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Southwest Research Institute

Authors:
Edward D. Esparza, P.E.

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3801 Kirby Drive, Suite 340
Houston, Texas 77098
Tel: 713-630-0505
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SUMMARY

This report describes a blasting research project conducted by Southwest Research Institute for the Pipeline Research Committee of the American Gas Association. The objective of this investigation was to record and analyze the stresses on a pipeline induced by highway construction blasting in rock and compare the data with previous results from blasts in soil. In aprevious blasting research program, Southwest Research Institute recorded test data in an extensive set of primarily laboratory experiments conducted in a homogeneous soil and developed equations and methods for estimating pipeline stresses for a variety of explosive sources detonated simultaneously in close proximity to pipelines.

In this research project, 21 highway construction blasts were used to record pipeline strain data from production shots that consisted of small explosive arrays with delays among the explosive holes. A 30-in pipe section and a 12-in pipeline in the vicinity of the highway construction work were instrumented with strain gages to measure the pipe response to the blasting. The data provided the first opportunity to determine if the estimating equations and techniques developed with soil data could be modified and applied to real world blasting situations in rock. The construction shots were fired in a solid rock area through which trenches for the pipes had been cut, and the pipes installed with a soil and fragmented rock backfill. In trying to record the field data, considerable obstacles and delays were encountered before the data presented in this report were finally obtained.

The maximum pipe stresses induced by the blasts were computed from the measured strains in the circumferential and longitudinal directions. Analysis of these stresses and comparisons with theprevious soil blasting equations revealed that the single-point source equation provided a realistic upper-bound estimate of the maximum stress to be expected in bench type construction blasting similar to that monitored in this investigation. However, because of the limited rock blasting data available, additional work is required in model scale and actual scale experiments to better define stress estimation equations for the large variety of blasting configurations used in the field.

In addition to the pipe stress results, additional discussions on delays are also presented. Some analysis of ground vibration data was also performed. Several particle velocity prediction equations are reviewed, as well as the problems associated with relating peak particle velocity data to pipe stress data. Whenever practical and in critical situations, the use of pipe stress data to develop safe blasting criteria for buried pipelines is advocated instead of the traditional particle velocity which originated with the need to protect above ground structures from blast damage. Experimental

pipe stress data from another blasting study related to ditch construction parallel to an existing operational line are also presented and analyzed. Finally, many of the problems that one can encounter in a research blasting study, or in simply monitoring and enforcing blasting criteria, are detailed.

ACKNOWLEDGEMENTS

This program was sponsored by the Pipeline Research Committee of the American Gas Association and conducted by Southwest Research Institute. The author thanks Mr. J. M. Holden, Director, Pipeline Research of the A.G.A. office, for the guidance and assistance provided during this program, and Mr. Othon Medina, P.E., of El Paso Natural Gas for coordinating this project for the Line Pipe Research Supervisory Committee, and for his continued technical and logistical support in accomplishing the objectives of the program. The author is also very grateful for the support, assistance, and cooperation provided by Algonquin Gas Transmission Company in conducting the field experiments in New Jersey, in particular, Mr. W. E. Lawson for his enthusiastic interest and support to initiate this program, Mr. D. H. Brown for his logistical assistance, and Mr. J. F. Luskay for providing the field contact, coordination, and support throughout the project. Ground vibration data were obtained through the efforts of Mr. A. F. McKown, C. J. Kittridge, E. J. McSweeney, and H. Shirkhanni of Haley & Aldrich, Inc., the blast monitoring consulting firm working for Algonquin Gas in the relocation project. In addition, Mr. J. Sergent, a contract inspector working for Algonquin Gas, provided on-site blasting progress information and coordination with the blasting contractor. The author also thanks Texas Eastern Gas Pipeline Company for allowing strain gaging on their 12-inch line adjacent to the highway construction.

