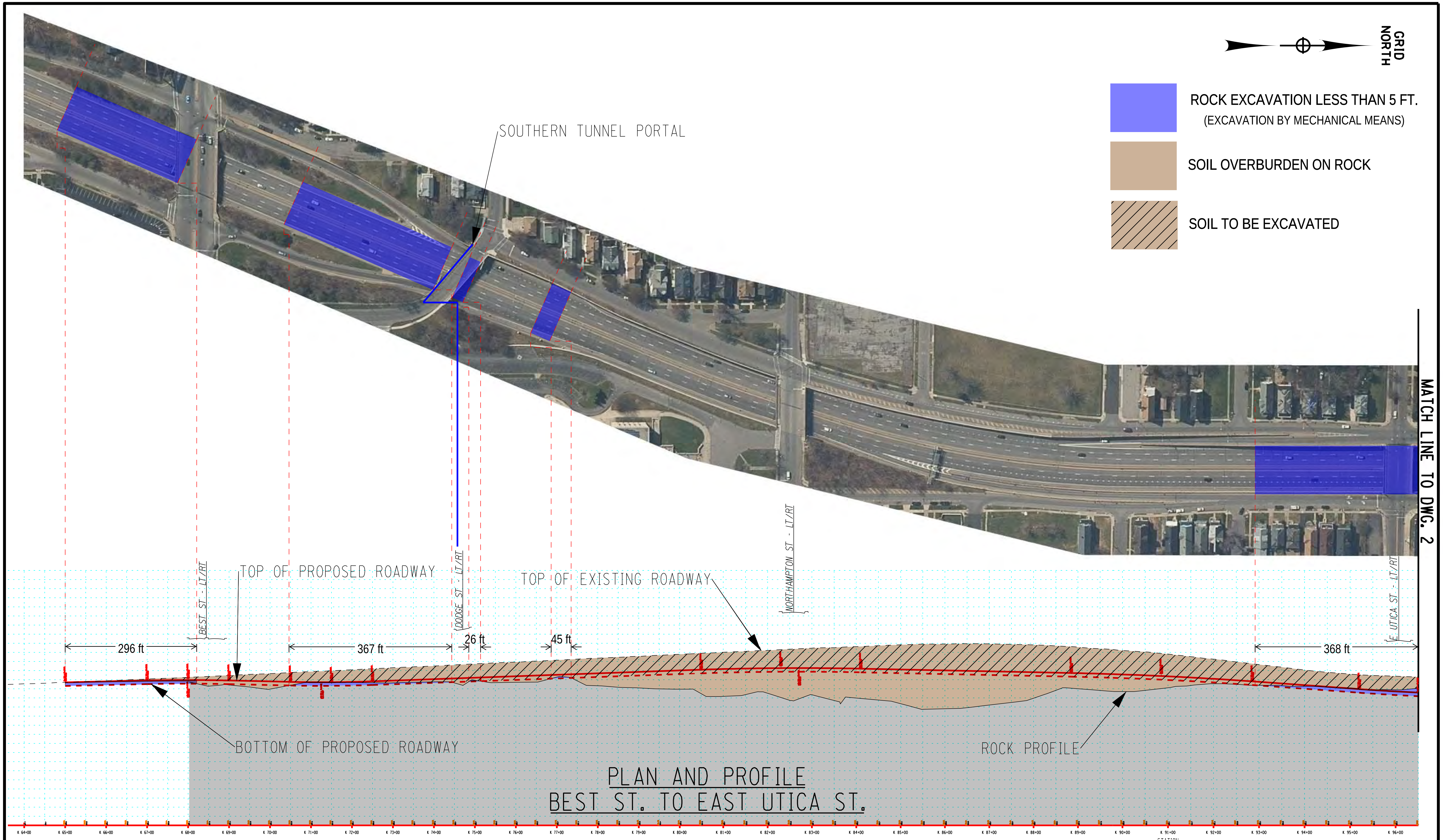
5. Recommendations

Prior to release of Requests for Proposals for rock removal for the Kensington Expressway project, new specifications will need to be developed, based upon modified versions of the Standard Specifications and GEM-22. Such modifications are based primarily upon updates in industry-standard blasting practices since the release of GEM-22. In addition, the Standard Specifications and GEM-22 are directed principally toward highway highwall blasting, which has different concerns than the blasting anticipated for this project.

Review of such modifications, as well as other recommendations, will be made in conjunction with and reviewed by NYSDOT personnel as appropriate.

Appendix A:

Soil and Rock Excavation Plans and Profiles



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AS-BUILT REVISIONS DESCRIPTION OF ALTERATIONS:	COUNTY: REGION:	PIN	BRIDGES	CULVERTS	ALL DIMENSIONS IN ft UNLESS OTHERWISE NOTED	CONTRACT NUMBER DRAWING NO. SHEET NO.

IT IS A VIOLATION OF LAW FOR ANY PERSON, UNLESS THEY ARE ACTING UNDER THE DIRECTION OF A LICENSED PROFESSIONAL ENGINEER, ARCHITECT, LANDSCAPE ARCHITECT, OR LAND SURVEYOR, TO ALTER AN ITEM IN ANY WAY. IF AN ITEM BEARING THE STAMP OF A LICENSED PROFESSIONAL IS ALTERED, THE ALTERING ENGINEER, ARCHITECT, LANDSCAPE ARCHITECT, OR LAND SURVEYOR SHALL STAMP THE DOCUMENT AND INCLUDE THE NOTATION "ALTERED BY" FOLLOWED BY THEIR SIGNATURE, THE DATE OF SUCH ALTERATION, AND A SPECIFIC DESCRIPTION OF THE ALTERATION.

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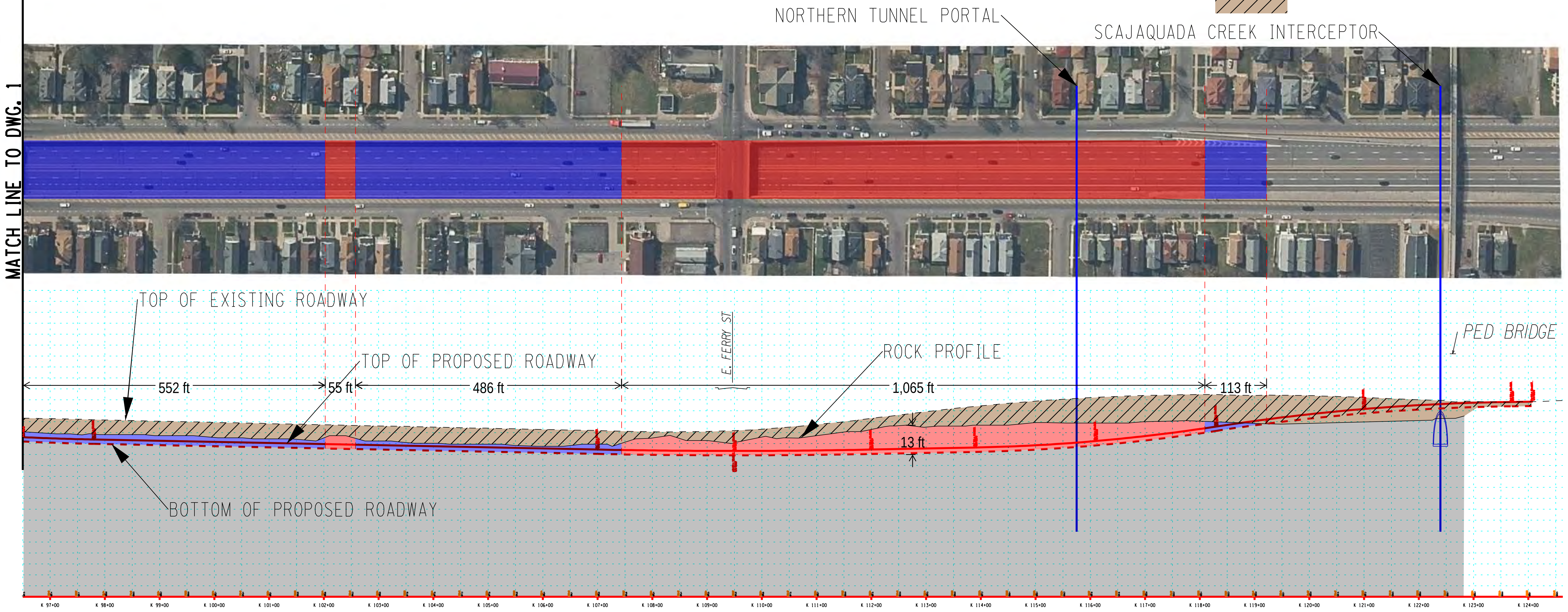
🟦 ROCK EXCAVATION LESS THAN 5 FT.
(EXCAVATION BY MECHANICAL MEANS)

🟥 ROCK EXCAVATION IN EXCESS OF 5 FT.
(BLASTING OF ROCK LIKELY; SEE NOTE 1)
MAXIMUM DEPTH = 13 FT.

🟫 SOIL OVERBURDEN ON ROCK

▨ SOIL TO BE EXCAVATED



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NOTE:

1. LOCATION AND LIMITS OF BLASTING WILL BE DETERMINED DURING CONSTRUCTION WITH THE DEVELOPMENT OF A BLASTING PLAN. THE BLASTING PLAN WILL TAKE INTO ACCOUNT PROXIMITY TO EXISTING AND PROPOSED STRUCTURES AND ESTABLISHED VIBRATION LIMITS PRIOR TO ANY BLASTING OPERATIONS.

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Appendix B:

NYSDOT Standard Specifications Section 203

Payment will be made under:

Item No.	**Item**	**Pay Unit**
202.01nnnn	Disposal of Buildings	Lump Sum
202.03nnnn	Relocating Buildings	Lump Sum
202.11nnnn	Dismantling and Storing Existing Superstructures	Lump Sum
202.12nnnn	Removing Existing Superstructures	Lump Sum
202.19	Removal of Substructures	Cubic Yard
202.2201	Removal of Steel Supported Structural Slabs (with shear connectors) – Type A	Square Foot
202.2202	Removal of Steel Supported Structural Slabs (with shear connectors) – Type B	Square Foot
202.2301	Removal of Steel Supported Structural Slabs (without shear connectors) – Type A	Square Foot
202.2302	Removal of Steel Supported Structural Slabs (without shear connectors) – Type B	Square Foot
202.24	Removal of Concrete Superstructure Supported Concrete Slabs (with shear connectors)	Square Foot
202.25	Removal of Concrete Superstructure Supported Concrete Slabs (without shear connectors)	Square Foot

NOTE: nnnn denotes serialized pay item for each building or structure.

SECTION 203 - EXCAVATION AND EMBANKMENT

(Last Revised January 2020)

203-1 DESCRIPTION. This work shall consist of excavation, disposal, placement and compaction of all materials that are not provided for under another section of these Specifications, and shall be executed in conformance with payment lines, grades, thicknesses and typical sections specified in the contract documents.

203-1.01 Definitions.

A. Unclassified Excavation. Unclassified excavation shall consist of the excavation and disposal of all materials, of any description, encountered in the course of construction, unless otherwise specified in the contract. Estimated limits and descriptions of subsurface deposits and formations which may be shown in the contract documents are supplied as a part of Base Line Data.

B. Embankment. The embankment is the portion of a fill section situated between the embankment foundation and the subgrade surface, excluding any material placed under another section of these specifications.

C. Embankment Foundation. The embankment foundation is the surface upon which an embankment is constructed after all work required under §203-3.03A. *Embankment Foundation* has been completed.

D. Subgrade Surface. The subgrade surface is the surface of the road section upon which the select materials and/or subbase are placed.

E. Subgrade Area. The subgrade area is that portion of an embankment situated above either of the following, but excluding any material placed under another section of these specifications.

1. A line located 2 ft. below the subgrade surface and extended to the intersection with the embankment side slopes, or

2. The embankment foundation, whichever is higher.

The material and compaction requirements for the subgrade area in embankments are found in §203-2.01A. *Subgrade Area Material* and §203-3.03C. *Compaction*, respectively.

In cut sections, the subgrade area is not defined except where undercut and backfill with a select material item is specified or ordered: in such cases, the payment lines for undercut work shall define the subgrade area.

F. Embankment Side Slope Area. The embankment side slope areas are those cross-sectional areas of an embankment situated outside of lines projected downward and outward on a one on one slope from the edges of the subgrade surface to their intersection with the embankment foundation, but excluding any portion lying within a subgrade area.

G. Topsoil. See Section 713 *Topsoil*.

H. Suitable Material. A material whose composition is satisfactory for use in embankment construction is a suitable material. The moisture content of the material has no bearing upon such designation. In general, any mineral (inorganic) soil, blasted or broken rock and similar materials of natural or man made (i.e. recycled) origin, including mixtures thereof, are considered suitable materials. Contaminated material is not considered suitable. Determinations of whether a specific natural material is a suitable material shall be made by the Engineer on the above basis.

Recycled materials that the Department has evaluated and approved for general use shall be considered to be suitable material for embankment construction subject to the conditions for use as determined by the Department. The Regional Geotechnical Engineer and Geotechnical Engineering Bureau are available to provide guidance on the use of such materials. In general, the use of recycled materials must be also sanctioned by the Department of Environmental Conservation, usually in the form of a Beneficial Use Determination (BUD).

Glass from recycling facilities meeting the requirements of §733-05 *Glass Backfill* shall be considered suitable material for embankment construction.

Reclaimed Asphalt Pavement (RAP), and Recycled Portland Cement Concrete Aggregate (RCA) shall be considered suitable materials for embankment construction, subject to the following conditions for use:

RAP - The Contractor shall provide and place RAP conforming to the requirements of §733-06 *Reclaimed Asphalt Pavement for Earthwork and Subbase*.

RCA-The Contractor shall provide and place RCA conforming to the requirements of §733-07 *Recycled Portland Cement Concrete Aggregate*.

Pieces of broken up concrete pavement from on-site pavement removal or in-place recycling (i.e. rubblizing, crack and seat, break and seat, etc.) may be used in embankment construction. Refer to §203-3.03A. *Embankment Foundation* and §203-3.03B. *Embankments*.

I. Unsuitable Material. Any material containing vegetable or organic matter, such as muck, peat, organic silt, topsoil or sod, or other material that is not satisfactory for use in embankment construction under §203-1.01H. *Suitable Material* is designated as an unsuitable material. Certain man made deposits of industrial waste, toxic or contaminated materials, sludge, landfill or other material may also be determined to be unsuitable materials, based on an evaluation by the Department's Geotechnical Engineering Bureau and Office of Environment, and the Department of Environmental Conservation.

J. Borrow. Borrow is material required for earthwork construction in excess of the quantity of suitable material available from the required grading, cuts and excavations. Borrow may be necessary even though not shown in the contract documents.

K. Embankment Construction Control Devices. Embankment construction control devices allow real-time observations of embankment construction to assess the actual performance of the embankment compared to that envisioned in the design phase. Settlement and pore water pressure are common measures of embankment performance. Techniques for monitoring settlement include a settlement rod or a surface settlement gauge. A settlement rod is an optical survey technique to monitor settlement of the embankment surface. The settlement rod(s) establish monitoring point(s) in relation to a reliable bench mark.

A surface settlement gauge is an optical survey technique to monitor settlement of the existing ground surface, below the embankment installation. The surface settlement gauge is installed prior to placing the embankment and extended upwards through the fill.

Pore water pressure monitoring may be used to determine the effective overburden diagrams (the basis of all geotechnical analyses), monitoring consolidation progress of embankments constructed over soft soils, evaluating seepage in natural slopes or earth dams (slope stability), checking the effectiveness of subsurface drainage facilities, or monitoring water well tests.

A piezometer is an instrument which provides measurements of pore water pressure at the elevation of the installed sensor. Pore pressure data is needed in a foundation soil to assess the excess pore water pressure and hence the undrained strength of the soil. Piezometers are used at various depths within cohesive foundation soils. Some piezometers are used in granular foundation soils to assess their drainage behavior.

L. Proof Rolling. Proof rolling consists of applying test loads over the subgrade surface by means of a heavy pneumatic-tired roller of specified design, to locate and permit timely correction of deficiencies likely to adversely affect performance of the pavement structure.

M. Select Granular Fill – Slope Protection. Select granular fill – slope protection is a material used to protect the grade of a slope from erosion and sloughing from runoff and groundwater seepage. Seepage is the slow movement of water through small openings and spaces in the surface of unsaturated soil into or out of a body of surface or subsurface water. Sloughing is a shallow surface failure caused by erosive removal of supporting material.

Select granular fill – slope protection is highly permeable while also providing sufficient frictional resistance to resist seepage forces and remain in place.

N. Applying Water. Under this work, the Contractor shall furnish and apply water for dust control. Moisture control for compaction purposes is the Contractor’s responsibility. Water shall not be applied in inclement weather or when the temperature is 32° F or less.

O. Modifying Cut Slopes and Other Means of Obtaining Borrow. The Regional Director may approve the modification of cut slopes and other means of obtaining material, which is not part of the contract, so long as provisions are made to prevent unsafe conditions, damage, and nuisances to property, wildlife areas, and haul routes within and outside the contract limits. Such approval may be granted only after review of a written proposal by the Contractor showing the final deposition of the material, the haul route, hauling hours, and provisions necessary to comply with the above. Should unanticipated conditions arise resulting in any unsatisfactory situation, the Engineer shall immediately rescind the approval pending satisfactory correction.

The following procedure shall apply to areas within the R.O.W. limits which are not designated as available sources of borrow by a Special Note in the contract proposal where the Contractor requests and is granted permission to modify slopes to obtain material for use on State contract work only. The Contractor will be required to reimburse the State with a rebate for the material obtained in these areas. Permission will not be granted to excavate material beyond the design slopes if it is to be used on other than State contract work.

The rebate to be obtained from the Contractor for this material is comprised of 1) A royalty based on the actual value of the excavated material, and 2) A credit for the difference in the Contractor's handling costs if these handling costs have been reduced. The royalty which is to be obtained for the excavated material shall be appropriate for the item for which it is to be utilized and shall be comparable to the current price being paid to purchase similar material in the area.

If the Contractor's handling costs associated with obtaining material from within the R.O.W. limits are greater than those for obtaining material from other acceptable sources, these additional handling costs must be borne by the Contractor. The royalty shall not be reduced to offset any increased handling costs incurred by the Contractor.

If the Contractor's handling costs associated with obtaining materials from within the R.O.W. limits are less than those for obtaining material from other acceptable sources, the differences shall be reimbursed to the State as a credit in addition to the royalty.

The difference in the Contractor's handling cost shall be determined by an analysis based on a comparison of haul lengths, hauling equipment, hauling operation, use of haul roads or public highways, preparation and restoration of the borrow areas, and any other variables involved.

Prior to modifying rock cut slopes, the Geotechnical Engineering Bureau must be consulted. If rock cut slopes are flattened sufficiently to eliminate the need for presplitting, an additional rebate will be necessary.

All special requirements to be fulfilled by the Contractor, at the Contractor's own expense, shall be clearly stated in the agreement. The foregoing requirement of receiving a rebate from the Contractor for material obtained by modification of slopes shall apply only to locations not designated in the Contract Documents.

P. Winter Earthwork. Compaction of soil during cold weather is difficult and can be impractical. Water acts as a lubricant aiding in the process of compaction. As the temperature decreases, the water becomes more viscous (less slippery) and inhibits efforts to pack the soil particles together. Eventually, the water becomes ice, at which point compaction is impossible. For this reason, New York State does not permit normal earthwork placement between November 1st thru April 1st unless there is an approved Winter Earthwork submittal.

Winter Earthwork is defined as construction operations requiring soil compaction performed from November 1st thru April 1st. The execution of Winter Earthwork requires modifications to compaction procedures, changes to material requirements, and/or additional equipment and structure assembly for controlling the weather effects on the material and existing ground conditions.

Although Winter Earthwork may be performed when the air temperature, ground temperature, or material temperature is at or below 32° F, frozen material will not be placed, nor will fill material be placed on ground frozen to any depth, in any work incorporated into the final product

203-2 MATERIALS

203-2.01 General. The requirements for select materials and subgrade area materials are described below. All processing operations including washing, removal of oversize material, blending, or crushing shall be completed at the source of the material. The procedure for acceptance or rejection of these materials shall be in conformance with the procedures contained in the geotechnical control procedure "*Procedure for the Control and Quality Assurance of Granular Materials*".

A. Subgrade Area Material. Subgrade area material shall consist of any suitable material having no particles greater than 6 in. in maximum dimension, unless Select Granular Subgrade with the well graded rock option is used. In that case, refer to §733-13 *Select Granular Subgrade*. If concrete is used, any exposed mesh or rebar shall not exceed 1 in. in length. RAP is also permitted.

B. Glass Backfill. Provide backfill material meeting the requirements of §733-05 *Glass Backfill.*

C. RAP. Provide backfill material meeting the requirements of §733-06 *Reclaimed Asphalt Pavement for Earthwork and Subbase.*

D. RCA. Provide backfill material meeting the requirements of §733-07 *Recycled Portland Cement Concrete Aggregate*.

E. Miscellaneous. Necessary fill material for cleaning, grading and shaping the existing roadside section shall conform to the requirements of §203-2.01A, *Subgrade Area Material*.

203-2.02 Unclassified Excavation and Disposal. None Specified.

203-2.03 Embankment In Place. Provide backfill material meeting the requirements of §733-08 *Embankment In Place*.

1. Embankment In Place – Winter Earthwork. If modified methods and procedures are not outlined in the Winter Earthwork Submittal, provide backfill material meeting the requirements of §733-16 *Winter Earthwork Material for Embankment In Place*.

203-2.04 Select Borrow. Provide backfill material meeting the requirements of §733-09 *Select Borrow*.

1. Select Borrow – Winter Earthwork. If modified methods and procedures are not outlined in the Winter Earthwork Submittal, provide backfill material meeting the requirements of §733-16 *Winter Earthwork Material for Select Borrow*.

203-2.05 Select Fill. Provide backfill material meeting the requirements of §733-10 *Select Fill*.

1. Select Fill – Winter Earthwork. If modified methods and procedures are not outlined in the Winter Earthwork Submittal, provide backfill material meeting the requirements of §733-16 *Winter Earthwork Material for Select Fill*.

203-2.06 Select Granular Fill. Provide backfill material meeting the requirements of §733-11 *Select Granular Fill*.

1. Select Granular Fill – Winter Earthwork. If modified methods and procedures are not outlined in the Winter Earthwork Submittal, provide backfill material meeting the requirements of §733-16 *Winter Earthwork Material for Select Granular Fill*.

203-2.07 Select Granular Fill Slope Protection. Provide backfill material meeting the requirements of §733-12 *Select Granular Fill Slope Protection*.

1. Select Granular Fill Slope Protection – Winter Earthwork. If modified methods and procedures are not outlined in the Winter Earthwork Submittal, provide backfill material meeting the requirements of §733-16 *Winter Earthwork Material for Select Granular Fill Slope Protection*.

203-2.08 Surface Settlement Gauges. Provide materials for the embankment construction control device surface settlement gauge meeting the requirements of §733-17 *Surface Settlement Gauge*.

203-2.09 Settlement Rods. Provide materials for the embankment construction control device settlement rod meeting the requirements of §733-18 *Settlement Rod*.

203-2.10 Piezometers. Provide materials for the piezometer installation meeting the requirements of §732-11 *Open Well Piezometer*.

203-2.11 Applying Water. Water used for dust control purposes may be obtained from any source.

203-2.12 Select Granular Subgrade. Provide backfill material meeting the requirements of §733-13 *Select Granular Subgrade*.

1. ***Select Granular Subgrade – Winter Earthwork.*** If modified methods and procedures are not outlined in the Winter Earthwork Submittal, provide backfill material meeting the requirements of §733-16 *Winter Earthwork Material for Select Granular Subgrade*.

203-2.13 Select Structural Fill. Provide backfill material meeting the requirements of §733-14 *Select Structural Fill*.

1. ***Select Structural Fill – Winter Earthwork.*** If modified methods and procedures are not outlined in the Winter Earthwork Submittal, provide backfill material meeting the requirements of §733-16 *Winter Earthwork Material for Select Structural Fill*.

203-2.14 Sand Backfill. Provide backfill material meeting the requirements of §733-15 *Sand Backfill.*

203-3 CONSTRUCTION DETAILS

203-3.01 General. The Contractor shall remove all soil, rock, and other material, and utilize or dispose of these materials as required by the contract documents. All excavation and embankment work shall be executed to payment lines shown in the contract documents.

All graded earth surfaces outside the roadway limits shall be smoothed and trimmed in reasonably close conformity (6± in.) of true grade. After trimming, the area shall be left in a compact and satisfactory condition, free of large stones or other objectionable materials, as determined by the Engineer.

Earthwork construction operations requiring compaction shall not be performed from November 1st thru April 1st except with a Winter Earthwork submittal subject to the provision of this Section and approved by the Regional Director or his designated representative. Winter earthwork operations constitute an additional risk to the Department and Winter Earthwork submittals should not be expected to be automatically approved. Winter Earthwork will be subject to the following restrictions:

- Transitioning from the normal construction season to the exempt winter earthwork months between November 1st and April 1st, the use of standard earthwork materials may be permitted only under the conditions where the air temperature, ground temperature and material temperature are all above 32° F at the time of placement. Modifications to compaction procedures, including but not limited to the use of thinner lifts, may be required when the temperatures are above 32° F but below 40° F at the time of placement.
- Between November 1st and April 1st, if the air temperature, ground temperature, or material temperature is at or below 32° F, earthwork may only proceed using material that meets the requirements of §733-16 *Winter Earthwork* and/or standard earthwork material placement utilizing the modified methods and procedures contained in the approved Winter Earthwork Submittal.

In all work incorporated into the final product, the Contractor shall not place material that is frozen, or place fill material on ground that is frozen to any depth regardless of the date.

A. Winter Earthwork Submittal. For Contractors choosing to proceed with earthwork construction operations requiring compaction between November 1st thru April 1st, provide the Engineer with a Winter Earthwork submittal, with a copy to the Regional Geotechnical Engineer, outlining the modifications to the materials and/or methods including the following:

1. Material Requirements. The material meets the requirements of §733-16 *Winter Earthwork.* Provide information on material composition and source substitute, if proposed.

2. Material Placement. Provide information on the proposed methods for controlling the weather effects on the material and existing ground conditions (i.e. insulation, enclosures, canvas and framework). Devise a plan to be outlined in the Winter Earthwork Submittal such that all snow, ice, and frozen material shall be removed from the surface of the ground on which embankment or backfill material is to be placed, and from the surface under construction before succeeding lifts are added.

3. Procedures. Provide verification procedures to ensure the existing ground is not frozen to any depth (e.g. test pits). Provide procedures to address freeze-thaw action in earthwork that has remained idle during temperature fluctuations (e.g. re-roll and seal the surface prior to placement of succeeding lift).

4. Seasonal Adjustment Acceptance. Provide acknowledgement of a transition period allowing the continued use of standard earthwork materials between November 1st and April 1st only under conditions where the air temperature, ground temperature and material temperature are all above 32° F at the time of placement. Provide acknowledgement of the winter earthwork restrictions stating that, if the air temperature, ground temperature, or material temperature is at or below 32° F, earthwork will only proceed using material that meets the requirements of §733-16 *Winter Earthwork* and/or standard earthwork material placement utilizing the modified methods and procedures contained in the approved Winter Earthwork Submittal.

Proceed with Winter Earthwork only after receiving written approval by the Regional Director or his designated representative subject to the provisions of this Section.

B. Scheduling of Work to Minimize Soil Erosion and Water Pollution. The Contractor shall ensure effective and continuous soil erosion and sediment control throughout the construction period. The Contractor shall prepare and submit for approval, plans and schedules for all excavation, stripping, embankment, fill and grading operations. Such plans and schedules shall include but are not limited to temporary and permanent erosion control measures specified in Section 209 *Soil Erosion and Sediment Control*, Section 610 *Turf and Wildflower Establishment* and Section 612 *Sodding*.

C. Drainage and Grading. The Contractor shall provide and maintain slopes, crowns and ditches on all excavation and embankments to ensure satisfactory surface drainage at all times. Ditches and other drainage facilities necessary to remove ponded water shall be constructed as soon as practical to have the work area dry during the progression of work. All existing culverts and drainage systems shall be maintained in satisfactory operating condition throughout the course of the work. If it is necessary to interrupt existing surface drainage, sewers or under-drainage, then temporary drainage facilities shall be provided until the permanent drainage work is complete. Top-of-slope interceptor ditches, where shown on the contract documents, shall be completed before adjacent excavation operations are begun. In earth cuts, the Contractor shall progress excavation operations in such a manner that the portion of the cut immediately adjacent to the design slope is at least 5 ft. lower than the general level of the cut at all times until the lower payment line is reached.

The construction of these temporary drainage facilities shall be considered as incidental to the construction of the project and no additional payment will be allowed.

Any portion of an embankment or subgrade which has been damaged by the Contractor's equipment during the course of construction, shall be repaired and re-compacted by the Contractor at no additional cost to the State.

Where seepage causes instability of slopes, excavation and backfill or other corrective measures shall be performed as ordered by the Engineer and paid for under the appropriate item. Excavation for the installation of slope protection may be necessary at any time and location throughout the duration of the contract and may not necessarily coincide with the Contractor's performance of the general excavation work.

D. Suitable Materials. Moisture content has no bearing on the suitability of material to be used for embankment construction, however, the moisture content of a material may be such that its use will require manipulation. It is the Contractor's responsibility to determine the economics of using, or disposing of and replacing, such materials. Material determined by the Contractor to be uneconomical for use may be disposed of as specified under §203-3.02B. *Disposal of Surplus Excavated Materials* and replaced with other material at no additional cost to the State.

When a contract includes the item “Unclassified Excavation and Disposal”, all excavated suitable materials, including the excavation performed under “Structure Excavation” and “Trench and Culvert Excavation,” shall become the Contractor's property for disposal or use under another item of these specifications.

E. Unsuitable Materials. All excavated unsuitable materials shall be the Contractor's property for disposal as surplus materials under the provisions of §203-3.02B. *Disposal of Surplus Excavated Materials*.

F. Borrow. The management of a borrow source and the acceptability of all borrow material shall be subject to the approval of the Engineer at all times. The Contractor shall notify the Engineer at least ten (10) work days in advance of opening any borrow area, and request approval of the source under the pay item involved. Test pits required by the Engineer to evaluate the acceptability and limits of the source, shall be provided by the Contractor at the Contractor's own expense. Concurrent removal of material for more than one pay item from a single source or pit shall be prohibited except with the written permission of, and under such conditions and restrictions as may be imposed by the Engineer. All borrow pits shall be stripped of sod, topsoil and vegetable matter well in advance of any working face. The minimum distance by which stripping shall lead excavation for a given source shall be established by the Engineer to suit local conditions. Where a borrow source is not under direct control of the Contractor or where special conditions exist, the Engineer may waive any of the above requirements and establish alternative provisions for the control and acceptability of borrow.

Ordinary borrow will be accepted for use where the material qualifies under the definition of Suitable Material, §203-1.01H. *Suitable Material*. All borrow placed within the limits of Embankment or the Subgrade Area shall be placed in conformance with §203-3.03B. *Embankments* or §203-3.01G. *Subgrade Area* respectively, as appropriate, or where used for fill or backfill at structures, culverts and pipes, in conformance with §203-3.06 *Select Granular Fill* and §203-3.17 *Select Structural Fill.*

G. Subgrade Area. Where a subgrade area is defined in an embankment by §203-1.01E. *Subgrade Area*, the material placed shall conform to §203-2.01A. *Subgrade Area Material*, placed and compacted in conformance with §203-3.03B. *Embankments* and §203-3.03C. *Compaction*. Where longitudinal and transverse changes from cut to fill are encountered in the work, a subgrade transition section shall be provided in conformance with Standard Sheet *Earthwork Transition and Benching Details*. Where a subgrade area becomes defined by §203-1.01E. *Subgrade Area* in a cut section, the materials placed and other details shall be as specified under §203-3.02C. *Proof Rolling in Cut Sections* 3. *Procedure*, unless otherwise required by the contract documents. Prior to subbase course placement, the surface on which the subbase is to be placed shall be thoroughly compacted to the satisfaction of the Engineer.

1. Subgrade Surface Tolerance. After compaction, the subgrade surface shall not be above design elevation at any location.

203-3.02 Unclassified Excavation and Disposal.

A. Rock Excavation. Presplitting is required where the design rock slope is 1 vertical on 1 horizontal or steeper and the vertical height of the exposed rock slope exceeds 5 ft. Ripping will not be allowed within 10 ft. of a slope that requires presplitting. Test sections will be required at the outset of presplit drilling and blasting operations for the evaluation of the presplit rock slopes by a Departmental Engineering Geologist. The Contractor will be required to completely expose the presplit rock face in the test section for evaluation prior to any further presplit drilling.

All rock slopes shall be thoroughly scaled and cleaned. For rock excavations involving multiple lifts, scaling of upper lifts shall be completed prior to drilling and fragmenting of lower lifts. Scaled rock slopes shall be stable and free from possible hazards of falling rocks or rock slides that endanger public safety. If, after scaling, such conditions still exist, a determination of the cause will be made by a Departmental Engineering Geologist and if it is determined that the conditions are the result of poor quality work or improper methods employed by the Contractor, the Contractor shall provide approved remedial treatment, at no expense to the State. Such treatment may include, but is not necessarily limited to, laying back the slope, rock bolting, or shotcreting. In no case shall the subgrade be trimmed prior to the completion of the scaling operation at any location.

1. Presplitting. Prior to drilling presplitting holes, the overburden shall be completely removed to expose the rock surface along the presplitting line. The methods of collaring the holes to achieve required inclination and alignment shall be approved by the Engineer.

The presplitting holes shall be a maximum of 4 in. in diameter, spaced not more than 3 ft. center to center along the slope, and drilled at the designed slope inclination for a maximum slope distance of 60 ft. When excavation operations are conducted in multiple lifts, the presplitting holes for successive lifts may be offset a distance of not more than 3 ft. for a design slope of 1 vertical on 1 horizontal and not more than 1 ft. for slopes of steeper design; however, a presplitting hole shall not be started inside the payment line. The Contractor shall control the presplit drilling operations by using proper equipment and technique to achieve the design slope and maximum bench between lifts. If presplitting is conducted in lifts, each lift shall be of approximately equal depth. All presplitting holes shall be checked and cleared of obstructions immediately prior to loading any holes in a round. All presplitting holes shall be loaded with a continuous column charge manufactured especially for presplitting which contains not more than 0.35 lbs. of explosive per foot. The top of the charge shall be located not more than 3 ft. below the top of rock. A bottom charge of not more than 3 lbs. of packaged explosive may be used; however, no portion of any bottom charge shall be placed against a proposed finished slope. Each presplitting hole shall be filled with No. 1A crushed stone stemming meeting the gradation requirements of §703-02 *Coarse Aggregate*. The presplitting charges shall be fired with detonating cord extending the full depth of each hole and attached to a trunk line at the surface. Detonation of the trunk line shall be with blasting cap(s) and shall precede the detonation of fragmentation charges within the section by a minimum of 25 milliseconds. Presplitting shall extend for a minimum distance equal to the burden plus 3 ft. beyond the limits of fragmentation blasting within the section.

2. Fragmentation Blasting. Fragmentation holes, or portions thereof, shall not be drilled closer than 4 ft. to the proposed finished slope. Where presplitting is required, fragmentation holes adjacent to the presplitting holes shall be drilled parallel to the presplitting holes for the full depth of the production lift at a spacing not exceeding the spacing of the production pattern. Only packaged explosives shall be used 10 ft. or less from a design slope which requires presplitting regardless of the construction sequence.

Fragmentation charges shall be detonated by properly sequenced millisecond delay blasting caps.

3. Explosive Loading Limits. In the absence of more stringent requirements, the maximum quantity of explosives allowed per delay period shall be based on a maximum particle velocity of 2 in./s at the nearest structure to be protected. In the absence of seismic monitoring equipment, the following explosive loading limits shall apply:

DISTANCE EQUAL TO OR LESS THAN 212 ft. FROM THE NEAREST STRUCTURE

a. When the distance from the proposed blasting area to the nearest structure to be protected is 6 ft. or less, no blasting shall be allowed.
b. When the distance between the blasting area and the nearest structure to be protected is greater than 6 ft. and equal to or less than 15 ft., a maximum of ¼ lb. of explosives per delay period (minimum of 25 milliseconds) blasting cap shall be allowed.
c. When the distance between the blasting area and the nearest structure to be protected is greater than 15 ft. and equal to or less than 212 ft., a Scaled Distance of 30 ft. shall be utilized to determine the maximum amount of explosive allowed per delay period (minimum of 25 milliseconds) blasting cap. The Scaled Distance Formula is as described below:

$$SD = \frac{D}{\sqrt{E_{\max}}}$$

where: $SD =$ Scaled Distance
$D =$ Distance from blasting area to nearest structure to be protected in feet

or

$$E_{\max} = \frac{D^2}{(SD)^2}$$

where: $E_{\max} =$ Maximum pounds of explosive per delay period (minimum of 25 milliseconds) blasting cap

DISTANCE GREATER THAN 212 ft. FROM THE NEAREST STRUCTURE

a. When the blaster elects to utilize more than 50 lbs. of explosive per delay period (minimum of 25 milliseconds) blasting cap, a seismograph shall be employed to monitor the blasting vibrations generated. The initial loading shall be computed using a Scaled Distance of 30 ft. The resulting particle velocity measured by the seismograph shall be evaluated by a

Department Engineering Geologist. The Geologist's evaluation shall be the basis for adjusting the Scaled Distance.

No separate payment shall be made for this work. The cost shall be included in the appropriate excavation item. The above requirements shall in no way relieve the Contractor of liability for any damage incurred as a result of the blasting operations.

B. Disposal of Surplus Excavated Materials. Only unsuitable materials, or that portion of suitable material excavated in excess of the quantity required to construct all embankments on the project, shall be considered as surplus.

Where disposal of surplus materials cannot be accommodated within the right of way, the excess shall become the Contractor's property for disposal. Surplus material disposed of within the right-of-way shall be placed in accordance with §107-10 *Managing Surplus Material And Waste*.

C. Proof Rolling in Cut Sections. Immediately prior to final trimming of the subgrade surface and placement of subbase materials in cut sections, all areas of the subgrade surface within roadway limits shall be proof rolled according to the requirements of this subsection. This work, and any delays due to this work, shall be considered incidental to the excavation item.

1. Purpose. In cut sections, the purpose of proof rolling is to determine the location and extent of areas below the subgrade surface that require corrective undercutting and are not so specified in the contract documents.

2. Equipment. The proof roller used in embankment sections, as specified in §203-3.03D. *Proof Rolling in Embankment Sections* 1. *Equipment*, shall be employed for proof rolling in cut sections except that the roller shall be loaded to achieve a single stress level in operation, using a gross ballasted weight of 30 tons and all tires inflated to 40 psi.

3. Procedure. Two complete passes shall be applied over all elements of the area to be proof rolled. Where any portion of the cut subgrade surface other than that which has been damaged by the Contractor's operations fails to provide a satisfactory support for the proof rolling operation, the Engineer may order corrective undercut and backfill work performed. Backfill of undercuts shown in the contract documents or ordered by the Engineer shall be in conformance with §203.3-13 *Select Granular Subgrade*. Where natural soil below this course will not support the weight of the construction equipment, and when ordered by the Engineer, the course shall be placed in one lift. No additional proof rolling shall follow corrective work.

4. Exceptions. Proof rolling of the subgrade surface in cut sections will not be required in any area where the subgrade surface is in a rock cut, or where undercut and backfill has been previously performed. The Engineer may order undercutting and backfill without proof rolling of any cut where the need for corrective work, as determined by the Engineer, is obvious without actual proof rolling. The Engineer may also delete proof rolling in any cut section where, based upon a written evaluation by a Departmental Geotechnical Engineer, proof rolling would be detrimental to the work.

203-3.03 Embankment In Place.

A. Embankment Foundation. After completion of the work required under Section 201 *Clearing and Grubbing*, and Section 202 *Removal of Structures and Obstructions*, the embankment foundation shall be prepared. Sod and topsoil shall be removed where the final pavement grade is 6 ft. or less above the existing ground surface and in other areas designated in the contract documents or by the

Engineer. Prior to embankment construction and subbase course placement, the surface on which the embankment and/or subbase is to be placed shall be thoroughly compacted to the satisfaction of the Engineer. Unsuitable materials other than sod and topsoil shall be removed to the depths shown in the contract documents or as directed by the Engineer. Underwater areas shall be filled in accordance with §203-3.04 *Select Borrow* or §203-3.05 *Select Fill* and paid for under its appropriate item.

Where embankments are to be constructed over ground that will not adequately support embankment construction equipment, an initial layer of fill may be allowed to form a working platform. The need, manner of construction, and thickness of such a layer shall be subject to approval of the Engineer, and the layer will be permitted only where the lack of support is, as determined by the Engineer, not due to deficient ditching, grading or drainage practices or where the embankment could be constructed in the approved manner by the use of different equipment or procedures. Thicknesses of up to 3 ft. may be permitted for such a layer. Concrete or asphalt slabs may be used at the bottom of such a layer, provided they are placed horizontally.

In locations where embankments are to be constructed on hillsides or against existing embankments with slopes steeper than 1 vertical on 3 horizontal, the slopes shall be benched. Required benches shall be constructed as shown on the Standard Sheet *Earthwork Transition and Benching Details*.

Where old pavement is encountered within 2 ft. of the top of the subbase course, it shall be broken up or scarified.

B. Embankments. The embankment shall be constructed of suitable material as defined by §203-1.01H. *Suitable Material*. Embankment material shall not be placed on frozen earth, nor shall frozen soils be placed in any embankments. Embankment material shall be placed and spread in lifts (layers) of uniform thickness, then uniformly compacted as specified under applicable portions of §203-3.03C. *Compaction*. During embankment construction operations, earth moving equipment shall be routed so as to prevent damage to any compacted lift. Damage to any compacted lift at any time during the course of construction, such as rutting under the loads imposed by earth moving equipment, shall be fully repaired by the Contractor at his/her own expense prior to placement of any overlying materials. At the close of each day's work, the working surface shall be crowned, shaped and rolled with smooth steel wheel or pneumatic tired rollers, for positive drainage.

Particles with a dimension in excess of ⅔ of the loose lift thickness are designated as oversized particles. Oversized particles shall be removed prior to compaction of the lift and may be placed in the Embankment Side Slope Area.

Pieces of concrete or asphalt may be used provided that the voids between the pieces are completely filled, and the greatest dimension of any piece does not exceed ⅔ the loose lift thickness. Exposed mesh or rebar shall not exceed 1 in. in length.

Embankments constructed using rock products or pieces of concrete shall be spread by bladed equipment on each lift to minimize the formation of large voids as the work progresses. The top lift of a rock or concrete fill shall be chinked.

When permitted by a note in the contract documents, stumps, logs, and other materials may be placed in the Embankment Side Slope Area, provided that: 1) such matter is deposited and compacted concurrent with the adjacent embankment, and; 2) any stumps or woody material are covered by not less than 2 ft. of soil beneath the exposed side slope surface.

Glass shall not be placed in contact with synthetic liners, geogrids, geotextiles or other geosynthetics.

C. Compaction

1. General Requirements. It shall be the Contractor's responsibility to properly place and compact all materials in the road section and other locations specified in the contract documents, and to correct any deficiencies resulting from insufficient or improper compaction of such materials throughout the contract period. The Contractor shall determine the type, size and weight of compactor best suited to the work at hand, select and control the lift (layer) thickness, exert control over the moisture content of the material, and other details necessary to obtain satisfactory results. During the progression of the work, the Department will inspect the Contractor's operations and will permit the work to continue where:

a. Lift thickness is controlled and does not exceed the maximum allowed according to the equipment classifications in subparagraph 2. *Compaction Equipment*, of this subsection, and the equipment meets all specified class criteria. Thinner lifts and lighter equipment than the maximum allowed may be necessary for satisfactory results on some materials.

b. The compactive effort (number of passes and travel speed) is uniformly applied and not less than that specified for the given equipment class and lift thickness. Higher efforts than the minimum allowed may be necessary for satisfactory results on some materials.

c. The Engineer concludes from a visual observation that adequate compaction has been attained, with the exception of backfill at structures, culverts, pipes, conduits, and direct burial cables. However, the State reserves the right to perform density tests at any time. When tests are performed, the results shall indicate that not less than 90% of Standard Proctor Maximum Density is attained in any portion of an embankment, or 95% in a subgrade area, or as specified for other items with a percent maximum density requirement.

d. Significant rutting under the action of the compactor is not observed on the final passes on a lift.

Whenever the Contractor's operations do not conform to the above criteria, or requirements contained in other subparagraphs of this subsection, the Engineer will prohibit placement of an overlying lift until the Contractor takes effective corrective action.

As part of the Department’s Quality Assurance (QA) program, the Engineer or his representative may verify the adequacy of the compaction at any time through QA testing. When the Engineer determines that QA tests are necessary, the Contractor shall provide any assistance requested to facilitate such tests. Such assistance shall include but will not be limited to excavation and backfill of test pits and holes. This work shall be considered to be incidental construction.

Damage to any compacted lift at any time during the course of construction such as rutting under the loads imposed by earth moving equipment, shall be fully repaired by the Contractor at his/her own expense prior to placement of any overlying materials.

2. Compaction Equipment. The selection of compaction equipment is the Contractor's responsibility, but shall be subject to meeting the requirements of this subparagraph and approval by the Engineer with respect to its provisions. All compaction equipment shall be marked by a permanently attached manufacturer's identification plate designating the name of the manufacturer, model number and serial number of the machine as minimum identification. This plate shall be installed in a readily visible location. Compaction equipment lacking such an original manufacturer's identification plate, or with altered or illegible plates, will not be recognized as acceptable compaction equipment. Any equipment not principally manufactured for soil compaction purposes and equipment which is not in proper working order in all respects shall not be approved or used. The Engineer will also withhold approval of any compactor for which the Contractor cannot furnish manufacturer's specifications covering data not obvious from a visual inspection of the equipment and necessary to determine its classification.

The term, “pass,” for any type of compactor, shall denote one direct vertical application of compactor effort over all elemental areas of a lift surface. Terms in common parlance, such as “coverage,” “trips,” etc., have no significance, equivalence, or application under these specifications.

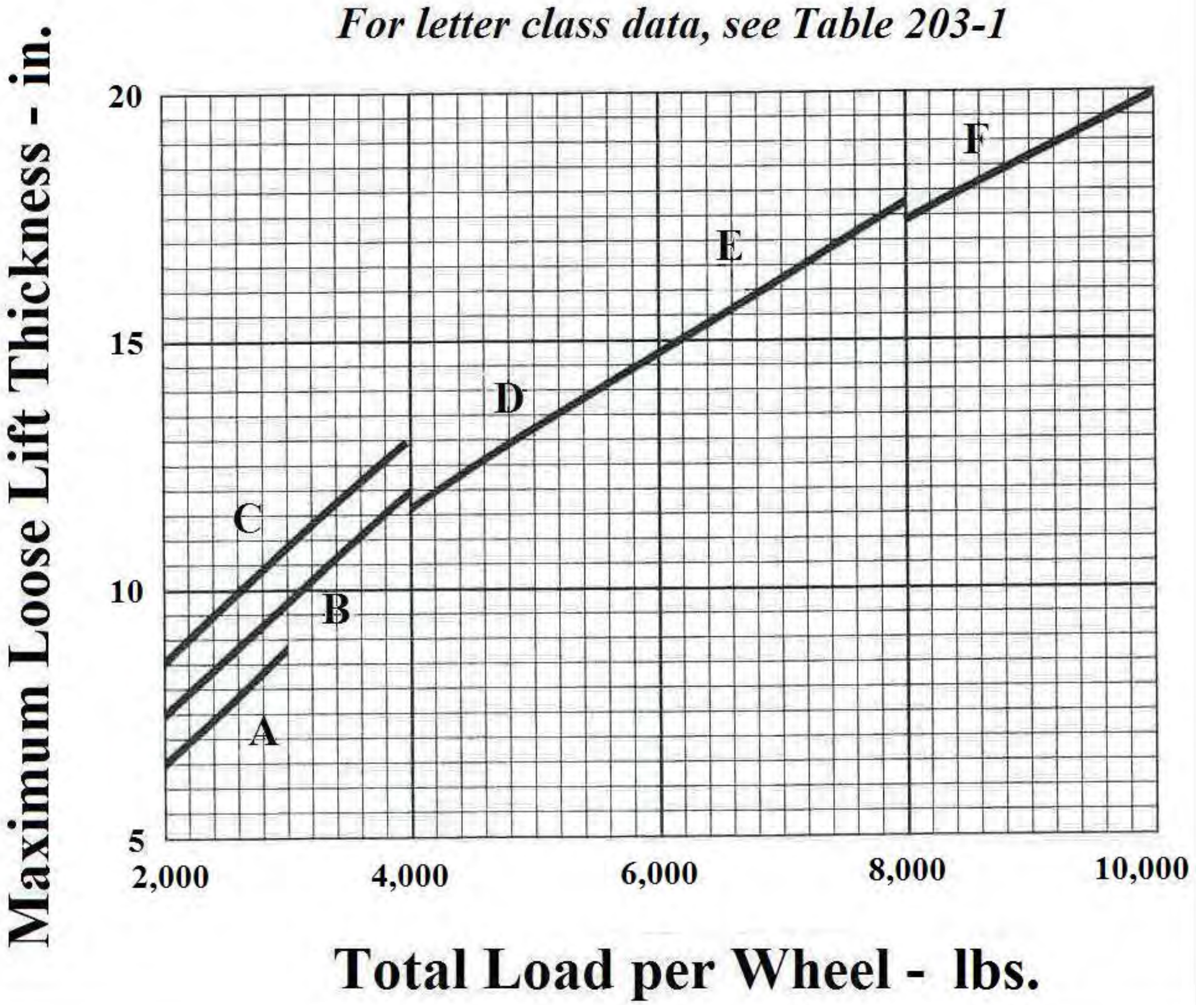
TABLE 203-1 PNEUMATIC-TIRED COMPACTOR CLASSIFICATIONS

Pneumatic Compactor Class	Tire Requirements			Range of Ballasted Wheel Loads (lbs. per Wheel)
	Tire Size	No. Plys	Inflation Pressure (psi)	
A	7.50 x 15	4	35	2,000 – 3,000
B	7.50 x 15	6	60*	2,000 – 4,000
		10	90*	
C	7.50 x 15	14	130*	2,000 – 4,000
D	9.00 x 20	10	75*	4,000 – 6,000
		12	90*	
E	11.00 x 20	12	90*	6,000 – 8,000
		18		
F	13.00 x 24	18	100*	8,000 – 10,000

* Inflation pressure for not less than the last two passes on each lift. May be reduced during earlier passes and gradually increased to this level.

a. Pneumatic-Tired Compactors. This type of compactor shall be classified for use according to the requirements of Table 203-1. For the lift thickness selected by the Contractor, the minimum class and wheel load which will be allowed on that lift thickness, shall be as shown in Figure 203-1.

FIGURE 203-1 PNEUMATIC-TIRED COMPACTORS



For letter class data, see Table 203-1

The minimum effort for all pneumatic compactors shall be 6 passes, at speeds up to 12 ft./sec on no more than the first 2 passes, and all subsequent passes at speeds of 6 ft./sec. or less.

b. Smooth Drum Vibratory Compactors. This type of compactor is defined as a machine which primarily develops its compactive effort from the vibrations created and is classified for use according to the developed compactive force rating (CFR) per linear inch of drum width.

The CFR is defined as follows:

$$\text{CFR} = \frac{\text{Unsprung Drum Weight (lbs.) + Dynamic Force (lbs.)}}{\text{Drum Width (in.)}}$$

The unsprung drum weight is the static weight of the drum and appurtenances without any reaction transmitted to the drum from the main chassis of the compactor. The dynamic force produced is dependent on the frequency of vibration, and therefore, CFR ratings shall be determined for the actual operating frequency of the compactor. Approval for vibratory compactors shall be confined, however, to equipment operating at not less than 1100 vpm, nor more than 1500 vpm, and those where the actual dynamic force at the actual operating frequency is at least 2.5 times the unsprung drum weight.

