GROUND VIBRATION MONITORING FOR CONSTRUCTION BLASTING IN URBAN AREAS

F-00-OR-10

Final Report

April 2001

Caltrans

STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION

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TECHNICAL REPORT DOCUMENTATION PAGE

TR0003 (REV. 10/98)

1. REPORT NUMBER	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER
FHWA/CA/OR-2001/03		

4. TITLE AND SUBTITLE	5. REPORT DATE
GROUND VIBRATION MONITORING FOR CONSTRUCTION BLASTING IN URBAN AREAS	April 2001
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
J.Egan, J.Kermode, M.Skyrman, L.Turner	59-324, 65-680302
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. WORK UNIT NUMBER
California Department of Transportation Division of Structural Foundations 5900 Folsom Blvd. MS-5 Sacramento, CA 95819	11. CONTRACT OR GRANT NUMBER F-00-OR-10
12. SPONSORING AGENCY AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
California Department of Transportation Sacramento, CA 95819	Final Report
	14. SPONSORING AGENCY CODE

15. SUPPLEMENTAL NOTES

16. ABSTRACT

The primary objectives of this study were to determine a recommendation for the pre-blast area for surveys, and to obtain actual field vibrations from rock blasting operations, in populated regions within specific geologic units. The area confined within a pre- and post-construction survey covers a region where vibrations or vibration induced settlements have the potential to cause real structural damage as well as perceived damage from residents.

17. KEY WORDS	18. DISTRIBUTION STATEMENT	
vibrations, blasting, monitoring, peak particle velocity	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161	
19. SECURITY CLASSIFICATION (of this report)	20. NUMBER OF PAGES	21. PRICE
Unclassified	40	

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INTRODUCTION

There has been a significant increase in construction blasting activity near Caltrans facilities and a concomitant increase in nearby structure density that can be detrimentally affected by Caltrans construction operations and blasting. There is a need to update Caltrans standards related to vibration monitoring programs and equipment, acceptable tolerances for vibrations for various classes of urban structures and the recommended limits for pre-blast damage surveys.

As population density increases, Caltrans construction operations, including blasting and pile driving, expose ever larger numbers of nearby facilities and individuals to what are perceived to be intolerable levels of ground vibrations. Hard data is required to develop a basis for new standards for Caltrans vibration monitoring programs. The synthesis of the gathered data will provide a basis for project Resident Engineers to confirm that on-going construction operations are staying within tolerable limits to prevent damage due to ground vibrations. These data can also be used in defense of the State for unreasonable claims of damage.

The primary objectives of this study were to determine a recommendation for the pre-blast area for surveys, and to obtain actual field vibrations from rock blasting operations, in populated regions within specific geologic units. The area confined within a pre- and post-construction survey covers a region where vibrations or vibration induced settlements have the potential to cause real structural damage as well as perceived damage from residents.

PROJECT BACKGROUND

Ground vibrations are a significant factor when considering highway construction activities such as pile driving and rock blasting operations. These activities create the potential for real damage to surrounding building structures and facilities, as well as a perceived damage from human sensitivities to detectable yet non-damaging ground motions. Caltrans practice has typically involved the use of specifications requiring the contractor to develop a vibration-monitoring plan. These plans have included requirements for photo and video surveys, crack monitoring, survey of elevations, and use of vibration monitoring equipment for nearby structures during construction operations. However, the Statewide application of vibration monitoring specifications has been inconsistent with varying degrees of equipment requirements, damage thresholds, and limits of surveys.