At Southwest Research Institute, the author acknowledges the contributions of Mr. E. R. Garcia, Jr.,Mr. Joe Elizondo, and Mr. M. R. Castle in installing the strain gages and cables, recording the strain data, and processing the data. In addition, Mr. V. J. Hemandez assisted with the illustrations, Ms. D. J. Stowitts edited the manuscript, and Ms. T. L. Sloan processed and printed the manuscript.

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I. INTRODUCTION AND BACKGROUND.

This technical report completes a recent research investigation conducted by Southwest Research Institute (SwRI) for the Pipeline Research Committee (PRCI) of the American Gas Association (A.G.A.). The objective of the investigation was to record strain data and analyze the resulting stresses on buried gas transmission pipelines in the vicinity of highway construction blasting in rock and to compare the data with the previous results from blasts in soil. The monitoring and control of blast related pipeline stresses are of interest to the gas pipeline industry. Blasting near buried gas pipelines is a common occurrence, and the blast-induced stresses can be significant relative to normal operational stress limits on a pipeline. Use of explosives for trench blasting in construction of pipelines adjacent to older ones, for strip mining, for highway construction, for quarry blasting, for seismic exploration, for utility construction, etc., in the vicinity of in-service pipelines occurs quite frequently. Consequently, pipeline companies need effective engineering procedures estimate blast-induced stresses for use in developing realistic blasting guidelines and criteria for specific blasting situations near their pipelines. Blasting activities Without limitations would certainly not be safe realistic.

For a long time ground motion criteria have been and continue to be used by many for establishing safe c-distance limits in blasting situations near buried pipelines. For example, a surface peak particle velocity limit of 1.0 or 2.0 inches/second (ips) specified by many states for above ground structures is commonly specified also for buried pipelines. This soil particle velocity criterion evolved from work published by Crandell(1949) for the effects of blast-generated ground vibrations on buildings. More recent experimental Work investigating the effects of buried charges on buildings, such as that of Dvorak (l962) in Czechoslovakia and Nicholls, et al. (1958), Edwards and Northwood (1960) and Siskind, et al., (1976,1980), shows that threshold soil particle velocity criteria are reasonable when applied to above-ground structures. However, pipeline is not a building. The 2 ips velocity criterion per se is mostly applicable to residential structures; it is for vibration amplitudes in the ground adjacent to the structure of interest not within the structure, and it is independent of frequency and distance.

In 1964 McClure, et al., presented pipeline stress prediction equations developed at the Battelle Memorial Institute under contract for the PRCI. These equations were theoretical elasticity solutions based upon Morris' empirical equation (1950) for ground displacement and the assumptions that: 1) a pipeline movement equals exactly that of the surrounding soil, and 2) no

diffraction of shock front occurs. No experimental data were available to compare with the Battelle equations when they were developed. The empirical equation for soil displacement on which the Battelle equations are based was recommended for use only for explosive-to-pipe distances greater than 100 feet. However, these equations can easily be misapplied if one is not aware of the original distance limitation.

Because of the limitations on surface ground motion criteria and the Battelle equations, a better method was needed to estimate pipeline stresses induced by nearby blasting. In 1975, the PRC initiated a blasting research program with Southwest Research Institute for the purpose of developing engineering procedures for predicting pipeline stresses induced by nearby buried explosive detonations, particularly those within 100 feet of a natural gas pipeline. In the first project begun in 1975, SwRI reviewed the literature pertinent to the research effort, and using similitude theory, developed functional relationships for the forcing function and pipe response. Then, 43 model and full-scale tests were conducted to obtain the data necessary to define and validate stress solutions for point and parallel line explosive sources buried in a homogeneous soil. Westine, et al., (1978) presented their results in a complete engineering report (A.G.A. Catalog No. L51378) covering the first project in detail.