Conversion of manufacturer's published ratings, at a given frequency, shall be made with the following equation:

$$F_2 = \frac{F_1(V_2)^2}{(V_1)^2}$$

where: F_1 = Dynamic Force at Rated Frequency

F_2 = Dynamic Force at Operating Frequency

V_1 = Rated Frequency

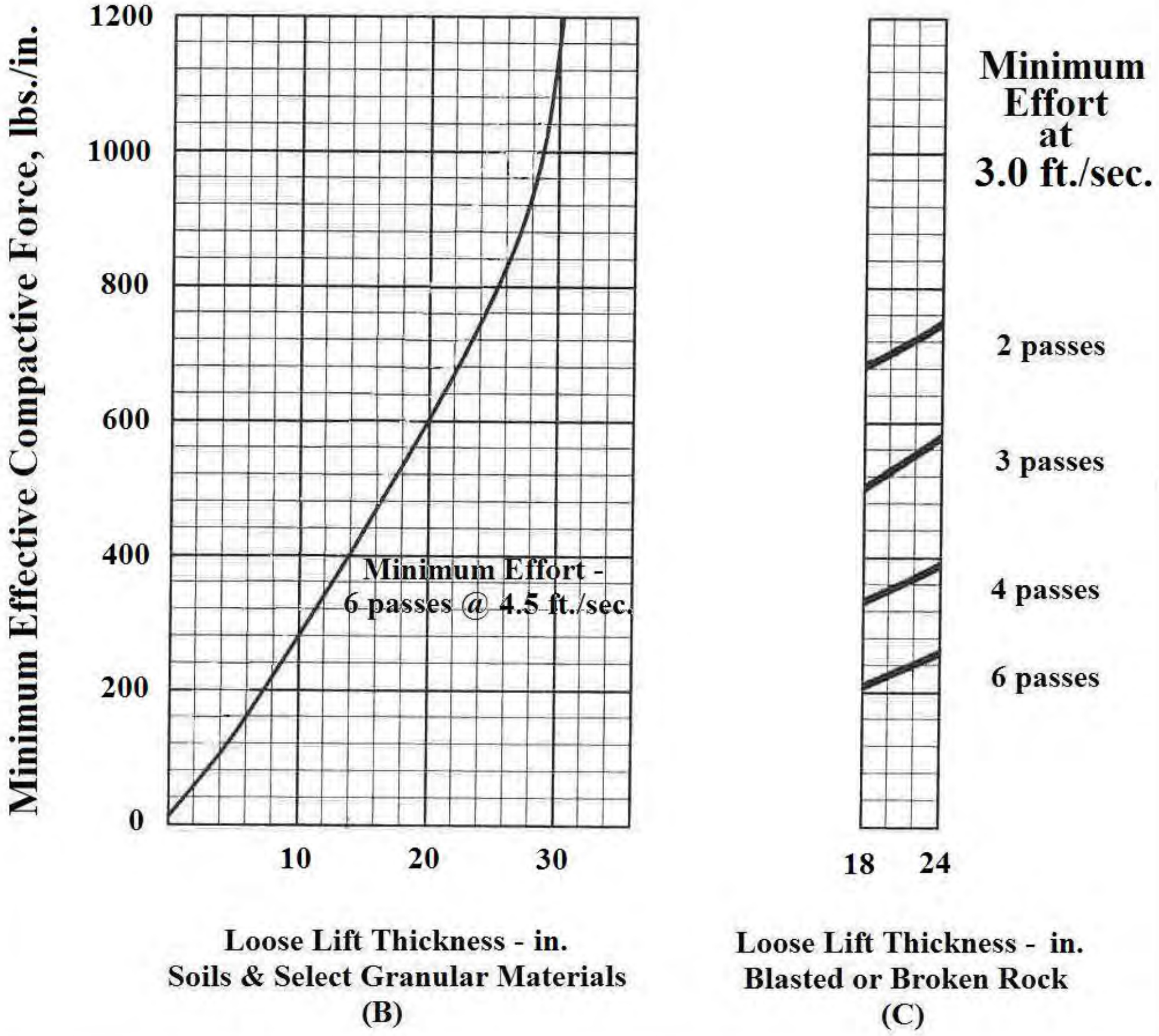
V_2 = Operating Frequency

For the lift thickness selected by the Contractor, the minimum CFR rating and minimum effort on such a lift, shall be as shown in Figures 203-2B&C, respectively. Non-Centrifugal (Vertical force only) types of vibratory compactors shall be approved as above, less 175 lbs./in. before using Figures 203-2 B&C as a minimum number of passes at a single specified speed. An equivalent effort, relating varying numbers of passes to other speeds is given by the equation:

$$\textbf{Speed X} = \frac{\textbf{(Specified Speed) (Min. Passes at Speed X)}}{\textbf{(Specified Min. Passes)}}$$

The Contractor may choose to alter the specified minimum pass requirement, provided that speed is adjusted to the value given by this equation and does not exceed 6 ft./sec.

FIGURE 203-2 VIBRATORY COMPACTORS



Where vibratory compactors are used on a project, the Contractor shall furnish for the exclusive use of the Engineer, one vibrating reed tachometer per project, plus one additional tachometer for each group of two vibratory compactors in excess of two per project. Tachometers shall have a frequency range adequate to cover operating frequencies of all vibratory compactors used on the project and shall have scale divisions of 50 vpm or less. Tachometers may be placed on the ground surface near the compactor when making readings, or with suitable damping materials interposed, placed directly on the compactor drum frame.

The dispensations permitted under this specification for vibratory compactors are contingent upon proper operation of the equipment at all times during compaction operations. In any instance where the Engineer encounters any problems with operators rolling without vibration, for any reason, and immediate and effective corrective action is not taken by the Contractor, the Engineer will halt the work until the problem is resolved. If continuing problems of this nature occur, the Engineer may suspend all provisions of this subparagraph and consider the vibratory compactors as smooth steel wheel rollers classified according to their gross weight.

c. Sheepsfoot and Segmented Pad Foot Rollers. This type of compactor shall be defined as a machine which is primarily designed to compact a lift from the bottom to the top.

The maximum loose layer thickness of the material to be compacted shall be equal to the length of the feet plus 15%. The end area size and configuration of the feet shall be selected by the Contractor to suit the characteristics of soil being compacted.

Where sheepsfoot and segmented pad foot rollers are used, with or without vibration, the number of passes required for job control shall be determined by a jobsite test in which the feet penetrate into the loose lifts and, with further passes, eventually and substantially “walk out” of the layer. This job control shall then be established for that machine, lift thickness and material, provided that adequate moisture control is continuously maintained per §203-3.03C. *Compaction* 3. *Moisture Control*. Sheepsfoot and segmented pad foot rollers shall be operated at speeds not exceeding 6 ft./sec., when towed and 15 ft./sec. when self-propelled.

d. Smooth Steel Wheel Rollers. Smooth steel wheel rollers shall be considered as primary compactors on layers whose maximum thickness, after compaction, is 8 in. When so used, the roller shall have a nominal gross weight of not less than 10 tons, exert a minimum force of not less than 300 lbs/in. of width on the compression roll faces, and a minimum of 8 passes shall be applied over each lift with the roller operating at a speed not exceeding 6 ft./sec.

When the Contractor employs smooth steel wheel rollers exclusively for surface compaction, leveling or finishing operations on lifts previously compacted by other types of primary compactors, the above restrictions shall not apply.

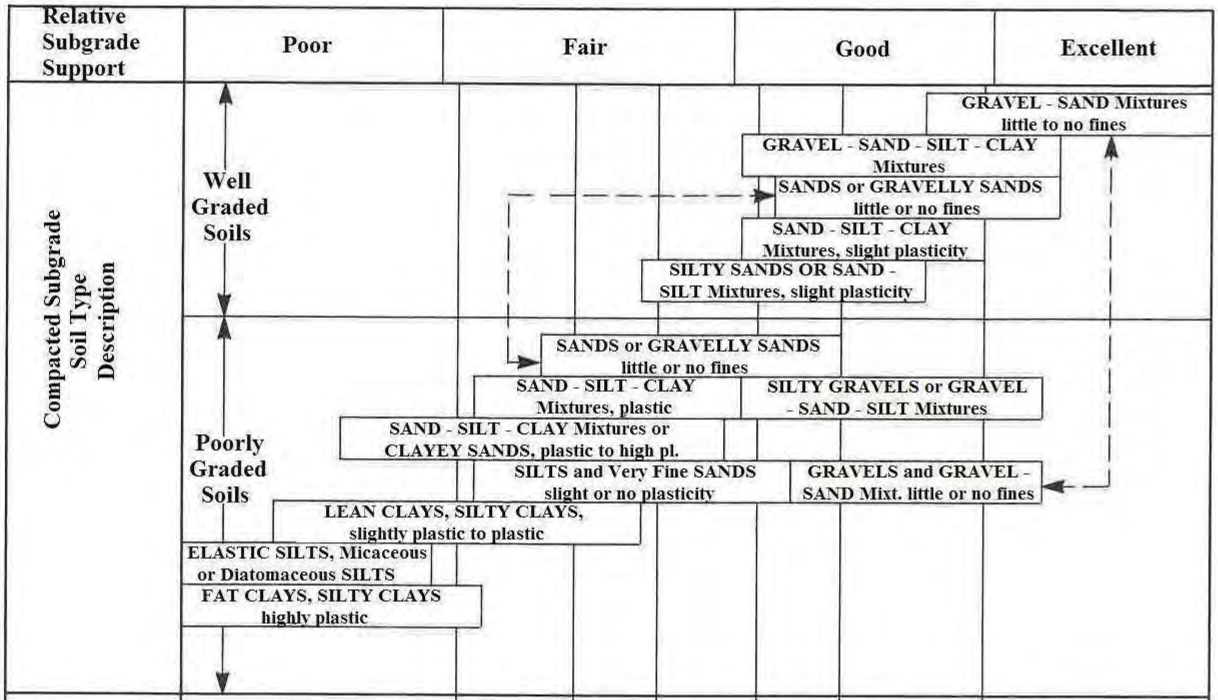
This section applies to non-vibratory rollers or vibratory rollers operated in the static mode only.

e. Other Type of Compactors. Compactor types other than those classified above, may be employed by the Contractor, subject to approval by the Engineer of the proposed minimum applied effort (minimum number of passes and travel speed) and maximum lift thickness. Such approval by the Engineer will be based upon the results of appropriate on-site field tests.

f. Compaction Equipment for Confined Areas. In areas inaccessible to conventional compactors, or where maneuvering space is limited, impactor rammers, plate or small drum vibrators, or pneumatic buttonhead compaction equipment may be used with layer thickness not exceeding 6 in. before compaction. Hand tampers shall not be permitted. The Engineer may approve or reject any of the above described mechanical devices based upon the results of appropriate on-site field tests.

3. Moisture Control. All fill or backfill material to be compacted, shall be at a moisture content for adequate compaction of that material using the compactor selected by the Contractor to perform the work. The Contractor shall be responsible for determining the appropriate moisture content, and for controlling it within the proper limits as the work is progressed. When water must be added to a material, it may be added on the lift or in the excavation or borrow pit. Water added on the lift, however, shall be applied by use of an approved pressure distributor. Distributors must be approved and documented by the Engineer. Documentation by the Engineer shall be adequate evidence of approval. Water added shall be thoroughly incorporated into the soil, and the soil shall be manipulated to attain uniform moisture distribution. When the moisture content of a lift about to be compacted exceeds the required amount, compaction shall be deferred until the layer has dried back to the required amount. Natural drying may be accelerated by blending in a dry material or manipulation alone, to increase the rate of evaporation. Increased loose lift thickness caused by blending in a dry material, however, may necessitate a change in compaction equipment and/or methods to meet the minimum provisions of subparagraph 2. *Compaction Equipment* of this subsection.

FIGURE 203-3 GUIDE FOR SELECTING THE INITIAL STRESS LEVEL FOR PROOF ROLLING EMBANKMENT SECTIONS



Stress Level	Minimum	1	2	3	4	5	Maximum
Gross Tons	30	34	38	42	46	50	50
Tire psi	40	50	60	70	80	90	130

D. Proof Rolling in Embankment Sections. Immediately prior to final trimming of the subgrade surface and placement of subbase materials in embankment sections, all areas of the subgrade surface within roadway limits shall be proof rolled according to the requirements of this subsection. This work, and any delays due to this work, shall be considered incidental to the embankment item.

1. Equipment. The proof roller shall consist of a chariot type rigid steel frame with a box body suitable for ballast loading up to 50 tons gross weight, and mounted on four pneumatic tired wheels acting in a single line across the width of the roller on its transverse load center line. The wheels shall be equipped with 18.00 x 24 or 18.00 x 25, 24 ply tires, and shall be suspended on articulated axles such that all wheels carry approximately equal loads when operating over uneven surfaces.

2. Determination of Roller Stress. Initially, the gross ballasted weight and tire inflation pressure of the proof roller shall be adjusted to the highest stress level shown in Figure 203-3 based on:

a. The general description of the subgrade soils.

b. The estimation of the relative subgrade support within the subgrade soil description range.

The initial roller stress for embankments constructed of rock shall be the maximum level listed in Figure 203-3 (50 Gross Tons, 130 Tire psi).

The roller shall be operated briefly to establish the acceptability of the initial stress level. Proof rolling of the embankment shall be performed at the next lower stress level whenever operation of the roller at a higher stress level is accompanied by consistent lateral displacement of soil out of the wheel paths.

3. Procedure. After an acceptable stress level is established, two complete passes of the roller shall be applied over all elements of the area to be proof rolled. Any deficiencies disclosed during the proof rolling operation shall be corrected. Subsidence depressions shall be filled with material similar to the subgrade soil and then compacted in a normal manner. After compaction, these areas shall be proof rolled again. Corrective work shall be judged complete and accepted by the Engineer when all elements of the subgrade surface over a given embankment show a satisfactory uniform response to the proof roller.

4. Exceptions. Proof rolling of the subgrade surface in embankment sections will not be required in any area where:

a. Due to restrictions in available access and/or maneuvering space, use of the proof roller may damage adjacent work;

b. The proof roller will approach a culvert, pipe or other conduit closer than 5 ft. in any direction.

203-3.04 Select Borrow. The management of a select borrow source and the acceptability of all select borrow material shall be in conformance with §203-3.01F. *Borrow*.

Underwater areas shall be filled with select borrow to 2 ft. above the water surface at the time of placement and in conformance with the details shown on the appropriate Standard Sheet or as noted in the contract documents.

All select borrow placed within the limits of Embankment or the Subgrade Area shall be placed in conformance with §203-3.03B. *Embankments* or §203-3.01G. *Subgrade Area* respectively, as appropriate, or where used for fill or backfill at structures, culverts and pipes, in conformance with §203-3.06 *Select Granular Fill* and §203-3.17 *Select Structural Fill.*

203-3.05 Select Fill. Underwater areas shall be filled with select fill to 2 ft. above the water surface at the time of placement and in conformance with the details shown on the appropriate Standard Sheet or as noted in the contract documents.

All select fill placed within the limits of Embankment or the Subgrade Area shall be placed in conformance with §203-3.03B. *Embankments* or §203-3.01G. *Subgrade Area* respectively, as appropriate, or where used for fill or backfill at structures, culverts and pipes, in conformance with §203-3.06 *Select Granular Fill* and §203-3.17 *Select Structural Fill.*

203-3.06 Select Granular Fill. The type of material to be used in bedding, filling and backfill at culverts, pipes, conduit and direct burial cable shall be in conformance with the details shown on the appropriate Standard Sheet or as noted in the contract documents. Do not use RAP. Do not use slabs or pieces of either concrete or asphalt.

Fill or backfill material at culverts and pipes shall be deposited in horizontal layers not exceeding 6 in. in thickness prior to compaction. Compaction of each layer shall be as specified under §203-3.03C. *Compaction*. A minimum of 95% of Standard Proctor Maximum Density will be required. When placing fill or backfill around culverts and pipes, layers shall be deposited to progressively bury the pipe or culvert to equal depths on both sides. The limits to which this subsection will apply shall be in accordance with the Standard Sheets or as modified in the contract documents.

Fill or backfill for conduit or cable placed in a trench shall be carefully placed in a horizontal layer to a depth of 6 in. over the top of the conduit or cable. This layer of material shall not be compacted, however, the remaining portion of the trench shall be backfilled in accordance with the preceding paragraph. Where cables or conduits are placed and backfilled by a machine in one operation, the above requirements for backfilling do not apply.

Where sheeting has been used for the excavation, and incremental removal of sheeting is not specified in the contract documents, sheeting shall be pulled when the trench has been backfilled to the maximum unsupported trench depth allowed by 29 CFR 1926.

203-3.07 Select Granular Fill Slope Protection. The Contractor shall perform the excavation in accordance with the requirements for “Unclassified Excavation and Disposal” as described elsewhere in these specifications. The Contractor shall then spread material conforming to the requirements given in §733-12 *Select Granular Slope Protection*, in one layer to its full thickness by a method approved by the Engineer. The work shall be performed where shown in the contract documents or where directed by the Engineer in accordance with the Standard Sheets, and details shown on the contract documents. Compaction of the slope protection is not required. Slope Protection shall be either of two types, as described below:

A. Select Granular Fill, Slope Protection - Type A. Under this type, the Contractor shall furnish and install the slope protection where shown in the contract documents in accordance with the details shown on the Standard Sheets.

B. Select Granular Fill, Slope Protection - Type B. Under this type, the Contractor shall furnish and install the slope protection where directed by the Engineer in accordance with the details shown on the Standard Sheets.

203-3.08 Surface Settlement Gauges. Surface settlement gauges shall be constructed, installed, and maintained where shown in the contract documents and in accordance with the details contained in the geotechnical control procedure “*Settlement Gauges and Settlement Rods*” covering construction, installation, maintenance, and abandonment of these devices.

Where surface settlement gauges are called for, it will be the Contractor's option to install pipe gauges or manometer gauges, unless a definite type is specified in the contract documents. Surface settlement gauges will be accepted for conformance with the specification requirements on the basis of an inspection of the installation by the Departmental Geotechnical Engineer.

203-3.09 Settlement Rods. Settlement rods shall be constructed, installed, and maintained where shown in the contract documents and in accordance with the details contained in the geotechnical control procedure “*Settlement Gauges and Settlement Rods*” covering construction, installation, maintenance, and abandonment of these devices.

Settlement rods will be accepted for conformance with the specification requirements on the basis of an inspection of the installation by the Departmental Geotechnical Engineer.

203-3.10 Piezometers. Piezometers shall be constructed, installed, and maintained at the locations shown in the contract documents and in accordance with the detailed drawings included in the contract documents.

203-3.11 Applying Water. None Specified.

203-3.12 Select Granular Subgrade. The type of material to be used in fill or backfill of undercuts shall be in conformance with the details shown in the contract documents or as ordered by the Engineer.

Fill or backfill material shall be deposited in horizontal layers not exceeding 6 in. in thickness prior to compaction. Compaction of each layer shall be as specified under §203-3.03C. *Compaction*. A minimum of 95% of Standard Proctor Maximum Density will be required.

203-3.13 Select Structural Fill. The type of material to be used in bedding, filling and backfill at structures shall be in conformance with the details shown on the appropriate Standard Sheet or as noted in the contract documents or as ordered by the Engineer. Do not use RAP. Do not use slabs or pieces of either concrete or asphalt.

Fill or backfill material at structures shall be deposited in horizontal layers not exceeding 6 in. in thickness prior to compaction. Compaction of each layer shall be as specified under §203-3.03C. *Compaction*. A minimum of 95% of Standard Proctor Maximum Density will be required. When filling behind abutments and similar structures, all material shall be placed and compacted in front of the walls prior to placing fill behind the walls to a higher elevation. The limits to which this subsection will apply shall be in accordance with the Standard Sheets or as modified in the contract documents.

Where sheeting has been used for the excavation, and incremental removal of sheeting is not specified in the contract documents, sheeting shall be pulled when the trench has been backfilled to the maximum unsupported trench depth allowed by 29 CFR 1926.

203-3.14 Sand Backfill. The type of material to be used in bedding and filling shall be in conformance with the details shown in the contract documents or as ordered by the Engineer.

Bedding or fill material shall be deposited in horizontal layers not exceeding 6 in. in thickness prior to compaction. Compaction of each layer shall be as specified under §203-3.03C. *Compaction*. A minimum of 95% of Standard Proctor Maximum Density will be required.

203-4 METHOD OF MEASUREMENT

203-4.01 General. Quantities for all items of work with payment units in cubic yards will be computed from payment lines shown in the contract documents. Work performed beyond any designated payment line, including any offset required for the construction of presplit rock slopes in lifts, will not be included in the computation of quantities for the item involved.

For any item paid for in its final position, no additional quantity will be measured for payment to make up losses due to foundation settlement, compaction, erosion or any other cause.

Cross-sectioning, for the purpose of determining quantities for payment, will be employed only where payment lines are not shown in the contract documents or Standard Sheets, and cannot be reasonably established by the Engineer.

Quantities for benching will be computed for payment from the details and instructions shown on the Standard Sheet *Earthwork Transition and Benching Details*.

The excavation of unsuitable materials designated as topsoil under Section 713 *Topsoil*, will be included in the quantity measured for the appropriate unclassified excavation item, without distinction..

Where the item, "Embankment in Place," is designated for the project by the proposal, all borrow of ordinary suitable materials shall be incidental to the work of that item.

203-4.02 Unclassified Excavation and Disposal. Unclassified excavation and disposal will be measured in cubic yards, measured to the nearest whole cubic yard, computed in the original position for all excavation within right-of-way limits. No deduction shall be made for any pipes, culverts, structures, or other obstructions, unless these are measured for payment under another contract item. Excavation for borrow of suitable materials for embankment construction, shall not be included in the computation for this work.

203-4.03 Embankment in Place. Embankment in place will be measured in cubic yards, measured to the nearest whole cubic yard, computed in the final compacted position. Any additional quantity of material required to compensate for embankment settlement shall not be included in the measurement of this item. The quantities of embankment will exclude the total volume of pipes, culverts, other roadway items, and granular backfill within the payment lines for such granular backfill.

203-4.04 Select Borrow. Select borrow will be measured in cubic yards, measured to the nearest whole cubic yard, computed in the original position.

203-4.05 Select Fill. Select fill will be measured in cubic yards, measured to the nearest whole cubic yard, computed in the final compacted position.

203-4.06 Select Granular Fill. Select granular fill will be measured in cubic yards, measured to the nearest whole cubic yard, computed in the final compacted position. A deduction shall be made for pipes (based on nominal diameters) and other payment items when the combined cross-sectional area exceeds 1 ft^2 unless otherwise shown in the contract documents. No deduction will be made for the cross-sectional area of an existing facility.

203-4.07 Select Granular Fill Slope Protection. Select granular fill slope protection will be measured in cubic yards, measured to the nearest whole cubic yard, computed in the final position.

203-4.08 Surface Settlement Gauges. Surface settlement gauges will be measured by the number of devices satisfactorily installed.

203-4.09 Settlement Rods. Settlement rods will be measured by the number of devices satisfactorily installed.

203-4.10 Piezometers. Piezometers will be measured by the number of devices satisfactorily installed.

203-4.11 Applying Water. The unit of measurement of water will be one pressure distributor per calendar day, denoted hereafter as one p.d.d., for dust control. Where the Contractor works in more than one separate and distinct shift per calendar day, each shift shall be considered as one p.d.d. A single shift plus overtime work, however, shall be considered as one p.d.d. The quantity thus determined shall be applied directly as the quantity to be paid for where the distributors used have a capacity of 3,000 gal. or less.

Provided that the Engineer determines that the total operating distributor capacity (number and sizes of all distributors) employed is reasonably commensurate with the needs for water application, additional payment will be allowed for distributors exceeding 3,000 gal. in capacity as follows:

Distributor Capacity	**Pressure Distributor per Calendar Day Adjustment**
3,000 gal. < distributor capacity < 5,000 gal.	p.d.d.'s will be multiplied by 1.5
5,000 gal. ≤ distributor capacity	p.d.d.'s will be multiplied by 2.0

No additional quantity shall be measured for payment for compaction purposes.

203-4.12 Select Granular Subgrade. Select granular subgrade will be measured in cubic yards, measured to the nearest whole cubic yard, computed in the final compacted position.

203-4.13 Select Structural Fill. Select structural fill will be measured in cubic yards, measured to the nearest whole cubic yard, in the final compacted position. A deduction shall be made for pipes (based on nominal diameters) and other payment items when the combined cross-sectional area exceeds 1 ft^2 unless otherwise shown in the contract documents. No deduction will be made for the cross-sectional area of an existing facility.

203-4.14 Sand Backfill. Sand backfill will be measured in cubic yards, measured to the nearest whole cubic yard, in the final compacted position. A deduction shall be made for pipes (based on nominal diameters) and other payment items when the combined cross-sectional area exceeds 1 ft^2 unless otherwise shown in the contract documents. No deduction will be made for the cross-sectional area of an existing facility.

203-5 BASIS OF PAYMENT

203-5.01 General-All Items. The unit price bid shall include the cost of furnishing all labor, materials, and equipment as necessary to complete the work, except where specific costs are designated or included in another pay item of work. Incidental costs, such as acquisition of borrow pits or material outside of the right-of-way, rock drilling and blasting, compaction and special test requirements, stockpiling and re-handling of materials, precautionary measures to protect private property and utilities, to form and trim graded surfaces, proof rolling, re-proof rolling, corrective work disclosed by proof rolling and any delays caused by this corrective work, shall be included in the unit price of the pay item where such costs are incurred. The exception is that corrective work ordered in cut sections based on an evaluation of proof rolling will be paid for under the appropriate excavation and backfill items.

Quantities for any additional items of work or substitution of material in accordance with the approved Winter Earthwork submittal shall be furnished at no cost to the State.

203-5.02 Unclassified Excavation and Disposal. The provisions of §203-5.01 *General-All Items* apply including the following:

The unit price bid shall cover all costs of required excavation within the right of way limits, and all costs of disposal if the excavated materials are not used under another pay item.

203-5.03 Embankment In Place. The provisions of §203-5.01 *General-All Items* apply.

203-5.04 Select Borrow. The provisions of §203-5.01 *General-All Items* apply.

203-5.05 Select Fill. The provisions of §203-5.01 *General-All Items* apply.

203-5.06 Select Granular Fill. The provisions of §203-5.01 *General-All Items* apply.

203-5.07 Select Granular Fill Slope Protection. The provisions of §203-5.01 *General-All Items* apply.

203-5.08 Surface Settlement Gauges. The provisions of §203-5.01 *General-All Items* apply including the following:

The unit price bid shall cover all costs of providing, installing and maintaining each device, including excavation, trenching and backfill during the course of the work. No payment will be made under any other item of the contract for any work associated with these items.

When each installation is completed, 75% of the item unit price will be paid. The remaining 25% will be paid when each device has been properly maintained and is abandoned according to the procedures contained in the geotechnical control procedure "*Settlement Gauges and Settlement Rods*". Unless otherwise specified in the proposal, the unit price shall also include the costs of removal.

203-5.09 Settlement Rods. The provisions of §203-5.01 *General-All Items* apply including the following:

The unit price bid shall cover all costs of providing, installing and maintaining each device, including excavation, trenching and backfill during the course of the work. No payment will be made under any other item of the contract for any work associated with these items.

When each installation is completed, 75% of the item unit price will be paid. The remaining 25% will be paid when each device has been properly maintained and is abandoned according to the procedures contained in the geotechnical control procedure "*Settlement Gauges and Settlement Rods*". Unless otherwise specified in the proposal, the unit price shall also include the costs of removal.

203-5.10 Piezometers. The provisions of §203-5.01 *General-All Items* apply including the following:

The unit price bid shall cover all costs of providing, installing and maintaining each device, including excavation, trenching and backfill during the course of the work. No payment will be made under any other item of the contract for any work associated with these items.

When each installation is completed and the device placed in satisfactory operation, 75% of the unit price will be paid. The remaining 25% will be paid when all earthmoving and slope work is completed in the vicinity of each installation. Any installation rendered inoperative due to damage by construction equipment after partial or full payment, shall be immediately repaired or the full amount of such payment shall be deducted from other monies due the Contractor under the contract.

203-5.11 Applying Water. The unit price bid per one operating pressure distributor per calendar day for applying water shall include the costs of furnishing all labor, material and equipment necessary for dust control.

203-5.12 Select Granular Subgrade. The provisions of §203-5.01 *General-All Items* apply.

203-5.13 Select Structural Fill. The provisions of §203-5.01 *General-All Items* apply.

203-5.14 Sand Backfill. The provisions of §203-5.01 *General-All Items* apply.

Payment will be made under:

Item No.	**Item**	**Pay Unit**
203.02	Unclassified Excavation and Disposal	Cubic Yards
203.03	Embankment In Place	Cubic Yards
203.05	Select Borrow	Cubic Yards
203.06	Select Fill	Cubic Yards
203.07	Select Granular Fill	Cubic Yards
203.0801	Select Granular Fill, Slope Protection - Type A	Cubic Yards
203.0802	Select Granular Fill, Slope Protection - Type B	Cubic Yards
203.10	Surface Settlement Gauges	Each
203.12	Settlement Rods	Each
203.13	Piezometers	Each
203.1601	Applying Water	P.D.D.

203.20	Select Granular Subgrade	Cubic Yards
203.21	Select Structural Fill	Cubic Yards
203.25	Sand Backfill	Cubic Yards

SECTION 204 - FLOWABLE FILL

204-1 DESCRIPTION. The work shall consist of mixing and placing flowable fill at the locations shown in the contract documents.

204-1.01. Controlled Low Strength Material. Controlled Low Strength Material (CLSM) is an acceptable alternative to compacted soil backfill in confined spaces. CLSM consists of cement, water and, at the Contractor's option, fly ash, aggregate or chemical admixtures in any proportions such that the final product meets the strength and flow consistency requirements included in the specification. The mix is proportioned to be self leveling and does not require compaction. It is much lower in strength than concrete, making future excavation possible.

204-1.02. Lightweight Concrete Fill. Lightweight Concrete Fill is an engineered geotechnical material with a unique strength / density relationship which can be used to reduce loads on soft foundation soils, buried structures, or against retaining walls. Lightweight Concrete Fill consists of a Portland cement matrix containing uniformly distributed, non-interconnected air voids introduced by a foaming agent. The flowability and cementitious properties provide a product that is self leveling and does not require compaction.

204-2 MATERIALS.

204-2.01 Controlled Low Strength Material. Provide backfill material meeting the requirements for CLSM as stated in §733-01 *Flowable Fill.*

204-2.02 Lightweight Concrete Fill. Provide backfill material meeting the requirements for Lightweight Concrete Fill as stated in §733-01 *Flowable Fill*.

204-3 CONSTRUCTION DETAILS.

204-3.01 Controlled Low Strength Material.

A. CLSM Submittal. Submit to the Engineer (1) a mix design, with certified test results supplied by a qualified independent testing laboratory for the CLSM verifying the unconfined compressive strength meets the requirements of the specification, and (2) the methods of installation to be employed. Include in the CLSM placement sequence, a procedure to account for subsidence during the settling and curing process.

B. CLSM Production. Mix the materials at a stationary mixing plant which is either a continuous or a batch type plant. A batch is defined as the amount of material that can be mixed at one time. Design the mix of materials to accurate proportions, either by volume or by weight, so that when the materials are incorporated in the mix a thorough and uniform mix will result.

If the CLSM can be placed within 30 minutes of the end of mixing, then open haul units may be used for transport. If it cannot be placed within 30 minutes after the end of mixing, it must be transported by a rotating drum unit capable of 2-6 rpm.

Appendix C:

NYSDOT Geotechnical Engineering Manual GEM-22 Procedures for Blasting

GEM-22

PROCEDURES FOR BLASTING

GEOTECHNICAL ENGINEERING MANUAL
GEM-22
Revision #4

AUGUST 2015

NEW YORK STATE OF OPPORTUNITY. | Department of Transportation | Office of Technical Services | Geotechnical Engineering Bureau

GEOTECHNICAL ENGINEERING MANUAL:
PROCEDURE FOR BLASTING

GEM-22
Revision #4

STATE OF NEW YORK
DEPARTMENT OF TRANSPORTATION

GEOTECHNICAL ENGINEERING BUREAU

AUGUST 2015

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1. INTRODUCTION

A. Purpose

This document specifies the procedure that shall be followed when a Contractor or Permittee is proposing to blast. By following this procedure, the Engineer-In-Charge or the Permit Engineer can help ensure that the Contractor accomplishes the work in a safe and effective manner. Engineering Geologists from the Geotechnical Engineering Bureau are trained and experienced in blasting safety and blasting techniques, and are available to provide assistance during all phases of the blasting operations. Prior to blasting the Contractor shall submit a written blast plan to the Engineer for conditional approval. The Engineer will forward the blast plan to the Engineering Geology Section, Geotechnical Engineering Bureau for review and written comment. After approval of the blast plan, a preblast meeting will be held which shall be attended by the Engineer, the Contractor, the Project Blaster(s), an Engineering Geologist from the Geotechnical Engineering Bureau, and representatives of all interested Agencies to discuss the proposed blasting operations. Final approval to blast will be granted based upon the results of the meeting. Test blasts may be required and may result in modifications to the blast plan. All blasts on Department contracts will be documented by the Engineer using the *Blasting Report Form SM 469 US Customary Units (GE 469 International System of Units) (See Appendix C).*

B. General

Presplit blasting is required on State ROW when the design rock slope is one vertical on one horizontal or steeper and the vertical height of the exposed rock slope exceeds 5 ft. (1.5 m). The contract documents may also specify blasting. The Contractor may choose to use production blasting in conjunction with required presplit blasting or for general rock excavation. The Contractor may also elect to use blasting for trenching operations, structure excavations, and structure demolitions. Permit jobs that involve blasting on State ROW are subject to the same requirements as Department-let contracts. If the Permit Engineer is concerned or uncertain about the effects of blasting adjacent to State ROW, the Engineering Geology Section should be contacted for advice.

Blasters in New York State are required to posses a valid New York State Department of Labor (NYSDOL) issued Blaster Certificate of Competence. The Blaster Certificate of Competence permits the use of explosives specific to the following blasting operations. These are classified as follows: A Class A (Above\Below Ground) Certificate or Class B (Aboveground) Certificate is required for rock blasting. A Class D (Demolition) Certificate is required for demolition of bridge superstructures or substructures. A Class E (Seismic) Certificate is required for seismic surveys. In conjunction with a Blaster Certificate of Competence an Explosives License is also needed for the licensee to purchase, own, posses or transport explosives.

The blaster will conduct all blasting operations in a skillful manner so as not to cause injury, damage property, adversely affect traffic, or cause the migration/accumulation of noxious gases. Blasting activities can have negative consequences which include the following:

1. Flyrock

Flyrock can cause serious injury or damage when it travels outside the blast zone. Flyrock can be caused by: improper blast design; improper or insufficient stemming;

unanticipated geologic features such as voids, soft seams, and other planes of weaknesses; borehole deviation; insufficient burden; and poorly distributed explosives.

The Blaster should inspect any free rock faces for irregularities and geologic conditions that may affect the blast and adjust the drill hole locations accordingly. Profiling the rock face using simple measuring tapes, conventional surveying techniques, or more advanced laser profiling may be warranted. Driller's notes and logs should be kept and used by the Blaster to make adjustments to explosives loading to account for geologic conditions and borehole deviation. The use of Borehole Deviation Surveys may be feasible to determine boreholes that have wandered too close to each other or too close to the rock face. Monitoring of drilling operations will also provide feedback to the drillers so that they may make adjustments to their methods.

Flyrock can also be controlled by using blasting mats or soil cover to retain the exploded rock. It's important that the Blaster make sure that all personnel are outside the blasting area where fly rock can be expected.

2. Vibrations

Blasting generated vibrations can damage underground and aboveground structures. When the Contractor is using a seismograph to monitor vibrations on State ROW, the Standard Specifications (§203-3.02.A.3.) provides the maximum particle velocity unless directed otherwise by the Engineer or the Contract Documents. In the absence of seismic monitoring equipment, the explosives loading limits shall be based upon the scaled distance formula in the Standard Specifications. In certain circumstances, NYSDOT contract documents may also require monitoring of adjacent structures that are off the State ROW. NYSDOL regulations (12 NYCRR 61) restrict vibration levels at buildings in the vicinity of blasting operations based upon distance or vibration frequency. Even when vibrations are not at a level sufficient to cause damage, they can disturb individuals and result in complaints. Proper placement and operation of the seismograph is critical for obtaining accurate readings. Vibrations can be controlled by modifying the weight of explosives per delay, the loading density, and the delay pattern. A preblast condition survey of a structure may be required prior to blasting.

3. Displacement of Bedrock

Blasting, primarily trench and ditch blasting, can displace rock and damage adjacent pavement and underground utilities.

4. Noxious Fumes

Blasting generates carbon monoxide and other noxious fumes. The fumes generated during blasting operations, especially during trenching operations, can migrate and collect in excavations, manholes and D.I.'s, and nearby buildings. The build up of significant concentrations of gases can occur 12 hours or more after the blast. All blasting shall be conducted so that the noxious gases generated by the blast do not affect the health and safety of individuals.

When site conditions and blasting procedures indicate that there is the potential for the migration and accumulation of gases, the Contractor should specify information collection activities, modification of blasting procedures, and an action plan in the event of a high reading or alarm. Such site conditions could include but are not limited to: open jointed bedrock (i.e. karstic limestone); an impermeable soil layer overlying the bedrock (i.e. clay or saturated soil); and proximity to buildings. Blasting procedures that may increase the risk include confined (i.e. trenching), large, and frequent blasts. Information collection activities should include preblast surveys of all buildings within a minimum of 300 ft. (100 m) of the blast, which would identify potential sources of entry and potential pathways to the buildings such as buried utility trenches. Information collection activities should also include monitoring of carbon monoxide levels before, during, and after the blast. Modification of blasting procedures should include limiting the size and frequency of blasts to limit the production of noxious fumes, and stripping of the overburden prior to blasting and excavating the shot rock immediately after blasting to allow the venting of gases. The use of vent holes or vent pits may also be necessary. The action plan should cover both building occupants and monitoring personnel.

5. Airblast Overpressure

Although unusual, blasting generated air waves can reach a level where they can damage buildings. NYSDOL (12 NYCRR 61) specifies limits for airblast levels at buildings in the vicinity of blasting operations. Air waves not at a level sufficient to cause damage can disturb individuals, resulting in complaints. Factors that affect air blast overpressure include topography, blast design, and atmospheric conditions. Blasts may have to be redesigned or rescheduled for more favorable atmospheric conditions to minimize air waves.

6. Misfires

Misfires happen when a loaded hole, portion of a loaded hole, or several loaded holes fail to detonate during a blast. Misfires can be caused by failure of the detonation system or by explosive column cutoffs. Sometimes it is apparent immediately after a blast that a misfire has occurred. Other times it's not discovered until the blasted rock is being excavated and unexploded explosives are discovered within the shot rock pile. The Blaster-in-Charge is responsible for checking the shot immediately after the blast for misfired holes and, if discovered, re-detonating the loaded holes. If re-firing a misfired hole presents a hazard, the explosive may be removed by washing out with water or, if underwater, blown out with air. No drilling or digging shall be permitted until all missed holes have been addressed. When unexploded explosives are discovered mixed in with the shot rock, excavation will cease until a Project Blaster is notified and he is able to supervise the continued rock excavation and proper disposal of the unexploded explosives. All personnel involved with excavating shot rock should be vigilant for the presence of unexploded explosives.

Each Certified Blaster is required to report to the NYSDOL any unusual incident or event that occurs during the blasting operations. They are also required to report any instances of premature detonation, damage from air blast, damage from excessive ground vibration, or instances of fly rock. Damage must be reported even when it is alleged and/or the complaint is made after a substantial lapse of time.

C. Definitions

Airblast - The airborne shock wave generated by an explosion.

ANFO – A blasting agent composed primarily of ammonium nitrate and fuel oil.

Authorized Blasting Assistant – An individual who has been authorized by the certified blaster-in-charge to work on a blasting operation after such blaster-in-charge has confirmed that the individual is either a certified blaster, or otherwise meets the following qualifications:

(1) Is at least eighteen years old;
(2) Has been properly trained in the performance of the tasks to be assigned; and
(3) Has been made aware of and understands the blasting hazards and risks.

Backbreak – Rock broken beyond the limits of the last row of holes in a blast, synonymous with overbreak.

Base Charge – The main explosive charge in the base of a detonator or a heavy charge at the base of a column of presplit powder.

Battered Production Holes – The row of production holes closest to presplit line, drilled at the same angle as the presplit holes.

Bench – A horizontal ledge from which holes are drilled downward into the material to be blasted.

Binary Explosive – A blasting explosive formed by the mixing of two plosophoric materials, for example, ammonium nitrate and nitromethane.

Blast Pattern – The plan view of the drill holes as laid out for blasting.

Blast Plan – A written procedure that details the methods and manner by which a Project blaster will comply with pertinent laws, rules, regulations, and contract documents. The plan shall include all information, as detailed in Section 2A, necessary to evaluate the effectiveness and safety of the proposed blasting operations. Individual blasts on a project are rarely identical. The plan should show the details for a typical blast with the understanding that minor modifications in the field will be allowed. Significant changes to the blasting operations will require that a new blast plan be submitted for approval. When deemed necessary by the Engineer, approved blast plans will be required for each individual shot.

Blaster-in-Charge – The Project Blaster in charge of a specific blast. Responsibilities include delivery of explosives, storage, loading, and detonation of the blast. *A project may have several Project Blasters, but only one blaster is in charge of each blast.*

Blasting Agent – An explosive material, consisting of fuel and oxidizer that can't be detonated with only a No. 8 blasting cap.

Blast Area – An area near any blasting operation in which concussion, flying material or debris, or gases resulting from a detonation of explosives can reasonably be expected to cause injury or property damage.

Blasting Galvanometer – An electrical resistance instrument designed specifically for testing electrical continuity of electric detonators and circuits containing them. Other acceptable instruments for this purpose are Blasting Ohmmeters and Blaster's Multimeters.

Blasting Mat – A Mat of woven steel wire, scrap tires, or other suitable material to cover blastholes for the purpose of preventing flyrock.

Blasting Site – The specific place defined by the Blaster-in-Charge where explosives are used in blasting operations. A blast site is part of the blast area.

Blasting Superintendent – The Contractor may use a Blasting Superintendant to provide general oversight for drilling and blasting operations. However, the Blaster-in-Charge is responsible for each blast.

Blasting Vibrations – The energy from a blast that manifests itself in the form of vibrations which are transmitted through the earth away from the immediate blast area.

Booster – An explosive charge, usually of high detonation velocity and detonation pressure, designed to be used in the explosive initiation sequence between an initiator or primer and the main charge.

Bulk Strength – The strength per unit volume of an explosive calculated from its weight strength and density.

Burden – The distance from the borehole to the nearest free face or the distance between boreholes measured perpendicular to the spacing.

Certified Blaster – An individual who has been issued a "Blaster Certificate of Competence" by the NYSDOL for using explosives.

Collar – The mouth or opening of a borehole.

Column Charge – A long, continuous, unbroken column of explosives in a blasthole.

Continuity Check (Circuit) – A determination that an initiation system is continuous and contains no breaks or improper connections that could cause stoppage or failure of an ignition system. For an electric initiation system, the check is performed both visually and by using a blasting galvanometer or other device. For a non-electric initiation system, the check can only be done visually.

Deck Loading (Decking) – A method of loading blastholes in which the explosive charges, called decks or deck charges, in the same hole are separated by stemming or an air cushion. The separate decks may or may not be fired on the same delay.

Deflagration – An explosive reaction such as a rapid combustion that moves through an explosive material at a velocity less than the speed of sound in the material.

Delay Blasting – The practice of initiating individual explosive decks, boreholes, or rows of boreholes at predetermined time intervals using delay detonators, or other delaying methods, as compared to instantaneous blasting where all holes are fired essentially at the same time.

Delay Detonator – An electric or nonelectric detonator used to introduce a predetermined lapse of time between the application of a firing signal and the detonation of a charge.

Departmental Engineering Geologist – An Engineering Geologist of the Geotechnical Engineering Bureau authorized by the Director of the Geotechnical Engineering Bureau to perform the duties required under the NYS DOT Standard Specifications. Engineering Geologists are trained and experienced in blasting safety and blasting techniques, and are available to provide assistance during all phases of the blasting operations.

Design Rock Slope – A cut slope in rock constructed at the angle and location specified in the contract plans. Presplit blasting is usually used to construct the slope so that the finished slope is stable and free from significant rock hazards.

Detonating Cord – A flexible cord containing a center core of high explosives which may be used to initiate other high explosives.

Detonating Cord Trunkline – The line of detonating cord that is used to connect and initiate other lines of detonating cord.

Detonation – An explosive reaction that moves through an explosive material at a velocity greater than the speed of sound in the material.

Detonator – Any device containing an initiating or primary explosive that is used for initiating detonation in another explosive material.

Drilling Pattern – The location of blast holes in relation to each other and the free face.

Dynamite – A high explosive used for blasting, consisting essentially of a mixture of, but not limited to nitroglycerin, nitrocellulose, ammonium nitrate, sodium nitrate, and carbonaceous materials.

Electric Blasting Circuit – An electric circuit containing electric detonators and associated wiring.

Electric Detonators – A detonator designed for, and capable of, initiation by means of an electric current.

Emulsion – An explosive material containing substantial amounts of oxidizer dissolved in water droplets, surrounded by an immiscible fuel; or droplets of an immiscible fuel surrounded by water containing substantial amounts of oxidizer.

Explosion – A chemical reaction involving an extremely rapid expansion of gases usually associated with the liberation of heat.

Explosive – Any chemical compound, mixture, or device, the primary or common purpose of which is to function by explosion.

Explosives License – Own & Possess – A license issued by NYS Department of Labor for the purpose of purchasing, owning, possessing, or transporting explosives.

Explosive Loading Factor – The amount of explosive used per unit volume of rock. Also called Powder Factor.

Explosive Materials – These include explosives, blasting agents, and detonators. The term includes, but is not limited to, dynamite and other high explosives; slurries, emulsions, and water gels; black powder and pellet powder; initiating explosives; detonators (blasting caps); and detonating cord.

Extra (Ammonia) Dynamite – A dynamite in which part of the nitroglycerin is replaced by ammonium nitrate in sufficient quantity to result in the same weight strength.

Extraneous Electricity – Electrical energy, other than actual firing current or the test current from a blasting galvanometer, that is present at a blast site and that could enter an electric blasting circuit. It includes stray current, static electricity, RF (electromagnetic) waves, and time-varying electric and magnetic fields.

Flyrock – Rocks propelled from the blast area by the force of an explosion.

Fragmentation – The breaking of a solid mass into pieces by blasting.

Free Face – A rock surface exposed to air or water which provides room for expansion upon fragmentation. Sometimes called open face.

Fuel – A substance which may react with oxygen to produce combustion.

Fumes – The gaseous products of an explosion. For the purpose of determining the fume classification of explosive material, only poisonous or toxic gases are considered.

Gelatin Dynamite – A type of highly water resistant dynamite characterized by its gelatinous or plastic consistency.

Geology – A description of the types and arrangement of rock in an area; the description usually includes the bedding dip and strike, the type and extent of pre-existing breaks in the rock, and the hardness and massiveness of the rock, as these affect blast design.

Grains – A weight measurement where 7000 grains are equivalent to 1 lb. (0.45 kg).

Ground Vibration – Shaking the ground by elastic waves emanating from a blast. Usually measured in in/s (mm/s) of particle velocity.

High Explosives – Explosives which are characterized by a very high rate of reaction, high pressure development, and the presence of a detonation wave in the explosive.

Initiator – A detonator, detonating cord or similar device used to start detonation or deflagration in an explosive material.

Lift – The vertical thickness of rock fragmented from a single blast.

Loading – Placing explosive material in a blast hole or against the material to be blasted.

Loading Density – The weight of explosive loaded per unit length of borehole occupied by the explosive, expressed as lbs/ft (kg/m) of borehole.

Loading Limits – The maximum quantity of explosives allowed per delay period as specified by the Standard Specifications.

Loading Pole – A nonmetallic pole used to assist in placing and compacting explosives charges in boreholes.

Low Explosives – Explosives which are characterized by deflagration or low rate of reaction and the development of low pressure.

Magazine – Any building, structure, or container approved for the storage of explosives materials.

Mass Explosion – An explosion which affects almost the entire load or quantity of explosives virtually instantaneously.

Maximum Particle Velocity (Peak Particle Velocity) – The maximum velocity at which the ground surface moves as a wave passes under it. The customary practice is to apply vibration limits to the peak particle velocity of the largest single component on the seismograph.

Millisecond (ms) – One thousand part of a second (.001 or 1/1000 sec.).

Misfire – A blast or specific borehole that failed to detonate as planned. Also the explosive materials that failed to detonate as planned.

Muckpile – The pile of broken material resulting from a blast.

Nitroglycerin – An explosive chemical compound used as a sensitizer in dynamite.

Nonelectric Detonator – A detonator that does not require the use of electric energy to function.

Nonsparking Metal – A metal that will not produce a spark when struck with other tools, rock, or hard surface.

Overbreak – See backbreak.

Overburden – Material of any nature laying on top of the rock that is to be blasted.

Oxidizer – A substance, such as nitrate, that readily yields oxygen or other oxidizing substances to promote the combustion of organic matter or other fuel.

Particle Velocity - The velocity at which the ground surface moves as a wave passes under it.

PETN – An abbreviation for the name of the high explosive pentaerythritol tetranitrate.

Placards – signs placed on vehicles transporting hazardous materials (including explosive materials) indicating the nature of the cargo.

Plosophoric Materials – Two or more unmixed, commercially manufactured, prepackaged chemical materials which are not classified as explosives but which, when mixed or combined, form a blasting explosive.

Powder Factor – The amount of explosive used per unit volume of rock. Also called Explosive Loading Factor.

Preblast Survey – A documentation of the preexisting condition of structures near an area where blasting is to be conducted.

Premature Firing – The detonation of an explosive charge before the intended time.

Presplitting – A blasting method in which cracks for the final contour or payline are created by firing a single row of holes containing light, well distributed charges, prior to the initiation of the remaining holes in the blast pattern.

Prilled Ammonium Nitrate – Ammonium nitrate in a pelleted or prilled form.

Primer – An explosive charge used to initiate other explosives or blasting agents. The primer is initiated by a detonator or detonating cord to which is attached a detonator.

Production Blasting – A blasting method whose sole purpose is to fragment the rock.

Propagation – The detonation of an explosive charge by an impulse received from an adjacent or nearby explosive charge.

Project Blaster(s) – A certified blaster who has been approved to blast on State ROW (see Blaster-in-Charge).

Relief – The effective distance from a blast hole to the nearest free face (synonymous with burden).

Round – A group of boreholes fired or intended to be fired in a continuous sequence.

Scaled Distance – A factor relating expected vibration levels from various weight charges of explosive materials at various distances.

Secondary Blasting – Blasting to reduce the size of boulders resulting from a primary blast.

Seismograph – An instrument which records ground vibrations generated by blasting operations. Particle velocity displacement is generally measured and recorded in three mutually perpendicular directions.

Sensitivity – A physical characteristic of an explosive material classifying its ability to be initiated upon receiving an external impulse such as impact, shock, flame, friction, or other influence which can cause detonation.

Shaped Charges – An explosive with a shaped cavity specifically designed to produce a high velocity cutting or piercing jet of product reaction; usually lined with metal to create a jet of molten liner material. They are generally used to cut steel members during superstructure demolition.

Shock Tube – A small diameter plastic tube used for initiating detonators. It contains only a limited amount of reactive material so that the energy that is transmitted through the tube by means of a detonation wave is guided through and confined within the walls of the tube.

Short Delay Blasting – The practice of detonating blastholes in successive intervals where the time distance between any two successive detonations is measured in milliseconds.

Slurry – An explosive material containing substantial portion of a liquid, oxidizers, and fuel, plus a thickener.

Stemming – Inert material placed in a borehole on top of or between separate charges. Used for the purpose of confining explosive gases or to physically separate charges of explosive material in the same borehole.

Subdrilling – The practice of drilling boreholes below floor level or working elevation to insure breakage of rock to working elevation.

Sympathetic Detonation – The detonation of an explosive material as the result of receiving an impulse from another detonation through air, earth, or water. Synonymous with sympathetic propagation.

Tamping – The action of compacting the explosive charge or the stemming in a blasthole. Sometimes refers to the stemming material itself.

Warning Signal – An audible signal which is used for warning personnel in the vicinity of the blast area of the impending explosion.

Water Gel – An explosive material containing substantial portions of water, oxidizers, and fuel, plus a cross-linking agent.

Water Resistance – The ability of an explosive to withstand the desensitizing effect of water penetration.

Weight Strength – The energy of an explosive material per unit of weight.

2. PROCEDURE FOR BLASTING WITHIN NYSDOT ROW

A. Submittal of Written Blast Plan

A written blast plan prepared by a Project Blaster shall be submitted by the Contractor to the Engineer a minimum 10 working days prior to scheduling a preblast meeting. The Engineer shall send a copy of the Blast Plan to the Regional Geotechnical Engineer who shall forward a copy to the Geotechnical Engineering Bureau, Engineering Geology Section for review. The Blast Plan may be returned to the blaster for revision or clarification prior to scheduling the preblast meeting. The blast plan shall detail the methods and manner by which the Project Blaster will comply with pertinent laws, rules, regulations, and contract documents. The plan shall include all information necessary to evaluate the effectiveness of the proposed blasting operations. The blast plan shall included all steps necessary to ensure that the proposed blasting activity does not cause injury, damage property, adversely affect traffic, or cause the migration/accumulation of noxious gases. Individual blasts on a project are rarely identical. The plan should show the details for a typical blast with the understanding that minor modifications in the field will be allowed. Significant changes to the blasting operations will require that a new blast plan be submitted for approval. When deemed necessary by the Engineer, approved blast plans will be required for each individual shot. The blast plan shall include the following items:

1. Project Designations
    - Name of Project Blaster(s).
    - Photocopy of the Project Blaster’s Explosives License (Own & Possess) and Certificate of Competence.
    - Employer of the Project Blaster (Contractor or subcontractor).
    - Scheduled start date and length of blasting operations and blast monitoring operations.
    - Limits of blasting work.
    - Requirements for local permits.
    - Location of any State owned structures in proximity to the blasting.
    - Location of any utilities in proximity to the blasting.
    - Location of any contaminants or flammable liquids or vapors in the area to be blasted.

2. Safety and Health Requirements
    - Type of audible warning signals and signal sequence.
    - Name of company that will deliver explosives to the project site.
    - Location of any preblast surveys.
    - Location of any vibration monitoring at State owned structures, utilities on or off State ROW, or privately owned structures off State ROW.
    - Location of any air blast overpressure monitoring.
    - If seismographs will be used, provide the manufacturer’s name, model number, and documentation of calibration performed within the last 12 months. Also provide name(s) of seismograph operators and relevant training and experience.
    - List steps that will be taken to control flyrock (i.e. blasting mats).