At the time of this study, Caltrans had recently awarded several construction contracts that required considerable amounts of blasting to excavate rock in both commercial and residential environments where the ground vibrations could not only be a nuisance, but could also cause damage to facilities if blast charges and delay timing were such as to cause ground vibrations in excess of acceptable limits. A considerable number of facilities would need to be surveyed in the pre-blast documentation. Review of existing literature and discussion with other Caltrans personnel showed consensus that the radius of surveys could be significantly reduced; however, monitoring of the blasts would be necessary to validate a reduced radius of survey. On one of the projects, Route 54 in San Diego county (11-SD-54 KP 9.7/10.8 - 18.0/19.6 Stage II, EA 11-001923), an estimated 471 structures fell within the specified 366 m radius of the area to be blasted at an estimated cost of approximately $500,000 to conduct a single survey. Multiple surveys would be likely. If the survey radius could be reduced by 50%, projected single survey costs could be reduced to $100,000. Other projects included extensions to highway corridors in San Diego county such as Route 125, Route 56, and Route 78 (11-SD-125 stage IV, 11-SD-56, and 11-SD-78) which involved the construction of new freeways or widening of an existing freeways within urban environments. On the Route 125 project an estimated 674 structures fell within the specified 366 meter radius of the area to be blasted, at an estimated cost of approximately $800,000 to conduct a single survey. As with the other projects, if the survey radius could be reduced by 50%, projected survey costs could be reduced to $200,000.

ORIGIN OF CALTRANS VIBRATION SPECIFICATIONS

In the San Diego area (District 11), Caltrans' specifications have typically required a survey of all structures within a 366 meter radius of a proposed blasting operation, a maximum of 45 days prior to the commencement of the blasting. In addition, the areas had to be resurveyed within 45 days subsequent to blasting. Due to the absence of supporting data for the establishment of these limits during design, pre- and post- blast surveys limits have typically been identified or modified by the Caltrans Construction Engineer in the construction phase of the project.

In response to the requests from Caltrans designers, this study was undertaken to investigate the history and sources of the current specification and its development. Specifications from other Caltrans districts and offices as well as other agencies were also evaluated. Finally, published literature were reviewed to evaluate the state of the practice.

The current pre and post blast specifications were developed at a time when San Diego County was predominately rural, and construction adjacent to pre-existing structures was limited. The radius of the survey and specified time frames were based upon what was deemed prudent and conservative by the Office Engineer at that time. A survey of other work groups within Caltrans as well as in other agencies revealed not only the absence of a standard, but an increasing need to develop one.

The literature search revealed a plethora of papers on blasting physics and measurement techniques. Many developed relationships correlating structural damage to peak particle velocity. Most of them relied heavily upon the work and subsequent papers produced by the U.S. Bureau of Mines, as well as others produced by manufacturers of explosives, such as Dupont. In most cases the *peak particle velocity* was identified as the most useful parameter when correlating blast size to distance, with the *scaled distance* (distance from blast divided by the n^{th} root of the weight of explosive used in the blast) as another significant parameter. Thresholds for structural damage are typically based upon peak particle velocities. Although these correlations were very useful for blast design, they did not readily lend themselves to determining pre-blast survey radii during the design phase of project development.

The current Caltrans specifications permit a peak particle velocity of 50mm (2 inches) per second[6] at a nearby receptor that is susceptible to damage from such vibrations. In order to stay within the tolerable limits, Caltrans reviews the contractor's blasting plan for a particular blast as to the likelihood of exceeding the prescribed limit of vibration. Vibration monitoring is typically required when blasting occurs in close proximity to structures.

INSTRUMENTATION

To conduct this project and collect vibration data, three blasting seismographs and analysis software were acquired. Each seismograph consisted of a 3-axis velocity transducer, an air over-pressure transducer, and a data acquisition and storage device. The blasting analysis software provided features for graphical output of the wave forms in each of the three axes and comparison of the measured peak particle velocities and

Instantel Blastmate III Vibration Monitors frequency content with various accepted standards developed by the U.S. Bureau of Mines and others.

Each transducer measured velocities on three mutually perpendicular axes (V_x, V_y, V_z) corresponding to a radial, transverse, and vertical component. The data acquisition equipment simultaneously recorded each geophone, in digital format, time-domain data for each of the three mutually perpendicular axes at each of the four radial distances.