In 1979, a follow-on project was funded by PRC for SwRI to expand the application of the solutions developed in the earlier program to other explosive geometries and field situations. Five different blasting conditions were investigated experimentally and analytically by Esparza, et al., (1981). Seventy model scale tests were conducted to obtain data from explosive point sources buried at the same depth and deeper than the pipe, explosive line sources oriented at various angles to the pipe, explosive grid sources oriented parallel and angled to the pipeline, and point sources in a two-media layout. In addition, a literature study was conducted to determine the effect of an open trench between an explosive source and a pipeline. As a result of this second research project, improved prediction equations were derived for estimating maximum pipe stresses from point and parallel line explosive sources detonated in soil. Not only were these new equations more accurate than those developed in the earlier SwRI project, but they were also simpler to use. In addition to these new equations, Esparza, et al. (1980, 1981), developed empirically methods for simplifying the more complex, explosive geometries into equivalent parallel line or point sources for the purpose of estimating the blast-induced stresses. These equations and methods were presented in the final engineering report by Esparxa, et al., (1981, A.G.A. Catalog No. L51406).

In the course of the second SwRI project for the PRCI, a short literature study concerning the use of trenches to reduce blasting stresses on a pipeline was accomplished. It was found that Barkan (1962) in the USSR had done considerable work in evaluating the effectiveness of trenches and other barriers in reducing ground vibrations, and that R.D. Woods (1968) in the USA has tested the effectiveness of Some trench designs. These two references indicated that a trench of large dimensions relative to the wave length of the surface motions can reduce vertical soil displacements. A subsequent search through the literature and view of work by Lysmer and Waas (1972), Segol, et al. (1978), and May and Bolt (1982), showed that none of the computational and experimental data found modeled or used an explosive as the source of the seismic waves being affected by an open trench. This lack of information was the impetus for Esparza (1984 and 1985) to conduct a series of experiments funded by SwRI's Internal Research Program to generate experimental data on the effect of trenches on blast-induced stresses on a buried pipeline. The results of this limited test series showed that trenches can be effective in reducing blast-induced pipeline stresses by as much as 87% of the value without a trench. However; because of the large number of variables, no simple empirical method for predicting the effect of any specific trench was possible. More work in this area is required to better understand and predict the effect of trenches on blast-induced stresses.

In 1985, ,the PRCI, interested in the effects of blasting near well pipes, funded a small analytical investigation for SwRI to extend the application of the blasting stress prediction equations developed previously to well pipe. Esparza and Westine (1985) modified the stress prediction equations to handle blasting situations near vertical well pipes, as opposed to horizontal pipelines, and analyzed the influence of a wellhead on the response of a well pipe.

Because the equations developed for predicting pipeline stresses due to nearby blasting were developed from data of experiments conducted previously in uniform soils, their application to blasting situations in rock had not been confirmed. Consequently, beginning in 1985, several discussions were held between Algonquin Gas Transmission Company (AGTC) and SwRI concerning a highway construction project in New Jersey which had possibilities for monitoring pipeline strains near substantial rock blasting. With Algonquin's enthusiastic support and interest in obtaining such useable data using a section of their line to be relocated, SwRI proposed to the PRCI a limited research effort to obtain pipeline strain data from rock blasting and to compare these new data to the prediction equations previously developed using soil blast data. In early 1987, the PRCI-A.G.A. funded SwRI to proceed with a new blasting research effort PRCI Project PR-l5-712.

Because the supervisory committee on blasting research had been disbanded after completion of the 1981 final report, this new project was assigned to the NG- 18 Supervisory Committee with a former member of the blasting research committee as the project coordinator.

After several highway construction delays, contractor work stoppages, New Jersey court battles, ambiguous schedules, damaging lightning storms, relocation plan changes, and other situations beyond the control of SwRI, a series of 21 rock blasting shots was finally monitored in 1990. The maximum strains recorded by SwRI and its subsequent analysis are presented in this report. Adetailed description of the experiments arepresented, as well as a summary of thenumerous problems encountered in achieving the objectives of this project. The strain measurement system used by SwRI is alsodescribed, as well as the seismic recording systems used by others in conjunction with this effort. The pipe strain and ground motion &a are tabulated, and examples of the strain data traces are presented. A short discussion of the analysis of the results is included, together with comparisons with one of the previously developed soil equations, with discussions of ground motion and pipe stress, with discussions of blasting delays, and with application of results to other different blasting situations. Pipe strain data from a ditch blasting project recorded and used by a pipeline company to develop a safe, but realistic blasting criteria, are also presented and analyzed. This final report ends with a discussion of several field problems and observations, and with some conclusions and recommendations. In preparing this final report, it was assumed that the reader is familiar with the results presented by Esparza, et al., (1981). Those equations developed in that study, which are discussed in some detail or are used to compare with the rock blast data, are also presented in this report.