- Are carbon monoxide or other noxious fumes likely to migrate from the blast location or accumulate within nearby structures and, if so, what will be done to detect and prevent their migration.

3. Methods and Procedures
   - Type of drilling equipment.
   - Method of collaring and aligning presplit drill holes.
   - Hole diameter.
   - Drilling pattern.
   - Use of sequential timer.
   - Types of explosives, primers, initiators, and other blasting devices. Include manufacturer's technical data sheets and material safety data sheets for all products.
   - Loading parameters:
     A. Maximum and/or average weight of explosives per volume of rock.
     B. Maximum weight of explosives per delay.
   - Blasting cap delay patterns.

B. Scheduling Preblast Meetings

After approval is granted to schedule the meeting, the Engineer should contact the Engineering Geology Section via the Regional Geotechnical Engineer, and the Contractor, to schedule the meeting. The Contractor is responsible for inviting the Blaster (all Blasters whom the Contractor wants to be designated as Project Blasters must attend the meeting) and all interested parties (including but not limited to utilities, railroads, local political jurisdictions, local law enforcement agencies, and local emergency services) a minimum of 3 work days in advance of the meeting. Representatives for all utilities located within 200 ft. (60 m) of the blasting (300 ft. (90 m) for gas transmission lines) shall be invited.

C. Conducting Preblast Meetings

A preblast meeting shall be held at the site to discuss the proposed blasting operations. In attendance will be the Engineer, the Contractor, the Project Blaster(s) an Engineering Geologist from the Geotechnical Engineering Bureau, and other interested parties. Final approval to blast will be granted based upon the results of the meeting.

A preblast meeting is intended to initiate open communications with the Project Blaster(s) relating to the requirements for rock drilling and blasting, and demolition by blasting work on Departmental projects. An Engineering Geologist from the Geotechnical Engineering Bureau conducts the preblast meeting, which includes discussions on the blast plan and other pertinent information (see Appendix A).

A new preblast meeting will be required to designate new Project Blasters.

D. Inspection and Documentation

An Engineering Geologist will be available to train construction inspection staff in the proper method of inspecting blasting operations including ensuring that the blasting is carried out in a safe manner and documenting each blast using the *Blasting Report Form SM 469 US Customary Units (GE 469 International System of Units)* (see Appendix B, C, and D).

The State requires that, when seismographs are used to monitor vibrations, the Contractor will maintain seismograph records and make them available to the State if requested.

E. Test Blasts

Test sections are required for presplit slopes and test blasts may be required for other types of blasting situations. An Engineering Geologist will evaluate the test blast/section and determine if adjustments to the rock slope design and/or blasting operations are necessary (see Appendix F).

F. Blasting Progress Meetings

At the request of the Engineer, meetings may be held at any time during the project to review the progress of the blasting operations, discuss modifications to the methods and procedures of the written blast plan and/or discuss issues with upcoming blasts. In attendance will be the Engineer, the Contractor, the Project Blaster(s), an Engineering Geologist from the Geotechnical Engineering Bureau, and other interested parties.

As indicated previously, a new preblast meeting is required to designate new Project Blasters.

G. Blasting Review

If a blast causes injury, damage to property, adversely affects traffic, or causes gases to migrate and/or accumulate in a potentially harmful manner, all blasting operations shall cease by order of the Engineer for a review of the procedures. The review will be conducted by the Engineer in conjunction with an Engineering Geologist from the Geotechnical Engineering Bureau to ensure proper procedures and practices were used and to determine if the approved procedures need to be revised. Should the findings of the review indicate the injury, damage, traffic delay, or migration/accumulation of gases was attributed to improper blasting operations, the Blaster-in-Charge may be removed at the State's option.

APPENDICES

APPENDIX A Preblast Meeting Itinerary

1. Opening Remarks
    a. Verification of Attendance of Concerned Parties
    b. Statement of DOT Standard Specifications
    c. Description of Project by Engineer (Scope of Work, Stationing, etc.)
    d. Start Date for Blasting Operations
    e. Estimated Time to Complete Blasting
2. Project Designations
    a. Identify Prime Contractor
    b. Identify Project Blaster(s)
    c. Insurance Details
3. Safety and Health Requirements
    a. State and Federal Laws
    b. Local Permits/Laws
    c. Signage and Traffic Control (per MUTCD)
    d. Audible Warning Signal System
    e. Proper Delivery and Storage of Explosive Material
    f. Pre-Blast Survey
    g. Vibration and Airblast Monitoring (NYSDOL limits and qualified seismograph operators)
    h. Flyrock Control
    i. Control of Blast Generated Fumes
    j. Other concerns (Utilities, Municipalities, etc.)
    k. Duty to Report Unusual Incidents (12 NYCRR 61)
4. Blasting Specifics/Review of Blast Plan
    a. Verification of License/Certificate of Competence
    b. Methods/Procedures
        1. Type of Drilling Equipment
        2. Hole Size
        3. Drilling Pattern
        4. Timing of Blast/Type of System (Electric/Non-Electric)
        5. Explosives (Brand, Size, etc.)
        6. Blasting Caps (Type, Delay, etc.)
        7. Loading of Holes
5. Presplitting
    a. General Rules/Regulations/Specifications regarding presplit rock slopes
    b. Test Section
    c. Rules/Regulations regarding multiple lifts
    d. Scaling
6. Conclusion

APPENDIX B General Guidelines for Project Inspectors

1. Drilling

   Establish that:

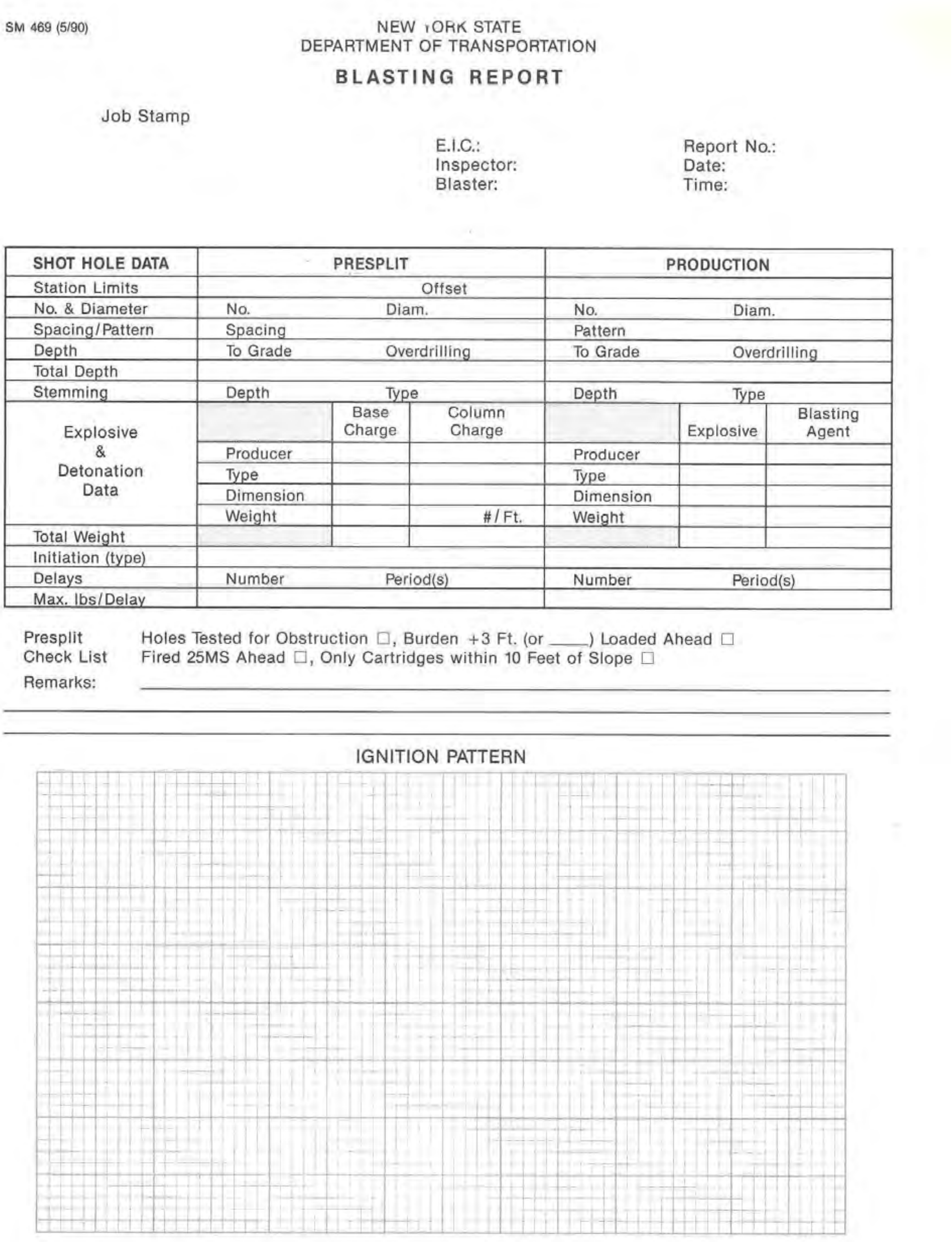
   a. Prior to blasting, no rock excavation is allowed within 10 ft. (3 m) of the presplit line.
   b. Overburden is stripped from bedrock along the top of the presplit line. Ensure that the bedrock surface is not overexcavated as in the case of weak shale.
   c. The drill steel is straight and in satisfactory condition.
   d. The plumb line for orienting the drill steel alignment is correctly located on a line parallel to the presplit line.
   e. The slope inclination template is the proper dimension and that a minimum 2 ft. (0.6 m) carpenter's level is attached to the template. (Preblast meeting agreement).
   f. The driller or the driller's assistant has achieved the proper drill steel alignment as the drill bit is collared by the bedrock surface. (The alignment can only be assured at this time since once the drill is progressed into the rock, it is very difficult to reconfigure alignment).
   g. The drill hole is of the proper depth (including sub-drilling) for each hole
   h. The pre-split drill holes are on 3 ft. (1 m) centers
   i. The driller is using carbide insert cross bits (preferable to button bits) and solid drill steel (preferable to spiral drill steel).
   j. The closest row of production (fragmentation) holes to the presplit line is drilled no closer than 4 ft. (1.2 m) to and on the same angle as the presplit holes.
   k. Driller's notes and logs should be kept.

2. Blasting

   Check:

   a. The depth of each presplit hole and clear any obstructions immediately prior to loading any explosives.
   b. The presplit explosive weight to insure that it is not heavier than the specified maximum weight of 0.35 pound per linear foot (0.5 kg per meter). It is recommended that the inspector count the number of sticks of explosive in a new box, multiply by the standard length of each cartridge to obtain the total cartridge length of each box and divide the box weight by the total cartridge length of box.
   c. That the presplit line is loaded first, and a minimum distance of burden + 3 ft. (1 m) in advance of the closest loaded production hole in the section
   d. That the earliest sequenced delay detonator is affixed to the presplit trunk line detonating cord, ensuring that the presplit slope is blasted prior to any adjacent production hole by a minimum of 25 milliseconds.
   e. That no free flowing explosives (ANFO, prills or water gels) be used in any production holes located within 10 ft. (3 m) of the presplit slope.
   f. That the stemming material to be used for presplit holes is #1A crushed stone rather than crushed gravel. (Crushed gravel has rounded edges and shotguns out of the hole rather than locking together to keep the presplit explosive gasses in the hole to split the bedrock).
   g. Driller's notes and logs should be used by the Project Blaster to make adjustments to explosives loading to account for geologic conditions and borehole deviation.

APPENDIX C Blasting Report Form SM 469 (US Customary Units)



SM 469 (5/90)

NEW YORK STATE
DEPARTMENT OF TRANSPORTATION

BLASTING REPORT

Job Stamp

E.I.C.:
Inspector:
Blaster:

Report No.:
Date:
Time:

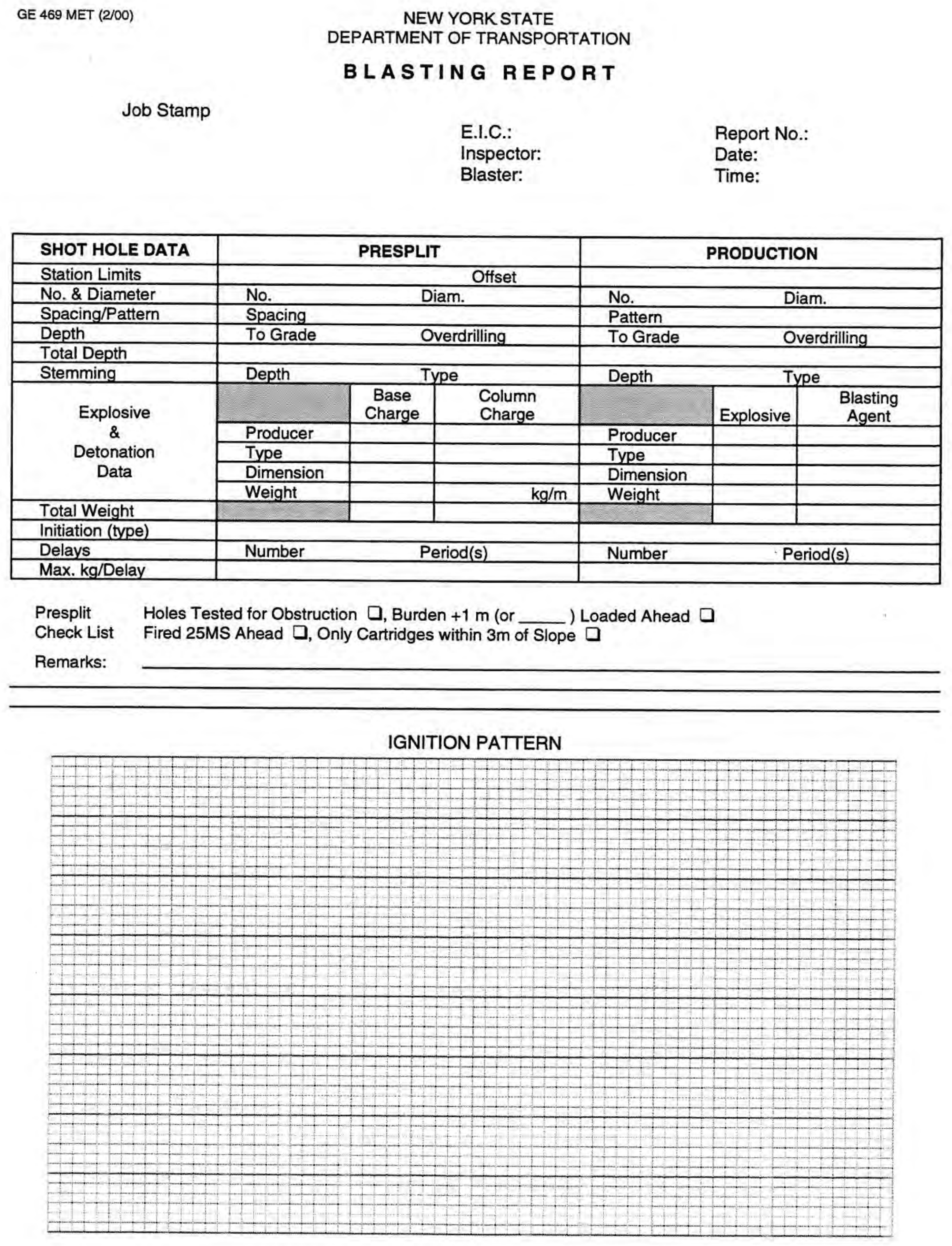
SHOT HOLE DATA	PRESPLIT			PRODUCTION		
Station Limits		Offset				
No. & Diameter	No.	Diam.		No.	Diam.	
Spacing/Pattern	Spacing			Pattern		
Depth	To Grade	Overdrilling		To Grade	Overdrilling	
Total Depth						
Stemming	Depth	Type		Depth	Type	
Explosive & Detonation Data		Base Charge	Column Charge		Explosive	Blasting Agent
	Producer			Producer		
	Type			Type		
	Dimension			Dimension		
	Weight		#/Ft.	Weight		
Total Weight						
Initiation (type)						
Delays	Number	Period(s)		Number	Period(s)	
Max. lbs/Delay						

Presplit Check List: Holes Tested for Obstruction ☐, Burden +3 Ft. (or ____) Loaded Ahead ☐
Fired 25MS Ahead ☐, Only Cartridges within 10 Feet of Slope ☐

Remarks: ____________________

IGNITION PATTERN

APPENDIX C Blasting Report Form GE 469 (International System of Units)



GE 469 MET (2/00)

NEW YORK STATE
DEPARTMENT OF TRANSPORTATION

BLASTING REPORT

Job Stamp

E.I.C.:
Inspector:
Blaster:

Report No.:
Date:
Time:

SHOT HOLE DATA	**PRESPLIT**			**PRODUCTION**		
Station Limits		Offset				
No. & Diameter	No.	Diam.		No.	Diam.	
Spacing/Pattern	Spacing			Pattern		
Depth	To Grade	Overdrilling		To Grade	Overdrilling	
Total Depth						
Stemming	Depth	Type		Depth	Type	
Explosive & Detonation Data	▨	Base Charge	Column Charge	▨	Explosive	Blasting Agent
	Producer			Producer		
	Type			Type		
	Dimension			Dimension		
	Weight		kg/m	Weight		
Total Weight	▨			▨		
Initiation (type)						
Delays	Number	Period(s)		Number	Period(s)	
Max. kg/Delay						

Presplit Check List: Holes Tested for Obstruction ☐, Burden +1 m (or _____) Loaded Ahead ☐
Fired 25MS Ahead ☐, Only Cartridges within 3m of Slope ☐

Remarks: ______________________________

IGNITION PATTERN

APPENDIX D Instructions for Filling Out the Blasting Report Form (SM 469 and GE 469)

Heading Data

Job Stamp -	Imprint job stamp under "Job Stamp'.
E.I.C. -	Enter the name of the Engineer-in-Charge.
Inspector -	Enter the name of the state or consultant blast inspector.
Blaster -	Enter the name of the Blaster-in-Charge.
Report No. -	Sequentially number from 1, beginning with the first blast detonated.
Date -	Enter the date of the blast. If the shot is loaded one day and detonated the next, enter the date of the detonation.
Time -	Enter the actual time and date (if different from loading) the blast is detonated (Hr. & Min).

Shot Hole Data

Station Limits -	Enter the stations of the beginning and end of the presplit holes to be detonated if presplit is involved. Do the same for production holes, if production only is loaded.
No. & Diameter -	Enter total number of presplit holes & diameter. Do the same for production holes.
Spacing/Pattern -	Maximum 3 ft. (1 m) on center for presplit holes. For production pattern enter average distance between holes in rows and average distance between rows (Spacing X Burden) in feet (meters).
Depth -	Enter range of depth to grade next to "To Grade", enter depth of overdrilling next to 'Overdrilling' (feet) (meters).
Total Depth -	The sum of 'To Grade' & 'Overdrilling' = total depth. Because ‘to grade’ and ‘overdrilling’ are usually ranges, ‘total depth’ will usually be a range also.
Stemming -	Depth in feet (meters), from top of drill hole to top of explosives. For presplit holes it’s required that the presplit powder be within 3 ft. (1 m) of the ground surface and the entire hole stemmed.
Type -	It’s required that No. 1-A crushed stone be used for stemming presplit holes. Production holes can be stemmed with drill cuttings or soil as long as it’s effective.

APPENDIX D Instructions for Filling Out the Blasting Report Form (SM 469 and GE 469)

Explosive and Detonation Data

Producer - Enter the manufacturer of each explosive (base charge, column charge, production explosive & blasting agent). Examples are Dyno Nobel and Austin.

Type - Enter the manufacturer's product name of each in the appropriate column. Also enter the strength percentage (40%, 60%, etc.) as on the container. Examples are Dynosplit and Unimax.

Dimension - Enter diameter and length of the individual cartridges in the appropriate columns.

Weight - Enter weight per stick of base charge, weight/foot (weight/meter) of presplit powder, weight per stick of production charges & weight of column for blasting agent. All weight is in pounds (kilograms).

Total weight - Enter the sum total for each type of explosive, base charge, column charge, production explosive & blasting agent.

Initiation (Type) - Enter 'electric blasting (EB) caps' or 'non electric blast (NEB) caps' or other method as used. List cap manufacturer brand and series.

Delays - Enter the number of different delay periods used. Period(s): enter the delay periods used. Examples are: electric – 25,75,100 ms; nonelectric – 25/350, 25/500 ms.

Max. lbs/Delay
Max. kg/Delay - Add the weight of explosives on each different delay per blast. The greatest weight of explosives detonated per delay is the max. pounds/delay (kilograms/delay) at 25 ms or 75 ms or 250 ms, etc.

APPENDIX D Instructions for Filling Out the Blasting Report Form (SM 469 and GE 469)

Presplit Check List

Before Loading any holes with explosives

1. The blaster must designate P-S holes in the section to be loaded.
2. Back up from end and designate the production section to be loaded.
3. Check all P-S holes for obstruction and clear all P-S holes before loading any P-S or production powder.

Holes Tested for Obstructions ☐ - check the box only after all presplit holes have been tested for clearance immediately before loading any explosives. Use either loading poles, measuring tape or some other device which can assure that the holes are clear to the full drilled length. All obstructed holes must be cleared before any explosives loading can begin.

Burden +3 ft. (or ______)

(Burden +1 m (or ___)) Loaded Ahead ☐ - check the box only after it has been determined that the presplit line is loaded with explosives a length which equals the burden + 3 ft. (+ 1 m) past the closest production hole to the end of the presplt line. Usually this works out to 3 presplit holes. No production holes can be loaded past a perpendicular line to the presplit line from the third hole back.

Fired 25 MS ahead ☐ - Presplit holes must be detonated a minimum of 25 MS ahead of the production holes in that section.

Only Cartridges within 10 ft. of Slope ☐ -

(Only Cartridges within 3 m of Slope ☐)- No uncontained or poured explosives are allowed in holes within 10 ft. (3 m) of the presplit plane.

Remarks - Utilized this area to report on the results of the blast, i.e. damage/no damage, cutoffs, flyrock, road closed, traffic delay, seismograph locations and readings, carbon monoxide monitor locations and readings, etc.

APPENDIX D Instructions for Filling Out the Blasting Report Form (SM 469 and GE 469)

Ignition Pattern- Utilize this area to draw an accurate plan view of drill holes, including:

a. edge of rock
b. north arrow
c. station and offset of beginning and end of presplit line
d. hole numbers
e. spacing
f. burden
g. timing of initiation of each hole (adjusted to sequential timer if one is used. Diagram wiring connections).
h. important geologic features, i.e., seams, boulders, etc.
i. hole depths and lbs. (kg) of explosives per hole & per deck, if used
j. show detonation cord type & location

APPENDIX E Highlights from State and Federal Safety Regulations

Transportation of explosives (12 NYCRR 39; 49 CFR 177; 29 CFR 1926 Subpart U)

- A vehicle carrying explosives shall not be left unattended or unguarded. Someone able to move the vehicle, familiar with the hazards of the material being transported and who knows what to do in an emergency must be awake in the vehicle or within 100 ft. (30 m) of the vehicle and have it in clear view.

- It is prohibited to park within 300 ft. (90 m) of a bridge, tunnel, building, a place where people gather, or an open fire unless absolutely necessary to perform their work.

- The vehicle shall not be parked within 5 ft. (1.5 m) of a traveled roadway.

- The vehicle shall make no unnecessary stops.

- Explosives shall be loaded/unloaded only when engine is off and parking brake is set.

- Do not travel through congested areas or heavy traffic unless it is a designated route.

- No device or material capable of producing spark, flame or heat shall be placed or carried on a vehicle containing explosives.

- Proper placards are required on both sides and the front and back of the vehicle.

- Fire extinguishers required with a rating of at least 10: ABC. If carrying 200 lbs. (90 kg) or more of explosives, two 10 to 12 lbs. (4.5 to 5.5 kg) carbon dioxide fire extinguishers or two 4 to 7 lbs. (1.8 to 3 kg) dry chemical fire extinguishers are required.

- Explosives shall not be transported on a trailer and a vehicle carrying explosives shall not have a trailer in tow.

- The sides and ends of an open-ended vehicle shall be high enough to prevent packages of explosives from falling off the vehicle and the explosives shall not be stacked higher than the sides of the vehicle.

- Up to 50 detonators may be carried on a vehicle containing explosives provided that: the detonators are in their original shipping containers, or a box constructed of 1 in. (25 mm) lumber lined with padding not less than ½ in. (13 mm) thick or wrapped in cloth with cloth separating each detonator, and the detonators must be in a place remote from the explosives that is easily accessible for quick removal.

- Exposed ferrous metal on the vehicle body that may come in contact with the explosive packages must be covered with wood or other non-ferrous material.

APPENDIX E Highlights from State and Federal Safety Regulations

Explosive safety and handling (29 CFR 1926 Subpart U)

- Smoking, firearms, matches, open flames lamps, flames, heat producing devices and sparks are prohibited in or near magazines or while explosives are being handled, transported or used.

- All explosives must be accounted for at all times. Explosives not in use shall be in a locked magazine.

- Explosives or blasting agents shall not be abandoned.

- Original containers or class II magazines shall be used for the transport of detonators and explosives from storage to the blasting area.

- Blasting operations above ground shall be conducted between sunup and sundown.

- Electric detonators shall be short-circuited and shunted in holes which have been primed until wired into the blasting circuit.

- Blasting operations shall be suspended and personnel shall leave the blasting area upon the approach and progress of an electrical storm.

- Blasting zone signs and signs warning against the use of mobile radio transmitters must be posted on all roads within 1000 ft. (300 m) of the blasting area.

- Mobile radio transmitters which are less than 100 ft. (30 m) from electric blasting caps shall be deenergized and effectively locked.

- Empty boxes and paper and fiber packing materials, which have previously held explosives, shall not be used for any purpose and shall be destroyed by burning.

- Blasting operations in the vicinity of overhead power lines, communication lines, utilities, or other services and structures will not be carried out until the Utilities are notified and measures for safe control have been taken.

- Use of black powder is prohibited.

- Smoking and open flames are not permitted within 50 ft. (15 m) of explosives and detonator storage magazines.

- Tamping will be done with wood rods or plastic tamping poles without exposed metal parts. No violent tamping is allowed.

- After loading holes, all unused explosives and detonators must be returned to an authorized magazine.

APPENDIX E **Highlights from State and Federal Safety Regulations**

- No person will be allowed to deepen drill holes which have previously contained explosives or blasting agents.

- Equipment will not be operated within 50 ft. (15 m) of loaded holes (no drilling, digging, etc.).

- Electric cables in the proximity of the blast area shall be deenergized and locked out.

- Holes will be checked prior to loading to determine depth and conditions of the hole.

- No drilling is allowed within 50 ft. (15 m) of a hole that has been loaded with explosives and has failed to detonate.

- All blast holes will be stemmed to the collar or a point that will confine the charge.

- Blasting cap leg wires will be kept short-circuited (shunted) until they are connected into the circuit for firing.

- A code of blasting warning signals (29 CFR 1926) shall be posted conspicuously at the operation and all employees shall be familiar with the signals.

- A loud signal must be given by the blaster of record prior to firing the blast.

- Flaggers must be safely positioned on roadways passing through the danger zone to stop traffic during the blasting operations.

- Following the blast, the blasting machine or other initiation devices shall be disconnected from the firing line or turned off in the case of power switches.

- The blaster shall check the surrounding rubble and blasting area to determine that all charges have been exploded.

- If a misfire occurs, only those employees necessary to do the work shall remain in the blast zone.

- No attempt will be made to extract explosives from any charged or misfired hole. A new primer shall be installed and the hole reblasted. If refiring the hole is a hazard, the explosives may be removed by washing out with water.

- No drilling, digging, or picking will be permitted until all missed holes have been detonated.

APPENDIX E Highlights from State and Federal Safety Regulations

Explosive licensing (12 NYCRR 39, 12 NYCRR 61)

- To purchase, transport, own and possess explosives, an explosives license is required.
- The handling and placing of explosives in preparation of a blast shall be performed by a certified blaster or by persons under the supervision of a certified blaster.
- Only a certified blaster may detonate explosives. The Blaster must be certified in the specific Department of Labor category in order to perform the work.

Explosive storage (12 NYCRR 39, 29 CFR 1926 Subpart U)

- Magazines and all enclosures used for storage of explosives shall be kept locked.
- Inventory of explosives shall be taken at the end of the day after blasting operations or whenever the magazine is opened.
- Magazines shall be inspected at least every 3 days.
- No smoking or flames are allowed within 50 ft. (15 m) of any explosive or magazine.
- No blasting equipment shall be stored in a magazine.
- Separate magazines shall be provided for explosives and detonators.
- No lights in magazine except battery activated electric flashlights or electric lanterns enclosed in rubber or other insulating cover.
- Ground around the magazine for a distance of 25 ft. (7.5 m) must be kept clean of flammable debris such as dry leaves and grass.
- No discharge of firearms at or within 500 ft. (150 m) of a magazine.
- Magazines must be located certain distances from buildings, railways, highways and other magazines based on the quantity of explosives stored in the magazine.
- The distances of separation can be decreased by 50% if the magazine or other structure containing explosives if protected by an efficient barricade.
- Explosive quantity conversion of detonators and detonating cord.
  - Cap size up to and including #8: 1000 caps are rated equivalent to 1.5 lbs. (0.7 kg) of explosives.
  - Cap size larger than #8: 1000 caps are rated equivalent to 3 lbs. (1.4 kg) of explosives.

  - Detonating cord up to and including 60 grains/foot: 1000 ft. (300 m) is rated equivalent to 9 lbs. (4 kg) of explosive.

  - Detonating cord above 60 grains/foot: 1000 ft. (300 m) is rated equivalent to 15 lbs. (6.8 kg) of explosives.

Underground utilities (12 NYCRR 53)

- Underground facilities within 15 ft. (4.5 m) of a proposed excavation or demolition must be staked, marked or otherwise designated.

- Verification shall be accomplished by exposing the underground facility or its encasement to view or by other means mutually agreed to by the excavator and operator.

- Powered equipment shall not be used within 4 in. (100 mm) of the verified location of an underground facility.

APPENDIX F Geologic Evaluation of Test Section

A test section is required on all newly constructed (or reconfigured) presplit slopes. The test section should be cleared and scaled in such a manner that its appearance and attitude be identical to that of the finished rock cut.

The test section exposes all discontinuities present in the bedrock. Since even the most advanced design exploration methods cannot reveal every feature present, the test section will enable the Engineering Geologist to determine if the slope will be stable as designed. If it is determined upon evaluation of the test section that the slope is unstable, the Engineering Geologist can change the slope design to one which will be stable.

The Engineering Geologist will inspect the test section, paying specific attention to drill butt traces. The geologist will examine:

1. Initial alignment of drill steel
2. Divergence, convergence or oversteepening of drilled holes
   Possible causes:
   a. Drill Bits (Cross Bits are preferable to Button Bits)
   b. Drill Steel (Solid Steel is preferable to Spiral Steel)
   c. Geology
      1. Alternating Beds (e.g. shale/sandstone/shale)
      2. Jointing/Fractures/Voids
      3. Soft Rock (leading to gravity caused oversteepening)
   d. Excessive down pressure
3. Final Appearance of Finished Slope
   a. Dimensions of Finished Product
   b. Rock Condition
   c. Unconformities/Significant Facies Changes
4. Concerns/Issues as the slope weathers

If the Engineering Geologist is not satisfied with the final appearance of the test section, or more information is needed, an additional test section may be required to fully address all concerns.

Appendix D:

U.S. Department of the Interior
Bureau of Mines
Report of Investigations 8507

MASTER

Report of Investigations 8507

Structure Response and Damage Produced by Ground Vibration From Surface Mine Blasting

By D. E. Siskind, M. S. Stagg, J. W. Kopp,
and C. H. Dowding

March 3, 1849

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STRUCTURE RESPONSE AND DAMAGE PRODUCED BY GROUND VIBRATION FROM SURFACE MINE BLASTING

by

D. E. Siskind[1], M.S. Stagg[2], J. W. Kopp[3], and C. H. Dowding[4]

ABSTRACT

The Bureau of Mines studied blast-produced ground vibration from surface mining to assess its damage and annoyance potential, and to determine safe levels and appropriate measurement techniques. Direct measurements were made of ground-vibration-produced structure responses and damage in 76 homes for 219 production blasts. These results were combined with damage data from nine other blasting studies, including the three analyzed previously for Bureau of Mines Bulletin 656.

SAFE ~~Save~~ levels of ground vibration from blasting range from 0.5 to 2.0 in/sec peak particle velocity for residential-type structures. The damage threshold values are functions of the frequencies of the vibration transmitted into the residences and the types of construction. Particularly serious are the low-frequency vibrations that exist in soft foundation materials and/or result from long blast-to-residence distances. These vibrations produce not only structure resonances (4 to 12 Hz for whole structures and 10 to 25 Hz for midwalls) but also excessive levels of displacement and strain.

Threshold damage was defined as the occurrence of cosmetic damage; that is, the most superficial interior cracking of the type that develops in all homes independent of blasting. Homes with plastered interior walls are more susceptible to blast-produced cracking then modern gypsum wallboard; the latter are adequately protected by a minimum particle velocity of approximately 0.75 in/sec for frequencies below 40 Hz.

Structure response amplification factors were measured; typical values were 1.5 for structures as a whole (racking) and 4 for midwalls, at their respective resonance frequencies. For blast vibrations above 40 Hz, all amplification factors for frame residential structures were less than unity.

The human response and annoyance problem from ground vibration is aggravated by wall rattling, secondary noises, and the presence of airblast. Approximately 5 to 10 pct of the neighbors will judge peak particle velocity levels of 0.5 to 0.75 in/sec as "less than acceptable" (i.e., unacceptable) based on direct reactions to the vibration. Even lower levels cause psychological response problems, and thus social, economic, and public relations factors become critical for continued blasting.

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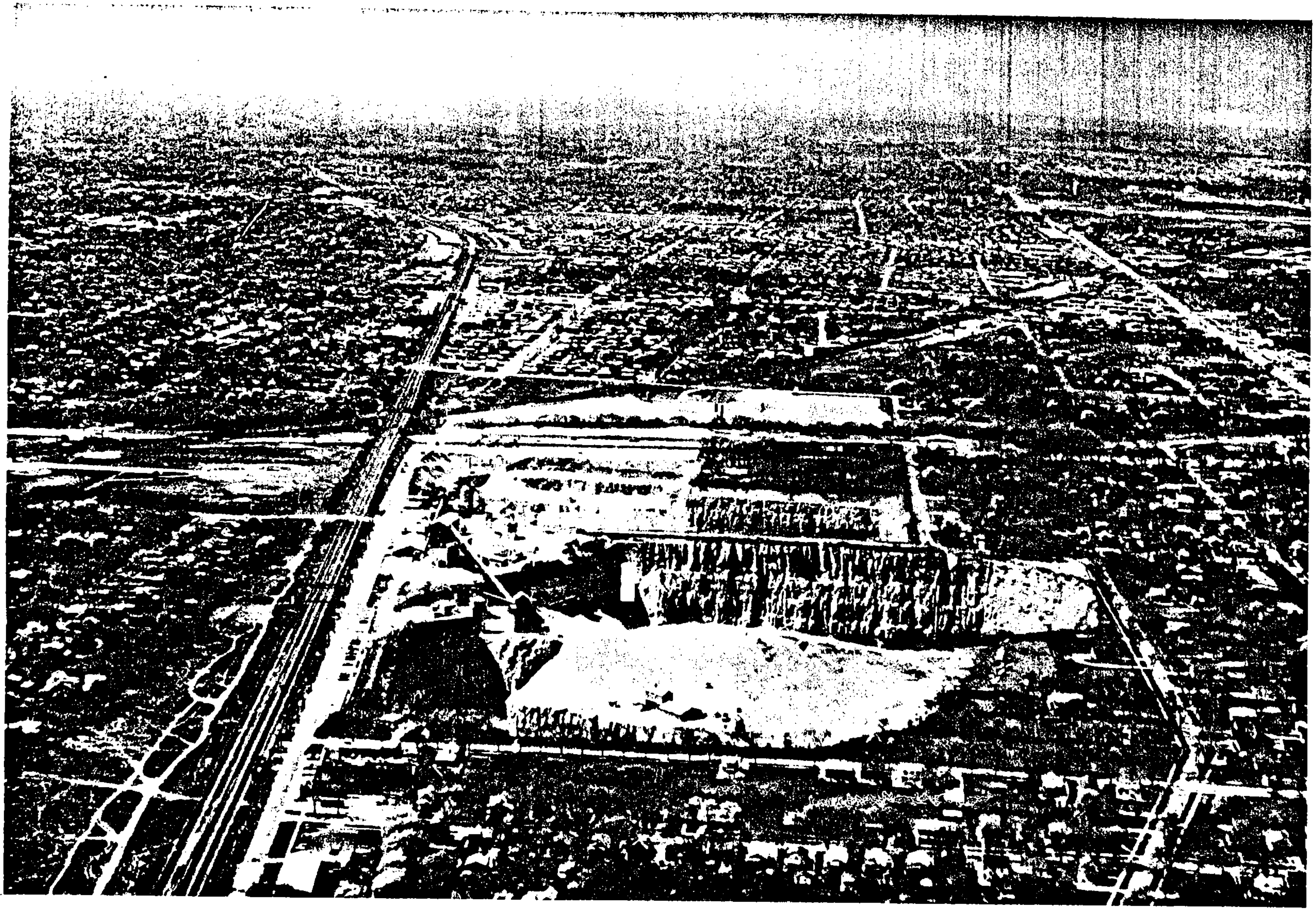

Figure 1.—Occupied residences near operating surface mine.

INTRODUCTION

Gound vibrations from blasting have been a continual problem for the mining industry, the public living near the mining operations, and the regulatory agencies responsible for setting environmental standards. Since 1930, the Bureau of Mines has studied various aspects of ground vibration, airblast, and instrumentation, culminating in Bulletin 656 in 1971(*37*)[5].

In that publication, Nicholls extensively reviewed blast design effects on the generation of vibrations, ground vibration and airblast propagation, and seismic instrumentation. Bulletin 656 established the use of peak particle velocity in place of displacement, a minimum delay interval of 9 msec for scaled distance calculations, and a safe scaled distance design parameter of 50 ft/lb$^{1/2}$ for quarry blasting in the absence of vibration monitoring. The authors also included a damage summary analysis originally published in 1962 by Duvall and Fogelson as Bureau of Mines Report of Investigations 5968 (*14*). New data available since the 1962 report were described in Bulletin 656, but a new analysis to include these data was not performed.

Recommended was the use of peak particle velocity to assess the damage potential of the ground vibrations, and 2.0 in/sec as an overall safe level for residential structures. These recommendations have been widely adopted by the mining and construction industry and incorporated into numerous State and local ordinances that regulate blasting activity. Soon after publication of the 2.0-in/sec safe level criterion, it became apparent that it was not practical to blast at this high vibration level. Many mining operations with nearby neighbors were designing their blasts to keep velocities as low as 0.40 in/sec. Severe house rattling caused fear of property damage below the 2.0-in/sec level, and many homeowners were attributing all cracks to the blast vibrations.

Pennsylvania was the first State to adopt the 2.0-in/sec peak particle velocity criterion as a safe standard in 1957. However, in 1974 it was forced to adopt stricter controls because of citizen pressure and lawsuits involving both annoyance and alleged damage to residences. There existed no technologically based and supportable criteria for mine, quarry, and construction blasting other than the 2.0-in/sec criteria from Bulletin 656 and RI 5968. The general growth of mining, the proximity of mining and quarrying to their residential neighbors, and greater environmental awareness have all required reexamination of blasting regulations and justified further research.

In 1974 the Bureau of Mines began to reanalyze the blast damage problem, expand the Duvall and Fogelson 1962 study, and overcome its more serious shortcomings through the following efforts:

1. Direct measurements were made of structural response, and damage was observed in residences from actual surface-mine production blasting.
2. Damage data from six additional studies, not available in 1962, were combined with three studies analyzed by Duvall and Fogelson, plus the new Bureau of Mines measurements.
3. Probabilistic analysis techniques were used on various sets of data, as well as the conventional statistical derivation of mean square fit and standard deviation for the various damage thresholds.
4. Particular emphasis was placed on the frequency dependence of structure response and damage, recognizing that the response characteristics and frequency content of the vibrations are critical to response levels and damage probabilities.
5. An analysis was made of various studies of human tolerance to vibrations, although most data are from steady-state rather than impulsive sources.

Italic

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[5] ~~Underlined~~ numbers in parentheses refer to items in the list of references preceding the appendixes.

An understanding of how houses respond to ground vibration and the vibration characteristics most closely related to this response will enable operators to design blasts to minimize adverse effects. The mining industry needs realistic design levels and also practical techniques to attain these levels. At the same time, environmental control agencies responsible for blasting and explosives need reasonable, appropriate, and technologically established and supportable criteria on which to base their regulations. Finally, neighbors around the mining operations and other blasting, as shown in figure 1, require protection of their property and health so that they do not bear an unreasonable personal cost.

This report summarizes the state of knowledge on damage to residences from surface mine, quarry, and construction blasting. Included are discussions of applicable data on fatigue and human response, although work is continuing in these areas. An analysis was also made on vibration production from mining blasts. The generation and propagation data in Bulletin 656 are for smaller quarry blasts, which are also typically characterized by thin overburden layers.

The damage criteria presented herein were developed to quantify the response of and damage to residential-type structures from small to intermediate-sized blasts as used in mining, quarrying, construction, and excavation. Application of these criteria by regulatory agencies will require an analysis of social and economic costs and benefits for the coexistence of blasting and an enviromentally conscious society.

ACKNOWLEDGMENTS

The authors acknowledge the generous assistance of many regulatory agencies, engineering consultants, powder companies, homeowners, and mine and quarry operators. Special thanks are due to the Pennsylvania Department of Environmental Resources for demonstrating the need for this ground vibration research. Much of the fieldwork and data reduction was done by Virgil J. Stachura, Alvin J. Engler, Steven J. Sampson, Michael P. Sethna, Bryan W. Huber, Eric Porcher, and John P. Podolinski. Valuable technical support was provided by G. Robert Vandenbos for all stages of the blasting research.

GROUND VIBRATION CHARACTERISTICS

Ground vibrations from blasting are an undesirable side product of the use of explosives to fragment rock for mining, quarrying, excavation, and construction. This ground vibration or seismic energy is usually described as a time-varying displacement, velocity, or acceleration of a particular point (particle) in the ground. It can also be measured as various integrated (averaged) energy levels. Three mutually orthogonal time-synchronized components are required to characterize the motion fully. Alternatively, the three components can be combined into a true vector sum for any instant in time or a pseudo vector sum derived from vector addition of the maximums of each component, independent of time (*50*).

The descriptors for motion are related by integration and differentiation:

$$V = \frac{d}{dt} D = \int Adt.$$

$$\text{and } A = \frac{d}{dt} V = \frac{d^2}{dt^2} D$$

where D is displacement, V is velocity, and A is acceleration. When the vibrations can be approximated by a sine wave (simple harmonic motion), the relationships above become:

$$\begin{aligned} D &= D_0 \sin(2\pi ft), \\ V &= D_0 (2\pi ft)\cos(2\pi ft) = V_0\cos(2\pi ft), \\ \text{and } A &= -D_0(2\pi ft)^2\sin(2\pi ft) \\ &= -A_0\sin(2\pi ft). \end{aligned}$$

where f is frequency, t is time, and, D_0, V_0, and A_0 are constants. Peak values correspond to the time when the trigonometric functions equal unity, and the relationships for these peaks values then become:

$$\begin{aligned} D_0 &= \frac{V_0}{2\pi f} = \frac{A_0}{(2\pi f)^2} \\ V_0 &= 2\pi fD_0 = \frac{A_0}{2\pi f} \\ \text{and } A_0 &= (2\pi f)^2D_0 = 2\pi fV_0 \end{aligned}$$

Complex vibrations cannot be approximated by the simple harmonic motion, and either electronic or numeric (computer) integration and differentiation become necessary for conversions.

Interactions between the vibrations and the propagating media give rise to several types of waves, including direct compressional and shear body waves, refracted body waves, and both horizontally and vertically polarized surface waves. These vibrational waves are of primary importance in studies of the earth's interior and earthquake characteristics, but their individual effects have been totally neglected in blasting seismology. Analysis of damage to structures does not require knowledge of what happens between the source and the receiver or of the type of wave. It requires only the vibrational input to the house at its foundation. Additionally, multiply-delayed shots are sufficiently complex vibration sources to make identification of individual waves difficult, if not impossible, under most conditions.

TIME AND FREQUENCY PROPERTIES OF MINING BLASTS

The amplitude, frequencies, and durations of the ground vibrations change as they propagate, because of (a) interactions with various geologic media and structural interfaces, (b) spreading out the wave-train through dispersion, and/or (c) absorption, which is greater for the higher frequencies. Close to the blast the vibration character is affected by factors of blast design and mine geometry, particularly charge weight per delay, delay interval, and to some extent direction of initiation, burden, and spacing (*56*). At large distances the factors of blast design become less critical and the transmitting medium of rock and soil overburden dominate the wave characteristics.

Particle velocity amplitudes are approximately maintained as the seismic energy travels from one material into another (i.e., rock to soil), probably from conservation of energy. However, the vibration frequency and consequently the displacement and acceleration amplitudes depend strongly on the propagating media. Thick soil overburden as well as long absolute (as opposed to scaled) distances create long-duration, low-frequency wave trains. This increases the response and damage potential of nearby structures.

Frequencies below 10 Hz produce large ground displacement and high levels of strain, and also couple very efficiently into structures where typical resonant frequencies are 4 to 12 Hz for the corner or racking motions. Racking is whole-structure distortion with characteristic shear stresses and failures. Previous studies described the frequency character of vibration from quarry (*37*) and coal mine blasts (*56*), and a recent report by Stagg on instrumentation for ground vibration summarized the frequency characteristics of vibrations from small to moderate-sized blast sources (*50*). Ground vibration frequencies from three types of blasts are shown in figure 2, all measured at the closest residence where peak particle velocities were within 0.5 to 2.0 in/sec. Although the shot types in figure 2 are labeled coal mine, quarry, and construction, the frequency-determining factors are the shot sizes, distances, and rock competence. The coal mine and quarry blasts were all more than 200 lb/delay at distances exceeding 350 ft. The construction (and excavation) shots ranged from 1¼ to 12¾ lb at distances of 30 to 160 ft. Soil overburdens were 0 to 5 ft for construction, under 10 ft for quarries, and generally above 5 to 10 ft for coal mines.

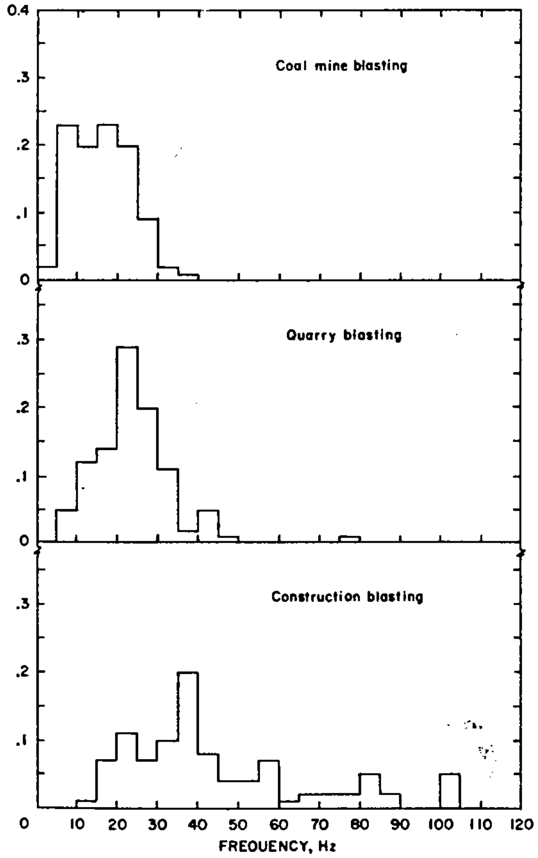


Figure 2.—Predominant frequencies of vibrations from coal mine, quarry, and construction blasting.

Time histories and Fourier frequency amplitude spectra from three typical blasts measured by a buried three-component transducer are shown in figures 3 to 5 (*50*). The coal mine shot is characterized by a trailing large-amplitude, low-frequency wave, which is probably a surface wave generated in the overburden layers. Quarry blasts do not usually show this low-frequency tail for one or more of the following reasons: smaller charge weights, smaller shot to instrument distances, and thinner soil overburdens. The combination of large shots, thick soil and sedimentary rock overburdens, relatively good confinement, and long-range propagation make coal mine blast vibrations potentially more serious than quarry and construction blasts because of their low frequencies. By contrast, coal mine highwall blasts are inefficient generators of airblast (*46*). Hard rock construction and excavation blasts tend to be shorter in duration and contain higher frequency motions than those of either coal mine or quarry.

Frequency characteristics of blast vibrations depend strongly on the geology and blast delay intervals. Except for the short-distance, all-rock case, they are difficult to predict and vary widely. Therefore, it is desirable to obtain complete time histories rather than simple peak values in any sensitive areas. Many examples of continual complaints about severe rattling at levels below 0.5 in/sec are attributable to the low frequencies. Research is continuing on the effects of blast design, face orientation, and near-surface geology on the character of both the ground vibrations and airblast.

OTHER VIBRATION SOURCES

Earthquakes, nuclear blasts, and very large scale, in situ mining shots all produce potentially damaging ground vibrations, as well as do other static and quasistatic vibration sources (traffic, pile driving, sonic booms, etc.). The first Bureau of Mines blast vibration summary in 1942 examined the levels of earthquake vibrations and the corresponding Mercalli intensities for damage, and concluded these did not apply to blasting (*51*). Earthquakes produce long-duration and very low frequency events.

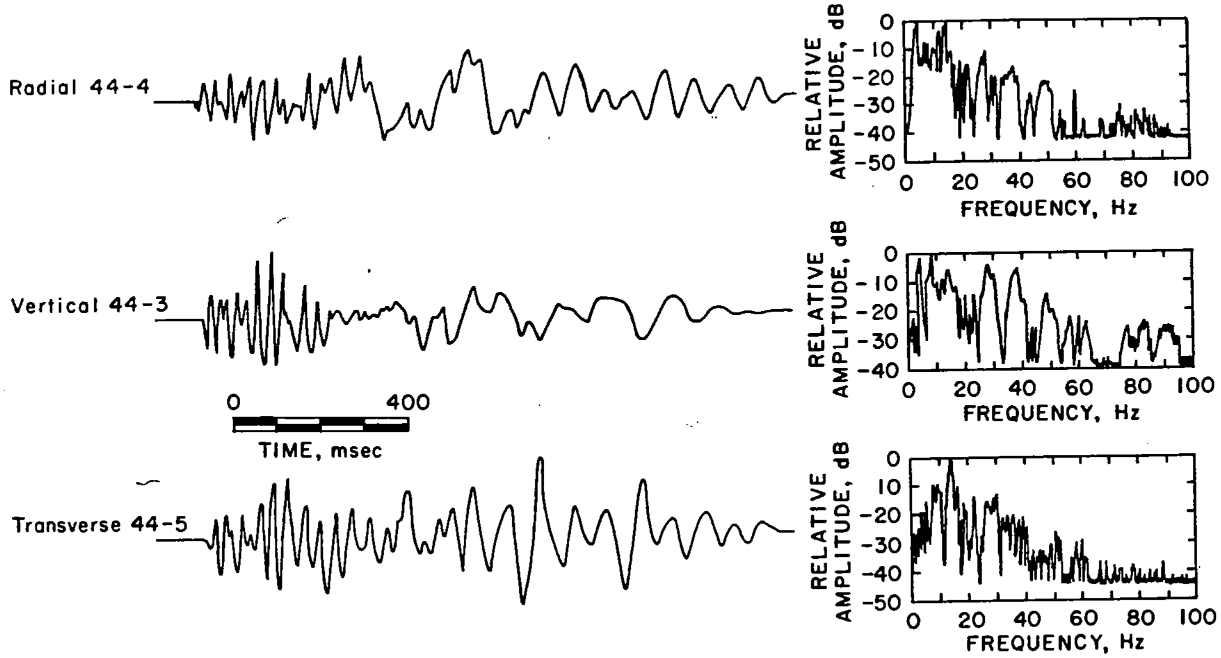


Figure 3.—Coal mine blast time histories and spectra measured at 2,287 ft.