BLAST RECORDS

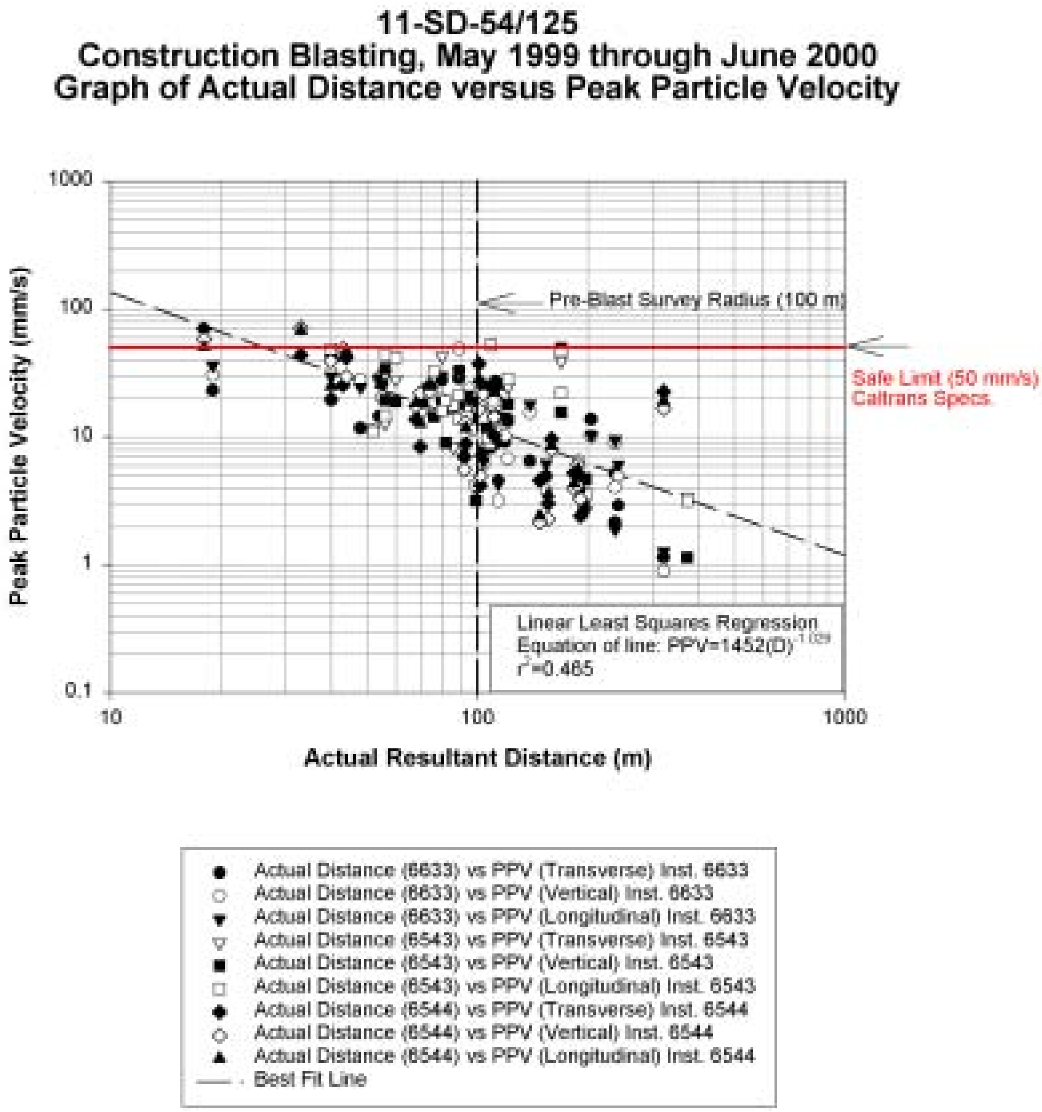
This study documents 27 blasts which occurred on the Route 54 project in San Diego county between June 18, 1999 and May 4, 2000. Blasting was performed within the Jurassic Santiago Peak Volcanic rock formation. Prior to construction, existing roadway cuts exposed foliated, welded siliceous tuff, jointed and fractured hornfels and andesite porphyry.

For each blast event, up to three blasting seismographs were deployed for measurements at varying distances from the blast site. The particle velocity time-history data for these 27 blasts are included in the appendix. Electronic files from the monitoring, both proprietary Instantel *Blastware* versions as well as exported ASCII text versions, are included on a compact disk with this report.