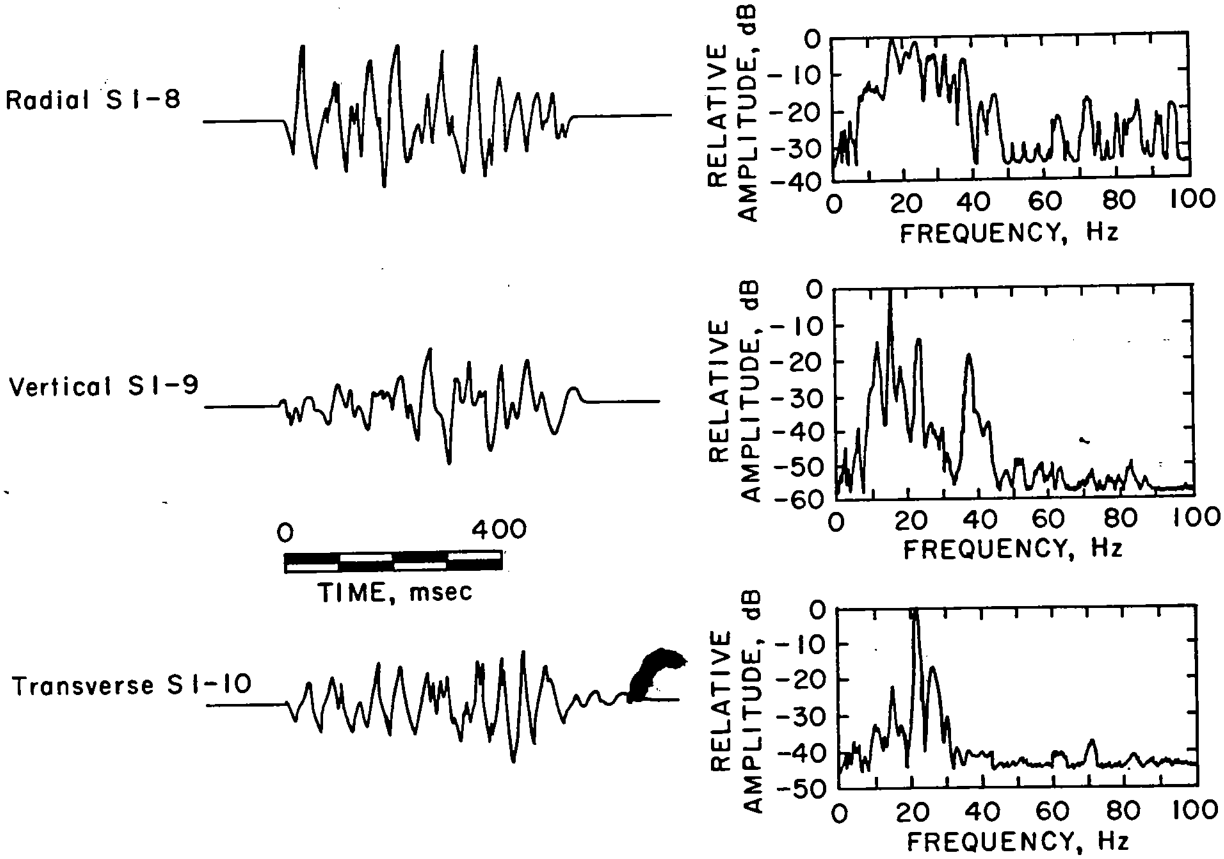


Figure 4.—Quarry blast time histories and spectra measured at 540 ft.

Acceleration levels are typically used by seismologists to quantify damage potential. These may be of moderate and even lower levels than found in blasting; however, their low frequencies produce large particle velocities and enormous displacements. As an example, Richter states that a 0.1 g acceleration at 1 Hz is ordinarily considered damaging in earthquake seismology (*41*). The corresponding particle velocity and displacement are 6.15 in/sec and 0.98 in, respectively, assuming simple harmonic motion. The same acceleration at 20 Hz would only produce 0.308 in/sec particle velocity and 0.0025 in displacement. Richter also observes that the damage potential of a given vibration is dependent on its duration, with 0.1 g at 1 Hz likely not to produce damage for events of a few seconds, but very serious for earthquake-type events of 25 to 30 sec (*41*).

A similar case is provided by the Salmon nuclear study and similar large blasts (*5, 35, 39, 42-43, 45*). These blasts all produced low-frequency and long-duration ground vibrations resulting from their sizes and distances. The Salmon vibration time history was 90 sec long at the structures (18 to 31 km) that were alleged to have been damaged. These durations are hardly comparable to those in mine, quarry, and construction blasting. Consequently, damage data of this kind cannot justifiably be correlated with the scale of blasting of concern in this analysis. However, the dynamic modeling techniques developed during the extensive research of earthquake and nuclear blast response can be applied to the study of blasting and the mechanisms of structural response.

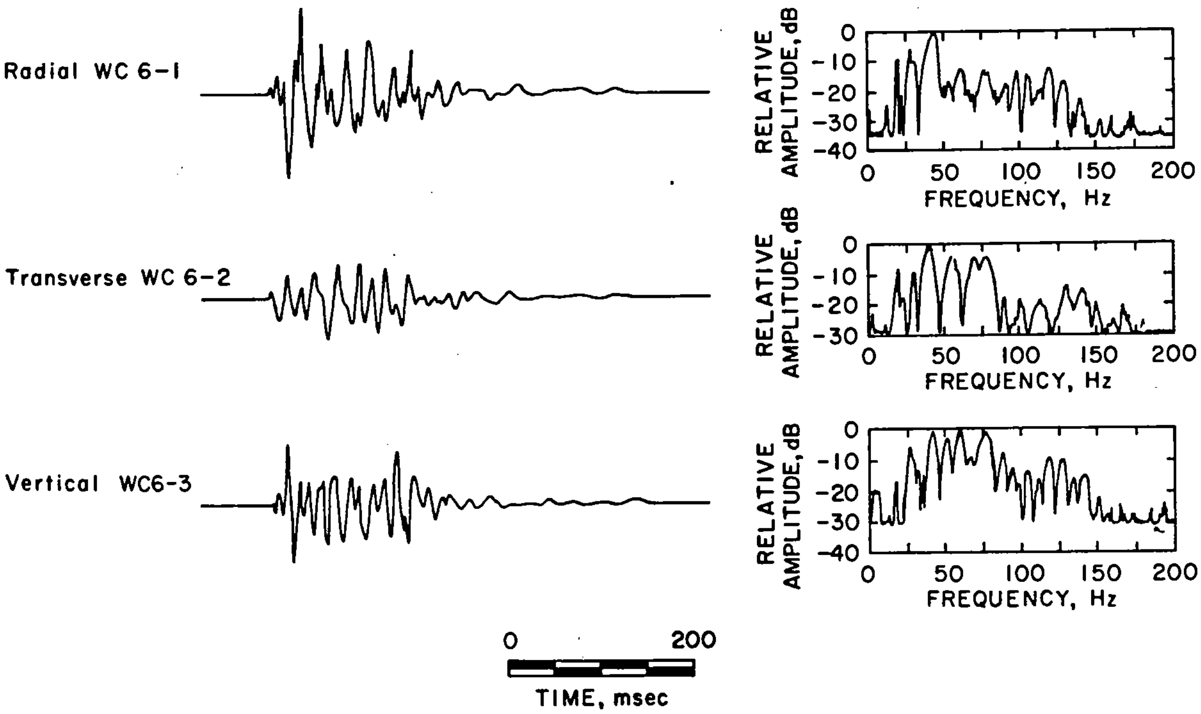


Figure 5.—Construction blast time histories and spectra measured at 75 ft.

GENERATION AND PROPAGATION

Much research has been conducted on ground vibrations. Generation and propagation of ground vibrations have been studied extensively to determine the effects of blast design and geology on vibration amplitudes and frequency character. In Bulletin 656, Nicholls summarized the Bureau's investigation of vibrations produced by blasting in 25 stone quarries, dating back to 1959 (*37*). The Bureau also conducted a series of studies of vibrations generated in four operating underground metal mines in 1974 (*45*). A major study was recently completed by Wiss that quantifies the influence of many of the blast design parameters on both ground vibration and airblast generation and propagation in five surface coal mines (*56*). Lucole also recently published the results of a year of routine monitoring of vibration levels generated by various types of blasting (*29*).

Prior to the last two studies, no data existed on vibrations generated by blasting in surface coal mines. It has been standard practice to apply the blast design rules developed for the small-hole, hard-rock quarry blasting to surface coal mines. Blast holes in surface coal mines have typical diameters exceeding 6 in, and in large area mines they are typically 9 to 15 in. These diameters are larger than those used in most quarries. The highwall blasts of surface coal mines are heavily confined, since they are used only to loosen the overburden and produce little or no throw. Decking is often used with complex timing systems, combining electronic and pyrotechnic delays. The rock being blasted is highly layered and of lower sonic velocity and strength than that in aggregate and lime quarries. Distances to houses are usually greater than for quarries, which are often in or near urban centers. Soil and incompetent rock overburden beneath structures near coal mines is normally tens of feet thick, far more than at most quarries.

Consequently, coal mine blasting is normally characterized as follows:

1. Relatively large charge weights per delay.
2. Complex delay systems that are optimized for efficient fragmentation but that may produce adverse ground vibration frequencies.
3. Relatively high ground vibration levels close-in from heavy confinement of highwall shots.
4. Relatively rapid falloff of ground vibration levels with distance because of attenuation in weak rock.
5. Ground vibrations having predominantly low frequencies because of thick soil overburdens, strong geologic layering that favors surface waves, and large blast-to-structure distances.

BLAST DESIGN AND GROUND VIBRATION GENERATION

As in studies on quarry blasting, most blast design parameters for surface coal mine blasts have little influence on the generated vibrations. Charge weights per delay were again the most influential parameter. A small decrease in ground vibrations was noted for shallow as opposed to great depths of burial. Also, the location of the receiver relative to both the face and direction of blast initiation influenced the delay intervals at which constructive wave interference was experienced (*56*).

The Bureau of Mines vibration data are given in table 1. Included are charge weights, distances, ground vibration, and structure vibration levels for the predominantly coal mine blasts. The two horizontal components of motion were alined with the walls of the nearby structures for analysis of response and did not necessarily correspond to the traditional "radial" and "transverse." The "structure number" of table 1 is for identification, and the "structure type" is the number of stories.

Vibration levels generated from one surface coal mine are shown in figure 6. The maximum horizontal and vertical ground motions were plotted for each blast. Equations and statistics for the various vibration propagations, including Site A (fig. 6), are given in table 2. All particle velocities are in inches per second, distances in feet, and charge weights in pounds. Propagation curves from a variety of surface coal mines are given in figures 7–9. Six of the propagation curves (Nos. 1–2 and 6–9) are from vertical hole blasts studied by Wiss (*56*). The remaining propagation curve (No. 19) is from a single Bureau of Mines site, where actual radial and transverse values were available.

Table 1.—Production blasts and ground vibration measurements

Shot	Facility	Shot type	Total charge, lb	lb per delay	Sealed distance, ft/lb$^{1/2}$	Peak ground vibration, in/sec			Peak structure motion, in/sec							Structure number (table 3)	Structure type
									Low corner			High corner		Midwall			
						H_1	H_2	V	H_1	H_2	V	H_1	H_2	H_1	H_2		
1	Coal	Highwall	6,000	500	38.00	1.07	1.07	0.80				0.76	0.49		1.41	27	1
2	Coal	do	7,200	600	33.00	1.38	1.19	.68				.87	.75		1.57	27	1
3	Coal	do	7,800	650	29.00	1.89	1.74	.59				.79	.54		1.55	27	1
4	Coal	do	7,200	1,200	20.00	1.91	1.85	.95				.81	.67		2.19	27	1
5	Coal	do	7,800	1,300	18.10	2.07	2.33	.94				.87	.56	2.37	3.18	27	1
6	Coal	do	7,800	650	24.00	3.73	1.73	.73				.82	.60	2.79	2.83	27	1
7	Coal	do	7,800	650	23.00	5.31	3.82	1.04				1.29	.70	4.96	1.55	27	1
9	Coal	do	6,600	550	22.00	2.34	1.97	.88				.82	.42	2.63	1.67	27	1
10	Coal	do	5,400	450	26.00	1.20	1.22	.61				.76	.39	1.24	1.72	27	1
11	Coal	do	3,600	300	33.00	.72	.52	.28				.33	.24	.82	.60	27	1
13	Quarry	Highwall	2,033	280	24.00	.76	.66	.49						1.02		1	1
14	Quarry	do	4,353	218	61.00	.29	.22	.32	0.90		0.85					1	1
15	Quarry	do	1,995	303	52.00	.18	.22	.36						.11		2	1
16	Quarry	do	2,850	187	88.00	.49	.24	.26						.37		3	2
17	Quarry	do	5,047	200	100.00	.21		.14						.33		1	1
17	Quarry	do	5,047	200	129.00	.16								.15		4	2
18	Quarry	do	2,367	305	22.90	1.00		3.82						1.53		1	1
18	Quarry	do	2,367	305	45.70	.53								.30		4	2
19	Quarry	do	2,450	160	86.00	.44		.33						.26		5	2
19	Quarry	do	2,450	160	119.00	.50								.32		6	1
33	Quarry	do	8,762	700	124.70	.15	.13	.07						.30		7	1
33	Quarry	do	8,762	700	124.70	.05								.16		8	1
35	Iron	Highwall		4.200	17.90		1.86								1.74.	10	2
35	Iron	do		4,200	17.90	.07		.09						.45		11	2
35	Iron	do		4,200	17.90	.07		.09						.33		12	2
35	Iron	do		4,200	17.90	.07		.09						.14		13	1
36	Iron	do		21,000	132.50	.02		.01						.04		14	2
36	Iron	do				.02		.01						.06		15	1
36	Iron	do		21,000	48.30	.03								.05		16	1
37	Iron	do		2,184	85.60	.18								.38		18	1
38	Iron	do		15,530	337.80	.01		.01	.01	0.01				.02		14	2
39	Coal	do	20,300	2,300	64.00	.25	.23	.12	.42	.11	.30			.46	.97	19	2
40	Coal	Parting	648	72	767.00	.01	.01	.01							.04	19	2
41	Coal	Highwall	21,800	2,600	58.00	.28	.20	.15	.40	.24	.24			.44	.79	19	2
43	Coal	do	20,700	2,600	56.00	.30	.39	.26	.34	.14	.34			.54	1.49	19	2
43	Coal	do	20,700	2,600	43.95	.87								1.37		20	1
44	Coal	do	20,600	2,300	57.00	.21	.36	.28	.29	.10	.42			.45	1.71	19	2
44	Coal	do	20,600	2,300	47.69	.91								1.20		20	1
45	Coal	Highwall	20,700	2,300	55.00	.33	.41	.20	.32	.10	.35			.68	2.27	19	2
45	Coal	do	20,700	2,300	48.94	1.13								.73		20	1
46	Coal	Ditch	3,600	600	91.00	.07	.11	.03	.05	.03	.14			.10	.84	19	2
46	Coal	do	36,000	600	71.57	.06								.23		20	1
47	Coal	Highwall	21,600	2,600	50.00	.26	.29	.24	.25	.10	.71			.54	1.09	19	2
47	Coal	do	21,600	2,600	47.32	1.10								.93		20	1
48	Coal	do	20,600	2,300	51.00	.24	.33	.25.	19	.10	.80			.48	1.00	19	2
48	Coal	do	20,600	2,300	51.71	.79								.68		20	1
49	Coal	do	19,800	2,200	54.00	.39	.28	.22	.28	.19	.29	.61	.35	1.07		20	1
50	Coal	do	19,700	2,200	56.00	.24	.15	.25	.22	.17	.36	.40	.28	.87		20	1
51	Coal	do	19,300	2,200	57.00	.13	.14	.13	.11	.08	.21	.26	.13	.67	.32	20	1
53	Coal	Parting	264	24	621.00	.01	.01	.01	.00	.01	.01	.01	.01	.05		20	1
54	Coal	do	360	36	425.00	.02	.02	.01	.01		.01	.03		.02		20	1
55	Coal	Highwall	18,400	2,100	60.00	.14	.13	.18	.13		.30	.21		.51	.36	20	1

56	Coal	---- do ------	17,700	2,000	64.00	.16	.08	.15	.08	.23	.16	.26		.51		20	1
57	Coal	---- do ------	6,000	2,000	65.00	.18	.08	.12			.18	.21		.18	.27	20	1
58	Coal	Parting -----	480	30	444.00	.02	.01	.01			.02	.05		.02	.04	20	1
59	Coal	---- do ------	294	30	788.00	.01	.01	.01			.01	.01	.01	.01	.06	19	2
60	Coal	Highwall ---	21,400	2,000	38.00	.49	.82	.88			.98	.31	.20	.52	1.12	19	2
61	Coal	---- do ------	24,700	2,100	35.00	.44	.90	.93		.65	.93	.42	.30	.67	2.51	19	2
62	Coal	Sweetner ---	1,500	150	138.00	.12	.20	.06		.23	.09	.12	.06	.23	.43	19	2
64	Coal	Highwall ---	24,600	2,100	33.00	.51	.62	.85		.51	.96	.43	.26		1.02	19	2
65	Coal	---- do ------	15,700	2,200	30.00	.45	.59	1.06		.47	1.06	.76	.26		1.33	19	2
66	Coal	---- do ------	15,800	1,900	31.00	.62	.77	1.53		.54	1.56		.30		1.45	19	2
67	Coal	---- do ------	13,540	1,900	29.00	.66	.81	.78		.59	.89	.25	.30		1.92	19	2
68	Coal	Parting -----	300	30	713.00	.01	.01	.01		.01					.07	19	2
69	Coal	Highwall ---	11,040	2,000	26.00	.53	.70	.94		.45		.29	.26		1.76	19	2
70	Coal	Sweetner ---	2,100	300	86.00	.19	.16	.07		.11	.10	.12	.04		.49	19	2
71	Coal	Hilltop ------	9,020	410	67.00	.21	.28	.17		.27	.26	.17	.10		.91	19	2
72	Coal	Ditch --------	3,060	510	93.00	.07	.09	.03		.03	.07	.07			.60	19	2
73	Coal	Highwall ---	19,600	2,000	24.00	1.24	1.24	2.24	.78	.97	2.22	.44	.33	2.08	2.77	19	2
74	Coal	---- do ------	17,100	2,000	23.00	.75	1.12	1.23	.62	.78	1.28	.38	.27	1.06	2.20	19	2
75	Coal	Ditch --------				.09	.07	.08	.07	.06	.14	.05	.05	.18	.35	19	2
76	Coal	---- do ------	3,360	280	93.00	.08	.12	.12			.18	.07	.08	.29	.50	19	2
77	Coal	---- do ------	1,200	220	102.00	.07	.07	.05			.08	.05	.03	.16	.36	19	2
78	Coal	Highwall ---	22,200	2,100	20.00	.68	1.14	1.58			1.79	.50	.39	1.66	2.38	19	2
79	Coal	---- do ------	24,900	2,200	18.20	1.58	1.69	2.45			2.93	.87	.71	2.55	3.24	19	2
80	Coal	Highwall ---	25,100	2,300	16.70	1.14	1.03	0.70			1.04	.63	.54	1.09	2.38	19	2
81	Coal	Sweetner ---	3,240	360	37.00	.35	.45	.24			.35	.25	.21	1.08	1.79	19	2
82	Coal	Hilltop ------	27,000	1,000	22.00	1.98	1.85	1.65			4.01	1.34	.84	3.26		19	2
83	Coal	Ditch --------	2,040	340	81.00	.06	.06	.05						.06	.12	19	2
84	Coal	Highwall ---	25,600	2,200	16.10	1.37	1.05	1.48			2.33	.87	.54	2.96	2.50	19	2
85	Coal	---- do ------	25,400	2,200	15.60	2.20	1.27	1.91			1.15	.87	.58	3.76	3.76	19	2
86	Coal	---- do ------	25,900	2,200	15.30	1.89	1.23	2.21			3.08	.95	.40	3.66	3.04	19	2
87	Coal	Ditch --------	1,320	220	98.00	.08	.05	.06			.07	.05	.03	.24	.30	19	2
89	Coal	Parting -----	360	36	372.00	.01	.01	.01			.02	.02	.02	.03	.04	19	2
90	Coal	Highwall ---	25,500	2,200	15.40	1.68	1.53	2.51			3.37	.94	.51	2.72	3.23	19	2
91	Coal	---- do ------	31,500	2,200	15.70	1.99	1.60	2.45			2.69	.74	.41	2.92	3.67	19	2
92	Coal	Ditch --------				.16	.12	.11			.19	.08	.04	.44	.62	19	2
93	Coal	Parting -----	114	12	626.00	.00	.01	.00						.02	.02	19	2
94	Coal	Highwall ---	30,700	2,200	17.10	.79	1.25	1.41			2.75	.63	.57	2.88	1.73	19	2
95	Coal	---- do ------	26,600	2,200	17.90	2.08	1.14	1.35			2.06	.63	.49	5.07	1.83	19	2
96	Coal	---- do ------	20,500	2,000	19.30	1.22	1.18	.99			2.41	.73	.49	3.07	1.66	19	2
97	Coal	---- do ------		450	118.00	.03	.01	.04	.06	.02				.11		21	1
98	Coal	---- do ------	14,400	450	127.00	.05	.01	.04	.04	.04				.16		21	1
99	Coal	Parting -----	20,880	773	50.00	.27	.19	.15	.34	.26				.61		21	1
100	Coal	---- do ------	18,000	200	53.00	1.26	.88	.72	.46	.59				1.68		21	1
101	Coal	---- do ------	17,500	350	96.00	.08	.05	.08	.13	.05				.29		21	1
102	Coal	---- do ------	27,040	208	48.00	1.20	.79		.69	.58				2.50		21	1
103	Quarry	Highwall ---	4,956	632	62.00	.32	.27	.19				.15	.14	.41	.28	22	2
103	Quarry	---- do ------	4,956	632	28.00	.82	.76	.53			.67	.49	.58	.90		23	1
104	Quarry	---- do ------	5,752	632	59.00	.22	.41	.13	.47	.22		.40	.24	.55	.62	22	2
104	Quarry	---- do ------	5,752	632	26.00	1.09	.77	.44			.60	1.04	.70	1.32		23	1
105	Quarry	---- do ------	4,350	615	22.00	.85	.61	.42			.70	.47	.52	.72		23	1
106	Quarry	---- do ------	17,604	852	144.00	.16	.19	.14	.12	.13		.26	.15	.44	.34	23	1
106	Quarry	---- do ------	17,604	852	79.00	.04	.03	.03	.03	.03		.03	.04	.08	.10	22	2
107	Coal	---- do ------				.17	.26	.20	.13	.26	.29			.53	.42	.26	1
108	Coal	---- do ------				.21	.20	.24	.21	.17	.20	.37	.22	.99	.92	28	1
109	Coal	---- do ------		300	105.00	.09	.04	.08	.08	.15		.11	.32	.30	.31	29	2
110	Coal	Parting -----	21,600	240	52.00	1.33	1.02	.52		.50		.33	.35	1.85	1.49	21	1
111	Coal	---- do ------		320	56.00	.79	.69	.34	.60	.28	.26	.57	.57	1.54	.80	21	1
112	Coal	Highwall ---		300	81.00	.43	.39	.20					.28	.93	1.02	30	1
113	Coal	Parting -----		320	61.00	.45	.69	.33			[illegible]			.86		21	1
114	Coal	---- do ------	23,680	370	68.00	.47	.51	.47			.26			.93	.17	21	1
116	Coal	Highwall ---	12,000	300	38.00	.24	.22	.23	.29	.25	.24	.37	.42	.53	.48	31	1
117	Coal	Parting -----	14,400	360	158.00	.04	.02	.02						.07	.02	21	1

Additional Info. in ERRATA

Table 1.—Production blasts and ground vibration measurements—Continued

Shot	Facility	Shot type	Total charge, lb	lb per delay	Scaled ~~Sealed~~ distance, ft/lb$^{1/2}$	Peak ground vibration, in/sec			Peak structure motion, in/sec							Structure number (table 3)	Structure type
									Low corner			High corner		Midwall			
						H_1	H_2	V	H_1	H_2	V	H_1	H_2	H_1	H_2		
119	Quarry	Highwall	16,608	782	154.00	0.03	0.04					0.04	0.04	0.04	0.11	32	2
120	Coal	do	15,120	120	137.00	.19	.09	0.11	0.25	0.09	0.18					31	2
122	Coal	do		15	430.00	.03	.05	.03	.02	.02	.02	.09	.13	.17	.27	28	1
124	Coal	Parting	1,340	20	447.00	.02	.02	.02	.03	.09	.05	.04				33	2
125	Coal	Highwall	10,200	200	141.00	.13	.13	.21	.09	.09	.01	.16		.72	.32	33	2
126	Coal	Parting	1,200	20	391.00	.02	.02	.03	.01	.02	.02					34	1
127	Coal	Highwall	12,000	400	88.00	.16	.13	.08	.15	.11	.16			.34	.36	34	1
129	Coal	do	15,000	350	166.00	.06	.09	.04	.06	.05	.06			.36	.30	35	1
130	Coal	Parting	890	20	391.00	.02	.02	.01	.05	.04	.07			.04	.05	34	1
131	Coal	Highwall	10,800	400	88.00	.15	.14	.10	.11	.10	.20			.36	.24	34	1
132	Coal	Parting	1,300	30	219.00	.05	.06	.04	.04	.03	.03	.09	.09	.24	.13	33	2
133	Coal	Highwall	24,000	400	60.00	.07	.07	.04	.07	.05	.05		.15	.12	.09	33	2
134	Coal	Parting	2,300	400	60.00	.23	~~.36~~ .32	.16	.22	.19	.12	.32	.23		.49	33	2
135	Coal	-------------				1.14	1.00	.02	.76	.66	.75	.61	.75	1.52	2.41	21	1
136	Coal	Parting	29,700	900	16.70	1.54	1.12	1.59	.94	.65		.70	.56	2.07	1.84	21	1
137	Coal	do	2,300	20	447.00	.03	.04	.02	.02	.02	.01	.03	.02	.20	.00	33	2
138	Coal	do	2,300	20	447.00	.03	.04	.02	.01	.01	.01	.05	.02	.20	.04	33	2
139	Coal	Highwall	19,200	400	100.00	.10	.12	.06	.11	.09	.07	.15	.12	.51	.20	33	2
140	Coal	Parting	1,000	20	783.00	.00	.01	.00	.04	.04	.02	.06	.03	.06	.05	35	1
141	Coal	do	1,000	20	537.00	.00	.00	.00		.00				.02		36	1
142	Coal	do	1,000	20	537.00	.00	.00	.00		.01				.02		36	1
143	Coal	Highwall	40,000	400	120.00	.06	.03	.02		.07	.03			.14	.17	36	1
144	Coal	Parting	2,400	10	750.00	.00	.00	.01		.00	.00			.02	.01	36	1
145	Coal	Highwall	40,000	400	120.00	.05	.05	.04	.03	.06	.05			.10	.19	36	1
146	Iron	do		4,580	86.00	.13	.22	.09	.13					.40		37	2
146	Iron	do		4,580	86.00	.05	.05	.04		.04				.08			2
146	Iron	do		4,580	86.00	.13	.22	.09	.42	.20				.50	.67		1
147	Iron	Highwall		8,800	74.00	.15	.17	.04	.15	.15	.03			.27	.22		1
147	Iron	do		8,800	74.00	.15	.17	.04	.39	.28				.70	.62	38	2
147	Iron	do		8,800	74.00	.15	.17	.04	.17	.11	.06			.14	.16	39	1
148	Iron	do		8,230	74.00	.11	.11	.03	.12	.12	.03		.14		.19	38	2
148	Iron	do		8,230	74.00		.11	.04	.11	.10	.03			.18			2
149	Iron	do	58,000	2,500	221.00	.00	.03	.00	.03	.01	.01	.04	.02	.05	.04	41	2
150	Iron	do		3,260	102.00	.07	.11	.07	.03	.04	.02	.07	.04	.16	.14	37	2
151	Coal	do					.02	.01	.03	.01	.01	.03	.05	.07	.05	42	2
152	Coal	do	3,585	255	132.00		.05	.05	.05	.04	.06	.07	.08	.11	.14	42	2
153	Coal	do	3,783	152	171.00		.09	.04	.09	.10	.06	.11	.15	.18	.25	42	2
154	Coal	do	3,000	125	51.00		.34	.51	.55	.38	.79	.44		.98	1.26	43	2
157	Coal	do	4,500	75	127.00		.14		.14	.11					.31		2
157	Coal	do	4,500	75	52.00	.34	.44	.26	.33	.38				.48	.58		1
158	Coal	do	2,450	41	180.00		.10		.10	.09				.25		45	2
158	Coal	do	2,450	41	56.00	.41	.32	.25	.52	.45				.66	.61		1
159	Coal	do	920	23	250.00		.04		.05	.03				.13		45	2
159	Coal	do	920	23	52.00	.33	.24	.33	.27	.25				.57	.46		1
160	Coal	do	5,460	78	51.00	.29	.23	.13	.11	.12		.17		.33	.55	47	1
161	Coal	do	3,280	41	34.00	1.17	.64	.64	.52	.37	.66	.62		2.02	1.72	48	2
162	Coal	do	13,040	602	61.00	.18	.19	.16	.12	.16				.41		49	2
163	Iron	do		8,530	6.50	.73	.53	.85	.81	.99	.87	.96	.61		1.15	50	1
164	Coal	do	3,510	351	45.00	.19	.15	.10	.16	.12	.19		.20	.37	.21	49	2
165	Coal	do	4,914	351	44.00	.25	.36	.13	.26		.25	.41	.48	.76	.64	49	2
166	Coal	do				.18	.17	.20	.13	.17	.19	.20	.23	.28	.32	49	2
167	Coal	do	1,750	35	51.00	.33	.42	.50	.38	.43	.49	.23	.44	.86	.94	51	2
168	Coal	do	4,300	86	27.00	.85	1.16	.72	.98	1.29	.77	.06	1.03	2.51	3.12	51	2

169	Coal	---- do ------	4,300	86	19.20	2.11	1.81	1.45	1.92	1.34	1.27		1.86	6.50	5.10	51	2
170	Coal	---- do ------	4,300	86	16.20	2.84	1.85	1.65	1.72	1.27	1.63	1.01	1.63	3.64	3.71	51	2
171	Coal	---- do ------	1,775	71	17.80	1.23	1.24	.97	.43	.62	.72	.82	.47	2.36	.79	51	2
172	Coal	---- do ------				.20	.17	.21	.19	.26	.29			1.04	.62	49	2
174	Coal	---- do ------	4,300	86	21.00	1.38	1.86	.85	.67	1.15	1.90	1.20	2.06	3.84	2.91	51	2
175	Coal	---- do ------	5,150	212	9.90	10.21	6.92	5.65	3.18	4.02	3.19	3.89	4.09	6.99	10.27	51	2
178	Coal	---- do ------	1,320	33	45.00	1.04	.64	.83	.33	.30	.64					51	2
179	Coal	---- do ------	2,145	33	31.00	1.84	2.08	1.47	1.38	1.32	1.78					51	2
180	Coal	---- do ------	1,620	18	4.00	10.58	2.02	2.92	3.69	1.33	2.12					51	2
181	Coal	---- do ------	1,980	22	18.50	7.25	4.90	4.76	1.65	2.55	2.75					51	2
182	Coal	---- do ------	1,620	18	3.30	6.37	3.46	3.46	3.06	2.60	2.70					51	2
183	Coal	---- do ------	2,375	125	206.00	.02	.02	.02	.02	.02				.16		52	1
186	Coal	---- do ------	350	35	127.00	.06	.04	.03	.05	.03						54	1
187	Coal	---- do ------	350	35	127.00	.04	.04	.04	.06	.03						54	1
189	Coal	Highwall ---	360	40	119.00	.05	.03	.07	.04	.01					.06	54	1
190	Coal	---- do ------	720	40	119.00	.06	.03	.03	.06					.22	.04	54	1
191	Coal	---- do ------	400	40	119.00	.04	.02	.06						.06	.07	54	1
192	Coal	---- do ------	960	40	119.00	.06	.03	.05						.18	.07	54	1
193	Coal	---- do ------	3,780	60	36.00	2.67	2.11	3.20	.81	.72				.72		55	2
194	Coal	---- do ------	320	40	174.00	.02	.02	.02				.01		.07		56	2
195	Coal	---- do ------	424	40	174.00	.02	.01	.02				.01		.08		56	2
196	Coal	---- do ------	680	40	174.00	.03	.02	.03	.02			.02		.12		56	2
197	Coal	---- do ------	4,160	80	38.60	.80	.94	.59								49	2
198	Coal	---- do ------	1,200	30	32.90	1.02	.92	.43								57	1
199	Coal	---- do ------	1,200	30	31.00	1.08	.98	1.20								57	1
200	Coal	---- do ------	5,510	276	66.20	.25	.35	.25								49	2
201	Coal	---- do ------	1,200	30	28.70	1.19	1.13	.77								57	1
202	Coal	---- do ------	1,200	30	25.00	2.06	1.13	1.29								57	1
203	Coal	---- do ------		100	24.70	1.35	.77	.58								58	1
204	Coal	---- do ------		100	24.20	2.23	.68	.65								58	1
205	Coal	---- do ------		100	24.20	1.05	.66	.39	.85		1.00				.43	58	1
206	Coal	---- do ------	1,800	100	24.50	.73	.75	.55		.75				.87		58	1
207	Coal	---- do ------	1,800	100	24.50	1.88	1.76	.49		1.02	.50			.76		58	1
208	Coal	---- do ------		80	19.00	1.45	1.38	1.92								58	1
W 1	Constr	Excavation -	80	6	65.30	.18	.21	.26				.04	.06	.31	.27	59	1
W 2	Constr	---- do ------	14	2	45.40	.49	.58	.67	.44	.04		.28	.12	.92		60	2
W 3	Constr	---- do ------	12	1	60.00	.05	.03	.03	.02				.01	.02		60	2
W 4	Constr	---- do ------	110	7	60.50	.68	.60	.77	.39	.69	.36	.18	.29	.45		61	1
W 5	Constr	---- do ------	110	7	20.80	1.94	2.03	2.23			1.84	.57	.47			61	1
W 6	Constr	---- do ------	32	6	30.60	.35	.19	.29		.31	.27	.09	.18		.28	62	2
W 7	Constr	---- do ------	120	12	46.20	.24	.23	.10	.28	.21	.14	.15	.09	.47	.64	63	2
W 8	Constr	---- do ------	100	6	49.00	.27	.27	.13	.19	.13	[illegible]	.14	.06	.39	.37	63	2
W 9	Constr	---- do ------	1	1	49.20	.04	.06	.08		.07	.05	.05	.03	.20	.26	64	2
W 10	Constr	---- do ------	4	1	30.00	.11	.10	.22	.22	.21	.20	.12	.06	.38	.32	64	2
W 11	Constr	---- do ------	18	4	98.90	.37	.32	.40	.15	.07	.06	.09	.07		.14	65	1
W 12	Constr	---- do ------	20	4	96.20	.25	.20	.22	.07	.06	.08	.07	.07		.20	65	1
W 13	Constr	---- do ------	27	8	17.50	.47	1.09	.52		.73	.41	.24	.47		1.81	66	1
W 14	Constr	---- do ------	30	9	23.00	.40	.40	.40		.65	.31	.38	.47		1.30	66	1
W 15	Constr	---- do ------	30	9	25.40	.15	.32	.18		.27	.14	.24	.32		.72	66	1
W 16	Constr	---- do ------	41	12	11.50		2.47	1.25	1.30	.64	1.17	.40	.18	1.18	1.01	67	2
W 18	Constr	---- do ------	119	10	44.80	.46	.69	.51		.11	.13	.18	.16	.22	.17	68	1
W 19	Constr	---- do ------	127	10	36.80	.72	.84	.93	.19	.47	.31	.21	.25	.29	.21	68	1
W 20	Constr	---- do ------	22	3	39.20	.53	.53	.30		.20		.14	.09	.28	.34	69	1
W 21	Constr	---- do ------	24	3	16.60	1.09	.77	.80	.19	.24	.12	.15	.17	.62	.64	69	1
W 22	Constr	---- do ------	46	7	38.50	1.56	.76	1.43	.54	.32	.45	.15	.13	.56	.55	70	1
W 23	Constr	---- do ------	42	7	11.70	3.73	2.08	3.20	2.49	1.44	2.70		.77		1.53	71	1
W 24	Constr	---- do ------	51	6	28.00	.64	.81	1.76	.55	.48	.73	.26	.41	.52	.35	72	2
W 25	Constr	---- do ------	50	6	63.30	.96	.85	.49	.30	.21	.39	.26	.43	.65	.24	73	1
W 26	Constr	Excavation -	70	6	64.00	1.61	1.32	.67	.47	.27	.58	.47	.53	.92	.26	73	1
W 27	Constr	---- do ------	70	6	61.20	1.16	1.20	.75	.38	.42	.25	.32	.46	.63	.25	73	1
W 28	Constr	---- do ------	43	5	41.60	1.14	.85	1.26	.62	.73	.52	.71	.17	1.09		74	1
W 29	Constr	---- do ------	58	7	30.20		1.44	1.80	.84	1.04	.70	.85	.29	.89	1.46	74	1
W 30	Constr	---- do ------	27	6	42.60	.27	.28	.21	.04	.17	.07	.09	.07	.30	.40	75	1
W 31	Constr	---- do ------	85	6	65.30	.53	1.22	.75	.23	.32	.39	.12	.29	.15	.89	76	1
W 32	Constr	---- do ------	85	6	32.00	1.82	1.19	1.55	.46	.50	.73	.15	.47	.19	1.09	76	1

*2σ → PPV= 438(SD)$^{-1.52}$

Table 2.—Equations and statistics for ground vibration propagation

Site and component	Equation	Correlation coefficient	Standard error, pct
Site A:			
Maximum horizontal	$GV = 84.5 (D/W^{1/2})^{-1.324}$	NA	NA
Vertical	$GV = 134.1 (D/W^{1/2})^{-1.569}$	NA	NA
Radial:			
Site 1.	$GV = 82 (D/W^{1/2})^{-1.324}$	0.977	35
Site 2	$GV = 68 (D/W^{1/2})^{-1.324}$	.971	35
Site 6	$GV = 54 (D/W^{1/2})^{-1.493}$	.973	35
Site 7	$GV = 44 (D/W^{1/2})^{-1.447}$	.902	85
Site 8	$GV = 135 (D/W^{1/2})^{-1.475}$	.981	42
Site 9	$GV = 281 (D/W^{1/2})^{-1.729}$	.980	47
Site 19	$GV = 79.2 (D/W^{1/2})^{-1.383}$	.937	41
Vertical:			
Site 1	$GV = 137 (D/W^{1/2})^{-1.531}$	.973	52
Site 2	$GV = 80 (D/W^{1/2})^{-1.551}$	.968	52
Site 6	$GV = 56 (D/W^{1/2})^{-1.553}$	.960	52
Site 7	$GV = 79 (D/W^{1/2})^{-1.676}$	.972	34
Site 8	$GV = 110 (D/W^{1/2})^{-1.312}$	.963	29
Site 9	$GV = 298 (D/W^{1/2})^{-1.823}$	.984	42
Site 19	$GV = 335 (D/W^{1/2})^{-1.825}$	.942	54
Transverse:			
Site 1	$GV = 64 (D/W^{1/2})^{-1.234}$	.951	66
Site 2	$GV = 51 (D/W^{1/2})^{-1.234}$	.931	66
Site 6	$GV = 55 (D/W^{1/2})^{-1.362}$	.975	44
Site 7	$GV = 40 (D/W^{1/2})^{-1.425}$	.944	54
Site 8	$GV = 50 (D/W^{1/2})^{-1.257}$	.937	45
Site 9	$GV = 106 (D/W^{1/2})^{-1.480}$	.940	59
Site 19	$GV = 64.2 (D/W^{1/2})^{-1.381}$	.946	37
All Bureau of Mines coal mine data:			
Maximum horizontal	$GV = 133 (D/W^{1/2})^{-1.50}$	.933	83
Vertical	$GV = 79 (D/W^{1/2})^{-1.46}$	.923	88
Total	$GV = 119 (D/W^{1/2})^{-1.32}$	.936	92
Mines[1]:			
Radial	$GV = 52 (D/W^{1/2})^{-2.37}$	NA	58
Vertical	$GV = 51 (D/W^{1/2})^{-2.49}$	NA	59
Transverse	$GV = 73 (D/W^{1/2})^{-3.13}$	NA	55
Quarries[1]:			
Radial	$GV = 14 (D/W^{1/2})^{-1.22}$	NA	57
Vertical	$GV = 13 (D/W^{1/2})^{-1.51}$	NA	61
Transverse	$GV = 10 (D/W^{1/2})^{-1.11}$	NA	57
Construction[1]:			
Radial	$GV = 5.0 (D/W^{1/2})^{-1.09}$	NA	85
Vertical	$GV = 8.9 (D/W^{1/2})^{-0.99}$	NA	72
Transverse	$GB = 5.9 (D/W^{1/2})^{-1.12}$	NA	80

NA = Not available
GV = Ground vibration, in/sec.
D = Distance, ft.
W = Charge weight per delay, lb.

[1] From Lucole and Dowding (*29*).

All Bureau coal mine vibration data are shown in figure 10. A vibration level of 1.0 in/sec was typically observed at a square root scaled distance of 23 ft/lb$^{1/2}$ and never observed beyond 60 ft/lb$^{1/2}$. The equivalent scaled distances for 0.5 in/sec peak particle velocity are 38 and 80 ft/lb$^{1/2}$. Wiss found that square root and cube root scaled distances required to enclose or envelope all his vibration data at 1.0 in/sec were 75 ft/lb$^{1/2}$ and 300 ft/lb$^{1/3}$, respectively (*56*). Two standard deviations of the summary data in figure 10 should leave roughly 2.5 pct of the points outside the upper limit. This corresponds to scaled distances of 55 and 90 ft/lb$^{1/2}$ at 1.0 and 0.5 in/sec, respectively. As alternatives to vibration monitoring or for statistical predictive purposes, the maximums represented by the envelopes (e.g., fig. 10) or two standard deviations from the mean regressions can be used; however, these will result in conservative vibration levels.

The Bureau of Mines coal data, as well as all of Lucole's (*29*), consist of relatively few measurements at each of a large variety of sites. Consequently, the pooled data representing each industry as a whole tends toward large scatter (high standard deviations).

Both Wiss (*56*) and Nicholls (*37*) utilized arrays of gages and found that the propagation from individual sites could reliably be quantified (fig. 7–9) and that vibration levels for individual sites could be reasonably predicted from scaled distances.

VIBRATION COMPARISONS: MINE AND QUARRY BLASTS

Vibrations from quarry blasting have been discussed extensively in Bulletin 656 (*37*). That report recommended two scaled distances intended to prevent the exceeding of 2 in/sec. For a site where propagation conditions were shown to be normal, a square root scaled distance of 20 ft/lb$^{1/2}$ was recommended. In the absence of any vibration monitoring, a scaled distance of 50 ft/lb$^{1/2}$ was to be used, based on the envelope of maximum observed values.

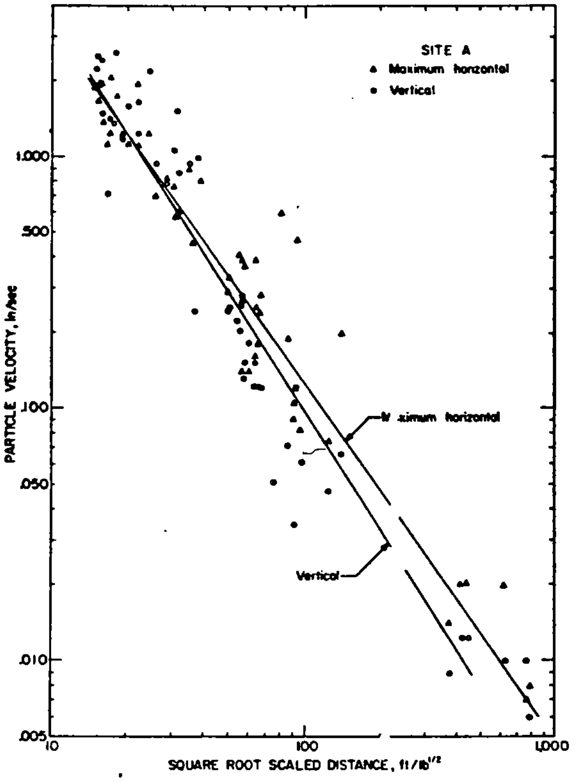


Figure 6.—Ground vibrations from a single coal mine. Equations are given in table 2.

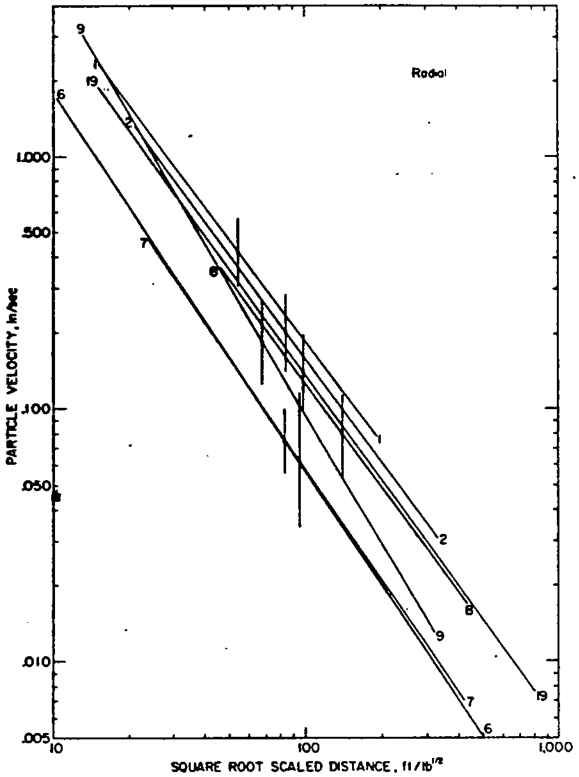


Figure 7.—Radial ground vibration propagations from surface coal mines.

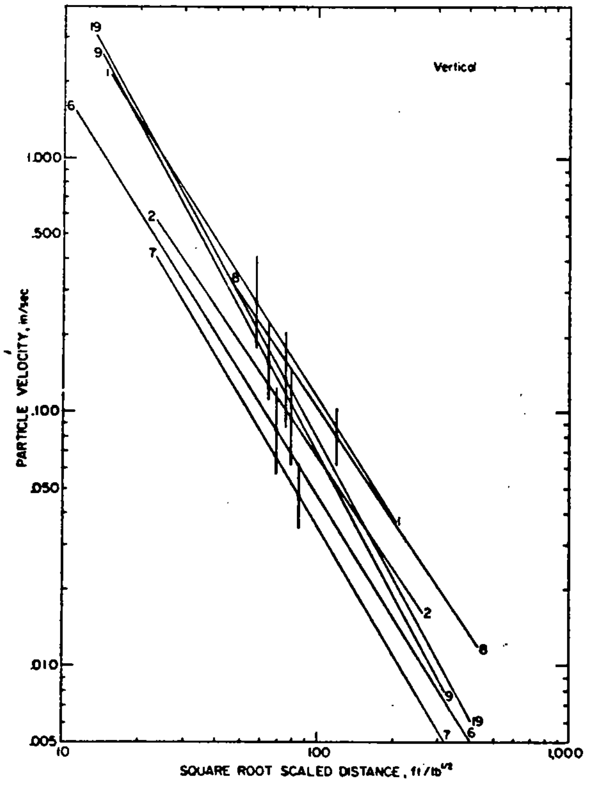


Figure 8.—Vertical ground vibration propagations from surface coal mines.

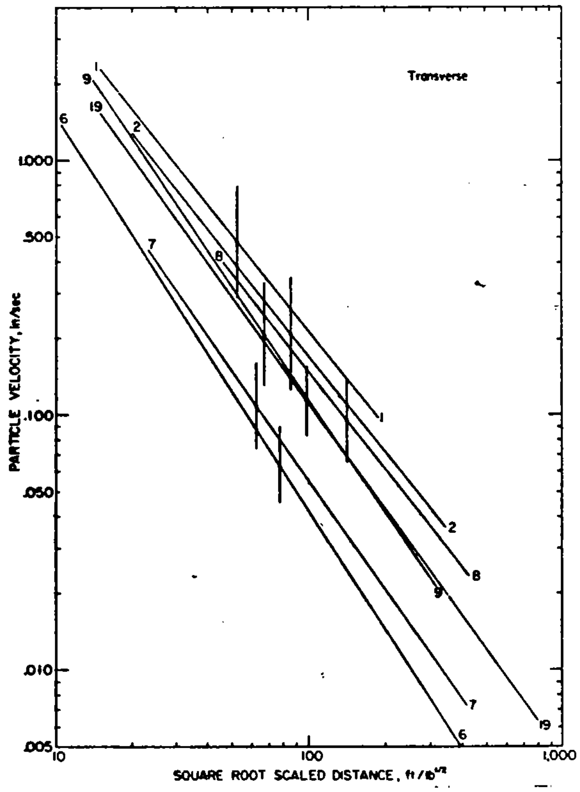


Figure 9.—Transverse ground vibration propagations from surface coal mines.

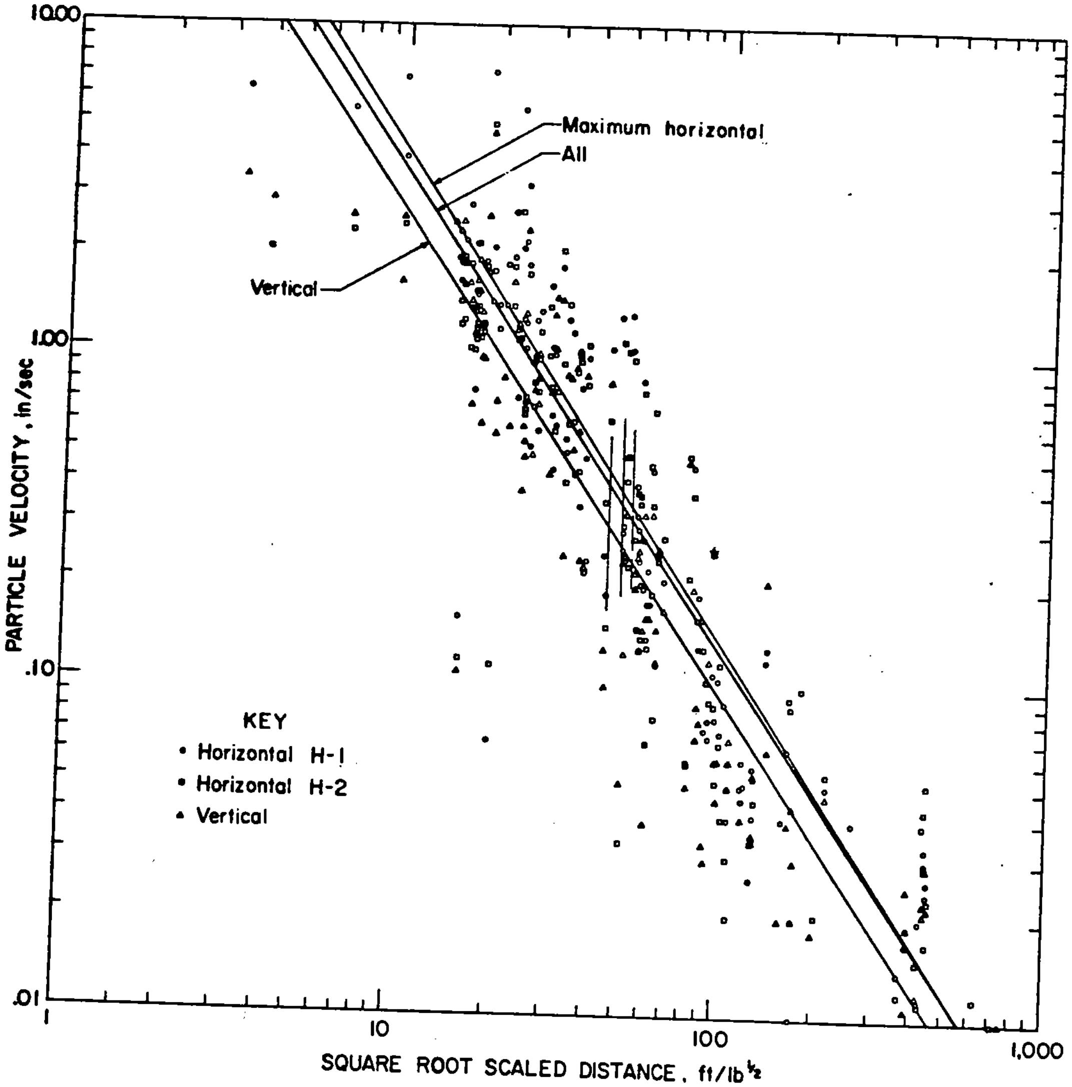


Figure 10.—Summary of ground vibrations from all surface coal mines. The component H–1 approximates "radial" and H–2 "transverse".

The overall zones encompassing the propagation regression lines for the radial motion (usually the largest) for coal mine and quarries are shown in figure 11. It is obvious that the vibration levels for coal and quarry blasting are similar, particularly at the smaller scaled distances that warrant most concern. Contrary to expectations, the coal mine vibrations were of greater amplitude than quarry vibrations at larger scaled distances. This is probably the result of larger absolute distances involved (for the relatively large charge weights) and the possible existence of slower decaying surface waves and dispersion-produced interference between delays at these distances. The Lucole study found different relative amplitudes between coal and quarry blasting to be more in agreement with the theoretical predictions (fig. 12). However, their data were also characterized by larger scatter and only a rough approximation to a Gaussian distribution (*29*). Their maximum envelope at 1.0 in/sec exceeded 200 ft/lb$^{1/2}$ for all kinds of blasting. Two standard deviations (95 pct) of the propagation data at 2 in/sec was less than 41 ft/lb$^{1/2}$ for coal mines and 33 ft/lb$^{1/2}$ for quarries and construction. These are both significantly lower than the Bureau's coal mine summary value of 55 ft/lb$^{1/2}$ from figure 10.

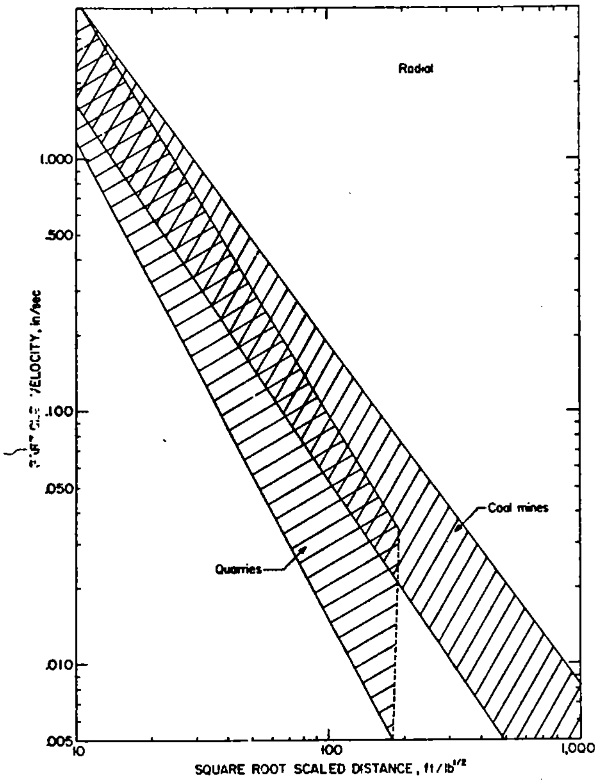


Figure 11.—Zones of mean propagation regressions for two major types of blasting.

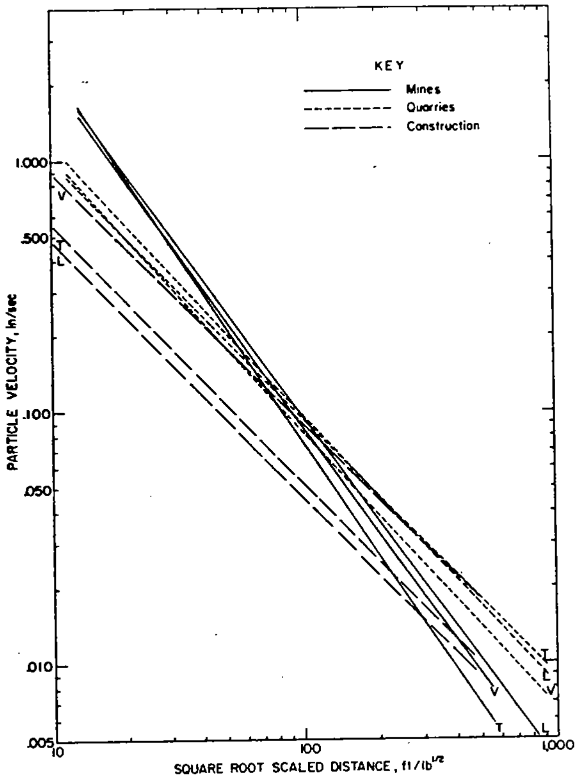


Figure 12.—Ground vibration propagation for three types of blasting as found by Lucole (*29*). Longitudinal (L), transverse (T), and vertical (V) components.

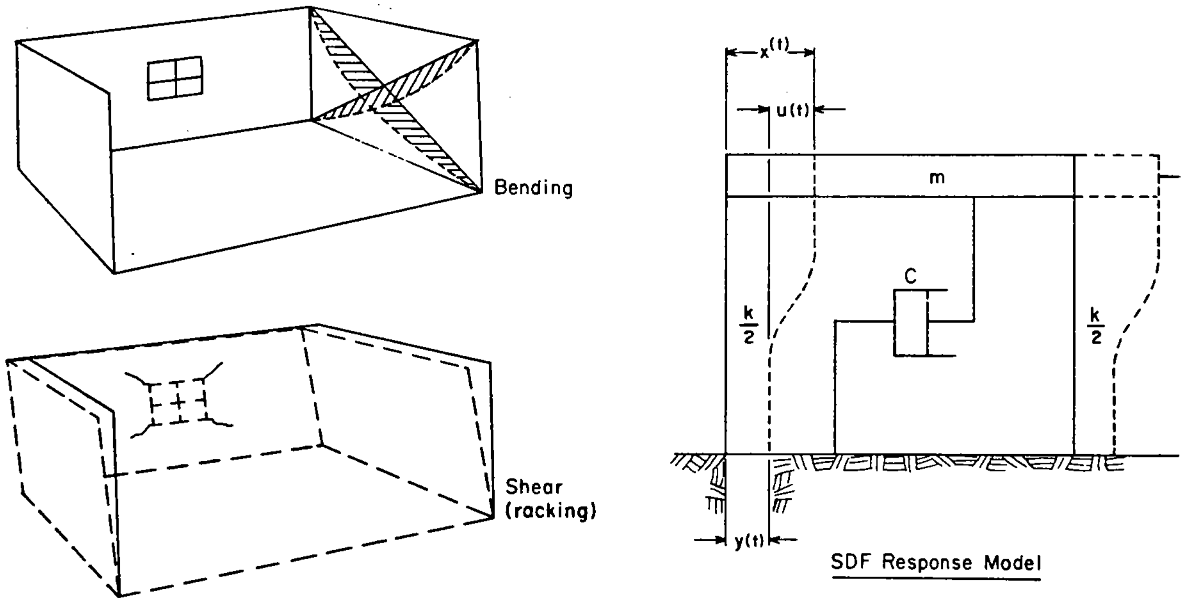
RESPONSE OF RESIDENTIAL STRUCTURES

The measured response of residential structures is a critical indicator of troublesome or potentially damaging ground vibrations. Corner motion measurements were used to assess the racking motions (shearing) of the gross structure (fig. 13). Essentially, cracking from blasts occurs where excessive stresses and strains are produced within the planes of the walls or between walls at the corners. Consequently, the vibration in the corners is assumed to indicate cracking potential, because it corresponds to whole-structure response. Other types of response cause different but consequential results. Midwall motions (normal to the wall surface) were also measured and are primarily responsible for window sashes rattling, picture frames tilting, dishes jiggling, and knick-knacks falling. Structures are designed to resist normal vertical load; however, differential vertical motions can produce high strains in floors and ceilings. Vertical floor motions are also of concern for potential human response.

RESPONSE SPECTRUM ANALYSIS TECHNIQUES

A simple method for predicting structural responses to vibrations has developed from studies of building response to earthquakes. It is based upon the single degree of freedom (SDF) model of a structure shown in figure 13 (*8, 10, 13, 24, 30, 32, 42*). The relative displacement between the mass and the ground, u(t), can be mathematically calculated from a knowledge of the time-varying ground displacements, y(t). The simplifying assumptions behind this mathematical idealization are as follows:

1. The structure can be represented by a lumped mass, m.
2. The relative displacement and deformation of the structure produces a restoring force proportional to the stiffness of the structure, k.
3. During vibration, energy is dissipated through viscous friction, C, which is constant regardless of the amplitude of the motion.



Response

SDF Response Model

Figure 13.—Single degree of freedom (SDF) model and types of structures response. SDF symbols are explained in the text.

4. The structure responds or translates only in a single direction—hence the name single degree of freedom (SDF). Incorporation of simultaneous torsional rotation or additional components of motion requires additional degrees of freedom.

In an actual structure, m is the mass of the walls, floor, and roof; the restoring force is that produced by the walls resisting shear deformation, and frictional dissipation of energy results from portions of the structure working against each other. Nail pulling is one consequence. The equation of motion of the SDF system, subjected to a time varying motion, is

$$\ddot{u} + 2\beta\omega_n\dot{u} + \omega_n^2 u = -\ddot{y} \qquad (1)$$

where $\ddot{u}$, $\dot{u}$, u, are relative acceleration, velocity, and displacement,

$\ddot{x}$, $\dot{x}$, x are absolute acceleration, velocity, and displacement of mass,

$\ddot{y}$, $\dot{y}$, y are absolute acceleration,velocity, and displacement of the ground,

ω_n is the circular natural frequency (also $2\pi f_n$) and related to stiffness (k) and mass (m) by: $\omega_n = \sqrt{k/m}$, and

β is the damping ratio (pct of critical /100) and equal to $C/\sqrt{km}$,

where C is the viscous damping and is equal to $\sqrt{km}$ when critical.

The natural frequency, ω_n, describes the rate at which the mass will freely oscillate when displaced. The damping, β, controls the decay of the oscillation. When a structure is critically damped (β = 1.0), it will return to its equilibrium position without oscillating.

Equation 1 can be solved for the relative displacement at any time, t, when given a transient ground particle velocity time history, $\dot{y}$. The solution is shown in equation 2:

$$u(t) = \int_0^t \dot{y}(\tau)e^{-\beta\omega_n(t-\tau)} \left\{\cos\left[\omega_n\sqrt{1-\beta^2}\,(t-\tau)\right] + \frac{\beta}{\sqrt{1-\beta^2}}\sin\left[\omega_n\sqrt{1-\beta^2}\,(t-\tau)\right]\right\} d\tau \qquad (2)$$

When a ground particle-velocity time history, such as shown in figure 3, is processed by computer with this equation, the modeled time history is produced.

The time history produced by equation 2 is one of relative displacements, u, rather than the absolute velocity $\dot{x}$, which is normally measured on the structure. In this relative displacement time history there will be a maximum, u_{max}. If that maximum relative displacement is multiplied by ω_n (or 2πf), the resulting product, $2\pi f u_{max}$, is called the pseudo velocity, the PSRV, or the pseudo spectral response velocity. This pseudo velocity is a close approximation of the relative velocity, $\dot{u}$, when the assumption of simple harmonic motion is valid.

A response spectrum of a single ground motion, such as that of a hard-rock construction blast shown in figure 14, is generated from u_{max}'s from a number of different SDF systems. Consider two different components of the same structure, the 10 Hz gross structure and the 20 Hz wall. If the ground motions, $\dot{y}(t)$, of the construction blast are processed twice by equation 2 with β held constant at 5 pct and ω_n set to 2π(10) for the first time and 2π(20) for the second, two u_{max}'s will result: 0.01 in (0.25 mm) and 0.02 in (0.05 mm).

These u_{max}'s can be converted to two maximum pseudo velocities, 2π(10) (0.01) = 0.62 in/sec (15.7 mm/sec) and 2π(20) (0.02) = 2.5 in/sec (63.5 mm/sec); they are plotted in figure 14 as points *1* and *3*. If the ground motions from the construction blast are processed a number of times for a variety of ω's with β constant, the resultant pseudo velocities will form the solid line in figure 14.

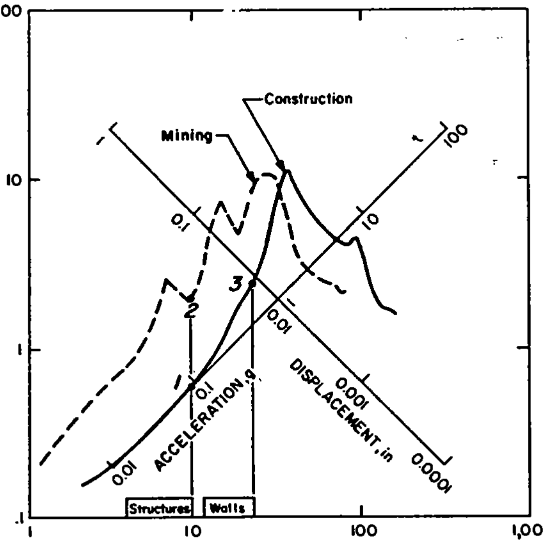


Figure 14.—Response spectra for mining and construction shots, after Corser (*8*).

The response spectra in figure 14 are plotted on four-axis tripartite paper. These four axes take advantage of the sinusoidal approximation involved in calculating a pseudo velocity. They are constructed so that the axis of the maximum relative displacement, u_{max}, is inclined upward to the left such that

$$u_{max} = PV/2\pi f,$$

where PV is the pseudo velocity, and that the axis of pseudo acceleration, PA, is inclined upward to the right such that

$$PA = PV \cdot 2\pi f.$$

The portion of a spectrum that is quasi-parallel to lines of constant displacement (less than 20 Hz for the mining blast in figure 14) is called the displacement bound. Likewise, the spectrum for the mining blast for frequencies greater than 50 Hz is the acceleration bound.

The response spectrum is similar to a Fourier frequency spectrum, since it shows the spectral content of a vibration time history. However, it is more useful as the pseudo velocity is calculated from a simplified measure of the maximum relative displacement, and as such it is related to wall strains that induce cracking.

Values of structure damping (β) must be assumed for computations of response spectra, and this value is 5 pct of critical in figure 14. This is a good approximation for a residence; however, the model response of residences is much more dependent on small changes in natural frequency than on small changes in damping (*32*).

Several researchers have applied response spectra techniques to blasting. Dowding examined responses from construction blasting (*10*). He shows the important relationship between the two frequencies (structure and ground motion) and how the ground motion descriptors of displacement, velocity, and acceleration affect response spectra of blasting vibrations. Most significant for blasting is that the principal frequencies of the ground motion almost always equal or exceed the gross structure natural frequencies of 4 to 10 Hz. This suggests either a displacement- or velocity-bound system in the 5- to 10-Hz range and supports the use of these motion descriptors to assess cracking potential. Earthquakes and nuclear blasts generate low principal frequency motions at the large distances of concern, and the 4- to 10-Hz range falls on the acceleration bound of the spectra.

Medearis developed response spectra for a variety of production blasts (*30*). This was one of the first attempts to show statistically that the structural response of residences (and consequently the cracking potential) is related to frequency content of the blasts. Medearis recommended safe particle velocities based on distances from the blasts that implicitly include the above-described frequency dependencies. These range from 3.20 in/sec (10 ft from a 2-story residence) to 0.62 in/sec (10,000 ft from a 1-story residence) and are based upon a 5-pct tolerance of damage. Medearis' suite of time histories was taken from quarry, excavation, and construction blasts, with an average spectral peak of 40 Hz. He therefore predicted that the relatively higher frequency 1-story homes with natural frequencies nearer 10 Hz are more damage-prone than taller 2-story homes with natural frequencies near 5 Hz. These results would not apply to mine blasts having ground vibrations at lower frequencies.

Corser calculated response spectra for a variety of blasts recorded by the Bureau of Mines (*8*). He found that, in the 5- to 10-Hz range (fundamental frequencies for wood frame structures), mining blasts generated SDF relative displacements that averaged 5.7 times (2.9 to 9.3) those of close-in construction shots. The time histories analyzed had peak particle velocities of 0.66 to 2.23 in/sec. Since the relative structure velocities will have similar ratios, the safe vibration levels for these two classes of blasts could differ by that same factor (5 to 6).

Figure 14 compares spectra from ground motions generated from surface coal mining and construction blasting in hard rock. Even though these two blasts produced peak particle velocities of 2.3 in/sec, the gross structure of a 1-story residence (represented by the 10 Hz response) would respond to the surface mining vibrations with relative displacements 3 times that of the higher frequency motions produced by the construction blasts.

Response-spectra analysis techniques are a powerful tool for research, engineering, and design because they include the important frequency effects. They can predict responses of a variety of structures for any type of time history. However, they do have some serious limitations in that their validity depends on how closely the structures fit the SDF model. They are not required for situations where responses can be determined empirically. They are not practical for regulatory purposes, as they are too complex and time consuming for agencies responsible for measurement and monitoring compliance. Where responses and damage potentials have been established for one type of structure, response spectra analysis allows predictions for quite different structures with unknown vibration character. Since taller structures better fit the SDF model, these techniques have been used widely for predictions of earthquake and nuclear blast effects on such structures.

DIRECT MEASUREMENT OF STRUCTURE RESPONSES

Measurements were made of structure motions, produced by both the ground-borne vibration and airblast, as part of the assessment of potentially damaging blasts. The measurement and recording systems have been described in Bureau reports (*45, 50*). Both ground and structure measurements were made with 2.50- and 4.75-Hz velocity transducers (Vibra-Metrics[6] 120 and 124) with flat frequency responses (-3 dB) of 3 to 500 Hz and 5 to 2,000 Hz, respectively. A few accelerometers, having low-frequency response down to 1 Hz, and a variety of blasting seismographs were used (*50*).

Test Structures

A total of 76 different structures were studied for ground vibration and airblast response and damage (table 3). All were houses except Nos. 13, 15, 16, and 50, which were 1- and 2-story structures somewhat larger than single-family residences, and No. 54, which was a mobile home. Some structures (Nos. 19 and 20) were studied in conjunction with highwall, parting, and surface blasts. The response of structures 1–6 was described in an earlier study (*45*). Of the 76 structures, only 14 were subjected to high enough levels for significant damage and nondamage data, although levels of response were measured for every structure. The 14 significant test houses are shown in figures 15–28.

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[6] Reference to specific brand names is made for identification only and does not imply endorsement by the Bureau of Mines.

Figure 15.—Test structure 19, near a coal mine.

Table 3.—Test structures and measured dynamic properties

Structure	No. of stories	Dimensions, ft		Construction				Natural frequency of structure, Hz		Damping, pct		Midwall natural frequencies, Hz	Midwall damping, pct	Shots (table 1)
		Plan NS × EW	Overall height	Superstructure	Exterior covering	Interior covering	Foundation	N-S	E-W	N-S	E-W			
1	1	22×30	14	Wood frame	Wood siding	Gypsum wallboard	Full basement					16		13,14,17,18
2	1	30×70	14	Masonry and wood	Stone	do	do							15
3	1½	35×35	16	Wood frame	Brick and wood	do	Partial basement					13		16
4	2	30×40	22	do	Wood siding	do	Full basement	8		2		19,22		17,18
5	2	40×40	22	do	Brick and wood siding.	do	Partial basement					19		19
6	1	40×40	14	do	Wood siding	do	Full basement	9				32		19
7	1	48×25	15	do	Asbestos siding	do	do							33
8	1	15×10	12	do	Wood siding	do	Concrete slab							33
9	1	61×29	14	do	do	do	Full basement							34
10	2	44×29	22	do	Asphalt sheathing	Plaster	do							35
11	2	26×32	30	do	Masonite siding	Gypsum wallboard	do					36		35
12	1½	27×36	20	do	Cedar shakes	do	do					25		35
13	1	54×100	16	do	Brick and stucco	do	Slab and crawlspace							35
14	1½	35×35	23	do	Wood siding	do	Full basement	10		7		14		36,38
15	1	125×25	12	Steel frame	Steel	do	Concrete slab	6		3		17		36,38
16	1	80×80	17		Brick and stucco	do	Full basement					8.3		36
17	1½	19×40	20	Wood frame	Wood shingles	do	do	10	9	5	7	18		37,146
18	1	44×28	13	do	Wood siding	do	Pillars in dirt	6	10	7	7	11.4		37,146
19	2	33×35	24	do	Wood siding	Plaster and lath	Partial basement	4	4	13	13	13,17	4.5,5.1	39–48,59–96
20	1½	39×29	21	do	do	Gypsum wallboard	Full basement	8	7	3	8	20	3.1	42–58
21	1	48×28	15	do	do	do	do	7	7	2	7	13.4,14.5	2.9,2.3	97–102,110, 111,113, 114,117, 135,136
22	2	27×76	26	do	Brick and masonite	Gypsum and paneling.	Crawl space	8	6	3	4	12.3,13.1	2.0,3.0	103,104
23	1	62×26	14	do	Asbestos shingles	Gypsum wallboard	do	9	7	2	5	18.5		103–105
24	1	24×55	15	do	Brick	do	Crawl space	10	10	2	4			106
25	1½	41×24	22	do	Wood siding	do	Full basement	8	10	8	3	13.7,16.3	1.8,3.6	106
26	1	40×31	15	do	Aluminum siding	do	Crawl space	7	8	6	4			107
27	1	51×30	15	do	Wood siding	Plaster and lath	Partial basement	7	6	10	6	17,24		1–11
28	1	42×28	14	do	Wood and aluminum.	Gypsum wallboard	Crawl space	7	8	6	4			108,122
29	2	26×35	22	do	Wood panel	do	do	7	8	2	2	17.7,13.0	1.1,2.2	109,120,121
30	1	34×48	16	do	Stone	do	Full basement							112
31	1	35×44	13	do	Wood siding	do	Crawl space	8	6	2	2	12.2,16.6	1.5,1.2	115,116,118
32	1½	58×26	22	do	Brick and masonite	Paneling and wallboard.	Concrete slab							119
33	1½	69×27	24	do	Stone	Gypsum wallboard	Full basement	8	9	2	2	16.0,19.7	1.5,2.1	124,125,132–134,137–139
34	1	33×33	18	do	Asphalt sheathing	Plaster	Crawl space	7	6	3	4			126,127, 130,131
35	1	32×37	18	do	do	Gypsum wallboard	do	7	6	1	4			128,129,140
36	1	28×40	14	do	Asphalt shingles	do	do	6	7	3		14,17		141–145
37	1½	32×26	20	do	Wood siding	Plaster and lath	Full basement	9	10	2	2	18.5,20		146,150
38	2	28×32	20	Masonry and wood.	Brick and aluminum.	Wood paneling	Concrete slab	4	6	5	3			147,148

Table 3.—Test structures and measured dynamic properties—Continued

Structure	No. of stories	Dimensions, ft		Construction				Natural frequency of structure, Hz		Damping, pct		Midwall natural frequencies, Hz	Midwall damping, pct	Shots (table 1)
		Plan NS × EW	Overall height	Superstructure	Exterior covering	Interior covering	Foundation	N-S	E-W	N-S	E-W			
39	1	34×29	15	Wood frame	Masonite siding	Paneling and wallboard	Full basement	5	5	7		14		147
40	1½	28×31	18	do	Stucco	Plaster and lath	Partial basement	5	8	7	2	13.6		148
41	2	40×28	22	do	Wood siding	Gypsum and plaster	Full basement	10	8	4	2	16.6		149
42	1½	44×30	20	do	do	Paneling	do	5	7	5	4	11.9,13.9		151–153
43	1½	28×46	23	do	do	do	do	8	5			18,18		154
44	1		15	do	do		do					11,11		155–156
45	2	55×44	32	Solid brick	Brick	Plaster on brick	do	9	10	3	3			157–159
46	1½	38×40	21	Concrete block	Concrete block	Plaster	do	10		4		11,11		157–159
47	1	87×38	15	Wood frame	Brick	Gypsum wallboard	do					12.5,13.3		160
48	1½	36×24	22	do	Wood siding	do	do					16.7,16.7		161
49	1½	41×35	27	do	do	Gypsum wallboard and plaster on lath						18.2,18.2		162,164–166, 172,197,200.
50	1	48×180	14	do	Aluminum siding	Gypsum wallboard	Concrete slab	9		2				163
51	2	50×43	28	Solid brick	Brick	Plaster on brick and lath	Full basement							167–171, 173–182
52	1	37×24	16	Wood frame		Wood paneling	do							183
53	1	24×35	15	do	Wood siding		Crawl space							184
54	1	12×60	15	Metal walls	Metal	Paneling	None							186,187, 189–192
55	1½	40×31	23	Wood frame	Wood siding		Full basement							193
56	1½	34×57	20	do	Wood siding		do							194,196
57	1	40×24	20	Wood frame	Aluminum siding	Plaster and lath and paneling	Sandstone blocks partial basement		8		9.6			198,199, 201,202 203–209
58	1	40.4×31	26	Brick and masonry	Brick and masonry	Brick and gypsum wallboard	Masonry basement							W–1
59	1	30.5×54		Wood frame	Wood siding	Gypsum wallboard	Continuous concrete footings							W–2
60	2	54×26.5		do	Aluminum siding	do	do							W–4,W–5
61	1	28.5×55.5		do	Brick and plywood	Gypsum wallboard and plaster	Concrete block							W–6
62	2	34.5×48		do	Board and bat	Gypsum wallboard	Slab on grade	11	5	3	8			W–7,W–8
63	2	76.8×80		do	Wood siding	Plaster	Wooden piers on spread footings							W–9,W–10
64	2	34.5×48		do	Board and bat	Gypsum wallboard	Slab on grade							W–11,W–12
65	1	26×25		do	Aluminum siding	do	Continuous concrete footings	8		6				W–13,W–14, W–15
66	1	26.5×34.5		do	Wooden shingles	do	do							W–16,W–17
67	2	19.5×46.5		do	Wood siding	Wood paneling except kitchen ceilings	Concrete block	8		6				W–18,W–19
68	1	55×34		do	Board and bat	Gypsum wallboard	do							W–20,W–21
69	1	41×37.5		do	Aluminum siding	do	do							W–22
70	1	33×44.5		do	Wood panels	do	Continuous concrete footings							W–23
71	1	23.5×23.5		do	Board and bat	Unfinished	do							W–24
72	2	41.5×28.5		do	do	Wallboard paneling	do							W–25,W–26, W–27
73	1	30.5×26.5		do	Asphalt shingles	Plaster	Concrete							W–28,W–29
74	1	28×45		do	do	Wallboard	Slab and concrete block	7	7	6	9			W–28,W–29
75	1	36.5×34		do	Plywood	Gypsum wallboard	Concrete							W–30
76	1	38.5×40.5		do	Wood plank	Wallboard	do							W–31,W–32

SEE ERRATA

Figure 16.—Test structure 20, near a coal mine.

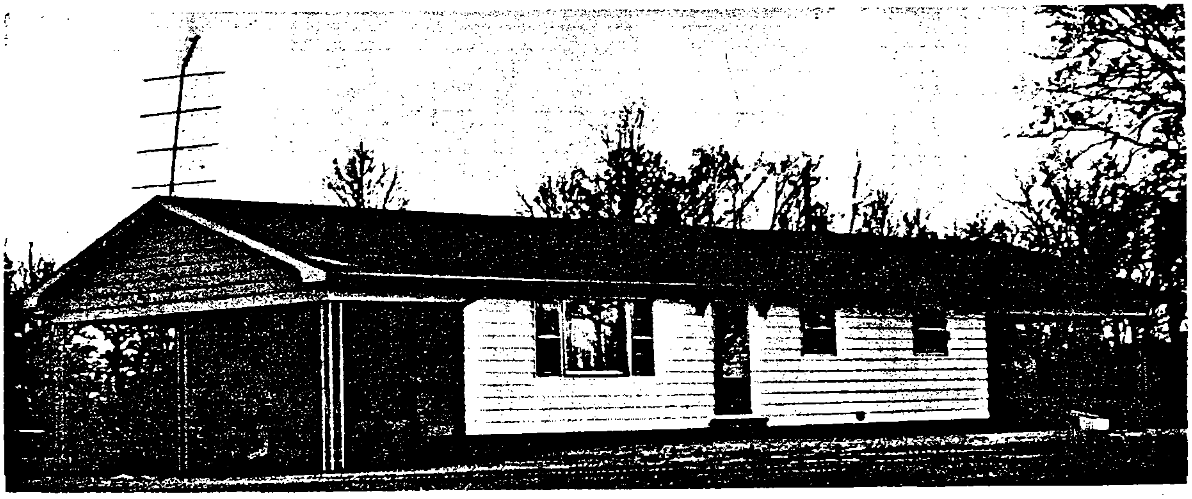

Figure 17.—Test structure 21, near a coal mine.

Figure 18.—Test structure 22, near a quarry.

Figure 19.—Test structure 23, near a quarry.

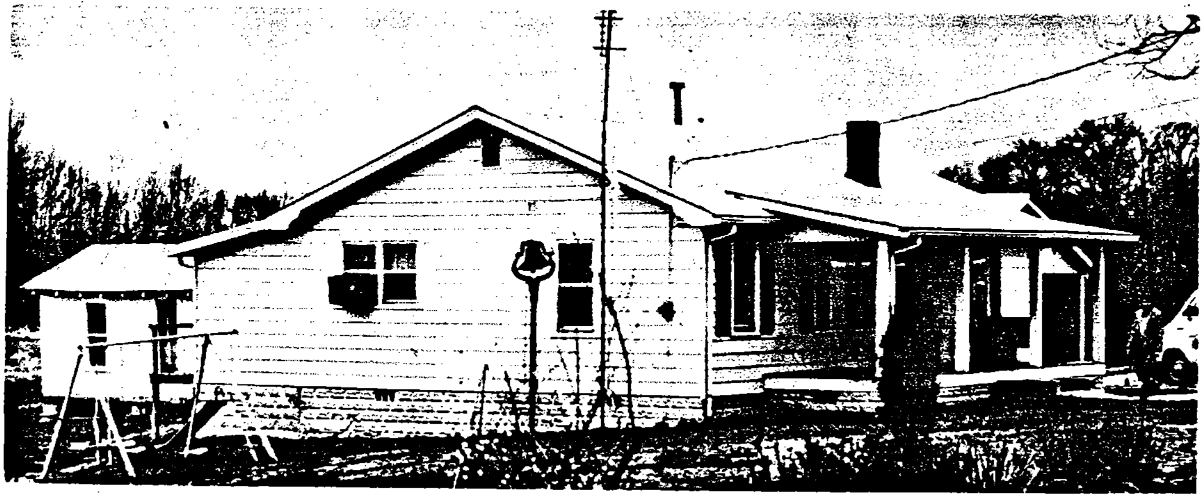

Figure 20.—Test structure 26, near a coal mine.

Figure 21.—Test structure 27, near a coal mine.

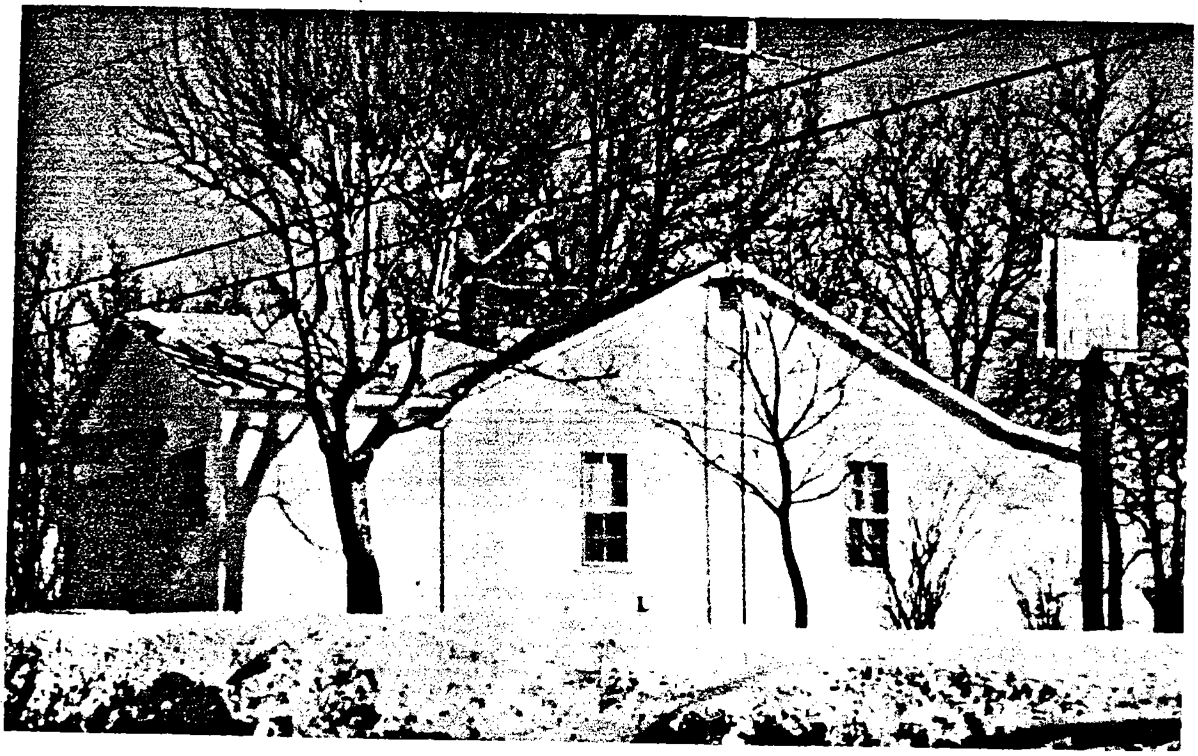

Figure 22.—Test structure 28, near a coal mine.

Figure 23.—Test structure 29, near a coal mine.

Figure 24.—Test structure 30, near a coal mine.

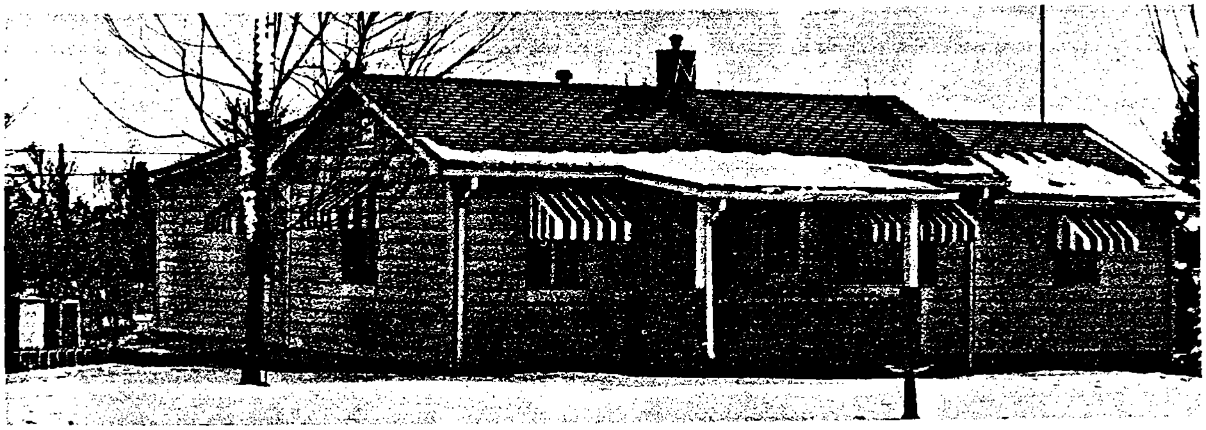

Figure 25.—Test structure 31, near a coal mine.

Figure 26.—Test structure 49, near a coal mine.

Figure 27.—Test structure 51, near a coal mine.

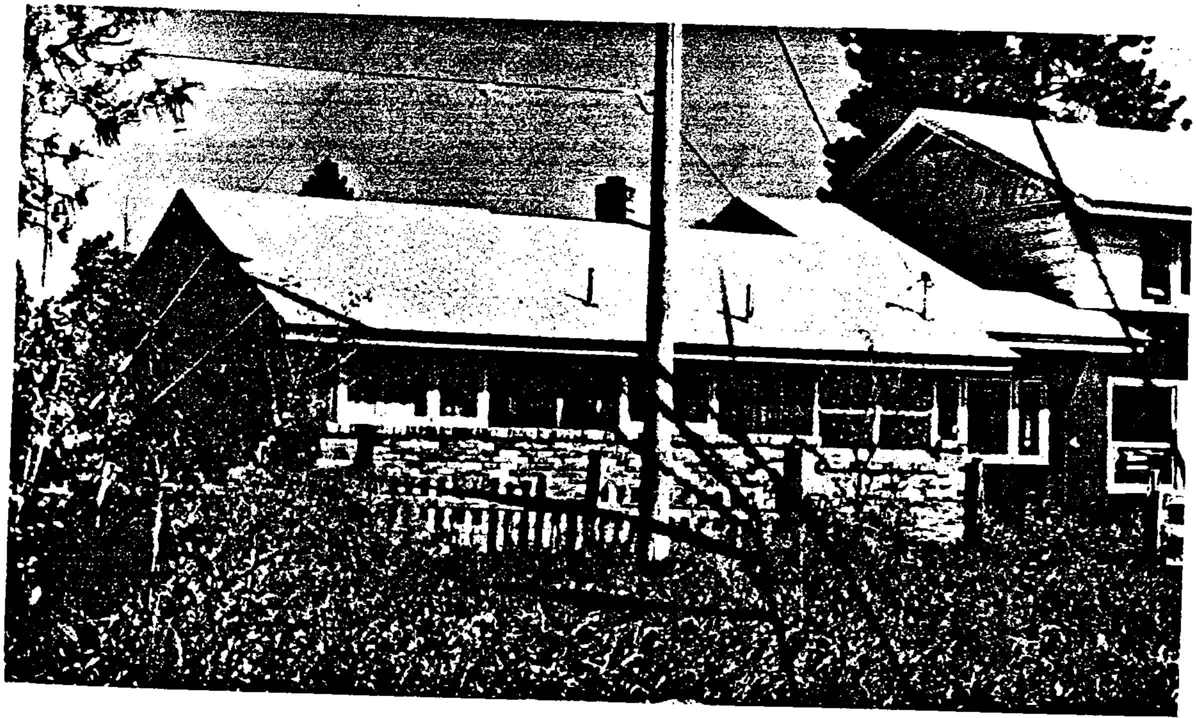

Figure 28.—Test structure 61, near a ~~coal mine~~.

Construction Site

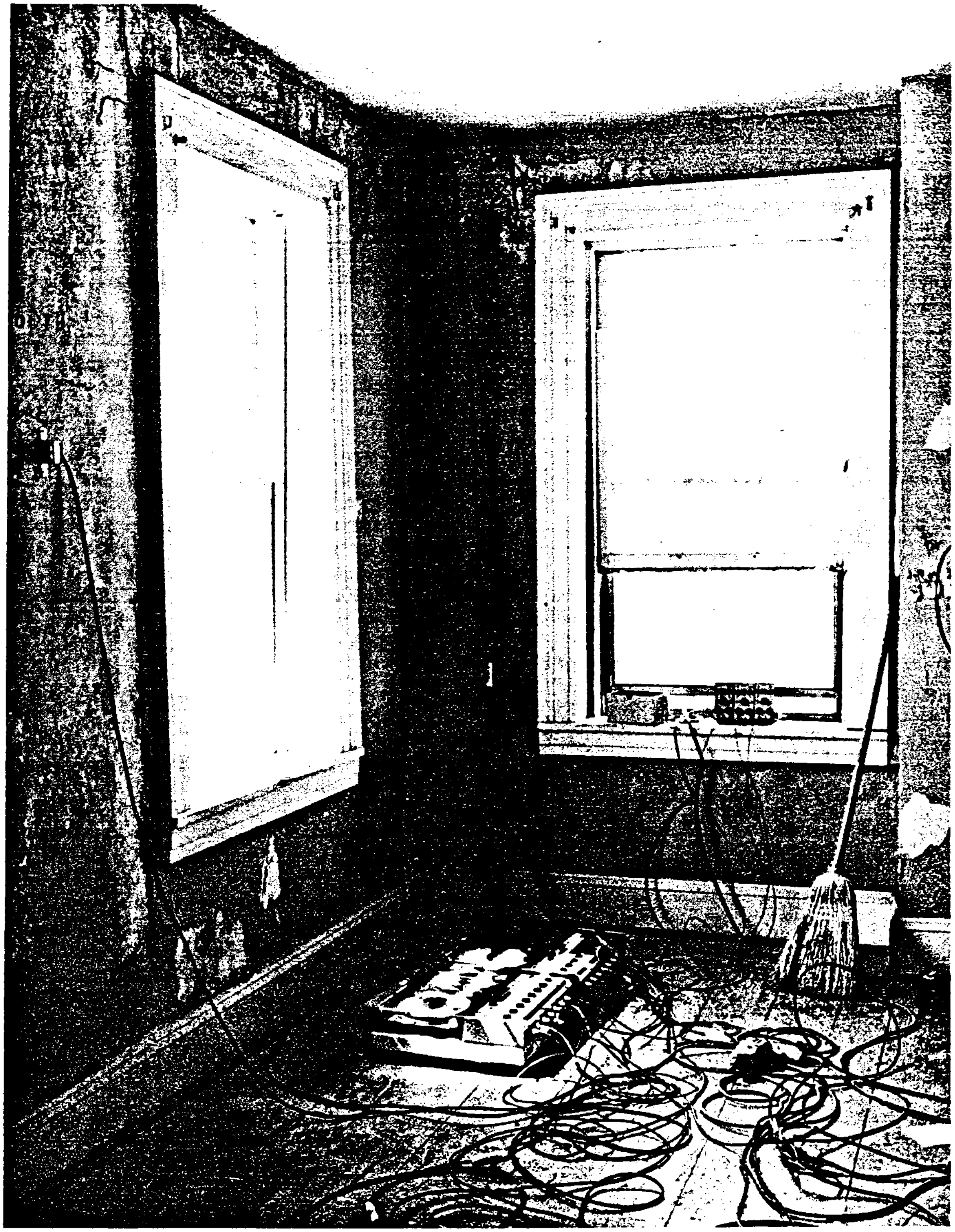

Figure 29.—Vibration gages mounted in corners and on walls for measuring structure response in structure 51.

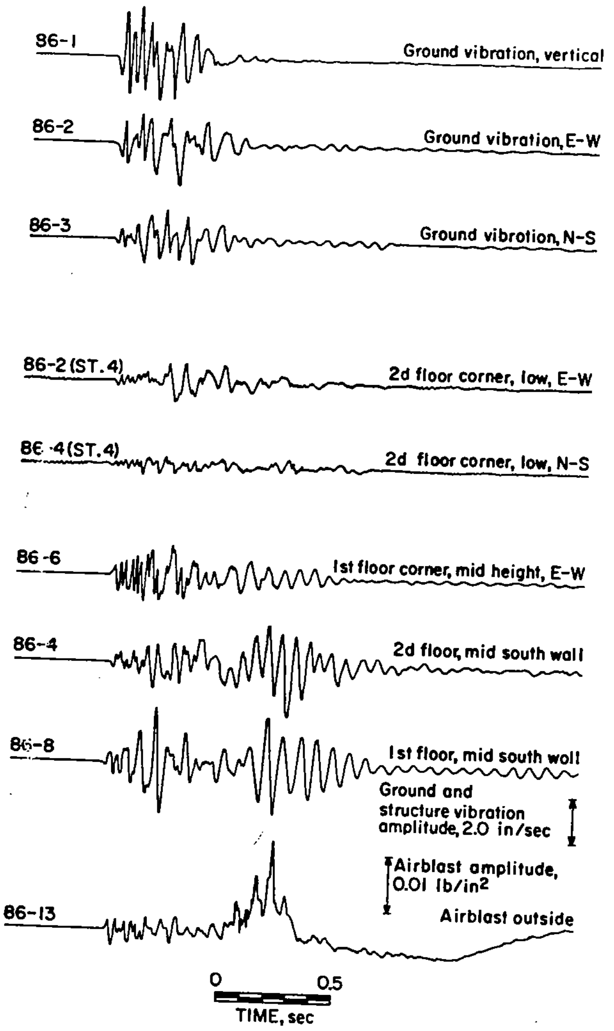

Figure 30.—Ground vibration, structure vibration, and airblast time histories from a coal mine highwall blast.

Instrumenting for Response

Outside ground vibration, airblast, structure corner, and midwall responses were measured for each shot. The ground vibration was measured by three orthogonal 2.5-Hz velocity gages buried about 12 inches in the soil next to the foundation (*50*). Outside airblasts were measured with at least one pressure gage and two sound level meters, one reading C-slow (*46*). The structures were instrumented for horizontal motions by a pair of gages mounted on the first-floor vertical walls in the corner closest to blasts and on one or more midwalls (fig. 29). Typically, the vertical motion was also measured in the same corner. Extra recording channels that were available were used for additional corner motions (at midheights, near the ceiling, or on the next floor); additional floor motions (e.g., midfloor verticals); basement wall horizontals; opposite corner responses (for torsional motions); and inside noise. A typical set of time histories is shown in figure 30. This particular shot produced strong airblast responses of the midwalls.

Natural Frequency and Damping

Natural frequency, ω_n, and damping, β, are the most important structure response characteristics. The structural natural frequencies as measured from blast-produced corner motions are summarized in figure 31, with individual values listed in table 3. Structures continue to vibrate after the sources (ground vibration and airblast) decay, and natural frequencies and damping can be measured from these free vibration time histories. The variations of structures, especially midwalls, are approximately sinusoidal; therefore, the natural frequencies are the inverse of the periods in seconds. Damping values calculated from free vibration motions are given by:

$$\beta = \frac{100}{2\pi m} \operatorname{Ln}(A_n/A_{n+m}),$$

where β is the percent of critical damping, A is the peak amplitude at the n^{th} cycle, and m is any number of cycles later. Dowding (*13*) and Langan (*24*) discuss the general problem of structure frequencies and damping. Their works include transfer function methods for calculating ω_n and β as well as amplitude-dependence of the damping value. Murray (*32*) computed many of the damping and frequency values in table 3, some of which were later reanalyzed by Langan (*24*).

Little difference in natural frequencies was observed among 1- and 1½-story homes; however, that for the 2-story homes was lower. Dowding (*13*) found average natural frequencies for the three types of homes of 8.0, 7.4, and 4.2 Hz, respectively. Medearis (*30*) measured frequencies and damping values for 61 houses and found similar results, except for some higher frequencies for the 1- and 1½-story homes. He found frequency ranges of 8 to 18 Hz (1-story), 7 to 14 Hz (1½-story) and 4 to 11 Hz (2-story). Damping, found by both investigators to vary between 2 and 10 pct, is summarized in figure 32.

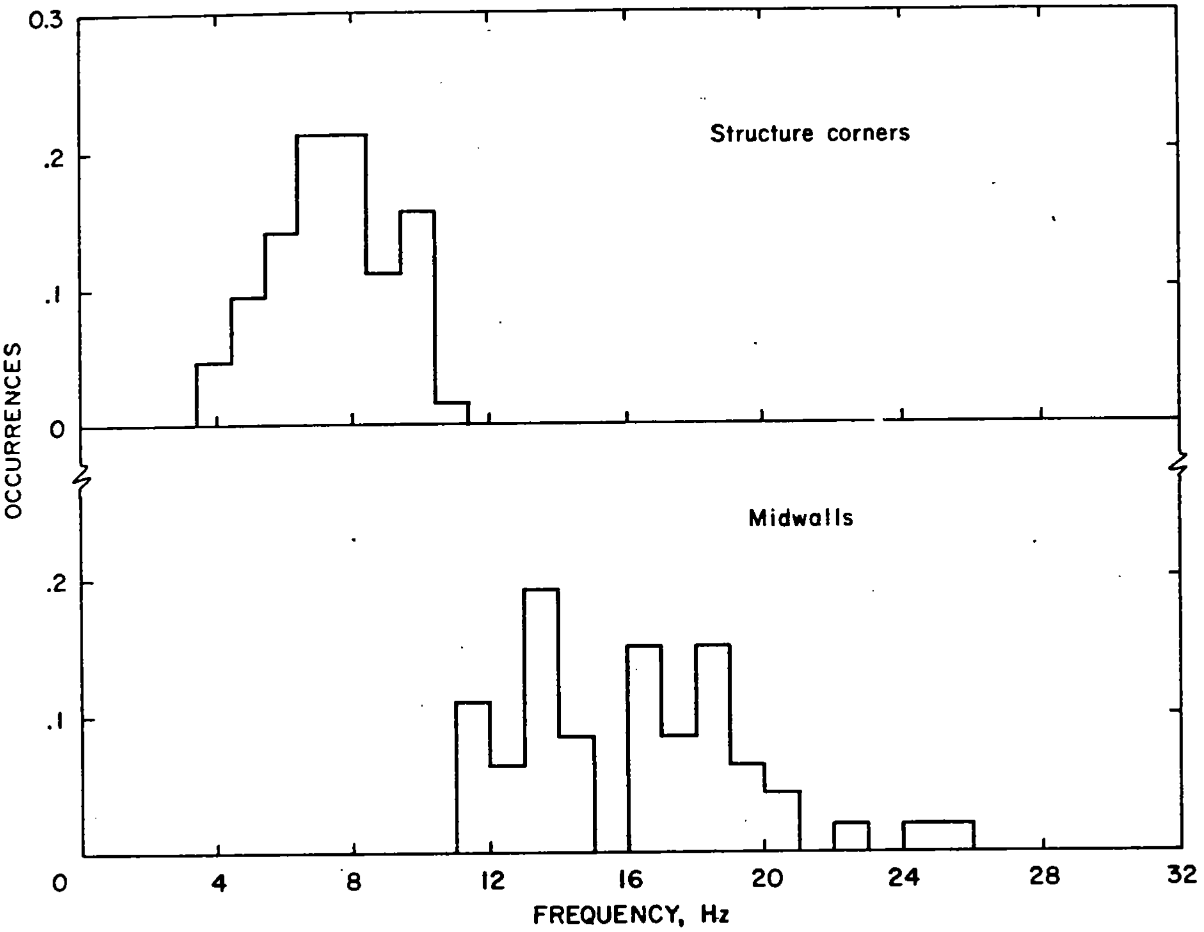

Figure 31.—Residential structure natural frequencies.

Production Blasting

Levels of structure response and incidents of damage were sought for 225 production blasts (table 2). A wide range of charge sizes, distances, geologies, and blast types produced vibrations of various peak values, durations, and frequency character. Quarries in urban areas had high free faces, used multiple decks, and had hole diameters seldom exceeding 5 in. Shots 21 to 30 were in an isolated quarry with high vibration levels at the close-in locations, but no house vibration measurements were made.

Coal mine highwall blasts varied from well-confined blasts producing no throw whatsoever, to quarry-type blasts with three free faces (top, front, and one side). Where ground vibration appeared to be more serious than airblast, design emphasis for production blasts was placed on sufficient relief (maximum number of free faces). Parting shots involved blasting a thin and often hard rock layer, and often produced high levels of airblast and low ground vibration. An extensive study of blast design and resulting vibration levels and character was made by Wiss (*56*) and will not be discussed further in this report.

Velocity Exposure Levels

In addition to analyzing particle velocity time histories for peak values and frequency character, ground vibrations were also processed for velocity exposure levels (VEL), which are analogous to sound exposure levels (SEL) for noise (*22, 49*). These methods measure the energy of a signal within specified frequency limits and time intervals. The use of VEL to assess structure response is a possible alternative technique to using the simple peak levels of the particle

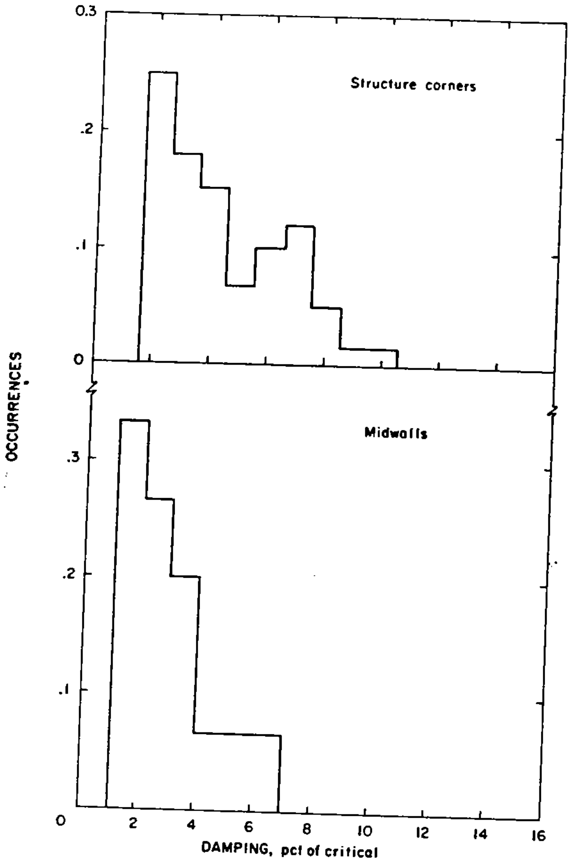

Figure 32.—Residential structure damping values.

velocity and also to response spectra techniques. The ideal VEL is normalized to 1 sec; therefore, this penalizes excessively long events (3 dB per doubling of duration) and allows higher levels for short-duration events. Current field practice involves the use of an rms system (e.g., sound level meter) with either ⅛- or 1-sec time constants and optional filtering.

Velocity exposure levels were determined for 200 of the measured blasts, with an rms detecting and filtering system described by Stachura (*49*) and defined by:

$$\mathrm{VEL} = 10 \log_{10} \left[\frac{1}{t_o} \int_o^T v^2 (t)\, dt \right]$$

where t_o = 1 sec, v(t) the time-varying filtered particle velocity, and T the various integration times. A filter range of 1 to 12 Hz was employed to include the range of whole-structure natural frequencies. Integration times were ⅛, ¼, 1, and 2 sec. The 1-sec time was an overall compromise that was long enough to include all the significant energy in a typical mine blast vibration measure near the source. VEL values were also determined for structure as well as ground motions.

Structure Responses From Blasting

Structure and midwall responses from production mine blasting are shown in figures 33–37, with the statistics given in table 4. In all cases, the corner and midwall responses from any given blast were plotted against the corresponding ground vibration components. The horizontal vibration components did not necessarily correspond to the true radial (or longitudinal) and transverse, since the velocity gages were oriented parallel to the structure walls.

Most interesting is that the racking response (absolute corner horizontal vibration) as shown in figures 33 and 34 is significantly lower than the input ground vibration velocity, when measured at either the first or second floor, or low or high in the corner. The vertical ground and structure corner vibrations were roughly equal as expected (figs. 33 and 36). The differences in the responses between types of blasts were significant. However, very little difference was observed between the 1- and 2-story structures.

All the responses discussed in this paper are applicable to residential-type structures with wood frame superstructures. The values do not apply to multistory steel frame structures or large structures with masonry load-supporting walls. The natural frequencies of vibration of these structures could be considerably lower than the 4 to 24 Hz range for residences and their midwalls.

The ground motion VEL did not correlate significantly better to the measured peak or VEL of the structure than the use of simple peak versus peak. Consequently it is recommended that peak velocities continue to be the primary measure of ground motion to assess the damage potential to residential-type structures and for regulatory purposes. However, it is recognized that for engineering, design, and research involving a variety of types of structures and sources, a measurement of simple peak particle velocity is an oversimplification. Some type of direct measurement of response (preferably dynamic strain) or model prediction (such as response spectra) would be appropriate in such cases.