Since the commencement of monitoring on May 28, 1999, approximately 70 blasts have been recorded among three projects in San Diego county. Of that number several blasts have had reports of disturbances by nearby residents. To date, none of the blasts have caused any known damage to private or public facilities. With few exceptions, the monitoring points have not exceeded the recommended specified peak particle velocity. The continued monitoring efforts on these ongoing projects is intended to add to the body of data available for a rigorous analysis of blasting related to Caltrans projects, perhaps statewide, to further the confidence in reducing the radius and thus the cost of pre-blast surveys.

OBSERVATIONS

Vibration measurements at every distance and on every axes from the 27 recorded blasts were plotted on a single log-log plot to demonstrate the attenuation relationship for groundborne vibrations propagating through the specific subsurface materials in the area of this project.

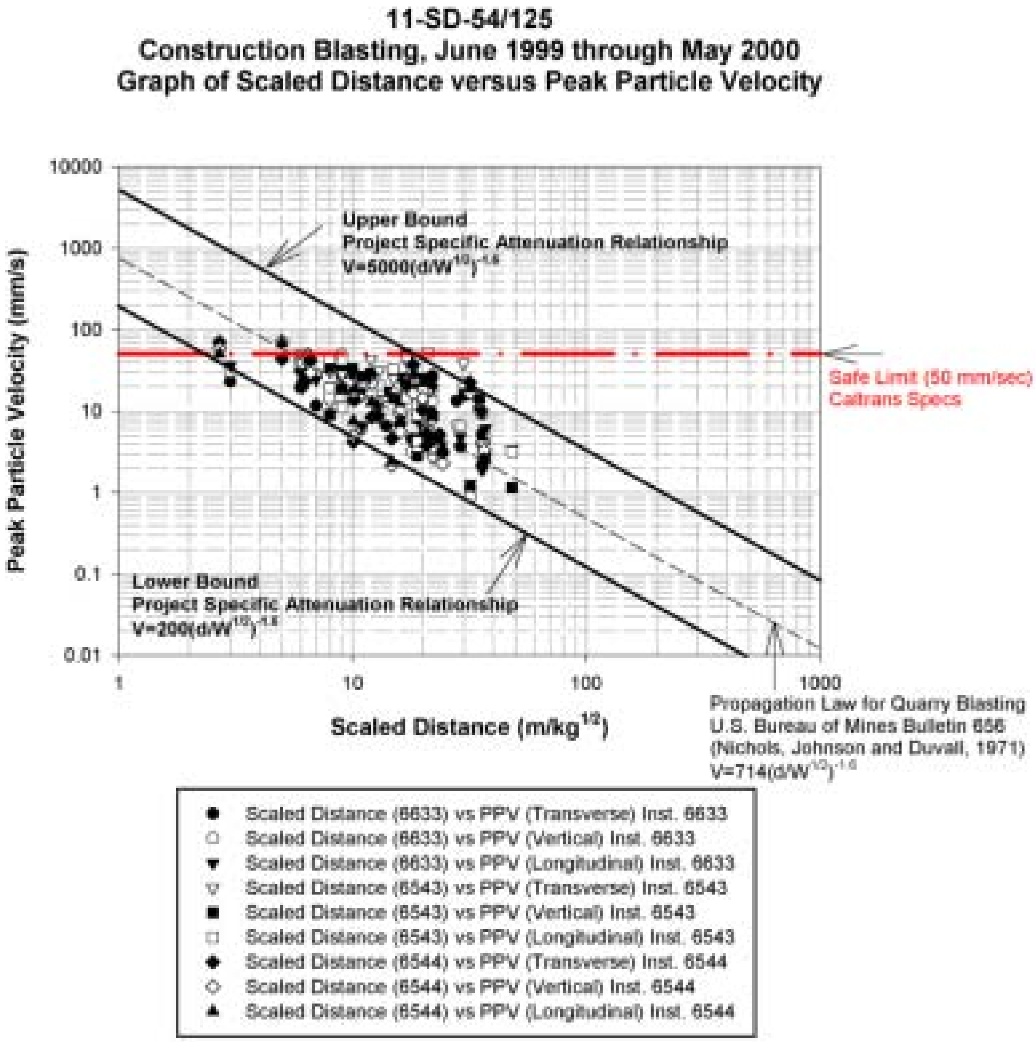


The above plot shows peak particle velocities as a function of actual distance. Significant observations resulting from the data collected in this study are as follows:

- Using Caltrans' threshold for structural damage of 2 inches per second (50 mm/sec), structures beyond approximately 35 meters from the blast location would be considered "safe" from any vibration-induced damage.

- The use of a 100 meter pre-blast survey radius appears to be a reasonable limit that would capture all structures susceptible to vibration-induced damage.

Plotting peak particle velocity normalized to charge weight, or scaled distance, yields the following plot:



Significant observations resulting from the data collected in this study are as follows:

- The attenuation relationship based upon the least squares regression analysis for this data set shows reasonably good agreement with those established by the U.S. Bureau of Mines.
  1) Data for this project is generally centered on the line (dashed) representing an upper limit of ground vibrations established by the U.S. Bureau of Mines (Bulletin 656) in 1971. This relationship was developed based on monitoring of quarry blast operations only, yet is seemingly applicable to construction blasting as well (this relationship was used by the blasting consultant on this project to predict vibrations at

nearby structures). The following equation represents this line in which the constant is the y-intercept and the exponent is the slope:

$$PPV = 714(D/\sqrt{W})^{-1.6}$$

where, D=actual distance (meters)

and W=mass of explosive (kg)

2) By inspection, approximately one-half of the data points lie above this line. Vibrations exceeding this line could be attributed to either contractor-specific blasting practices (including but not limited to blast timing, coupling and explosive properties) or site-specific characteristics including the geologic framework and directional effects. Preliminary analysis of blast data at another project site in San Diego County indicates a similar trend. Use of a cube root, rather than a square root, in the scaled distance variable may result in significantly more data points plotting below the USBM attenuation relationship line.

3) Lower and upper-bound attenuation relationships specific to this project were established such that approximately 95% of the data points fall within the lower and upper bounds. The rate of vibration decay with distance (slope of line) is maintained from the USBM equation.

Lower bound: $PPV = 200(D/\sqrt{W})^{-1.6}$

Upper bound: $PPV = 5000(D/\sqrt{W})^{-1.6}$

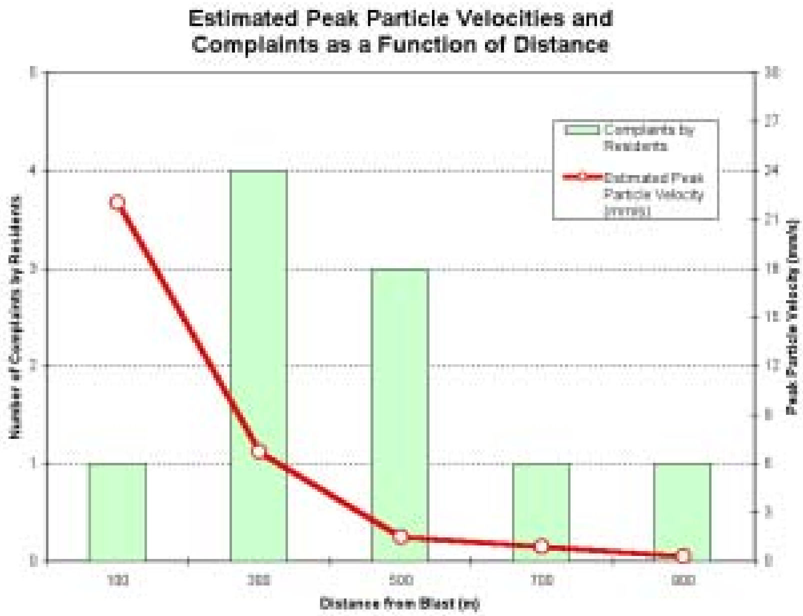
In the early stages of blast monitoring seismographs were located at points up to the 300 m radius, with very little to no energy received at that distance. Trigger velocities were set in the range of 3 mm per second at those distances to actuate the seismograph. After a few measurements at this distance, it was concluded that the possibility of damage was so slight as to not warrant further testing at these distances. The constraints set on the blast energy to be released were adequate to render no damage at the 300 m distance. As such, the subsequent pre-blast survey radius for the Route 54/125 project was reduced from 300 m to 100 m. Direct cost savings to Caltrans on this single project have been estimated to be $250,000.