Amplification Factors

Several analyses were made of structure response amplifications of the ground vibrations. The Bureau of Mines structure motion data were analyzed by Murray (*32*), Langan (*24*), and Dowding (*13*) for Fourier transfer functions and response characteristics. They discussed the problem of "ghost" resonances (dividing a small apparent response in the spectrum of the structure's motion by an even smaller spectral value in the ground motion).

A simpler amplification factor was determined directly from the vibration time histories. Maximum structure velocities and their times of occurrence were noted. Ground velocities and frequencies were then picked off the records at the corresponding moments of time or immediately preceding the time of the peak structure vibrations. The ratios of the two velocities are plotted in figures 38–40 against the frequency of the corresponding ground motion peak. Amplification factors for the racking response of a 1-story and a 2-story structure are shown in figure 38. Maximum amplifications were found to be associated with ground motions between 5 and 12 Hz, as expected from the natural resonance frequencies of the residences. Because

Table 4.—Equations and statistics f ›r peak structure responses from ground vibrations

Descriptor[1] and mine type	Stories, home	Equation	Correlation coefficient	Standard error, in/sec	Normalized std. error, in/sec	Regression line (figs. 33–37)	Number of points
Max.H SV versus Max. H GV:							
Coal	1	SV = 0.049 + 0.557GV	0.936	0.084	0.090	NAp	36
Do	2	SV = .075 + .553GV	.870	.151	.174	NAp	34
Do	All	SV = .060 + .559GV	.898	.120	.120	1	70
Construction	All	SV = .136 + .230GV	.599	.140	.234	2	13
Iron range	All	SV = .052 + [illegible]976GV	.894	.117	.130	3	10
All	1	SV = 0.87 + 435GV	.741	.169	.228	NAp	50
All	2	SV = .082 + [illegible]61GV	.862	.141	.163	NAp	53
All	All	SV = .084 + .496GV	.800	.157	.197	4	103
Vert. SV versus Vert. GV:							
Coal	1	SV = .048 + .771GV	.928	.063	.068	5	26
Do	2	SV = .070 + 1.124GV	.880	.335	.335	6	62
Do	All	SV = .044 + 1.131GV	.892	.286	.320	NAp	88
Construction	1	SV = .112 + .230GV	.568	.127	.223	7	11
Do	2	SV = .090 + .529GV	.859	.233	.271	8	7
Do	All	SV = .054 + .424GV	.741	.193	.260	NAp	18
All	1	SV = .035 + .738GV	.905	.208	.230	NAp	37
All	2	SV = .115 + .942GV	.896	.364	.406	NAp	69
All	All	SV = .073 + .907GV	.893	.330	.370	NAp	106
Max.H midwall, SV versus Max.H GV:							
Coal	1	SV = .154 + 1.347GV	.927	.228	.246	9	47
Do	2	SV = .153 + 1.636GV	.920	.358	.389	10	53
Do	All	SV = .146 + 1.534GV	.918	.310	.337	NAp	100
Construction	1	SV = .191 + .300GV	.754	.121	.160	NAp	8
Do	2	SV = .170 + .928GV	.754	.202	.268	NAp	7
Do	All	SV = .269 + .275GV	.524	.194	.371	11	15
Quarry	All	SV = .025 + 1.106GV	.886	.202	.228	12	19
Iron range	All	SV = .029 + 2.546GV	.722	.147	.203	13	16
All	1	SV = .196 + .904GV	.868	.331	.382	NAp	77
All	2	SV = .218 + 1.181GV	.776	.498	.642	NAp	82
All	All	SV = .217 + 1.002GV	.803	.431	.537	NAp	159
Coal, single home:							
Max.H SV versus MaxH GV	2	SV = .114 + .472GV	.894	.114	.161	14	35
H_1 SV versus H_1 GV	2	SV = .114 + .472GV	.894	.144	.161	NAp	35
H_2 SV versus H_2GV	2	SV = .019 + .370GV	.906	.091	.101	NAp	37
Max.H SV versus Max VEL H GV	2	SV = .128 + 2.451GV	.812	.189	.232	15	37
H_1 SV versus VELH_1GV	2	SV = .128 + 2.451GV	.812	.189	.232	NAp	37
H_2 SV versus VELH_2 GV	2	SV = .057 + 1.563GV	.854	.113	.132	NAp	38
Max.H SV versus TVS GV	2	SV = .110 + :299GV	.789	.143	.181	16	28
Max.HSV versus VELTVS GV	2	SV = .158 + 1.171GV	.763	.211	.276	NAp	29
Vert.SV versus Vert.GV	2	SV = .140 + 1.119GV	.852	.403	.472	17	33
Max.H midwall SV versus MaxH. GV	2	SV = .152 + 1.567GV	.905	.428	.472	18	28
Midwall H_1 SV versus H_1 GV	2	SV = .151 + 1.567GV	.905	.428	.472	NAp	28
Midwall H_2 SV versus H_2 GV	2	SV = .514 + 1.517GV	.830	.431	.519	NAp	37
Max.H SV versus PVS GV	2	SV = .092 + .267GV	.781	.128	.164	19	26

NAP = Not applicable.

[1] Symbols
SV = Structure vibrations, in/sec (unless specified "midwall" all SV are corner vibrations).
GV = Ground vibration.
Max.H = Maximum horizontal component of vibration.
Vert. = Vertical component of vibration.
H_1 = Horizontal component of vibration best approximating radial.
H_2 = Horizontal component of vibration perpendicular to H_1.
VEL = Velocity exposure level (1-second integration, 1–12Hz).
TVS = True vector sum.
PVS = Pseudo vector sum.

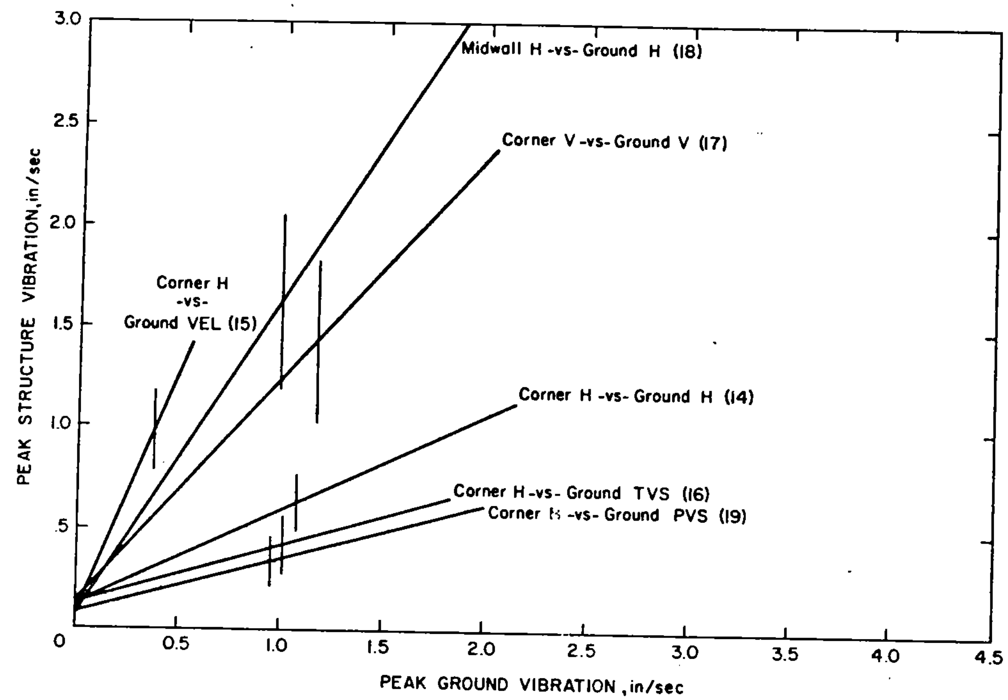

Figure 33.—Corner and midwall responses for a single structure (No. 19). Symbols, equations, and statistics are given in table 4.

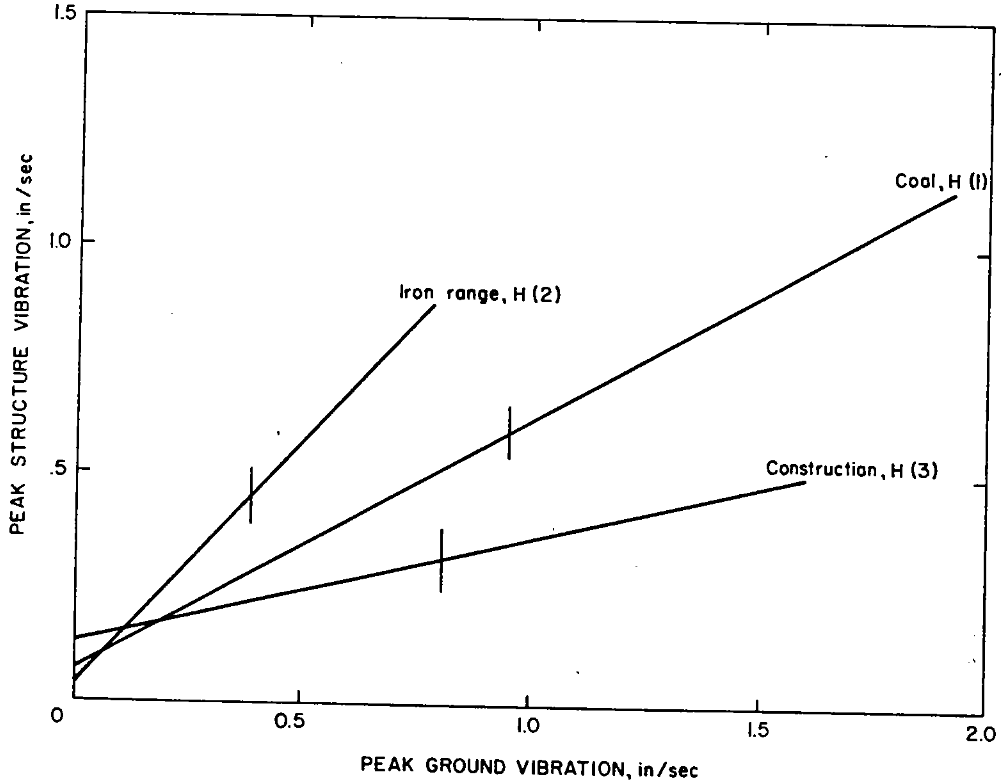

Figure 34.—Structure responses (corners) from peak horizontal ground vibrations, summary. Symbols, equations, and statistics are given in table 4.

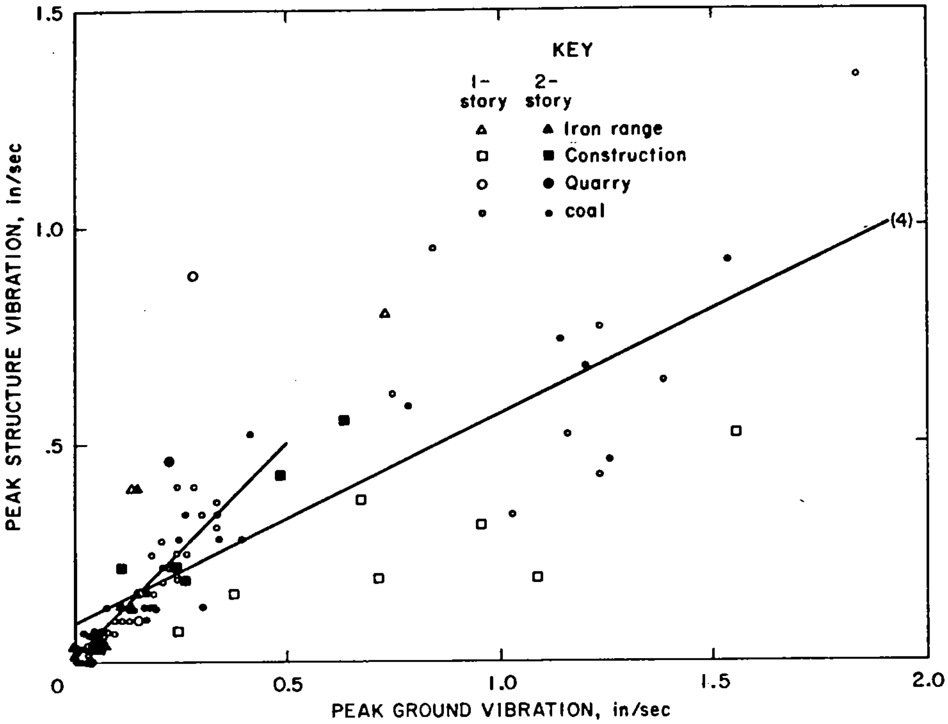

Figure 35.—Structure responses (corners) from peak horizontal ground vibrations with measured values. Equations and statistics are given in table 4.

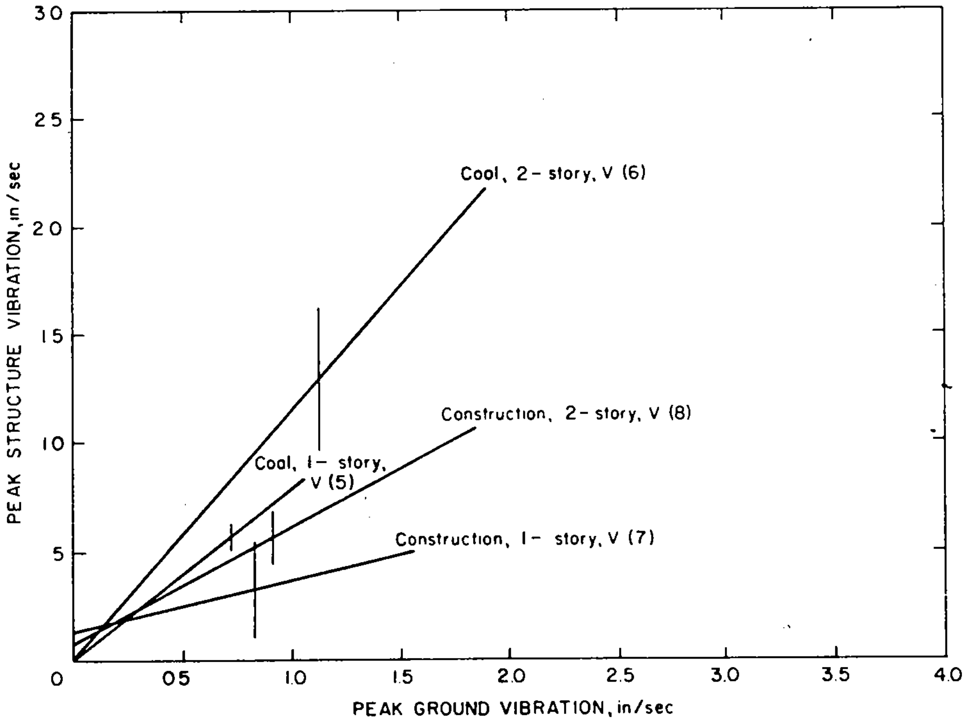

Figure 36.—Structure responses (corners) from peak vertical ground vibrations. Symbols, equations, and statistics are given in table 4.

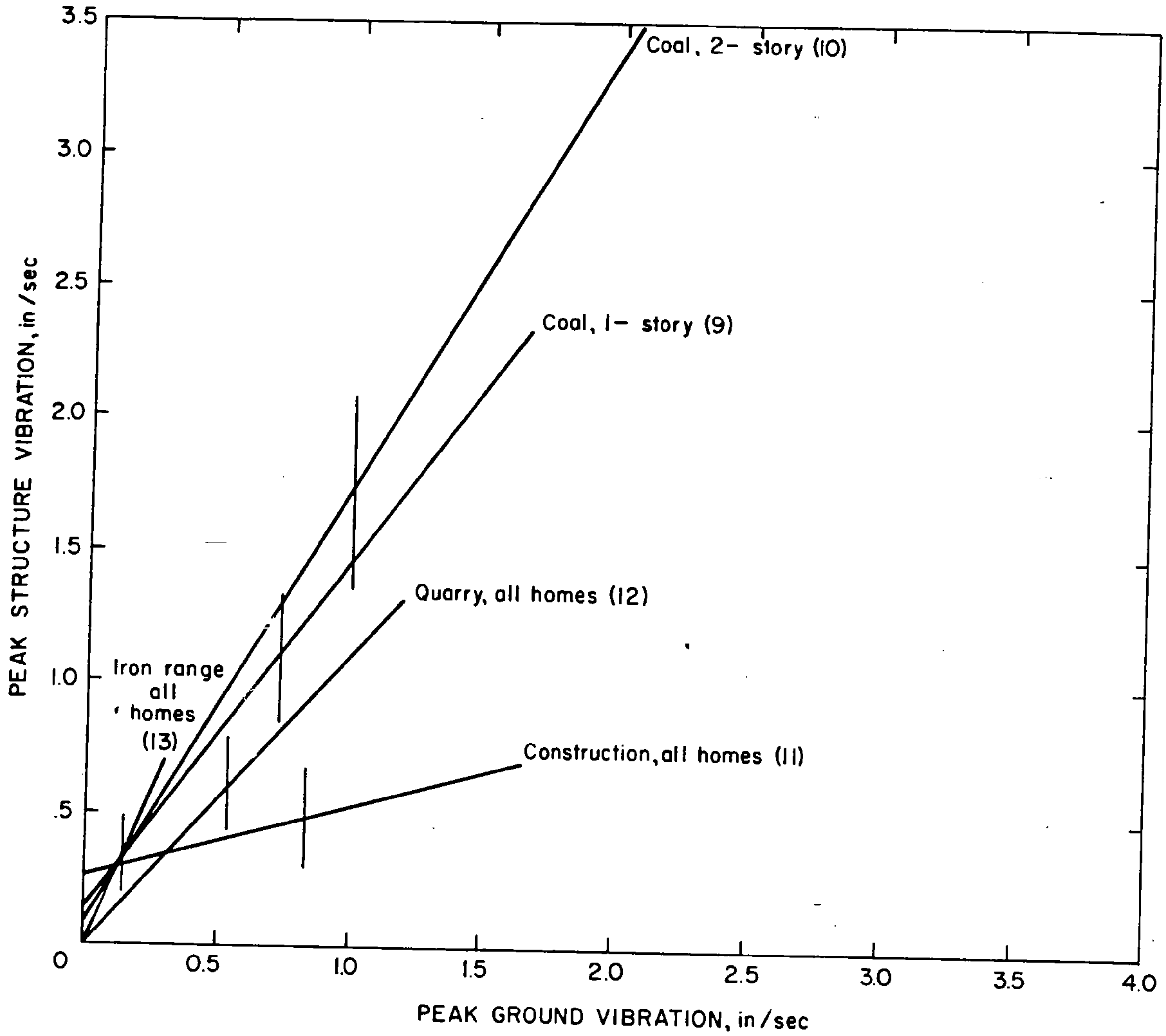

Figure 37.—Midwall responses from peak horizontal ground vibrations. Equations and statistics are given in table 4.

absolute, rather than relative, structure motions were measured, the responses at ground motion frequencies lower than the resonant frequencies theoretically should be unity; however, no ground motions with significant energy at frequencies lower than 5 Hz were encountered in this investigation. A summary of corner motion amplification factors for all of the homes studied is shown in figure 39. The highest amplifications were approximately 4, with 1.5 being a typical value. Ground motions above about 45 Hz produced little or no amplification of the corner-measured structure motion.

Midwall motion amplification factors are shown in figure 40. The maximum amplifications are greater than for the corners, with many responses occurring at higher frequencies, particularly up to 25 Hz. As with corner motions, amplification factors for ground motions above 45 Hz were less than unity.

These results suggest that frequencies below 10 Hz are most serious for potential damage from structure racking. Vibrations below about 25 Hz can excite high levels of midwall motion (typically wall motions are amplified 4 times that of the ground motions) and generate most of

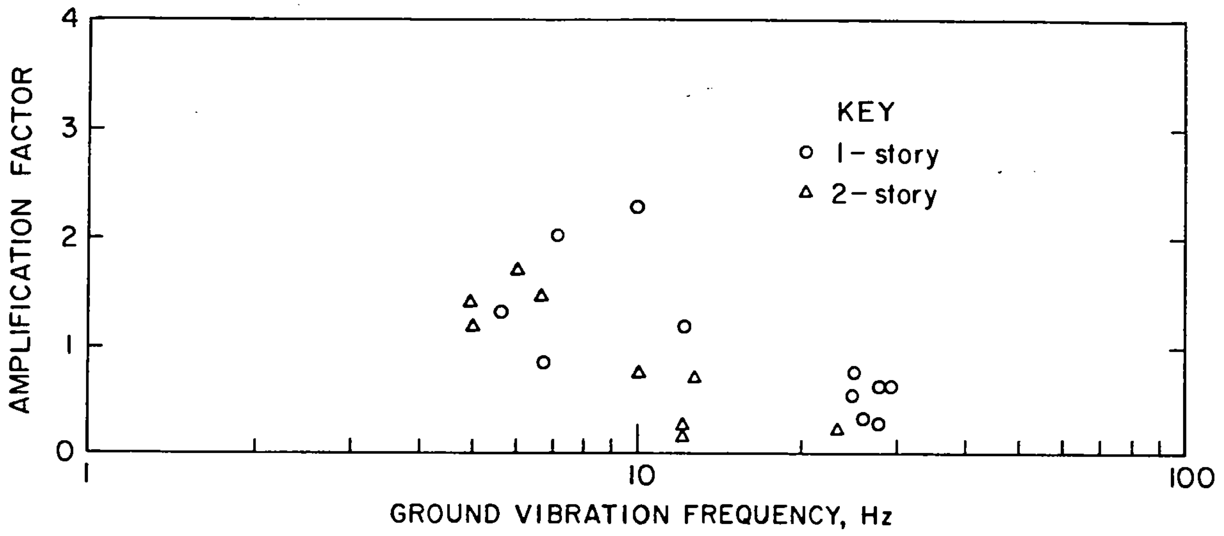

Figure 38.—Amplification factors for blast-produced structure vibration (corners) of a single 1-story and a single 2-story house.

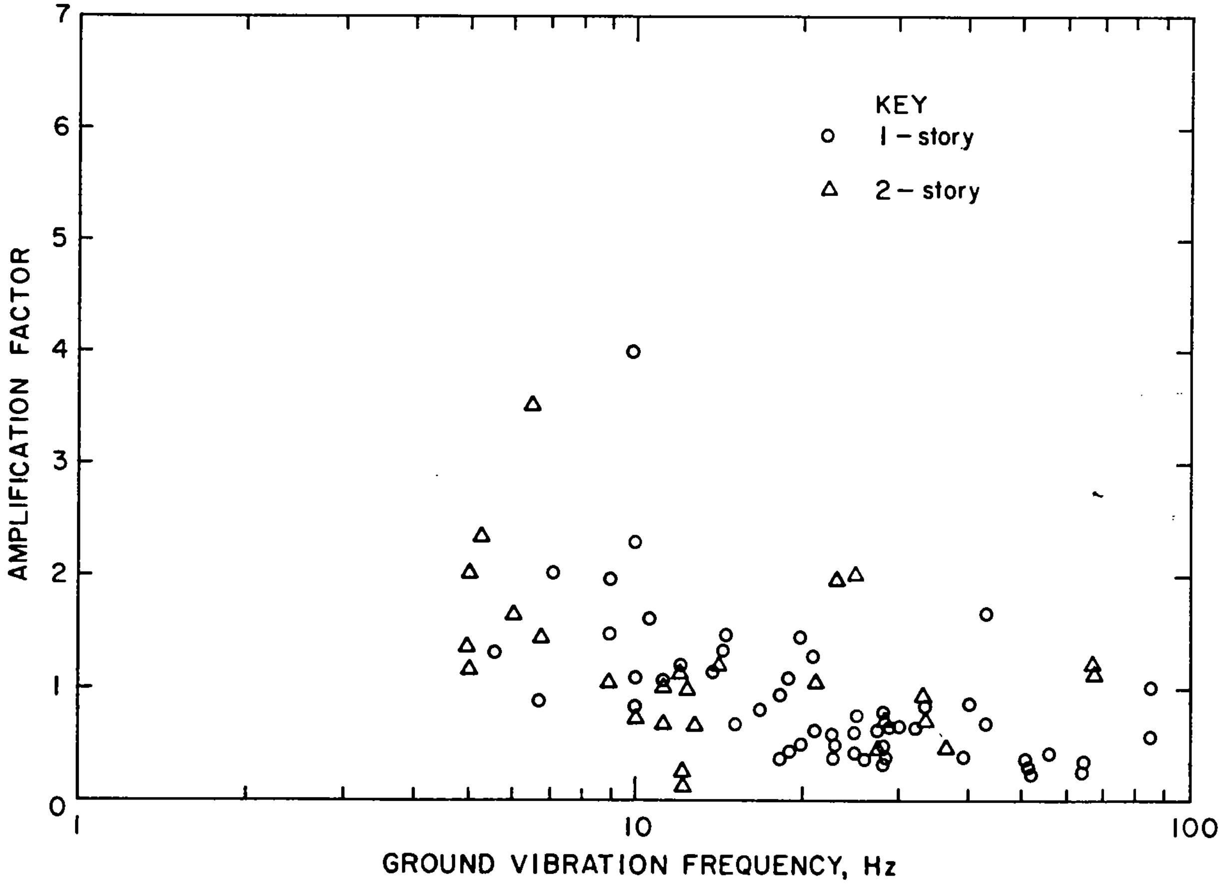

Figure 39.—Amplification factors for blast-produced structure vibration (corners), all homes.

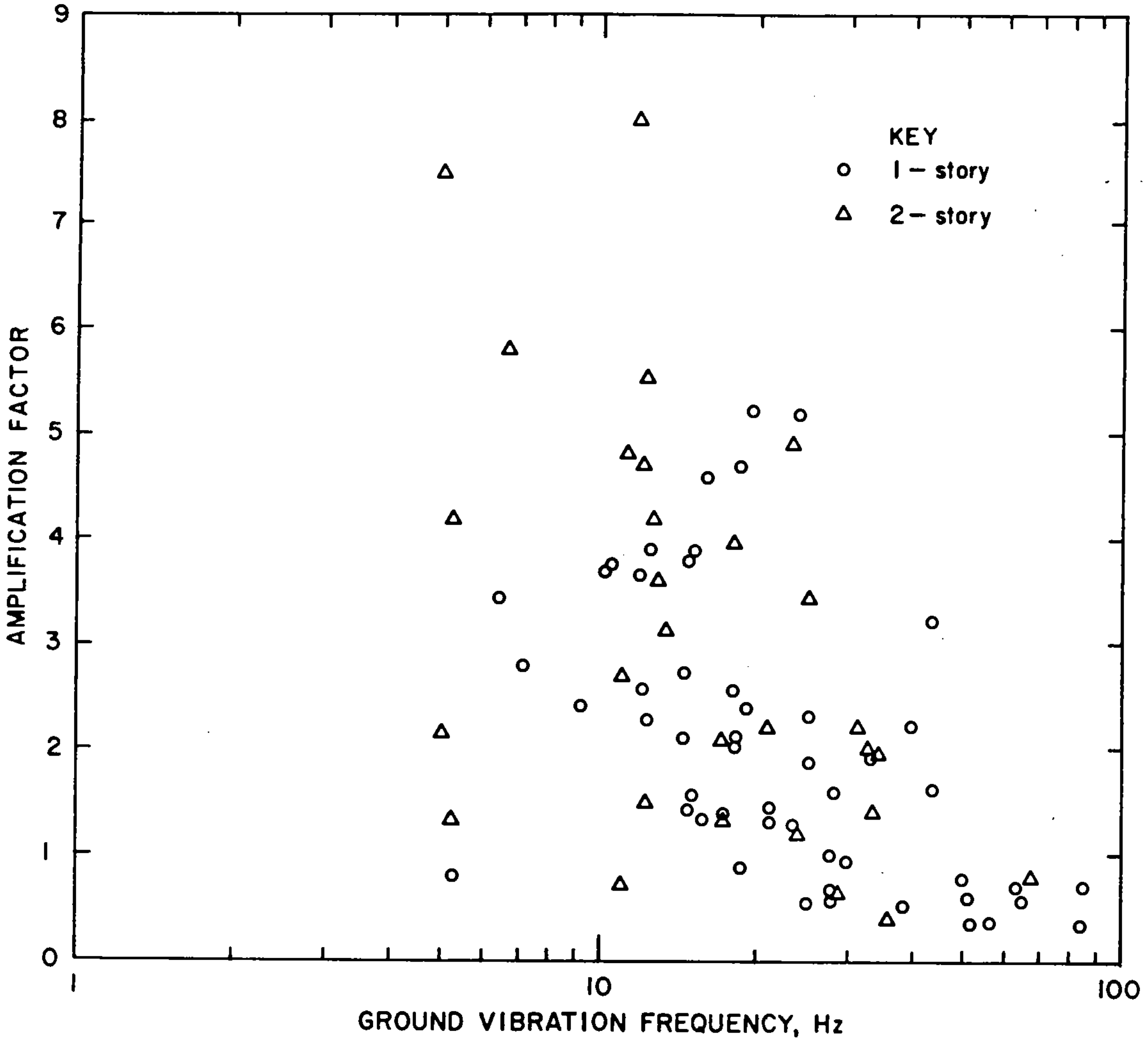

Figure 40.—Amplification factors for blast-produced midwall vibration, all homes.

the secondary noises, rattling, and other annoyances.

Kamperman studied transfer functions for residences subjected to quarry blasts (22). His concern was primarily with human response to midspan vertical floor motions, and an assessment of various airblast measurement descriptors. Kamperman made 23 comparisons between measured outside ground and inside floor motions from 18 blasts. He found amplification factors of 1.60 for vertical peak particle velocity and 1.04 for horizontal velocity (lateral or radial).

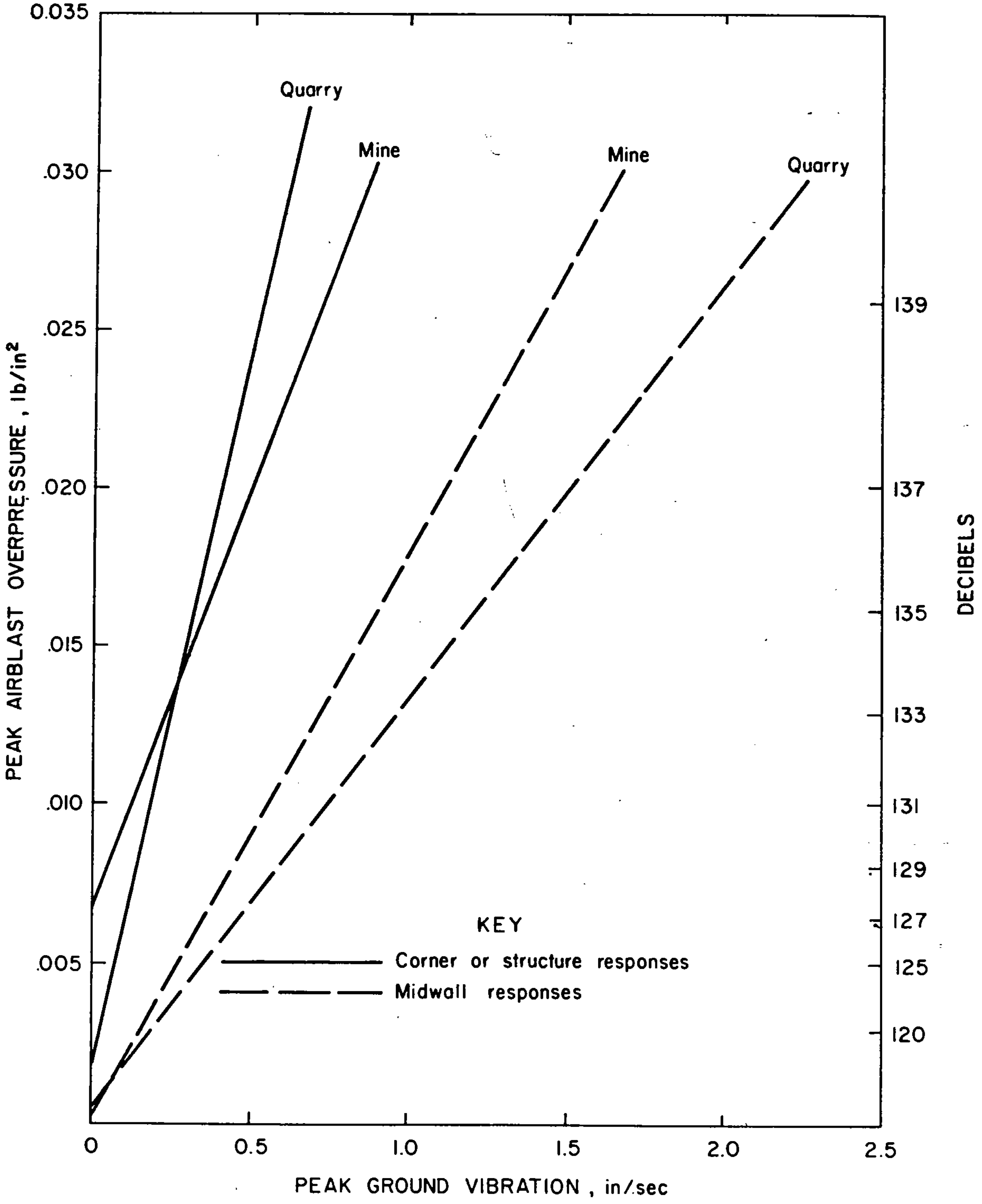

Figure 41.—Ground vibration and airblast that produce equivalent amounts of structure response, in frame residential structures of up to 2 stories.

Figure 42.—Test residential fatigue structure near surface coal mine. AYRSHIRE

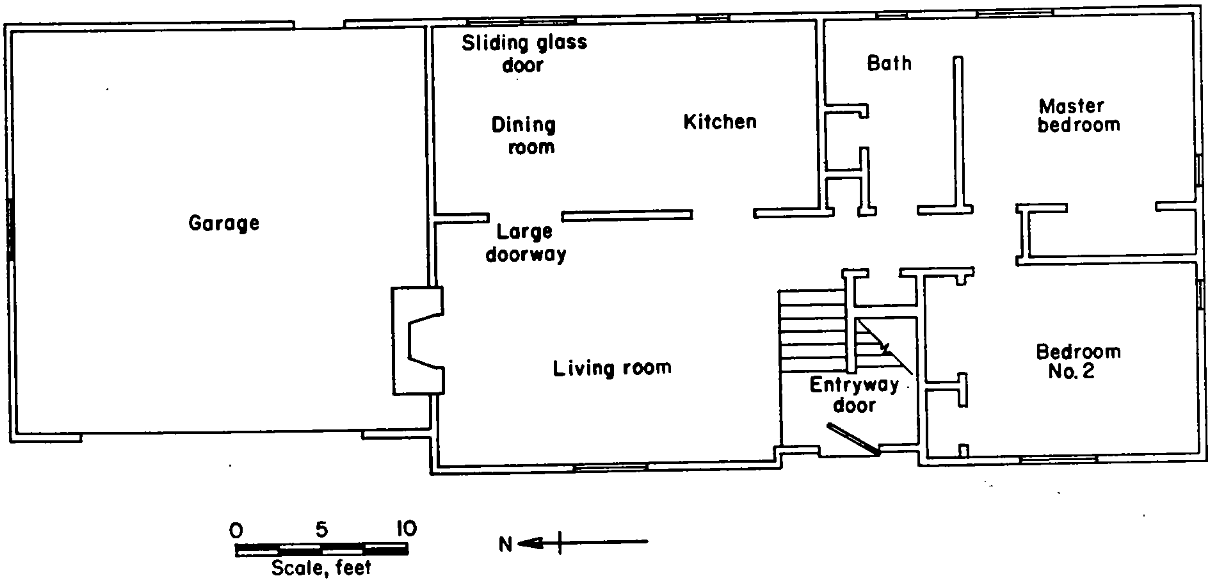

Figure 43.—Plan of main floor of test fatigue structure shown in figure 42.

Airblast Response

Structure responses from airblasts and sonic booms have been described in an extensive analysis of airblast from surface mine blasting (*46*). Levels of ground vibration and airblast that produce the equivalent structure motions are shown in figure 41, based on mean observed responses. The airblasts are those measured with 0.1-Hz low-frequency response systems. Typical 2- and 5-Hz commercial systems would give airblasts with sound levels in the range of 1 to 5 dB lower. Airblasts are relatively strong sources of midwall vibrations and poor sources of corner (whole-structure racking) vibration. The airblast levels producing the same amounts of corner vibration as 0.50 in/sec ground vibration are 0.020 to 0.024 lb/in^2 (137 to 138 dB). Relatively strong midwall vibrations are produced by airblasts, with only 0.007 to 0.009 lb/in^2 (128 to 130 dB) required to produce wall vibration equivalent to that from 0.50 in/sec ground vibration. From these equivalencies, airblast appears less likely to crack walls than ground vibration, as cracking occurs predominantly from shear and tensile wall strains that are produced by shearing rather than bending. Airblasts, however, are often responsible for the secondary rattling and annoyance effects produced by midwall motions (perpendicular to the planes of the wall surface).

Differences between mine and quarry blast-produced corner responses are not significant in the critical airblast range of 0.010 to 0.016 lb/in^2 (131 to 135 dB). By contrast, the midwall responses are very much different, probably because the relatively less confined quarry blasts produce more and higher frequency airblasts.

Structure Responses From Everyday Activities

Houses are subjected to a variety of vibrations and strains from human-produced transients and from slower processes of settlement from soil consolidation and changes in both the house and ground from natural environmental influences. The Bureau of Mines has measured strain and vibration from both human activities and from five mine blasts as the beginning of a study on fatigue effects in a residential structure.

The test structure and plan view are shown in figures 42 and 43. Strains were measured at critical places over windows and doorways using gages developed from a Northwestern University model (*11*). The maximums of the three strains measured at each location are given in table 5. The maximum principal strains would be slightly greater. Vibrations were measured in low and high corners, midfloors, and midwalls for both the blasts and the other activities (table 6).

Surprisingly high levels of strain and vibration were generated by the human activities. Comparisons between the blast- and human-produced effects suggests that house superstructures are continuously subjected to transients producing localized strains equivalent to ground vibrations of up to 0.50 in/sec. Additionally, it was found that effects produced in one part of the house (i.e., a front door slam) could produce significant strains all over the structure. No measurements have yet been made on the masonry facade or the basement floor or walls.

Table 5.—Strains in fatigue test structure from blasting and human activity

Strain locations	Maximum structure strains, µin/in						
				Door slams			
	Mine blasts	Jumps	Heel drops	Entrance	Sliding glass	Nail pounding	Walking
Over sliding glass door	[1]22,[2]15	24	9.2	13	22	21	Low
Over south window in master bedroom	[3]18	42	20	12	19	9.3	9.1
Over large doorway in living room	[4]24,[5]11	17	6.1	8.3	6.2	28	Low
Over picture window	[4]33	17	11	21	3.6	32	3.2
Over entrance door	[4]36,[5]43	13	5.8	140	Low	Low	Low

[1] From peak ground vibration of 0.300 in/sec, 129 dB airblast.
[2] From peak ground vibration of 0.210 in/sec, 124 dB airblast.
[3] From peak ground vibration of 0.290 in/sec, 124 dB airblast.
[4] From peak ground vibration of 0.470 in/sec, ~~111~~ dB airblast. 119
[5] From peak ground vibration of 0.320 in/sec, 125 dB airblast.

Table 6.—Structure vibrations in test fatigue structure from blasting and human activity

Vibration location	Mine blasts	Maximum structure vibrations, in/sec					
		Jumps	Heel drops	Door slams		Nail hammering	Walking
				Entrance	Sliding glass		
NW corner, low horizontal living room	[1]0.~~472~~ .377 [2].483	0.190	0.055	0.220	0.110	0.100	0.056
NW corner, low vertical living room	—	.200	.069	.120	.041	.180	.180
NW corner, high horizontal living room	[1].316 [2].345	.170	.037	.260	.100	.064	.054
SE corner, low horizontal master bedroom	[3].227 [4].222	.310	.139	.182	.164	.508	.157
SE corner, low vertical master bedroom	[5]~~.392~~.314 [3].194	.286	.133	.121	.029	.118	.126
Midsouth wall, master bedroom	[5].508 [4].700	1.44	.783	1.29	.136	.241	.225
Mideast wall, master bedroom	—	2.63	1.42	.934	.111	3.81	.285
Midwest wall, living room	[1].964 [2]1.37	1.00	.486	1.05	.124	.365	.086
Midfloor, [illegible]room	—	5.58	4.08	1.25	.031	.063	1.49
Midfloor, living room	[1]1.18 [2].85	10.1	5.84	.453	.272	.067	.286

[1] From peak ground vibration of 0.470 in/sec, ~~117~~ dB airblast. 119
[2] From peak ground vibration of 0.320 in/sec, 125 dB airblast.
[3] From peak ground vibration of 0.210 in/sec, 124 dB airblast.
[4] From peak ground vibration of 0.300 in/sec, 129 dB airblast.
[5] From peak ground vibration of 0.290 in/sec, 124 dB airblast.

FAILURE CHARACTERISTICS OF BUILDING MATERIALS

Most of the damage concern from the relatively low-level blasting vibrations involves cosmetic cracking of the interior walls of residences. Modern construction uses interior walls of gypsum plaster board (Drywall) with a covering of paint, wallpaper, or a plaster wash. Older homes often have interior walls of thick plaster over wood lath support. The strength of interior construction materials is not well understood, as they are not explicitly used as shear force resisting elements and homes tend to be nonengineered structures. However, it is evident that wall coverings stiffen their responses to forces acting in the planes of the walls. Early Bureau of Standards work on the strength of construction materials is discussed by Beck (*3*).

GYPSUM WALLBOARD FAILURE

Gypsum wallboard or Drywall consists of a panel of ⅜- to ⅝-in-thick gypsum plaster with a paper laminate covering on both sides. The 0.015-in-thick paper contributes greatly to the strength of the board and conceals cracking of the plaster core.

Strength tests on gypsum wallboard and plaster are summarized in table 7. Included are tests with and without paper laminates, preloaded static, and fatigue tests for various thicknesses of boards. Initial cracking could be seen on uncovered plaster but was masked by the laminate paper on covered wallboard.

Leigh studied plaster panels subjected to simulated sonic booms (*28*). In his fatigue study, he found only one failure out of 13 panels tested, and this he attributed to the experimental design. He also performed static failure tests.

Wiss measured strains on the walls of a home as part of his study of damage from blasting on the Mesabi Iron Range in Minnesota (*57*). His is the only failure strain measured under field blasting conditions. Wiss related his measured strains to peak ground particle velocities and found that 1.0 in/sec corresponded to interior strains of up to 50 µin/in, with 15 µin/in being a typical value. Drywall failure strains were also determined from laboratory tests of samples removed from the structure. Failure strains were very high but compare well with results of Bureau of Mines tensile tests on Drywall sections.

Table 7.—Failure characteristics of plaster and gypsum wallboard

Author and type for failure[1]	Strain, µin/in	Stress, lb/in²	Material	Thickness, in	Prestrain, µin/in	Cycles to failure
Leigh (*28*): Tensile	460	300	Plaster beam	NA	0	Static.
Do	365	300	Plaster panel	⅜	0	1
Do	260	200	do	⅜	0	10,000
Wiss and Nichols (*57*): Tensile	[2]1,230	[2]920	Gypsum wallboard with longitudinal section.	⅜	0	Static.
Do	[3]3,300	[3]1,460	do	⅜	0	Static.
Do	[2]1,100	[2]650	do	½	0	Static.
Do	[3]4,700	[3]1,100	do	½	0	Static.
Do	[2]840	[2]580	Gypsum wallboard with transverse section.	⅜	0	Static.
Do	[3]3,770	[3]785	do	⅜	0	Static.
Do	[2]910	[2]380	do	½	0	Static.
Do	[3]2,400	[3]580	do	½	0	Static.
Do (in situ)	1,162	NA	Gypsum wallboard	NA	NA	Blasting.
Dowding and Beck (*11*): Shear[4]	130	NA	Gypsum wallboard core with paper laminate removed.	⅝	0	Static.
Do	80	NA	do	⅝	0	1,000
Do	50	NA	do	⅝	0	18,000
Do	90	NA	do	⅝	26	330
Do	76	NA	do	⅝	26	1,900
Do	56	NA	do	⅝	26	8,500
Do	[2]340	NA	Gypsum wallboard	⅝	26	Static.
Do	[3]>1,400	NA	do	⅝	0	Static.
Bureau of Mines (this study):						
Tensile	[2]1,240	[2]175	do	⅜	0	Static.
Do	[3]3,400	[3]285	do	⅜	0	Static.
Do	[2]1,420	[2]170	do	½	0	Static.
Do	[3]3,210	[3]250	do	½	0	Static.
Do	[2]1,445	[2]140	do	⅝	0	Static.
Do	[3]3,450	[3]230	do	⅝	0	Static.
Shear	[2]3,000	[2]95	do	½	0	Static.
Do	[3]8,450	[3]136	do	½	0	Static.

NA = Not available.

[1] All laboratory tests except as noted in parentheses.

[2] Initial gypsum core failure.

[3] Ultimate failure, paper laminate damage.

[4] Beck's strains involved measurement on test sample. Others used platen displacement.

Beck sheared gypsum panels to failure, while investigating both fatigue behavior and the effects of preloading (*3, 11*). Most of his tests were on commercially cast panels from which the paper laminate had been removed. He found that after 5,000 cycles the panel would fail at about half the maximum strain that corresponds to static failure. Beck also found that preloading or prestraining reduced the number of cycles required for failure and also the failure strain. The principal failure strains for this study and the two points from Wiss' study are plotted in figure 44, along with observed static failure levels. Large variances are shown for Drywall core failures (e.g., 340 to 1,200 µin/in), which can be attributed to experimental load setup, moisture differences, and method of strain determination. Additional fatigue testing of building materials is needed.

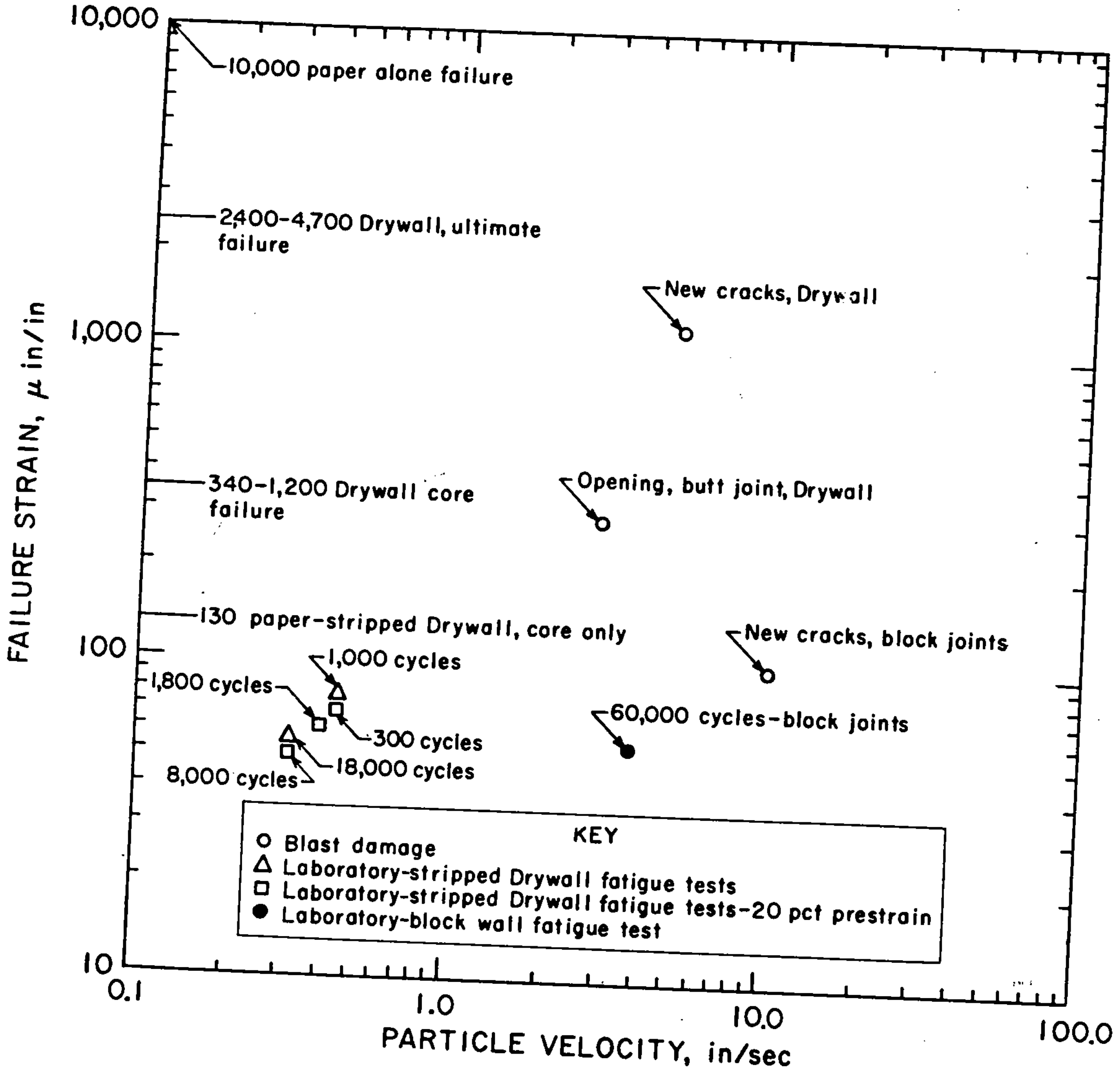

Figure 44.—Failure strains for residential construction materials from a variety of sources (tables 7 and 8).

The ultimate tensile failure strain for typical gypsum wallboard appears to be about 1,000 µin/in (*57*). Assuming that a stress concentration of 10 corresponds to the space above doorways or large windows, a shear deformation producing a uniform 100 µin/in would be potentially damaging. Projecting this over a typical house wall length (30 ft) gives peak differential displacements of approximately 0.036 in.

Complicating comparisons between different studies is that some measurements are made directly on the test specimens, while others are made using the machine platens. These values can differ by a wide margin.

MASONRY AND CONCRETE FAILURE

The two Canadian studies of blasting vibration damage included measurements of strains in basement walls of thick stone and mortar (table 8). Edwards and Northwood (*16*) found dynamic strains corresponding to initial cracking of > 375 µin/in and permanent induced strains of > 150 µin/in. Later measurements by Northwood found very much lower cracking thresholds of 45 µin/in (*38*).

Crawford and Ward studied masonry cracking induced by blasts in an 8- by 8-foot block and poured concrete box filled with sand (*9*). They found that poured concrete walls were much stronger than block walls and required high levels of both strain and particle velocity to induce cracking. The mortar joints of the concrete block wall failed at considerably lower strains, but the blocks themselves had the same ratio of strain to velocity as the concrete walls. The walls of concrete block and mortar did not act as monolithic bodies but as concentrated strains at the mortar joints. Crawford and Ward measured strain levels across the mortar joints that were 10 times those on the adjacent blocks (*9*).

Table 8.—Failure of masonry and concrete

Author and type of material	Dynamic strain at failure, µin/in	Particle velocity, in/sec	Type of cracking
Edwards and Northwood (*16*):			
On stone mortar basement walls, 18 to 24 in thick	375	3.1	Threshold.
Do	[1]150	3.1	Do.
Northwood, Crawford, and Edwards (*38*): On stone and mortar walls perpendicular to shot (radial)	40	3.4	None.
Do	45	4.5	Threshold.
Do	75	7	Minor.
Do	80	10	Major.
Crawford and Ward (*9*):			
8- and 10-in concrete block	30	3	Threshold.
Mortar joints	300	NAp	Do.
7- and 9-in poured concrete	100	10	Do.

NAp = Not applicable.

[1] This is permanent strain. All the remaining are dynamic.

Cracks appeared in the mortar joints when strains of 30 µin/in were measured on the blocks, consistent with Northwood's values (*38*). The strains across the joints were 300 µin/in. These results are consistent with the observations that cracks in the mortar between the blocks or bricks are the first signs of damage in masonry. Crawford and Ward recommended particle velocity as an index of damage independent of masonry type, with failure at 3 in/sec measured radially to the blasting and perpendicular to the block surface. This corresponds to surface strains of 35 to 40 µin/in on the blocks. Monolithic concrete, on the other hand, did not crack until particle velocities exceeded 10 in/sec and strains of 100 µin/in. Even then, the concrete cracked at the corners of the box. This location of cracking suggests that expanding gas pressures may have deformed the box and cracked the concrete at strain concentrations in the corners.

The measurement of strain is a useful engineering tool. It may provide the most appropriate method of assessing cracking potential for instances where locations of maximum strains can be predicted beforehand and material failure characteristics are understood.

FATIGUE

A very limited amount of work has been done on fatigue or damage from long-term repeated blasting. For engineered materials, fatigue strengths are typically a significant fraction of the ultimate strengths (e.g., 50 pct).

The U.S. Army Corps of Engineers, Civil Engineering Research Laboratory (CERL), conducted a fatigue damage test for the Bureau of Mines as the first phase of a full-scale fatigue study (*54*). An 8-foot-square by 8-foot-high test structure (model room) was built on the CERL 12- by 12-foot biaxial vibration table (fig. 45). This structure represented a typical residential room with a 7-foot doorway and two window openings. It was constructed of 2- by 4-inch wood studs and ⅜-inch-thick gypsum wallboard. Joints were taped and finished in the standard manner, with metal beads on the outside corners.

The vibration simulator that shook the base was programed with one of the horizontal components and the vertical component of an actual

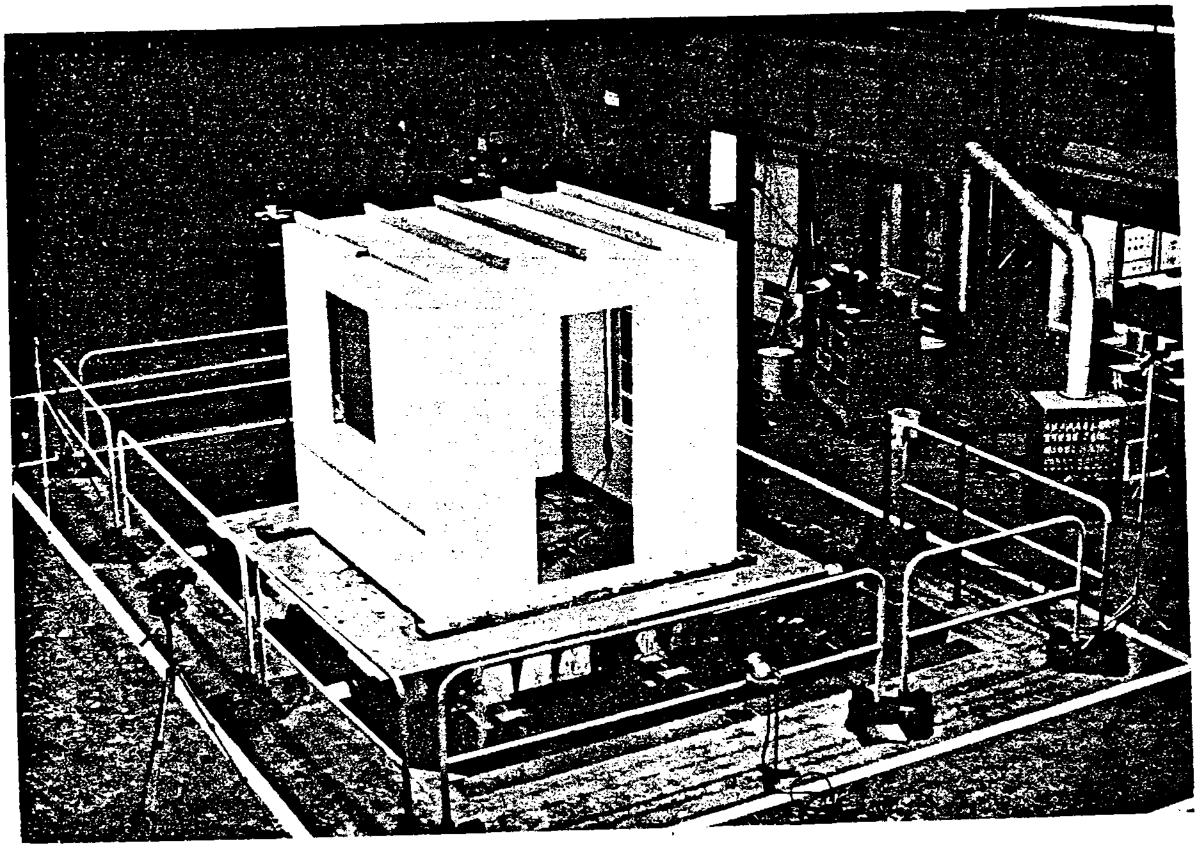

Figure 45.—Fatigue test model on biaxial vibrating table.

quarry blast from Bulletin 656 (*37*). The predominant horizontal and vertical component frequencies were 26 and 30 Hz, respectively. Testing consisted of a series of "blasts" at increasing platform vibration levels with inspections between each series. The sequence of number of events for each level of vibration was 1, 5, 10, 50, 100, and 500. The vibration levels run were 0.1, 0.5, 1.0, 2.0, 4.0, 8.0, and 16.0 in/sec. The first damage was observed after six events (blasts) at 4.0 in/sec, when the Drywall pulled away from the bottom plate. After six events at 8.0 in/sec nails began to work out, and after 66 events the corners cracked. A level of 16 in/sec produced cracks at window openings. The vibration levels from this study cannot be directly related to the full-scale case, because the excitation motions were not scaled (e.g., the natural frequency of the model was too high because the mass was too low). However, the existence of fatigue was demonstrated as each new degree of damage was observed after several complete events at that vibration level.

Fatigue and cracking of masonry walls have been studied by Koerner (*23*). He subjected 1/10-scale block masonry walls to sinusoidal vibrations at their resonant frequencies of 40 to 50 Hz. Failure was observed after approximately 10,000 cycles at peak particle velocities of 1.2 to 2.0 in/sec. More cycles were required for damage at frequencies outside of resonance. Recent tests by Koerner on 1/4-scale block walls also found fatigue effects, including the cracking of three walls at particle velocities of 1.69 to 1.95 in/sec, requiring 60,000 to 400,000 vibration cycles. Koerner predicted that the prototype natural frequency values would be half those of his model walls, and that the failure particle velocities would then be double the model results (*23*). Applied to full scale, these results correspond to more than a thousand 1-sec-long, 40-Hz events. In addition to Koerner's study, other fatigue studies are in progress to quantify the failure potentials from long-term blasting as well as the other stress-producing environmental factors.

SAFE VIBRATION LEVELS FOR RESIDENTIAL STRUCTURES

There are a large number of publications on ground vibrations and blasting; however, few contain actual observations of damage[7] and corresponding measurements of ground motions. In 1962, the Bureau of Mines published RI 5968 by Duvall and Fogelson (*14*). This was a summary analysis of the three existing blasting damage studies, one from Canada (*16*), one from Sweden (*26*), and data from Bureau of Mines Bulletin 442 dating back to 1942 (*51*). RI 5968 was revolutionary in several respects. It recommended the use of a single motion descriptor, particle velocity, in place of displacement and acceleration. Based on the use of particle velocity, a single safe value damage criterion of 2.0 in/sec was recommended, which was frequency independent over the wide range of 2.5 to over 400 Hz.

In 1971, the Bureau of Mines published Bulletin 656, a comprehensive summary of the many problems of blasting, including generation, propagation, and damage from both ground vibration and airblast (*37*). The ground vibration damage data in Bulletin 656 were those collected for RI 5968. A single new point from a study by Wiss (*57*) was included, but no new statistical analysis was conducted to include studies made since the 1962 report. It later became evident that the Bureau-recommended vibration criterion was not applicable under some conditions and that damage was occurring below 2 in/sec. Consequently, in 1974 the Bureau of Mines started a new program to examine damage from blasting. This included an analysis of data that had become available since 1962, and also the collection of new damage data, particularly from large-scale blasting operations in coal mines.

Review of the RI 5968 indicated that low-frequency vibrations (e.g., 2.5 to 40 Hz) were a significant problem and required additional study, such as response spectrum analysis. The 2.0-in/sec safe level had been based on a mixture of both high- and low-frequency damage data. Consequently, the inferred 5-pct damage probability was somewhat artificial and depended on the relative amount of each kind of data available. Using any given number of standard deviations from the mean of the high- and low-frequency data separately would give widely differing safe values for the two cases. The derivation of 2.0 in/sec as the safe level was based on 2.0 standard deviations from the 5.4-in/sec mean of all the minor damage points. Five values for minor damage were outside the 2.0 standard deviation damage envelope (at approximately 1.2, 1.36, 1.24, 0.75, and 0.32 in/sec), all from Bureau of Mines shaker tests that only approximately modeled transient blast loads (*51*). The last of these values was dropped for statistical reasons. Because 2.0 in/sec was also lower than all the individual major damage points, and because it included all actual blasting damage data, it was recommended as a boundary between damage and nondamage.

The large amount of scatter in the summary analysis at low frequencies is undoubtedly caused by the presence of structure resonances and initial strain states. The lower frequency vibrations also result in large displacements (and strains), and it is strain that ultimately produces cracking. RI 5968 had not presented sufficient data for separate analyses of the low and high frequencies because it was based upon only three studies, one of which was not blasting. Since the 1962 report, four major sets of additional data have become available, including new damage data obtained from Bureau of Mines research. Three other studies have supplied a few new damage points each, bringing the total number of relevant studies to 10 (table 9). Direct statistical treatment of the type used in RI 5968, probability analysis, and response spectra analysis were all applied to quantify blasting damage potentials.

PREVIOUS DAMAGE STUDIES

Few studies have been made that actually produced data useful for determination of thresholds and probabilities of damage. Required are actual structures near enough to blasts for damage and careful preblast and postblast inspections. All homes are cracked from natural causes, including settlement and periodic changes of humidity, temperature, and wind. Soil moisture changes are notorious for causing foundation cracks (e.g., from tree roots). The widths of old cracks change seasonally and often daily; however, the number of cracks continues to increase with age, independent of blasting.

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[7] The term "damage" is used in this report and those referenced (*14, 16, 26, 37, 51*) to refer to cracking of either interior superstructure walls or masonry. The special nature of the damage is discussed in later sections of this report (and in table 10); however, it is understood that the observed damage refers to cosmetic and superficial effects, and that the structural integrity of the homes is not being questioned here.

Table 9.—Studies of damage to residences from blasting vibrations

Study	Damage classifications	Types of damage	Overburden type	Structures studied	Distances to shots, ft	Shot sizes, lb/delay	Frequency range, Hz	Total shots	Damage observed, uniform classification				Instrumentation
									Non-damage	Threshold	Minor	Major	
Thoenen and Windes, Bureau of Mines (*51*).	Threshold and minor.	Plaster cracks and fall of plaster.	None	6 frame, brick, and stone, 1 to 3 story.	None	None	4–40	[1]163	103	26	34	0	Displacement.
Langefors, Westerberg, and Kihlstrom (*26*).	Minor and major.	---- do	Rock	NA	NA	NA[2]	48–420	105	57	0	32	16	NA.
Edwards and Northwood (*16*).	Threshold, minor, and major.	Cracks in masonry, bricks, or stone basement walls.	Soft, wet sand with clay 20 ft down, and well-consolidated glacial till.	6 total: 4 with 12-in brick and plaster interiors, 2 frame.	30–200	47–750	2.5–25	22	22	6	8	5	Displacement and acceleration measured on basement walls.
Northwood, Crawford, and Edwards (*38*).	---- do	Basement wall damage close in, and super-structure plus basement damage far out.	Glacial till and limestone overlain by thin till layer.	6 total: 1 frame, 1 stone, 4 9- to 12-in brick.	3–300	0.3–1,600	[3]7–120	60	51	10	4	5	Velocity, MB-120 gage, measured on basement walls.
Thoenen and Windes, Bureau of Mines (*51*).	Threshold and minor.	None	10 quarries	14 total	715–2,500	36–1,200	3–16	43	11	0	0	0	Displacement and acceleration.
Morris and Westwater (*31*).	Threshold	Plaster and partition cracks.	1 quarry and 1 surface coal mine.	2 stone with plaster interiors.	115–820	200–14,000	3.7–5.7	3	1	2	0	0	Displacement.
Dvorak (*15*)	Threshold, minor, and major.	Plaster and masonry cracks.	Semihard clay with sand lenses.	4 brick and masonry.	30–164	2.2–44	1.5–15	58	7	25	15	11	Do.
Wiss and Nicholls (*57*).	Minor	Drywall cracks	Glacial till	Single structure, rubble stone foundation.	35–200	1–85	NA	10	9	0	1	0	Velocity, MB-120 gage.
Jensen and Rietman (~~*37*~~). 31	---- do	---- do	Rock with 0 to 7 ft of soil overburden.	18 frame structures.	[4]30–185	1.75–12.75	[5]11–126	29	27	0	2	0	Do.
Bureau of Mines new data.	Threshold and minor.	Plaster, Drywall, and masonry cracks.	Various, usually with soil overburdens.	17 frame structures.	14–2,500	18–2,600	6.3–71	225	~~57~~ 76	~~23~~ 28	3	0	Do.

[1] Shaker tests.
[2] Excavation in rock, small shots.
[3] Predominantly 12 to 26 Hz for damage data.
[4] Plus 1 at 5 ft.
[5] Mostly >30 Hz.
NA = Not available.

Analysis of damage probabilities is particularly difficult because of the low probabilities being sought. For example, reliable determination of the 2-pct damage probability theoretically requires 49 nondamage measurements for every one of damage. Consequently, it is necessary to pool all the available data while avoiding the use of data that are clearly not similar to actual blasting. Examples of the latter are teleseismic blast vibrations and earthquakes, whose low-frequency content and long durations make them more likely to produce damage to structures. Thoenen and Windes' (*51*) early analyses recognized the nonapplicability of the Mercalli intensity scale developed for earthquakes, and Richter's observations on duration effects were discussed in the section on ground vibration characteristics. The shaker damage results of Thoenen and Windes are also questionably applicable, being of longer duration than actual blasting.

All the applicable blast-vibration damage studies are summarized in table 9, all involving preblast and postblast inspections. A detailed analysis of these studies is not made in this paper. Many are discussed in Bulletin 656 (*37*), and only the last two represent entirely new data. The first three studies in the table had been analyzed in RI 5968; summary results are in figure 3.4 of Bulletin 656 and figure 6 of RI 5968 (*14*). In some cases, measurements were made on foundation walls, and in others in the ground next to the structure. Obviously, uniform measurements are highly desirable. Stagg (*50*) discusses measurement methodology. The degrees of damage (threshold, minor, and major) are given in table 10.

The Canadian researchers made the second study of damage from blasting (*38*) published after RI 5968. This followed the Edwards and Northwood investigation (*16*), involved more shots and a wider range of both shot-to-house distances and shot sizes, and utilized similar experimental design.

Thoenen and Windes reported on a series of quarry blasts intended to study damage to residences (*51*). In the absence of damage, they used structure vibrators to induce cracking. The quarry nondamage data were not useful in the mean square analyses of damage thresholds performed for RI 5968; however, they are useful for probability analysis where numbers of damage and nondamage observations are compared.

Morris and Westwater described early studies on blast damage at a time when all measurements and damage criteria were based on ground displacements (*31*). In addition to discussing the Thoenen and Windes study, they describe three monitored blasts in Britain where inspections were made. They concluded that 0.040-in peak displacement would be a safe value criterion, and that a previously recommended maximum of 0.008 in had a considerable margin of safety. The damage data all involved low frequencies (3.7 to 5.7 Hz) with the 0.040-in displacement corresponding to a 1.0 in/sec particle velocity at 4 Hz, assuming simple harmonic motion. Prior to the use of particle velocity and going back to 1947, the State of Pennsylvania had a maximum safe blasting criterion of 0.030-in peak displacement for vibration frequencies below 10 Hz (*27*).

Dvorak (*15*) examined damage to masonry residences in a study published soon after RI 5968. Bulletin 656 discusses the Dvorak study, but did not include it in the summary analysis. The Bulletin raised questions about the old instrumentation used by Dvorak. It is not possible to verify the reliability or accuracy of any of the old studies, particularly those that published few of their actual data and for which the original time histories have been lost.

Recognizing the problems caused by old instrumentation, and particularly the low levels of damage observed by Dvorak, the analyses for this study were run both with and without the Dvorak data.

Table 10.—Damage classification

Uniform classification	Description of damage	Studies of blasting damage
Threshold	Loosening of paint; small plaster cracks at joints between construction elements; lengthening of old cracks.	Threshold: Dvorak (*15*); Edwards and Northwood (*16*); Northwood, Crawford, and Edwards (*38*). Minor: Thoenen and Windes (*51*).
Minor	Loosening and falling of plaster; cracks in masonry around openings near partitions; hairline to 3-mm cracks (0 to ⅛ in.); fall of loose mortar.	Minor: Dvorak (*15*); Edwards and Northwood (*16*); Northwood, Crawford, and Edwards (*38*); Jensen and Rietman (*21*); Langefors, Westerberg, and Kihlstrom (*26*). Major: Thoenen and Windes (*51*).
Major	Cracks of several mm in walls; rupture of opening vaults; structural weakening; fall of masonry, e.g., chimneys; load support ability affected.	Major: Dvorak (*15*); Edwards and Northwood (*16*); Northwood, Crawford, and Edwards (*38*); Langefors, Westerberg, and Kihlstrom (*26*).

Wiss and Nicholls (*57*) examined the blast damage characteristics of a single well-constructed residence on a soil type similar to that of the Canadian studies (*16, 38*). Their single damage observation was from a very high particle velocity for this damage-resistant, rubble-stone foundation structure with gypsum Drywall. This point was shown in the Summary of Bulletin 656 (*37*, fig. 3.8) for comparison to the other three studies.

Jensen and Rietman measured vibration effects from construction blasts for the Bureau of Mines (*21*). The goal was to collect response data for residences from small-scale excavation blasting for comparisons of the relative responses from shots of widely differing frequency character. Damage observations were also made, and the resulting values were used in this study. One shot was so close to the foundation (5 ft) that damage was caused by permanent ground strain, or inelastic effects. This value was not used in the analyses.

Two recent studies in Sweden became available too late for the analyses in this paper (*4, 6*). They involved structures on solid rock, and their damage observations agreed with previous Swedish results (*26*). Bergling described a test of blast damage to a concrete and brick residence (*4*). Shots were in the range of 1 to 50 m distance, and the lowest level at which damage was observed was 110 mm/sec (4.33 in/sec). Bergling also discussed the strict German DIN 4150 Standards and British 117 (1970) Standards (appendix A). Bogdanoff described a house of similar construction, also directly founded on granite-gneiss bedrock (*6*). From 38 rounds at distances less than 100 m, he indicated no damage below a vertical peak particle velocity of 90 mm/sec. They concluded that 30 mm/sec was safe for this structure (and geology), since many nondamaging shots occurred at this level.

The Salmon nuclear blast generated damage and complaint data (*39*), as well as the structural responses discussed previously (*5*). The damage observed was at large distances and occurred at lower levels than those observed for blasting. Particle velocity was estimated to have been approximately 5 mm/sec in Hattiesburg, 34 km away from the blast. Complaints about damage were also very high, with 1 pct of all families complaining at particle velocities of 2 mm/sec (0.08 in/sec), and 10 pct at 10 mm/sec (0.40 in/sec). Little justification exists to applying the Salmon results to typical mine blasting. As discussed in the section on Ground Vibration Characteristics, the 90-sec-long, low-frequency wave is far more typical of earthquake ground motions than of blasting. As no preblast surveys were available, damage causation was impossible to determine.

J. F. Wall studied masonry structures in Mercury, Nev. (*53*). He tabulated rates of cracking and concluded that they were higher during times of blasting. He concluded that the nuclear blasts at 33 to 78 km, which produced peak particle velocities of 1 to 3 mm/sec, were generating 4 to 30 cracks in concrete block structures over the natural rate of 2.5 cracks/day (for all 43 structures). As in the Salmon study, there were no direct damage observations that could be attributed to the specific events. Also, as in the Salmon study, the vibration time histories were of character similar to teleseismic vibrations; that is, dispersed to long durations and dominated by low-frequency surface waves. Even if the damage observed were caused by the nuclear blasts, it provides no reliable insight into damage potentials from conventional blasts. Nelson (*36*) monitored crack widths in six of the Mercury structures. He observed that crack width changes during intervening periods (from wind, temperature, sun, and humidity variations) were larger than those attributed to the seismic events.

The Rulison 40-kiloton nuclear shot also provided damage data where the event durations (of 5.5 to 7 sec) were somewhat typical of mine or quarry blasting (*43*). Frequencies were probably again very low because of the long absolute distances. As with the other nuclear blast studies, no preblast inspections had been made and crack observations were based on postblast evaluations. Scholl's survey of five nearby towns found damage ratios of 3 to 6 pct at peak particle velocities of 0.79 to 1.07 in/sec, based only on postblast inspections. This is in fair agreement with the Bureau of Mines summary blast damage results discussed later in this report.

Scholl also studied the Handley nuclear blast and other similar events for complaints and damage (*42*). He related pseudo absolute accelerations and complaint ratios for these events of very low frequency ground motion, in the range of 0.25 to 1.5 Hz. No determinations were made of damage claim validity.

Esteves describes damage to a single concrete and tile residence near a quarry (*17*). The first damage observed was plaster cracks at 60 mm/sec (2.35 in/sec).

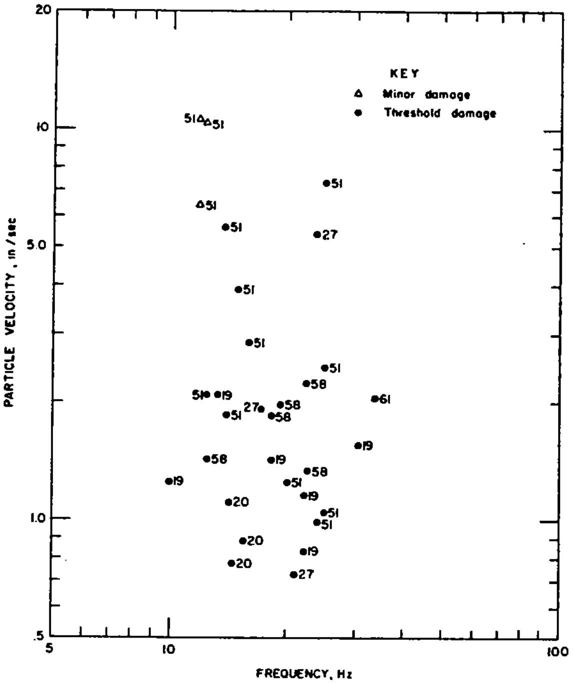

Figure 46.—Damage observations, new Bureau of Mines data from production blasting in surface mines. (Houses are listed by number in table 3.)

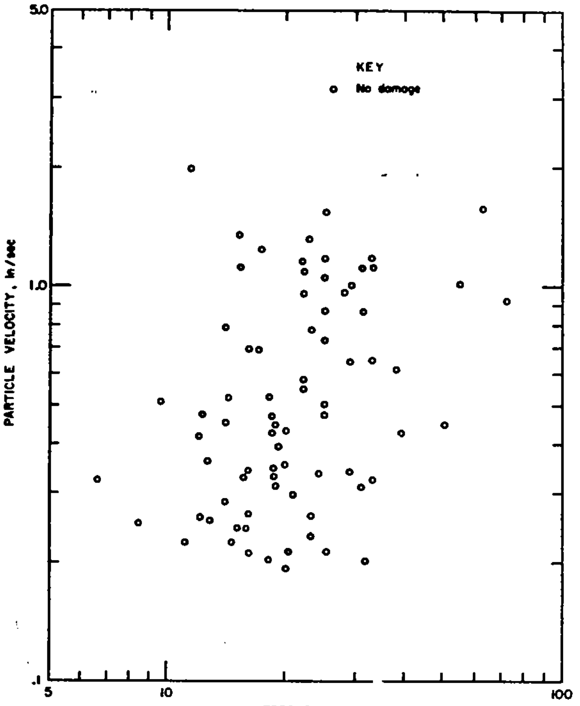

Figure 47.—Nondamage obs(rvations, new Bureau of Mines data from surface mine blasting.

NEW BUREAU OF MINES DAMAGE STUDIES

The Bureau conducted a series of field studies of ground vibration and airblast damage and responses from 1976 to 1979. Efforts were concentrated on actual measurements of wall, floor, and racking responses and the observations of damage that could be correlated to specific vibration events. A significant part of the work was done near large surface coal mines, with thick soil overburdens and large-diameter blastholes; cases of this sort had not been studied previously.

The production shots monitored for the damage analysis are listed in table 1. At five sites, houses were in the paths of the advancing mines and eventual damage was inevitable. Most of the homes, however, were not owned by the mines, and the blasts had been designed to protect them from damage. In all, 63 shots out of 225 produced useful high-level damage and nondamage data. Most of the other shots provided data on structural responses and airblast effects. Thirty-two of the shots (labeled "W" in table 1) were measured by Jensen and Rietman (*21*) under a Bureau of Mines contract. A total of 76 houses were studied (including 18 by Jensen and Rietman) and are listed in table 3. The houses that were subjected to high ground vibration levels and produced useful damage data are shown in figures 15–28.

Summaries of the damage and nondamage data from the high-level blasts are given in figures 46 and 47. Most of the damage was observed in homes with interior walls of plaster on wood lath (Nos. 19, 27, 51) and consisted of extensions of existing cracks and new hairline cracks. House 20 was notable in being a modern 1-story home with gypsumboard interior walls. Unfortunately, this structure was sold by the mine and moved before more than superficial cracking could be inflicted. The lowest level for observed damage in this structure was 0.79 in/sec (shot 48).

House 21 was also a modern 1-story residence and had been subjected to nine large blasts including six exceeding 1.0 in/sec. No damage was observed that could be correlated to specific blasts. However, this home had a significant number of cracks around windows and doors. The block basement wall on the mine side had been falling inward and was being supported by steel bracing. The foundation deformation undoubtedly contributed to the superstructure's cracking.

House 61 was also a modern 1-story structure with both gypsum wallboard and plaster interior walls. This home was subjected to a peak particle velocity of 2.23 in/sec, and several cracks propagated over windows and doors.

House 67 was also damaged (by shot W–17); however, the blast was within 5 feet and the cracking was likely produced by permanent ground strain rather than elastic energy. This shot was not considered useful for damage analysis.

Frequencies were determined directly from the vibration time histories and by real-time spectral analysis. In some cases, the records showed two dominant frequencies; high-frequency for the first few hundred milliseconds, and then a significantly longer low-frequency wave train. The values of amplitude and frequency used corresponded to the part of the vibration record that produced the larger structure response, which was invariably the low frequency (7 to 30 Hz).

Some long-term observations were made of numbers of cracks, and their widths and lengths. None of these parameters could be related quantitatively to the blasting. The number of cracks increased with time regardless of the vibration levels, and their widths varied irregularly from a variety of environmental stresses. Consequently, blast damage was assumed only when immediate preblast and postblast inspections found additional cracks or extensions.

In all cases, except three shown in figure 45, blast damage was superficial cracking of the same type as caused by natural settlement, drying of building materials (shrinkage), and variations in wind, temperature, humidity, and soil moisture. The three minor damage points in figure 46 represent cracks in masonry and large, new interior cracks exceeding 2 mm in width.

SUMMARY DAMAGE ANALYSIS

A summary analysis of damage was made using the 10 studies listed in table 9. To facilitate comparisons, a uniform classification of damage was adopted based on three levels of observed effects (table 10). The 10 studies of damage to residences from blasting produced a total of 553 observations, including 228 of various degrees of damage. These studies represent a variety of geologies, distances, and measurement methods. Data were analyzed in sets in order to group similar studies (table 11). Sets 1 and 3 were not unique enough to describe separately. Analysis involved both mean square fits and probability techniques.

Mean and Variance Analysis

The first analysis was made to determine mean and variance for the various damage classifications in terms of displacements as a function of frequency (figs. 48 to 52). This is analogous to the analyses performed for RI 5968 (*14*) and Bulletin 656 (*37*). A slope of minus 1 corresponds to a constant particle velocity, and a slope of minus 2 to a constant acceleration. A slope of zero is, of course, constant displacement.

Set 2 combines the two Canadian studies and that by Wiss, all giving similar results on glacial till. Sets 4 and 5 are the remainder of the low-frequency results with and without Dvorak's data, respectively. Set 6 is the high-frequency ground vibration data from Sweden (*26*) and from construction excavation (*21*). Set 7 is an overall summary of all the damage data.

Table 11.—Data sets used for damage analyses

Set and figures	Studies	Experimental conditions
1. (No plots)	Edwards and Northwood (*16*); Northwood, Crawford, and Edwards (*38*).	Low-frequency vibrations; glacial till soil/wallpaper on walls.
2. (Figs. 48, 53, and 55).	Edwards and Northwood (*16*); Northwood, Crawford, and Edwards (*38*); Wiss and Nicholls (*57*).	Do.
3. (No plots)	Morris and Westwater (*31*); Thoenen and Windes (*51*), quarry; Thoenen and Windes (*51*), shaker.	Low-frequency vibrations; walls stripped of wallpaper; plaster walls; shaker tests.
4. (Figs. 49 and 56).	Morris and Westwater (*31*); Thoenen and Windes (*51*), quarry; Thoenen and Windes (*51*), shaker, new Bureau of Mines (this study).	Do.
5. (Figs. 50, 53, and 57).	Dvorak (*15*); Morris and Westwater (*31*); Thoenen and Windes (*51*), quarry; Thoenen and Windes (*51*), shaker; new Bureau of Mines (this study).	As set 4 but with addition of masonry damage.
6. (Figs. 51, 53, and 58).	Jensen and Reitman (*21*); Langefors, Westerberg and Kihlstrom (*26*).	High-frequency vibrations.
7. (Figs. 52, 54, and 59).	Dvorak (*15*); Edwards and Northwood (*16*); Jensen and Reitman (*21*); Langefors, Westerberg, and Kihlstrom (*26*); Morris and Westwater (*31*); Northwood, Crawford and Edwards (*38*); Thoenen and Windes (*51*), quarry; Thoenen and Windes (*51*), shaker; new Bureau of Mines (this study).	Summary.

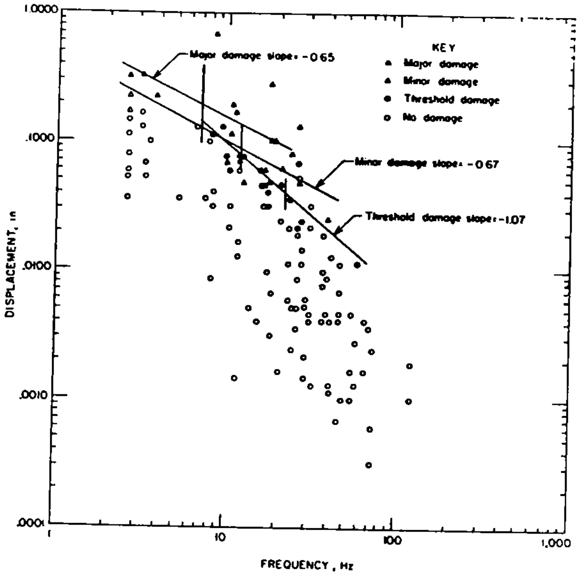

Figure 48.—Displacement versus frequency for low-frequency blasts in glacial till, set 2 mean and variance analysis.

Damage data for set 2 are shown in figure 48. The three mean regressions approximate constant particle velocities, particularly for the threshold case. All the individual damage points correspond to levels over 3 in/sec, with 2 in/sec roughly equal to three standard deviations[8] below the threshold line. The minor and threshold lines cross because of the occurrence of some minor damage at levels below some of the threshold points observed from other shots.

Set 4 analysis shows the low-frequency data, consisting mainly of the old Bureau of Mines mechanical shaker damage and new coal mine blast damage (fig. 49). All the damage points are included, even that anomalous 0.001-in displacement, 40-Hz observation from the shaker experiment (equivalent to 0.31 in/sec).

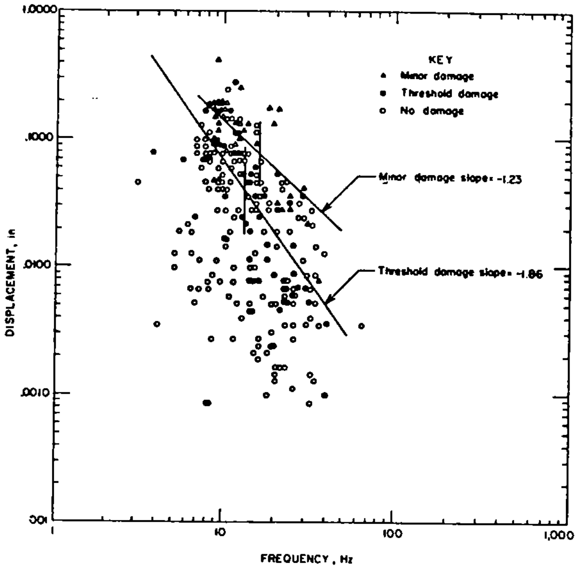

Figure 49.—Displacement versus frequency for low-frequency blasts and shaker tests, set 4 mean and variance analysis.

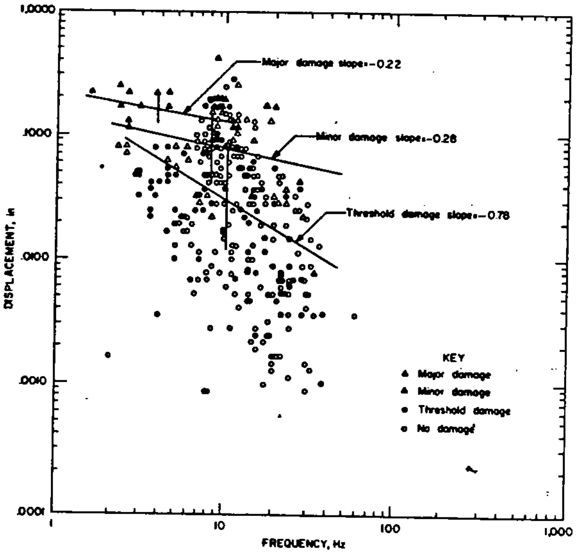

Figure 50.—Displacement versus frequency for low-frequency blasts, shaker tests, and masonry damage, set 5 mean and variance analysis.

Other than that single point, the lowest damage observed corresponded to approximately 0.72 in/sec, with quite a few points below 2 in/sec. The slopes are somewhat high, with the threshold line being almost equivalent to a constant acceleration that would have a slope of −2. The standard deviations are large, with 2

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[8] The use of these statistical techniques is based on the assumption of a Gaussian distribution about the mean square regression fit. For damage data, which have an increasing monotonic probability at increasing levels, this is not rigorously accurate. Since the observations were in categories (or degrees), the means are roughly halfway between the damage onset for that category and the onset of the next category. This makes the damage means somewhat approximate except for the open-ended "major" classification. Statistical theory puts the following probabilities on occurrences lying outside a given number of standard deviations:

Standard deviations	Total probability outside high and low limit,pct	Probability outside low limit only,pct
1	32	16
1.64	10	5.0
2	4.6	2.3
2.33	2.0	1.0
3	.4	.2

Problems involved in this type of statistical analysis were discussed in Bulletin 656 (37).

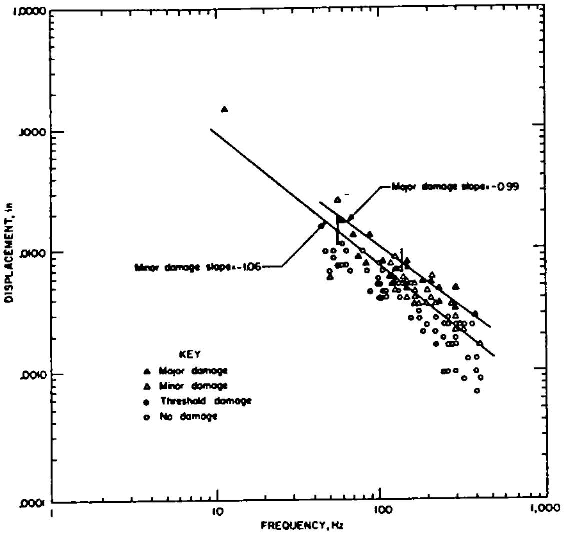

Figure 51.—Displacement versus frequency for high-frequency blasts, set 6 mean and variance analysis.

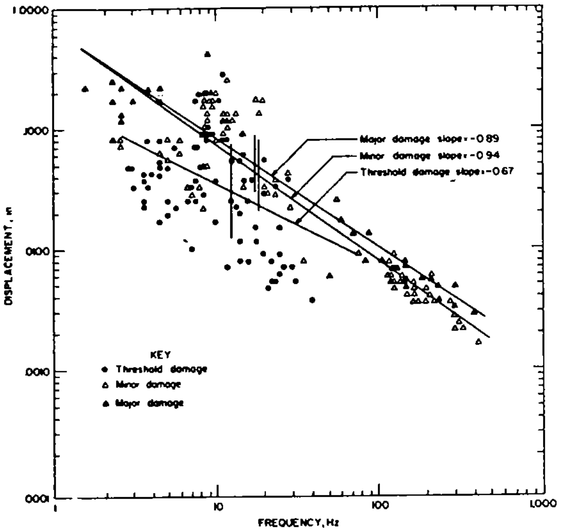

Figure 52.—Displacement versus frequency summary, set 7 mean and variance analysis.

and 3 deviations from the mean threshold giving approximately 0.7 and 0.3 in/sec, respectively.

Set 5 (fig. 50) is a rerun of set 4, but with the addition of Dvorak's data (*15*). Standard deviations increased as expected, but the slopes are reduced. The threshold line approximates a constant particle velocity of 2 in/sec, with 1 and 2 standard deviations corresponding to roughly 0.7 and 0.3 in/sec, respectively (1 standard deviation lower than the set 4 results). The lower limit of the cracking data is enveloped by the 0.51 in/sec, excluding the single maverick point. The shallow slopes suggest that these low-frequency data approximate a displacement-bound condition, which is consistent with the observation that low-frequency vibrations (e.g., 5 Hz) produce large displacements (and strains). As an example, 1 in/sec at 5 Hz is equivalent to 0.032-in displacement, which is twice the British recommended maximum of 0.016 in for vibrations below 5 Hz. The large amount of scatter in the low-frequency data is undoubtedly related to the structure response frequencies being in the same range. Between 4 and 25 Hz, the response, hence the damage for any given structure, will depend strongly on frequency. Therefore, the large amount of scatter is to be expected in a summary involving many shots and structures.

The high-frequency damage cases are shown by set 6 analysis (fig. 51), with the observation of only two classes of damage. Most notable are the minus 1 slopes (constant particle velocities), small scatter, and relatively high vibration levels for damage. No damage was observed below 2 in/sec. This level also corresponds to >3 standard deviations from the minor damage mean (lowest class of damage observed).

Set 7 (fig. 52) is an overall summary of all the damage data. The nondamage points have been omitted for clarity. This figure is analogous to the similar damage summaries in RI 5968 (*14*, fig. 6) and Bulletin 656 (*37*, fig. 3.4). The statistics corresponding to this summary analysis are somewhat arbitrary, being an artifact of the relative amount of high- and low-frequency data available. The large amount of scatter for the low frequencies shows that greater caution is required for equivalent damage probability as compared with that for high-frequency vibrations, those exceeding approximately 50 Hz. Regressions of the mean damage levels for the various sets have been plotted as particle velocities versus frequencies in figure 53, with the overall summary shown in figure 54. The maverick low point from figures 49 and 50 has been omitted as experimental error in the summary figures (figs. 52 and 54).

Probability Analysis

Probability analyses were also applied to the damage data as an alternative to regression analysis and were expected to produce more meaningful predictions. The number of damage observations within particle velocity intervals were plotted for the various sets of data. Four sampling methods were used on the damage and nondamage observations:

1. Simple counting of the numbers of points within an interval.
2. Smoothed sampling with variable-width particle velocity windows.
3. Assuming that every damage point excludes the possibility of higher level nondamage for that particular test with the reverse for nondamage.
4. Using only damage points and accumulated damage at increasing levels, and the same assumption for nondamage as for observation 3 above.

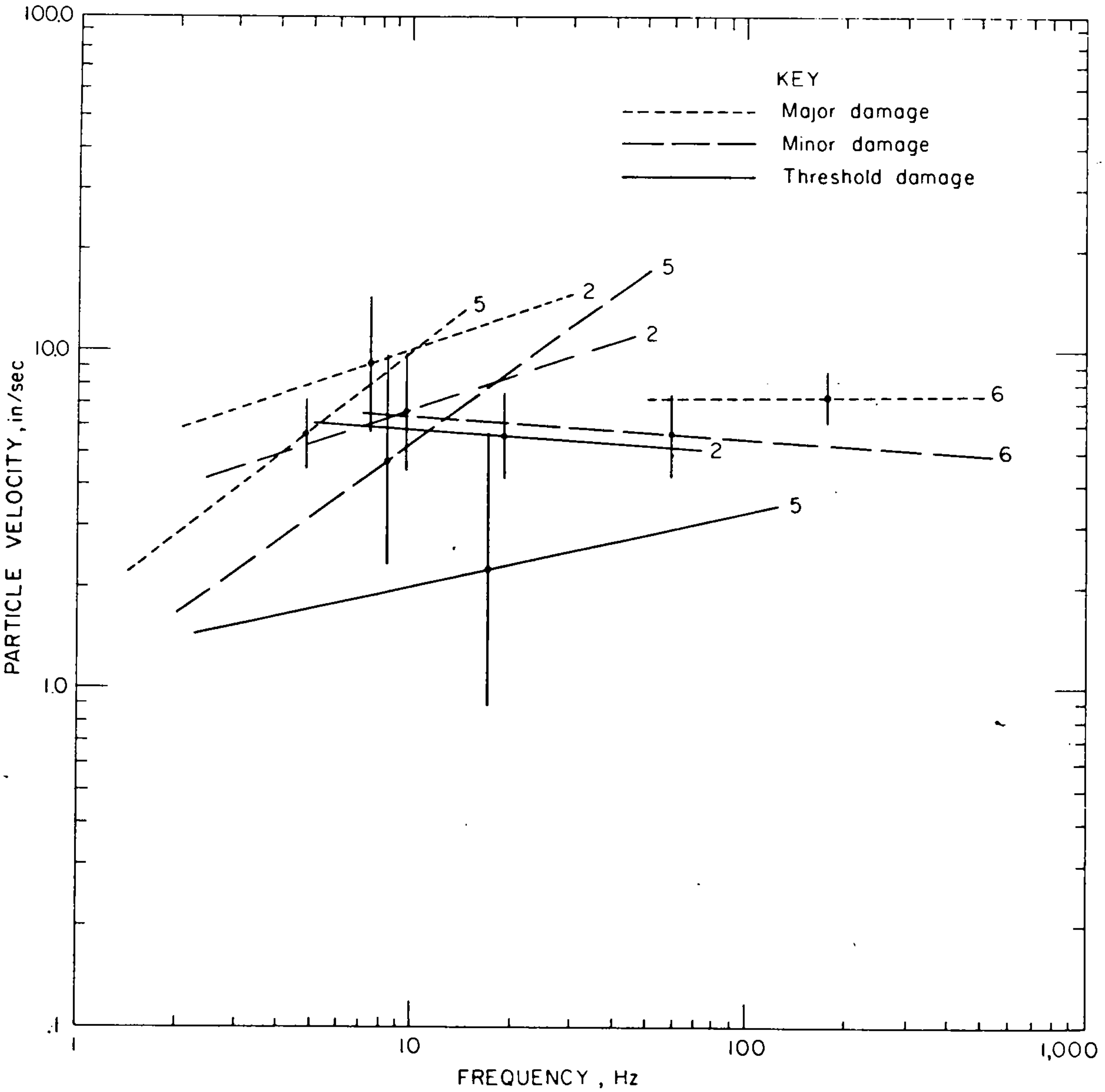

Figure 53.—Velocity versus frequency for the various damage data sets, mean and variance analysis. Sets are given in table 11.

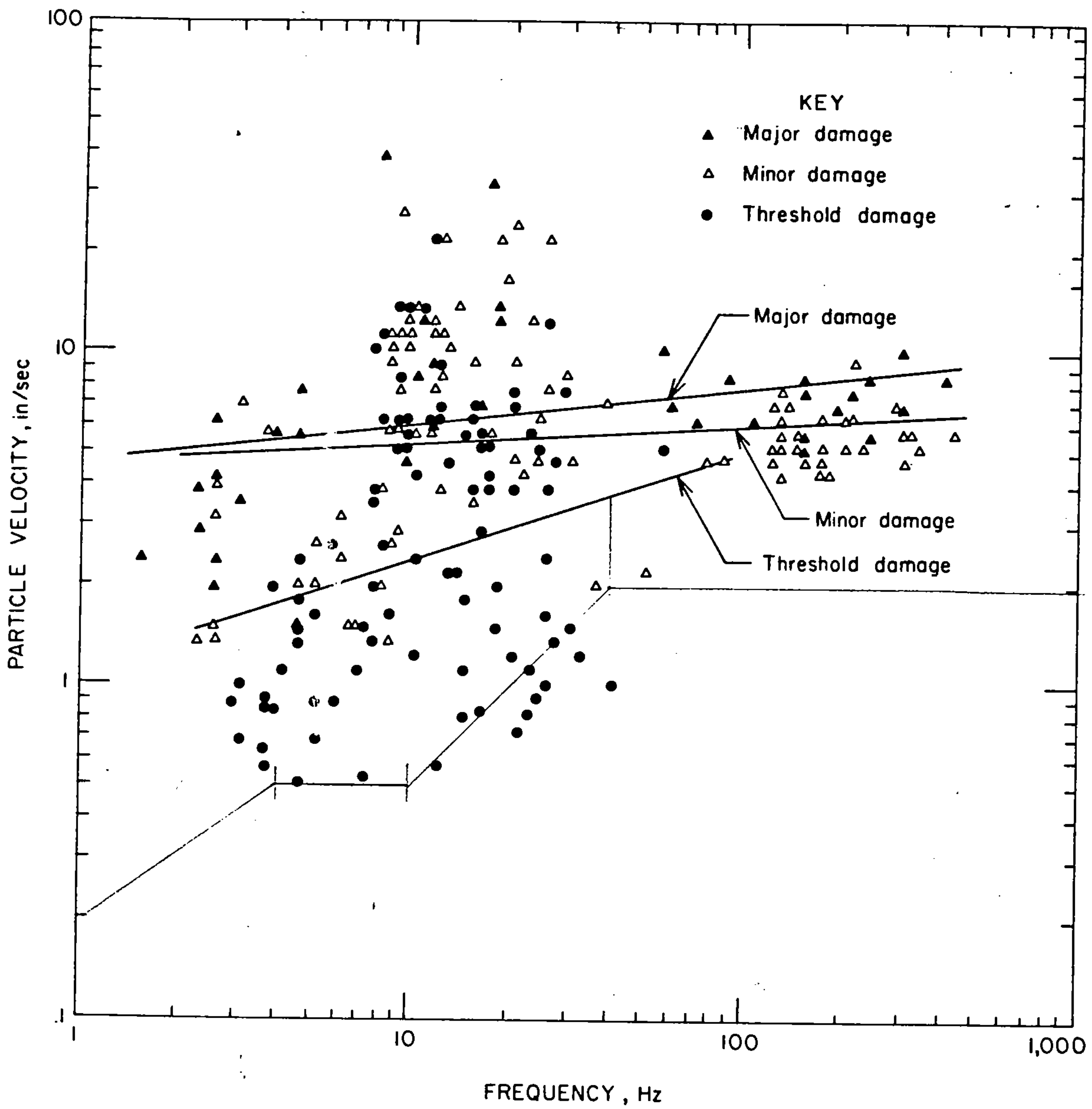

Figure 54.—Velocity versus frequency summary, set 7 mean and variance analysis.

All the sampling methods except the last violated one or more of the basic principles: (1) that the probability of damage must be independent of the sampling interval or (2) independent of the number of points (of damage or nondamage) in a given sample, and (3) that the number of new damage points must increase as levels increase. The first two principles are essential, that the probabilities concern the physics of the problem and are not a statistical artifact. The last is a result of the experimental design that involves steadily increasing levels of vibration until damage is observed. This places the observations on the upward curving part of the probability plot. When the cumulative damage was initially plotted on linear scales, they showed very little (essentially zero) damage at low levels and all damage (essentially 100 pct) at high levels. Between these extremes is the familiar S-shaped probability curve. On a log-normal ruled probability scale, the data plot as a straight line if they have the kind of log-normal distribution found for sonic boom glass breakage (*46*).

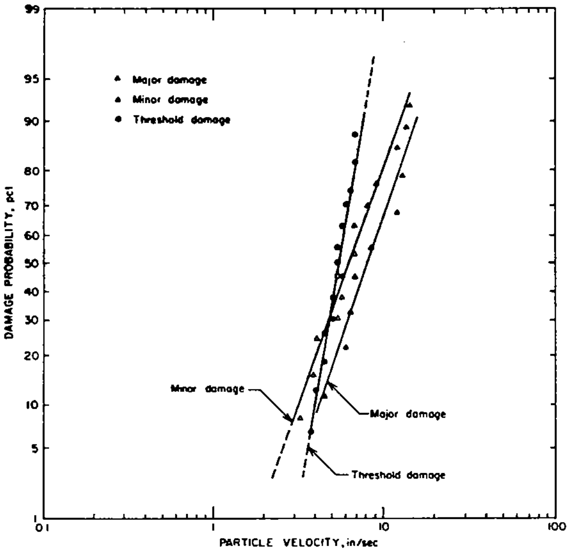

Figure 55.—Probability damage analysis for low-frequency blasts in glacial till, set 2.

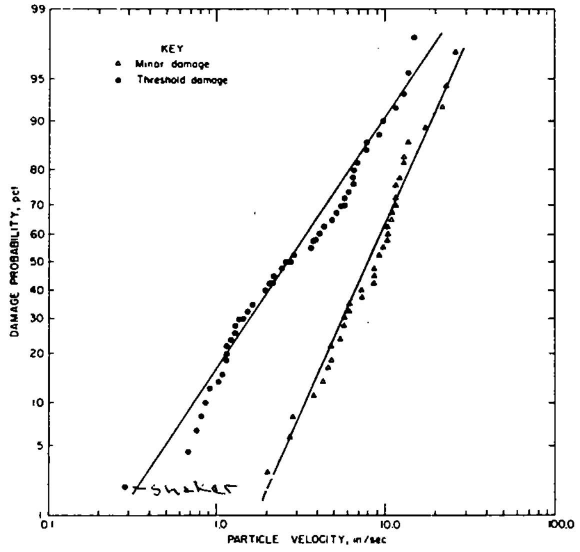

Figure 56.—Probability damage analysis for low-frequency blasts and shaker tests, set 4.

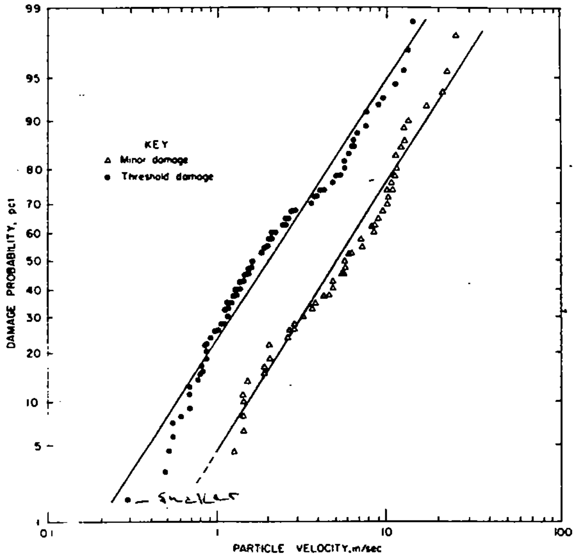

Figure 57.—Probability damage analysis for low-frequency blasts, shaker tests, and masonry damage, set 5.

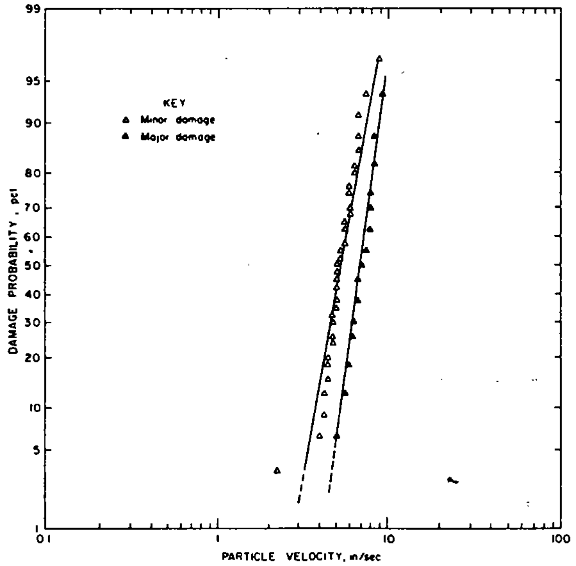

Figure 58.—Probability damage analysis for high-frequency blasts, set 6.

Log normal-scaled damage probability curves are shown in figures 55 to 59, for the same sets of studies analyzed for mean regressions. Data from the individual studies plotted as good straight-line fits, and even combining studies with apparent experimental differences still yielded high correlation coefficients.

The set 2 damage probabilities are shown in figure 55. This is primarily the two Canadian studies (*16, 38*), and as with the analysis of mean and variance, the threshold and minor damage lines cross. Projection of the probability lines for these data shows a low probability of damage below 2.0 in/sec (2 pct or less).

Sets 4 and 5 are shown in figures 56 and 57, respectively. These are again the low-frequency damage cases and the early Bureau of Mines shaker data. Set 5 includes Dvorak's study (*15*).

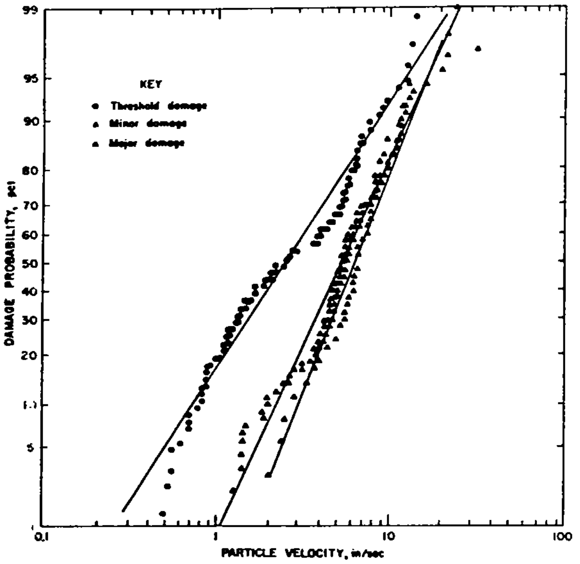

Figure 59.—Probability damage analysis summary, set 7.