Complaints by residents in the vicinity of the blasting operations were logged by the Caltrans Resident Engineer on the project. A summary of the complaints is shown in the following table:

Address	Date and Time Complaint Received	Nature of Problem	Distance to Blast(s) (m) and Corresponding Blast Number
431 Osage	6-21-99	Wall cracks	519 (3H)
8475 Avenida Angulia #28 (Sweetwater View Condos)	6-28-99 14:33	Ceiling Cracks	118 (9B)
529 Parkbrook St.	7-30-99	Newly constructed porch has shrunken post	324 (1H) 375 (3H)
8472 Avenida Angulia	07-27-99 08:02	Living Room and Driveway Cracks	162 (9B) 153 (10B)
523 Broadview St.	08-12-99 16:47	Cracks in ext. yard, back yard, hallway, crevice in garage slab	230 (1H) 277 (3H)
502 Broadview St.	09-21-99 15:28	Bedroom wall cracked	217 (1H) 271 (3H)
450 Broadview St.	11-02-99 17:54	Crack in dining room wall	302 (1H) 342 (3H)
Sweetwater Views Condos Swimming Pool Area	12-09-99 08:45	Pits in Plexiglass wall; Concrete pool apron cracks	56 (10B) 56 (22B) 71 (24B)
766 Parkbrook St.	12-27-99 10:05	One slab crack (living room, dining room, kitchen, bedroom)	870 (1H) 916 (3H)
411 Parkbrook St.	01-11-00 10:52	Cracks in ceiling/wall at kitchen, master bedroom and entry	465 (1H) 504 (3H)

Most of the complaints involved observations by the residents of cracks in walls, ceilings, and concrete slabs. Those filing complaints claimed that these cracks were not present prior to blasting operations. In general, it can often be very difficult to determine whether or not the cracks were a direct result of the construction operations. In one case, prior to the first scheduled blast for the 54/125 Route, a public notification was released to the local residents of the date of an upcoming blasting event. However, the blast was delayed for approximately a week, but a telephone call was received by the Resident Engineer on the originally scheduled blast day of cracking to the party's house.

It is well documented (Reiher 1931) that the human response to vibrations can be "disturbing," even though those same vibration levels would be considered "safe" with a low probability of damage to structures. To illustrate this, the peak particle velocities estimated at the locations of the complaints and the number of complaints were plotted as a function of actual distance from the blast. Estimates of peak particle velocity were calculated in accordance with the U. S. Bureau of Mines Bulletin 656 propagation law.



Significant observations from the combined plot are as follows:

- Measured particle velocities attenuated with distance, as did the number of complaints, as would be expected.
- 70% of the complaints came from residents located between 100 and 500 meters from the blast location.
- Within the range of distances where there were the most complaints, the majority of measured peak particle velocities in any direction were well below the Caltrans damage threshold of 50 mm/s.

IMPLEMENTATION OF RESULTS

Although this study produced significant findings, further research involving a wider range of site locations and blasting operations is warranted prior to a statewide implementation of revised pre- and post-blast survey limits and associated specifications. In addition, in urban areas the surrounding community’s perception of vibrations can be equally as important as the danger of structural damage due to the vibrations. A thorough understanding of this relationship is necessary to establish a survey limit that adequately documents the impacted area without being excessive.

CONCLUSIONS AND RECOMMENDATIONS

Future research into setting pre-blast survey radius limits is justified by the fact that having a scientific basis for determining the limits can lead to considerable savings. As the population increases urban density, and the insatiable need for ever more roadways and shorter commute times, new routes are being squeezed in amongst existing developments and into more difficult terrain for construction that requires significant cost increases in construction. Every opportunity needs to be explored to maximize the public's investment in highway development.

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