The single very low valued maverick point is still included, and it produces the apparent discontinuity at the lowest vibration level. For both sets 4 and 5 probability plots, the mean line, and the trend from the individual points differ considerably at the lower probabilities. Statistical reliability increases results when the actual statistical points rather than the mean line is used for predictions. Consequently, the 5-pct damage probabilities from sets 4 and 5 are 0.80 and 0.53 in/sec, respectively.

The probability of damage from high-frequency vibrations is shown in figure 58 for set 6 data. By contrast to sets 4 and 5, data for set 6 form an excellent straight-line fit and have very steep slopes. The damage occurs over a narrow range of particle velocities, and as with the mean analysis of damage (fig. 51), it strongly supports the use of particle velocity. The vibration levels are again very high, exceeding approximately 2 in/sec for probabilities of 5 pct and below. The Swedish data alone would support a somewhat higher level, such as 3.5 in/sec for 5 pct and 3.0 in/sec for 1 pct.

The set 7 analysis (fig. 59) again represents the overall summary of all 10 sets of data. That single odd point was removed for the same reasons that it was dropped in the earlier analyses (*14, 37*).

Most notable is the downward turn of the damage probabilities at low vibration levels, suggesting a departure from log-normal predictions and some kind of asymptotic probability toward zero damage. However, precise predictions at increasingly lower levels must necessarily become less reliable. Accurate probability figures require a large number of observations, and even this summary analysis does not have excess data, particularly for each of the principal experimental variables.

SAFE BLASTING LEVELS

The damage statistics from figures 48–59 are summarized in table 12. Safe vibration levels are suggested by the three sets of values, two from statistical analyses and a third from the simple observation of the lowest level at which damage occurred. The mean and variance values are of limited use, owing to several problems with the data. They show (for set 2) that minor damage is predicted at lower vibration levels than threshold damage. This is caused by the crossing of the means and different relative magnitudes of the standard deviations. They also produced particle velocity levels that are frequency dependent for cases where the slopes do not approximate minus 1 (set 4, threshold; set 5, minor and major; set 2, minor and major). For predictive purposes, the probability analysis results are more reliable. The lowest values of damage actually observed correspond quite closely to the 5-pct damage probabilities, except for the high-frequency data (set 6).

Safe vibration levels for blasting are given in table 13, being defined as levels unlikely to produce interior cracking or other damage in residences. Implicit in these values are assumptions that the structures are sited on a firm foundation, do not exceed 2 stories, and have the dimensions of typical residences, and that the vibration wave trains are not longer than a few seconds.

A minimum safe level of 0.50 in/sec for blasting was adopted from table 12 based on the probit analyses of set 5 (low-frequency shots) and set 7 (overall summary). This assumes a 5-pct probability for very superficial cracking. However, this vibration level is also lower than the lowest level in cases where damage was observed. The almost-constant particle velocities for the lower damage probabilities of 2 and 1 pct (threshold, set 7) strongly suggest that the

Table 12.—Summary of damage statistics by data sets

Type of damage[1]	Peak particle velocities, in/sec						
	Mean and variance analysis, standard deviations			Probability analysis			Envelope of lowest observed damage
	1.64(5 pct)	2.05(2 pct)	2.33(1 pct)	5 pct	2 pct	1 pct	
Threshold:							
Set 2	3.4	3.0	2.8	3.5	[2]3.2	[2]3.0	3.8
Set 4	.88	.63	.50	.70	NA	NA	.72
Set 5	.46	.31	.24	.52	.32	NA	.51
Set 7	.54	.36	.28	[3].53	[3].48	[3].46	.51
Minor:							
Set 2	3.0	2.6	2.3	[2]2.5	[2]2.1	[2]1.7	3.1
Set 4	3.0	2.3	2.0	2.5	[2]2.0	NA	2.0
Set 5	1.3	.98	.80	1.3	[2]1.0	NA	1.4
Set 6	3.3	3.0	2.8	3.1	NA	NA	2.2
Set 7	1.6	1.2	1.0	1.4	[2]1.2	[2]1.1	1.4
Major:							
Set 2	2.6	1.9	1.6	[2]3.3	[2]2.7	[2]2.4	4.5
Set 5	2.6	2.2	2.1	NA	NA	NA	2.0
Set 6	5.0	4.6	4.2	4.8	4.4	NA	5.5
Set 7	2.3	1.9	1.6	2.3	1.8	1.6	2.0

NA = Not available.

[1] No threshold analysis exists for set 6; no major analysis exists for set 4.

[2] Extrapolated line.

[3] Maverick point was deleted.

0.50-in/sec level will provide protection from blast damage in > 95 pct of the cases. The damage probabilities realistically refer to numbers of homes being affected by a given shot rather than the number of shots required to damage a single home. This results from the much wider variation of damage susceptibilities among structures with various degrees of prestrain as compared with a time-dependent susceptibility for a given structure. Additional work on fatigue and special soil and foundation types may later justify stricter criteria.

Data are insufficient for a thorough analysis of the damage potentials in structures of various construction types. However, the values in table 13 are obviously dominated by houses that are susceptible to cracking. Most of the observed damage listed in table 9 involved plaster cracking in older structures. Modern Drywall (gypsumboard) interior-walled homes are apparently more capable of withstanding vibrations, since the paper-backed wallboard is relatively stiff and nonbrittle. Only two studies specifically examined Drywall damage from blasting, Wiss' (57) and the new Bureau of Mines measurements. The lowest vibration level corresponding to very minor crack extensions was 0.79 in/sec (structure 20), and many nondamage observations were made at levels exceeding 2.0 in/sec. Consequently, there is little justification in using the conservative 0.50 in/sec or anything lower for modern construction, and in this case 0.75 in/sec is a good minimum criterion. The conservative 2.0 in/sec is justified for the high-frequency blasts, even though the 5-pct value is 3.2 in/sec. This is based on the lowest observed damage value of 2.2 in/sec and the fact that no observations were made of damage corresponding to the "threshold" criteria of the other studies. Construction and excavation blasting will often fall in this high-frequency category.

Table 13.—Safe levels of blasting vibrations for residential type structures

Type of structure	Ground vibration—peak particle velocity, in/sec	
	At low frequency[1] (<40 Hz)	At high frequency (≥40 Hz)
Modern homes, Drywall interiors	0.75	2.0
Older homes, plaster on wood lath construction for interior walls	.50	2.0

[1] All spectral peaks within 6 dB (50 pct) amplitude of the predominant frequency must be analyzed.

Estimation of the predominant frequency is still a problem. Where the wave train is simple, the period corresponding to the peak level can be directly measured. Otherwise, some kind of spectral analysis is required. Complex vibration time histories consist of a variety of frequencies and amplitudes, so a visual estimate of frequency can be misleading. Occasionally, the peak level occurs early in the wave and at a high frequency, with a long-duration wave train of somewhat lesser amplitude following. The safest approach is to consider the low-frequency part of the time history separately, and where it is below 40 Hz, use the 0.75 in/sec or 0.50 in/sec criteria. If Fourier spectral analysis is used, any spectral peak occurring below 40 Hz and within

6 dB (half amplitude) of the peak at the predominant frequency justifies the use of the lower criteria.

A more complex scheme of assessing the damage potential of blast vibrations is possible, using a combination of particle velocity and displacement (appendix B). This permits higher levels for the intermediate-frequency cases (15 to 40 Hz) but requires lower particle velocities for the lowest frequencies (< 4 Hz). The measurement complexity will make this impractical for many situations.

RESPONSE SPECTRA ANALYSIS OF DAMAGE CASES

Damaging and nondamaging blast vibration time histories were examined for single degree of freedom response by Corser (*8*). Four old houses were analyzed, Wiss' single structure (*57*) and three from the new Bureau analysis (houses 19, 27, and 51). Corser found that the shapes of the response spectra were not noticeably different for those that produced damage and for similar blasts that did not, but they had higher pseudo velocities. The response spectra were mostly displacement-bound at the lower frequencies (less than 20 Hz), which includes the range of whole-structure response frequencies.

The lowest damage line was equivalent to structural displacements of roughly 0.012 to 0.014 in, consistent with the old British practice of taking special precautions where ground vibration levels exceed 0.016 in at frequencies below 5 Hz.

EXISTING STANDARDS FOR VIBRATIONS

A variety of vibration standards are in use or under consideration. They are intended to prevent damage to structures as well as to a great variety of other objects (e.g., computers), and also to control annoyance effects. Establishing safe and appropriate levels for all situations is well beyond the scope of this study. However, these blast vibration studies represent a major part of the research effort in this technical area. The results are often applied to situations far removed from cracking prediction in houses from short-duration, ground-transmitted vibrations. For this reason, existing blast vibration standards and reported vibration tolerances are presented in the section on Human Response and in appendix A.

HUMAN RESPONSE

The tolerance and reactions of humans to vibrations are important when standards are based on annoyance, interference, work proficiency, and health. Humans notice and react to blast-produced vibrations at levels that are lower than the damage thresholds. Similar problems also exist for annoyance from sonic booms and airblasts, and these are discussed in a related study of airblasts (*46*). The technical problem of quantifying responses is complicated by the simultaneous presence of both ground vibration and airblast and the many secondary effects of wall-produced window, dish, and bric-a-brac rattling. Persons inside buildings will hear and feel the predominantly 5- to 25-Hz structure midwall and midfloor response vibrations (*45*). Ground vibrations are occasionally blamed for house vibrations when long-range airblasts propagating under favorable weather conditions are responsible. The very infrasonic airblast itself cannot be heard, but the house responds as if subjected to a ground vibration.

Critical to levels of response are the vibration characteristics (duration, peak level, vibration frequency, and frequency of occurrence), reaction descriptors (startle, fright, fear of damage, sleep, or other interference), and tolerance descriptors (health and safety endangered, work or proficiency, and comfort or annoyance boundaries). Running like a thread through the already complex fabric are social, economic, and legal factors, typified by the importance of the vibration source to the Nation, community, or individuals involved. Examples are the temporary or indefinite nature of this environmental intrusion, beliefs in the inevitability of the source, and the social consciousness of the blaster (as shown by his public relations program and blast design efforts that minimize ground vibrations and airblast).

Most studies of human tolerance to vibrations have been of steady-state sources or those of relatively longer duration than typical mine, quarry, and construction blasting. In the absence of data on tolerance to impulsive vibrations, these results have been assumed to be applicable to blasting. Additionally, most useful data are from tests involving human subjects directly, when not in their homes. The duration and frequency of occurrence of the events are obviously critical. The vibration limits required for reasonable comfort from a long-term vibration source (e.g., air conditioning, machinery, building elevators, and vehicle traffic) are certainly more restrictive than for sources of short duration and infrequent occurrence.

The classical study of subjective human tolerance to vibratory motion was done by Reiher and Meister in 1931 (*40*). They subjected 15 people to 5-min duration vertical and horizontal vibrations in a variety of body positions and established levels of perception and comfort. Responses of "slightly perceptible" occcurred at 0.010 to 0.033 in/sec, and the threshold of "strongly perceptible" was 0.10 in/sec, all essentially independent of frequency over the range 4 to 25 Hz.

More recent research on the effects of vibration on man have produced results similar to those of Reiher and Meister (*2, 18, 55*). Goldman analyzed human response to steady-state vibration in the frequency range of 2 to 50 Hz (*18*). His results were converted to particle velocities and presented in Bulletin 656 (*37*, fig. 3.9), where the lines represent means within each response category. One standard deviation of the reactions was at approximately half the level of the means. Goldman's "slightly perceptible" and "strongly perceptible" (unpleasant) levels at 1.65 standard deviations (including all but 5 pct at the low end) are approximately 0.0086 and 0.074 in/sec, respectively, at 10 Hz. Taking these as thresholds, they agree quite well with Reiher and Meister's data.

Several researchers recognized that the duration of the vibration was critical to its undesirability. Most evident was that a higher level could be tolerated if the event was short. Consequently, steady-state vibration data could not be realistically applied to blasting, except for events that exceed several seconds' duration. A good example of a long event was the Salmon nuclear blast (*37, 39*). This was technically a transient; however, the 90-sec-long, low-frequency wave train produced at large distances resulted in numerous complaints (10 pct of all families at 0.40 in/sec). This duration exceeds that of any kind of mining blasts. Chang analyzed the human vibration response literature with particular attention to event durations (7). He noted that Reiher and Meister's responses could be multiplied by a factor of 10 for short events. Atherton studied impact- and walking-

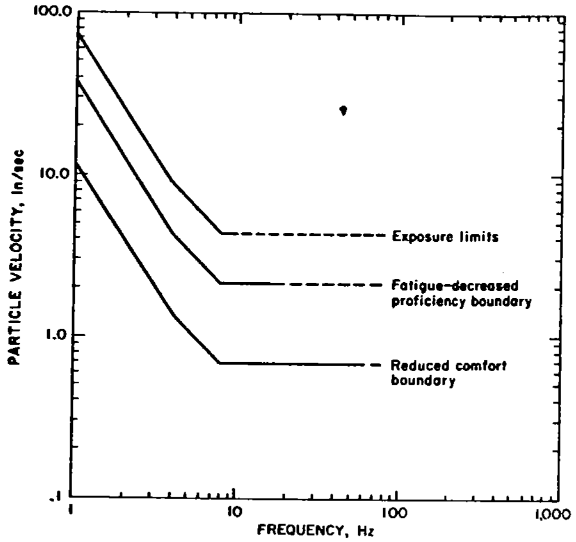

Figure 60.—Human tolerance standards for rms vibrations exceeding 1-minute-duration ISO 2631.

produced floor motions. His impact tests consisted of 3 to 5 cycles of motion at 19 Hz (the floor resonance), or events of approximately 200-msec duration. His "disturbing" level mean was 3.5 to 4.4 in/sec, or over 5 times Goldman's steady-state "intolerable" level of 0.77 in/sec at 20 Hz.

The International Standards Organization (ISO) published tolerable levels for whole body vibration in 1978 (*19*). The scope of their standard included durations of 1 min and longer, frequencies of 1 to 80 Hz, three-axis vibrations, and human tolerances for comfort, working efficiency, fatigue, and health and safety. Their recommendations for 1-min-duration events are shown in figure 60, having been converted from accelerations to particle velocities and corresponding to the worst-case body orientation (longitudinal or Z-axis). All values are rms and are constant particle velocities for frequencies above 8 Hz. Peak values would be larger by a factor of 1.4 to 3. The dashed part of the lines in figure 60 represent peak accelerations in excess of 1 g.

Wiss and Parmelee studied the responses of 40 people to transient vibrations consisting of damped 5-sec sinusoidal pulses (*58*). Damping ranged from zero to 16 pct and frequencies from 2.5 to 25 Hz. All subjects were standing on an open platform and subjected to vertical vibrations. They found that responses depended on vibration levels and damping but were independent of frequency, when plotted in units of frequency times displacement (velocity). Their results, and the two steady-state vibration studies, are shown in figure 61. The various experimental factors for the three studies are listed in table 14. The reaction descriptors were different, a sign of the subjective nature of this kind of work. "Thresholds" correspond to the responses of the most sensitive people tested. "Means" are the responses of the "average subject" within each response descriptor category. Between Goldman's "unpleasant" and "intolerable" (G–2 and G–3) lies the ISO "reduced comfort boundary". Wiss and Parmalee's results were reanalyzed for duration-of-vibration effects, with damping frequency and duration being interrelated. It was assumed that the vibration duration is the time during which the vibration level exceeds 10 pct of the peak (−20 dB). The following relationship was derived:

$$\tau = \frac{0.[illegible]67}{f\beta} + 0.018$$

where τ is the duration (sec), f the frequency (Hz), β is the damping ratio, and 0.018 the average input rise time (sec). Application of this equation to Wiss and Parmelee's test runs allows durations to be calculated for the various reactions that become slightly frequency dependent when plotted as particle velocities (fig. 62), and very much so when plotted as accelerations (fig. 63).

Table 14.–Studies of human response to vibration

Authors	Vibration duration, sec	Curve representations, response descriptors, and curve label for data plotted in figure 61
Goldman (*18*):		Mean values of subject response:
Various body positions, 5 sources	5	Perceivable (curve G–1).
Do	5	Unpleasant (curve G–2).
Do	5	Intolerable (curve G–3).
Reiher and Meister (*40*):		Thresholds:
Standing with vertical vibration	300	Barely noticeable (curve R–1).
Do	300	Objectionable (curve R–2).
Do	300	Uncomfortable (curve R–3).
Wiss and Parmalee (*58*):		Mean values of subject response:
Standing with vertical vibration	5	Barely perceptible (curve W–1).
Do[1]	5	Distinctly perceptible (curve W–2)
Do[1]	5	Strongly perceptible (curve W–3).
		Thresholds:
Do[1]	5	Barely perceptible (curve W–4).
Do[2]	5	Distinctly perceptible (curve W–5).
Do[2]	5	Strongly perceptible (curve W–6).
Do[2]	5	Severe (curve W–7).

[1] Transient with 1 pct damping. 5-sec duration is maximum.
[2] Zero damping.

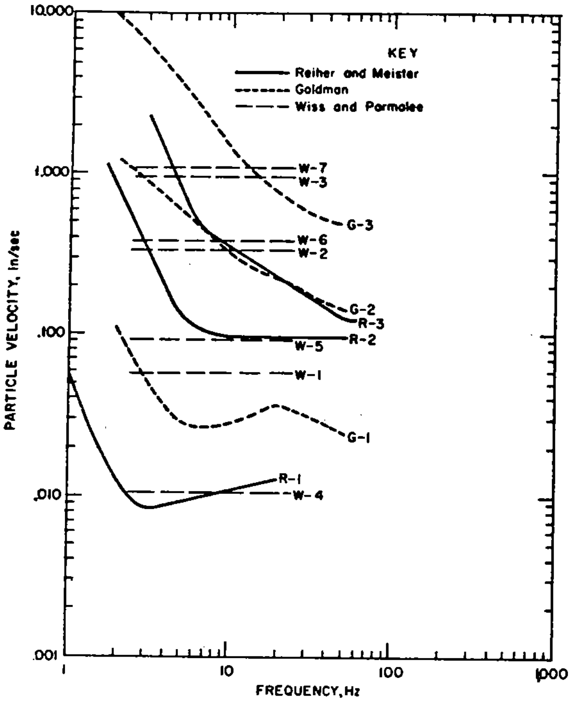

Figure 61.—Human response to steady-state and transient vibrations. Labels refer to measurements listed in table 14.

T. M. Murray investigated human reactions to vibrations of concrete floors (*33*). His summary of 91 observations of acceptable versus unacceptable cases indicated strong influences for amplitude times frequency (same units as particle velocity) and damping levels. He derived the following relationship for an acceptable concrete floor:

$$\beta \geq 35Af_0 + 2.5$$

where β is percent of critical damping (damping ratio × 100), A is initial amplitude from a heel-drop impact (in), and f_0 is the first natural frequency (Hz). Murray's data were converted to peak particle velocities and are shown in figure 64. The line represents the equation above and is Murray's eyeball separation between acceptable and unacceptable cases. Acceleration and displacement plots were also made from Murray's data and, unlike the particle velocity data, they showed a strong frequency influence.

As with Wiss' data, Murray's 91 points were converted into duration-amplitude form using the relationship:

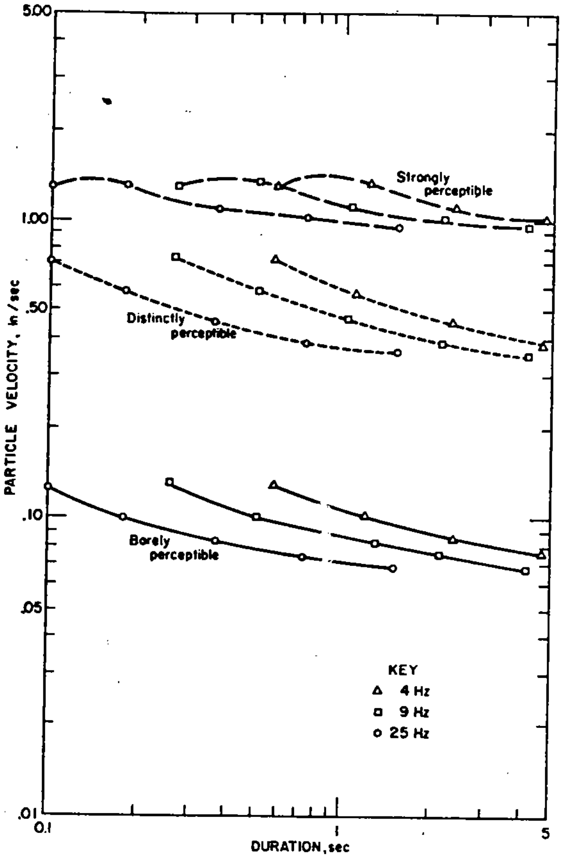

Figure 62.—Human response to transient vibration velocities of various durations.

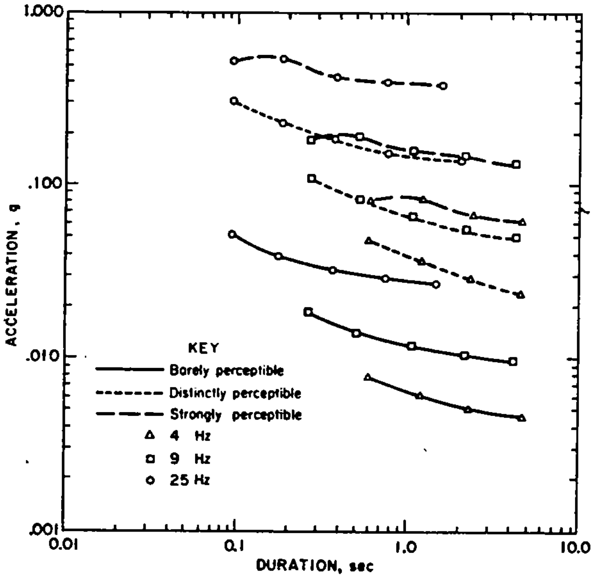

Figure 63.—Human response to transient vibration accelerations of various durations.

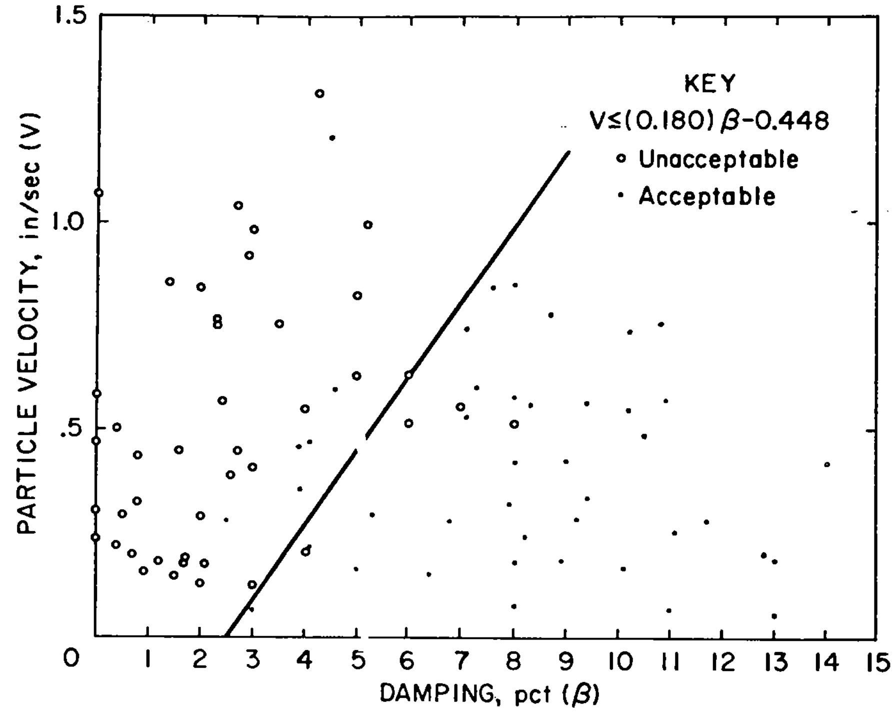

Figure 64.—Human response to vib ations of damped concrete floors, after Murray (*33*). Equatior defines acceptable zone.

$$\tau = \frac{36.7}{\beta f}$$

where β is the percentage of critical damping.

The results, given in figure 65, show a strong influence on acceptability of both floor velocity and vibration duration. As in Murray's analysis, a separation of cases was derived by visual means and produced the following acceptability criterion:

$$V \leq 0.415 \tau^{-1.29}$$

where V is the peak floor vibration (in/sec) and τ is the time (sec) from the peak to the minus 20-dB level (or 10 pct of peak amplitude). The amplitude-duration acceptability line shows a better defined separation of cases than Murray's original amplitude-damping version.

As with Murray's damping version of the data, the duration version did not produce simple relationships when plotted as accelerations and displacements, with frequency factors and nonlinear plots required. Murray suggests that his acceptability criteria for concrete floors may be conservative compared with that for wooden floors, where a greater amount of vibration is normally expected.

Human reactions to events of varying durations are summarized in figure 66, with the values given in table 15. In cases where "distinctly perceptible" applies (i.e., infrequent and short-duration events), these results suggest that levels of over 0.5 in/sec could be tolerated. The barely perceptible levels are still below 0.1 in/sec; consequently, it is impractical for blasting ever to be totally unobtrusive.

The studies just discussed all involve people in a test situation rather than in their own homes. None of the problems of damage fear, startle, house rattle, and other secondary effects were present. Undoubtedly, the addition of such effects lowers the thresholds at which people react. Relationships have been developed for people subjected to sonic booms and airblasts in their "normal" environment (*46*).

An estimate of annoyance from indoor-perceived ground vibration can be made by comparing airblast and ground vibration-produced midwall response (fig. 41), and the annoyance curves from airblast study. Estimated ground-vibration-produced human reactions are given in figure 67 based on the airblast responses from figure I-1 of RI 8485 (*46*). These are for coal mining; quarry levels are 20 pct higher. The three lines of the figure show the distribution

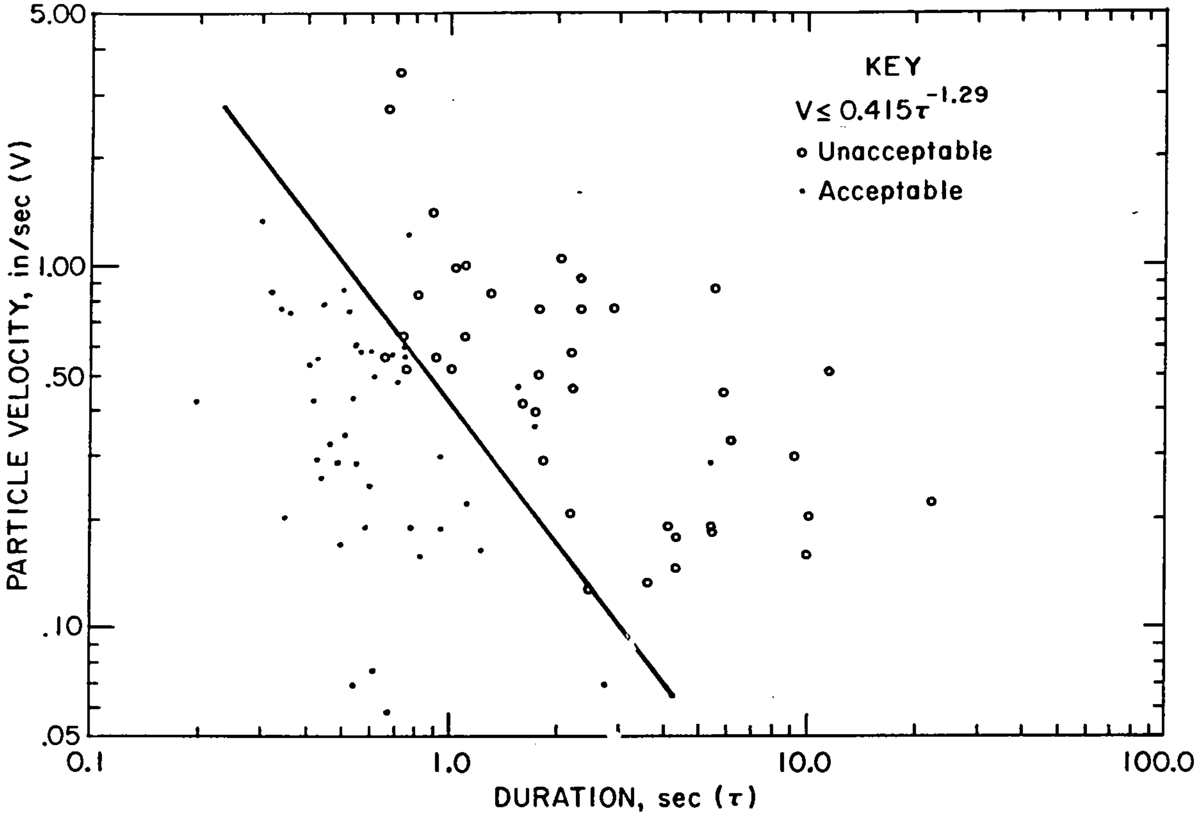

Figure 65.—Human response to concrete floor vibrations of various durations. Equation defines acceptable zone.

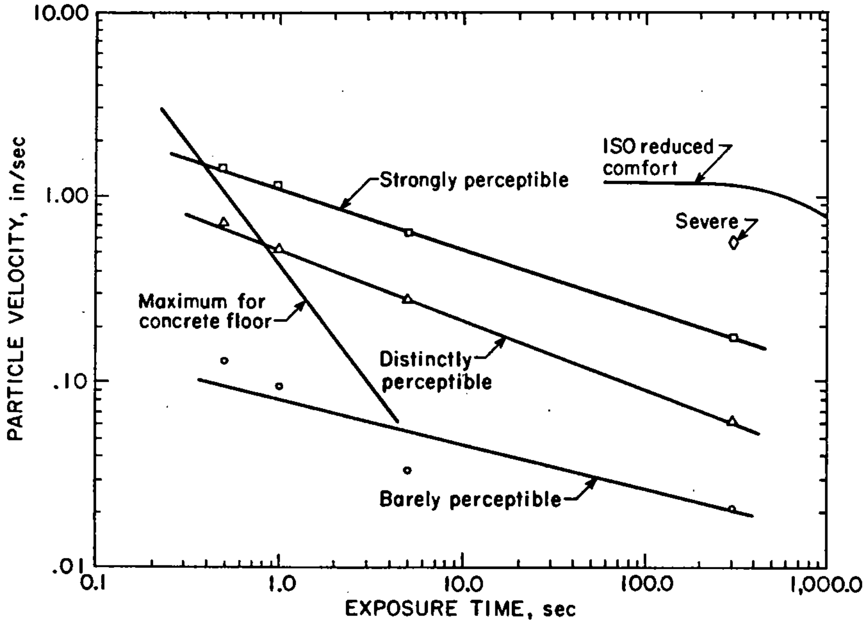

Figure 66.—Human response to vibrations of various durations, summary. ISO values are from Standard 2631.

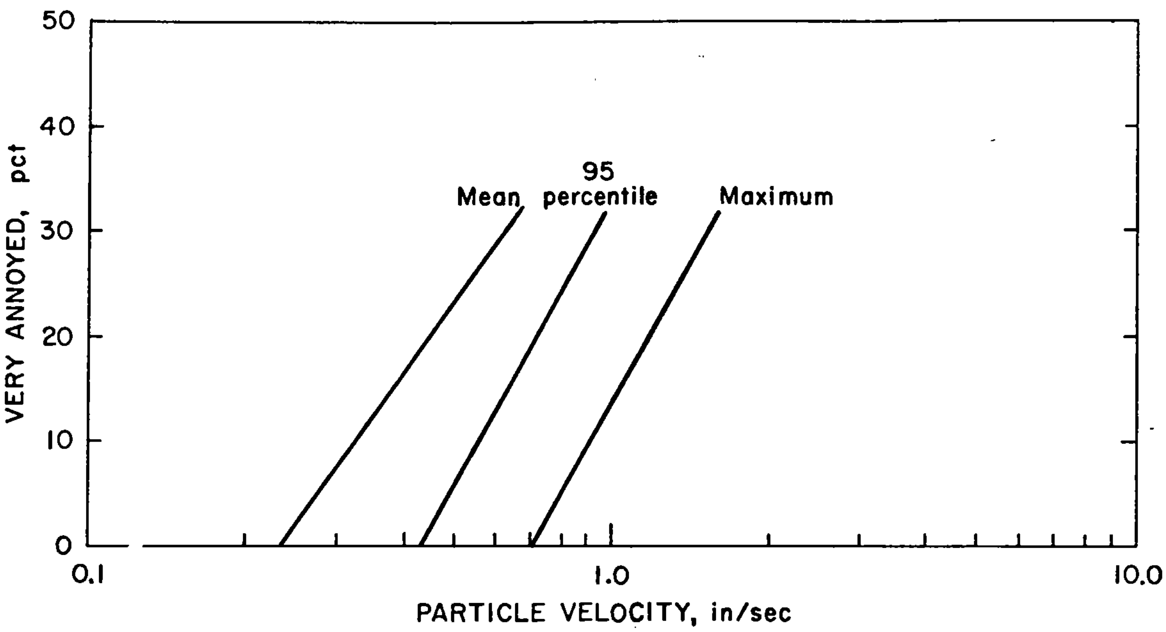

Figure 67.—Reactions of persons subjected to blasting vibration in their homes.

of the particle velocities. Since reactions are most likely from stronger events, actual public reaction would occur somewhere between that corresponding to the mean vibration level and the maximum, probably close to the 95th percentile. Exact determination of the airblast-produced human reactions (and also those produced by ground vibration) is not possible without knowing how closely the reported subjective reactions correspond to various levels of sonic boom experienced during the three test periods. It is possible and even likely that those interviewed reacted more to the higher level booms (e.g., maximum values). More work is needed to quantify reactions and specific levels. The potential for ground vibrations to produce strong public reaction is evident from figure 67. In the absence of a public relations program, it is expected that a mean ground vibration level of 0.50 in/sec in a community will produce 15 to 30 pct "very annoyed" neighbors. The 95-pct line gives 5 pct very annoyed at 0.5 in/sec. The blaster must convince the nearby homeowners that the rattling is to be expected and is not damaging. He can also demonstrate his sincerity by blasting as unobtrusively as possible, and using the best blast design principles.

Table 15.—Subjective responses of humans to vibrations of various durations

Type of response	Duration, sec	Particle velocity, in/sec	Source
Barely perceptible:			
Mean	0.5	0.130	Wiss and Parmelee (*58*).
Do	1	.095	Do.
Do	5	.033	Do.
Do	300	.020	Reiher and Meister (*40*).
Threshold	5	.011	Wiss and Parmelee (*58*).
Do	300	.011	Reiher and Meister (*40*).
Distictly perceptible:			
Mean	.5	.700	Wiss and Parmelee (*58*).
Do	1	.500	Do.
Do	5	.280	Do.
Do	300	.060	Reiher and Meister (*40*).
Threshold	.5	.300	Wiss and Parmelee (*58*).
Do	1	.230	Do.
Do	5	.100	Do.
Do	300	.033	Reiher and Meister (*40*).
Strongly perceptible:			
Mean	.5	1.400	Wiss and Parmelee (*58*).
Do	1	1.150	Do.
Do	5	.630	Do.
Do	300	.170[1]	Reiher and Meister (*40*).
Threshold	.5	.910	Wiss and Parmelee (*58*).
Do	1	.810	Do.
Do	5	.390	Do.
Do	300	.102	Reiher and Meister (*40*).
Severe:			
Mean	300	.550[1]	Do.
Threshold	5	1.13	Wiss and Parmelee (*58*).
Do	300	.301	Reiher and Meister (*40*).
Acceptable	0.2–4	$\leqq 0.415\tau^{1.29}$	Murray (*33*).[2]

[1] At 9 Hz.
[2] τ = duration (sec).

CONCLUSIONS

The problems of blasting vibration damage to residential structures and human tolerance to vibrations have been analyzed using data from a wide variety of studies. Statistical techniques of mean and variance analysis and probability plots have both been applied to the damage data from the 10 studies and demonstrated the following:

1. Particle velocity is still the best single ground motion descriptor.

2. Particle velocity is the most practical descriptor for regulating the damage potential for a class of structures with well-defined response characteristics (e.g., single-family residences).

3. Where the operator wants to be relieved of the responsibility of instrumenting all shots, he could design for a conservative square root scale distance of 70 ft/lb$^{1/2}$. The typical vibration levels at this scaled distance would be 0.08 to 0.15 in/sec.

4. Damage potentials for low-frequency blasts (< 40 Hz) are considerably higher than those for high-frequency blasts (> 40 Hz), with the latter often produced by close-in construction and excavation blasts.

5. Home construction is also a factor in the minimum expected damage levels. Gypsumboard (Drywall) interior walls are more damage resistant than older, plaster on wood lath construction.

6. Practical safe criteria for blasts that generate low-frequency ground vibrations are 0.75 in/sec for modern gypsumboard houses and 0.50 in/sec for plaster on lath interiors. For frequencies above 40 Hz, a safe particle velocity maximum of 2.0 in/sec is recommended for all houses.

7. All homes eventually crack because of a variety of environmental stresses, including humidity and temperature changes, settlement from consolidation and variations in ground moisture, wind, and even water absorption from tree roots. Consequently, there may be no absolute minimum vibration damage threshold when the vibration (from any cause, for instance slamming a door) could in some case precipitate a crack about to occur.

8. The chance of damage from a blast generating peak particle velocities below 0.5 in/sec is not only small (5 pct for worst cases) but decreases more rapidly than the mean prediction for the entire range of vibration levels (almost asymptotically below about 0.5 in/sec).

9. Human reactions to blasting can be the limiting factor. Vibration levels can be felt that are considerably lower than those required to produce damage. Human reaction to vibration is dependent on event duration as well as level. Particle velocities of 0.5 in/sec from typical blasting (1-sec vibration) should be tolerable to about 95 pct of the people perceiving it as "distinctly perceptible". Relevant to whole-body vibration reaction is the degree that the vibration interferes with activity (sleep, speech, TV viewing, reading), presents a health hazard, and affects task proficiency. For people at home, the most serious blast vibration problems are house rattling, fright (fear of damage or injury), being startled, and for a few, activity interference. Complaints from these causes can be as high as 30 pct at 0.5 in/sec, and this is where good public relations attitudes and an educational program by the blaster are essential.

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APPENDIX A.—EXISTING VIBRATION STANDARDS AND CRITERIA TO PREVENT DAMAGE

The German vibration standards (DIN 4150) are intended to protect buildings but are so strict as to be unworkable (table A–1). Reportedly, they are not enforced, at least for blasting. No technical data have been given to justify the levels specified (*4, 52*).[1]

The Australian standard (CA 23–1967) specifies maximums of

(1) 0.008-in displacement for frequencies less than 15 Hz and
(2) 0.75 in/sec resultant peak particle velocity for frequencies greater than 15 Hz.

The 0.008-in maximum displacement corresponds to 0.5 in/sec at 10 Hz and 0.25 in/sec at 5 Hz.

Skipp (*47*) lists a variety of national vibration limits, including the Czechoslovakian maximum code of 10 mm/sec (0.40 in/sec). Skipp states, "in countries without formal codes, good practice usually takes into account the intrusive element without specifying a particular damage state. In the U. K. for example for tunnel blasting, 10 mm/sec has been the aim in densely populated areas and 25 mm/sec in sparsely populated areas." The British Secretary of State specified that 12 mm/sec (0.47 in/sec) be used for surface coal mine blasts that generate frequencies below 12 Hz.

Table A–1.—German vibration standards, DIN 4150

Type of construction	Peak pseudo vector sum particle velocity mm/sec	Peak pseudo vector sum particle velocity in/sec
Ruins, ancient and historic buildings given antiquities protection	2	0.08
Buildings with visible damage and cracks in masonry	4	.16
Buildings in good condition, possibly with cracks in plaster	8	.32
Industrial and concrete structures without plaster	10–40	.39–1.56

Bogdanoff's damage paper (*6*) summarizes safe values from the text "Rock Blasting," by Langefors and Kihlstrom (*25*), given in table A–2. The propagation velocity (c) is related to particle velocity (V) and ground strain (e) according to:

$$e = \frac{V}{c}$$

Table A–2.—Damage levels from blasting, after Langefors and Kihlstrom (*25*)

Damage effects	Peak particle velocity					
	Sand, gravel, clay below water level; c = 1,000 – 1,500 m/sec[1]		Moraine, slate, or soft limestone; c = 2,000 – 3,000 m/sec		Granite, hard limestone, or diabase; c = 4,500 – 6,000 m/sec	
	mm/sec	in/sec	mm/sec	in/sec	mm/sec	in/sec
No noticeable crack formation	18	0.71	35	1.4	70	2.8
Fine cracks and falling plaster threshold	30	1.2	55	2.2	100	~~3.9~~ 4,3
Crack formation	40	1.6	80	3.2	~~150~~ 160	~~5.9~~ 6,3
Severe cracks	60	2.4	115	4.5	~~225~~ 230	~~8.9~~ 9,1

[1] Propagation velocity in media is given by c.

Table A–3.—Limiting safe vibration values of pseudo vector sum peak particle velocities, after Esteves (*17*)

Type of construction	Peak particle velocity					
	Incoherent loose soils, soft coherent soils, rubble mixtures: c < 1,000 m/sec[1] c < 3,300 ft/sec[1]		Very hard to medium consistence coherent soils, uniform or well-graded sand: c = 1,000–2,000 m/sec c = 3,300–6,600 ft/sec		Coherent hard soils and rock: c > 2,000 m/sec c > 6,600 ft/sec	
	mm/sec	in/sec	mm/sec	in/sec	mm/sec	in/sec
Special care, historical monuments, hospitals, and very tall buildings	2.5	0.10	5	0.20	10	0.40
Current construction	5	.20	10	.40	20	.80
Reinforced construction, e.g., earthquake resistant	15	.60	30	1.20	60	2.40

[1] Propagation velocity in media given by c.

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[1] Italic numbers in parentheses refer to items in the list of references preceding the appendixes.

Consequently, low-velocity materials will have higher ground strains (and potentials for failure) for a given particle velocity. Langefors and Kihlstrom did not give the experimental data to support their thresholds of table A–2. Esteves' study (*17*) includes safe values for a variety of conditions, including types of soil, construction, and frequency of blasting (table A–3). As with Langefors and Kihlstrom (table A–2), Esteves does not give the supporting experimental data. Ashley lists maximum particle velocities for a variety of structure types (*1*). Again, technical data to derive or support the recommended values are not given (table A–4).

Several survey papers have been written that combined nuclear blast, earthquake, and blasting data without pointing to the variations among vibration characteristics and the resulting response and damage potentials (*20, 34*). The worst-case experimental data are from the Salmon nuclear blast and the Mercury, Nev., studies. These results are overly conservative for blasting, and their use cannot be justified on technical grounds.

Cases occasionally arise where blasting vibration is considered a potential problem to equipment, or concern is expressed about the vibration sources such as traffic. The safe level criteria established for blasting are often applied to these situations with little justification. Traffic is usually a steady-state source of low amplitude. Appropriate safe levels would have to be lower than for blasting, which is relatively infrequent and of shorter duration. The British criterion for architectural damage from steady-state sources is 5 mm/sec (0.20 in/sec) (*55*). Vibration standards for laboratory instruments are given in table A–5.

Table A–4.—Limiting safe vibration values, after Ashley (*1*)

Type of construction	Peak particle velocity mm/sec	Peak particle velocity in/sec
Ancient and historic monuments	7.5	0.30
Housing in poor repair	12	.47
Good residential, commercial, and industrial structures	25	1.0
Welded gas mains, sound sewers, engineered structures	50	2.0

Table A–5.—Vibration limits for laboratory instruments, after Whiffin and Leonard (*55*)

Dimensional and electrical physical reference standards	g[1]	0.01
Do	in/sec	[2]0.031
Dimensional working standards	g	0.02
Do	in/sec	[2]0.062
Electrical, physical working standards	g	0.03
Do	in/sec	[2]0.093
General electronic apparatus	in/sec	0.19
Mettler analytical balance	in/sec	[2]0.0125
Sartorius analytical balance	in/sec	[2]0.10
Leeds—Northrup Reflection Galvanometer	in/sec	[2]0.0125
Photo microscope	in/sec	1.44
Phillips EM 300 electron microscope	in/sec	0.00013
HAAS standards barometer	in/sec	0.08

[1] g = acceleration of gravity 9.8 m/sec^2 (32.2 ft/sec^2).

[2] At 20 Hz.

APPENDIX B.—ALTERNATIVE BLASTING LEVEL CRITERIA

Safe blasting vibration criteria were developed for residential structures, having two frequency ranges and a sharp discontinuity at 40 Hz (table 13). There are blasts that represent an intermediate frequency case, being higher than the structure resonances (4 to 12 Hz) and lower than 40 Hz. The criteria of table 13 apply equally to a 35-Hz and a 10-Hz ground vibration, although the responses and damage potentials are very much different.

Using both the measured structure amplifications (fig. 39) and damage summaries (figs. 52 and 54), a smoother set of criteria was developed. These criteria have more severe measuring requirements, involving both displacement and velocity (fig. B–1).

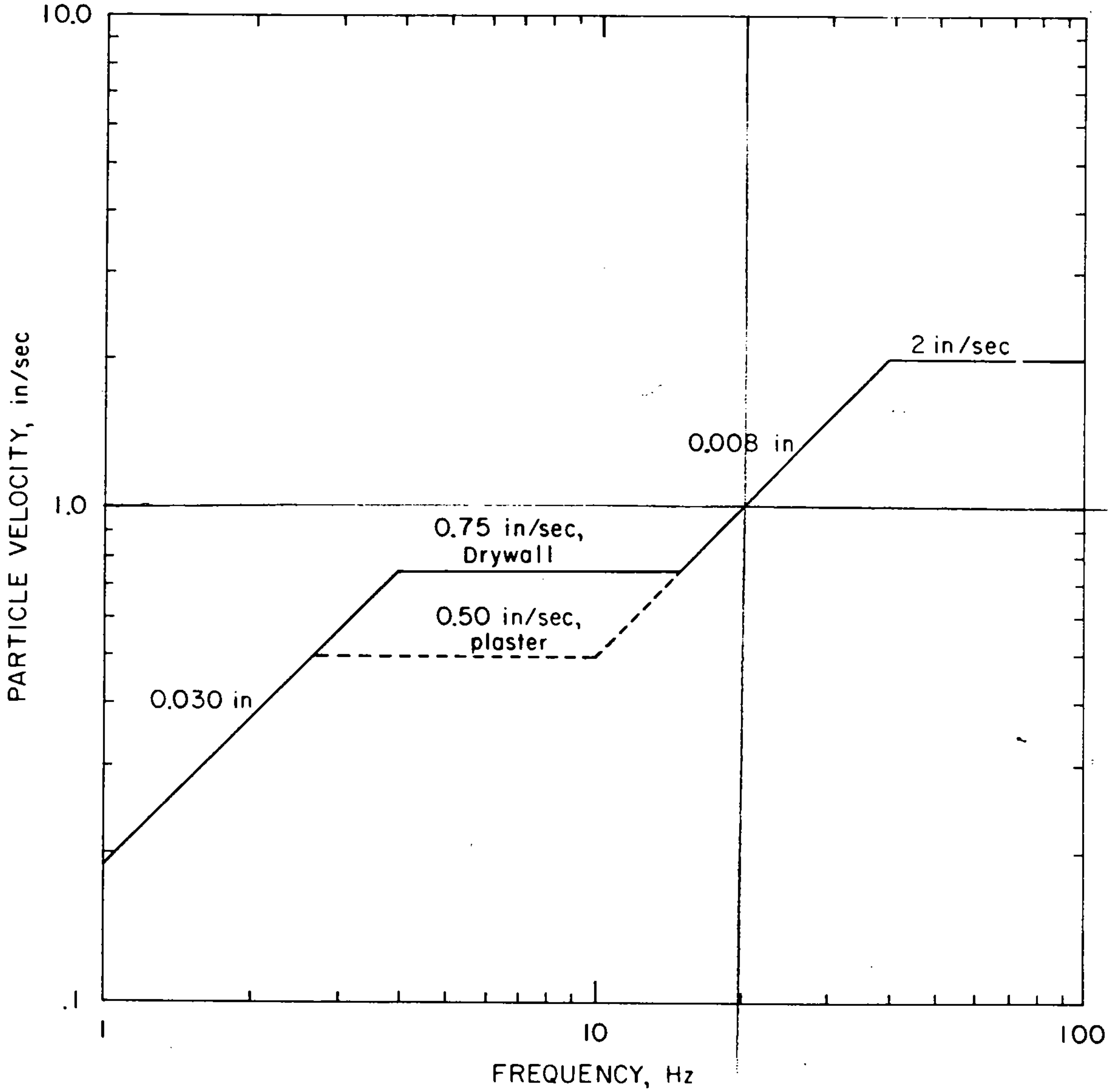

Figure B–1.—Safe levels of blasting vibration for houses using a combination of velocity and displacement.

Above 40 Hz, a constant peak particle velocity of 2.0 in/sec is the maximum safe value. Below 40 Hz, the maximum velocity decreases at a rate equivalent to a constant peak displacement of 0.008 in. At frequencies corresponding to 0.75 in/sec for Drywall, and 0.50 in/sec for plaster, constant particle velocities are again appropriate. An ultimate maximum displacement of 0.030 in is recommended, which would only be of concern where very low frequencies are encountered (< 4 Hz).

This scheme is based on the response and damage data, recognizes the displacement-bound requirement for house responses to blast vibrations, and provides a smooth transition for the intermediate frequency cases. This method of analyzing the damage potential of blasting vibrations has the disadvantage of possibly underestimating annoyance reactions. Midwall responses (fig. 40) do not decrease nearly as fast as structure (corner) responses as frequencies increase from 10 to 40 Hz. A very nearly linear decrease of velocity amplification was observed for the gross structure; however, the higher midwall response frequencies will make the 20- to 35-Hz vibrations relatively annoying if the maximum levels shown on figure B–1 are attained.

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Bureau of Mines
Report of Investigations 8507

STRUCTURE RESPONSE AND DAMAGE PRODUCED BY GROUND VIBRATION FROM SURFACE MINE BLASTING

by

David E. Siskind, Mark S. Stagg,
John W. Kopp, and Charles H. Dowding

ERRATA

Page 1, line 14 should read "Safe levels" instead of "Save levels."

Page 3, footnote should read "Italic numbers" instead of "Underlined numbers."

Page 12 (table 1): Seven shots that were omitted are given on the attached page. In addition, for shot 134 "Peak ground vibration (H_2)" should be 0.32 instead of 0.36, and the column heading labeled "Sealed distance" should read "Scaled distance."

Page 19 (equation 2): Sign before $\frac{\beta}{\sqrt{1-\beta^2}}$ should be minus instead of plus.

Page 23 (table 3): Structures numbered 58 and above have some of the shots improperly indicated. The attached table shows the correct values, and is consistent with table 1.

Page 28, caption of figure 28 should be "Test structure 61, near a construction site."

Page 41 (table 5): Footnote 4 should show 119 dB airblast instead of 111 dB.

Page 42 (table 6): Values in "Mine blasts" column should read 0.377 instead of 0.472 and .314 instead of .392. Footnote 1 should have 119 dB airblast instead of 111 dB.

Page 48 (table 9): Jensen and Rietman reference number should be 21 instead of 57. Also, under "Damage observed, uniform classification," Nondamage and Threshold values for "Bureau of Mines new data" should be 76 and 28, respectively, not 37 and 23.

Page 71 (table A-2): Values in the "Granite, hard limestone, or diabase" column should be as follows:

mm/sec	in/sec
70	2.8
110	4.3
160	6.3
230	9.1

ADDITIONAL VALUES FOR TABLE 1 OF RI 8507

Production blasts and ground vibration measurements

Shot	Facility	Shot type	Total charge lb.	Lb per delay	Scaled distance ft/lb 1/2	Peak ground vibration, in/sec			Peak structure motion, in/sec							Structure number (table 3)	Structure type
									Low corner			High corner		Midwall			
						H_1	H_2	V	H_1	H_2	V	H_1	H_2	H_1	H_2		
155	Coal	Highwall..	5,400	120	43.0		0.43	0.55						0.84		44	1
156	Coal	....do....	3,600	80	41.0		0.96	0.57						0.76		44	1
173	Coal	....do....	2,150	86	27.0	0.59	0.96	1.01	0.56	0.66	1.19			0.74	2.55	51	2
176	Coal	....do....	3,550	71	6.9	5.58	2.34	2.61	2.85	1.32	4.09	3.43	1.41	9.14	2.69	51	2
177	Coal	....do....	3,240	36	9.7	3.90	2.44	1.65	2.13	2.2	2.60	3.53	2.28	7.06	2.82	51	2
209	Coal	....do....		80	19.0	4.50	1.17	[illegible]								58	1
W-17	Constr	Excavation	50	13	1.4	5.83	11.87	6.49	8.05	[illegible]	9.02	4.77	2.03	5.8	8.69	67	2

CORRECTIONS FOR TABLE 3 OF RI 8507

Test structures and measured dynamic properties

Structure	Shots (table 1)
57	201,202
58	203-209
59	W-1
60	W-2, W-3
61	W-4, W-5
62	W-6
63	W-7, W-8
64	W-9, W-10
65	W-11, W-12
66	W-13, W-14, W-15
67	W-16, W-17
68	W-18, W-19
69	W-20, W-21
70	W-22
71	W-23
72	W-24
73	W-25, W-26, W-27
74	W-28, W-29
75	W-30
76	W-31, W-32