II. EXPERIMENTAL PROGRAM

Objective and Scope

The primary objective of this experimental research program was to record and analyze pipeline strains as a result of highway construction blasting in a rock environment and to compare these results with the previously developed soil blasting equations. To accommodate the construction of a section of Route I-287 in New Jersey, Algonquin Gas Transmission Company (AGTC) relocated two adjacent pipelines. These lines were offered by AGTC to be used in this project. Blasting was necessary to cut the highway right-of-way (R.0.W.) through a rocky geology, and this construction work provided an opportunity to obtain pipe strain data not available in the previous PRCI program conducted with underground blasting in soil. The original scope of the research project called for SwRI to strain gage the two parallel AGTC lines crossing the highway R.O.W.,and then record the strain data from a reasonable number of shots as the construction company blasted through the rocky geology and approached the existing pipelines. After the pipe strain data had been recorded on magnetic tape, the equipment was to be returned to SwRI, and the data were to be processed, analyzed, and compared to the previous soil data. Eventually the objectives of the program were achieved, and the research plan accomplished.

Project History

In late March 1987, a meeting was held in Wayne, N.J., concerning the highway construction project which was anticipated to begin in Wanaque, N.J., the area of interest to this project, in the spring of 1987. However, that meeting began a series of events that hampered the blasting research effort from the beginning. To the surprise of Algonquin Gas personnel and others in attendance, the New Jersey Department of Transportation (NJDOT) representative announced that the highway construction effort would not begin before April of 1988 because the rock storage site needed during construction would not be purchased before that date. In early 1988, the NJDOT notified AGTC that the necessary arrangements had been made for the highway contractor to begin blasting work on the highway project. Based on the approximate blasting schedule provided by the NJDOT's contractor, a crew from SwRI, with the support of AGTC, installed strain gages and cables on the two pipelines in late February 1988. Unfortunately, the blasting work progressed much slower than estimated, and then a work stoppage was effected by the construction company delaying the first blast monitoring trip until July 1988. With all these delays, AGTC also had to revise their relocation schedule, which now called for the relocation of both lines as soon as the

new pipeline right-of-way was completed. Thus, the old lines would no longer be available for monitoring when the blasting took place between the old and the new right-of-ways. Therefore, SwRI now had to complete all its data recording before the old lines were removed. Two blast monitoring sessions took place in July and August 1988. Unfortunately, the blasting work was not very systematic from the standpoint of data recording. In addition, the strain gage installations had deteriorated from being in the ground six months. To compound these problems, a severe lightning storm at the end of the first monitoring trip damaged some strain gages and the electronic equipment.

Because of the blasting vibration limit of 1.2 ips specified in the special provisions for controlled blasting near AGTC pipelines prepared by Haley & Aldrich, Inc., the largest level of pipeline strain recorded for the closest charge location of 130 ft was under 5 x 10^{-6} in/in (5 $\mu\varepsilon$) Consequently, the strain amplitudes were difficult to determine accurately due to the 60Hz noise present from the decrease in the insulation resistance of the strain gages. In addition, the maximum stress level induced on the pipes computed from the strain measurements was on the order of 100 to 200 psi, which for most situations would be insignificant relative to the stress from the operating pressure. In the meantime, AGTC decided that after the relocation was done they could leave a portion of the 30-inch line in the ground for SwRI to record larger amplitude strains as the blasting work continued between the new and the old right-of-ways. With this option available, a decision was made to conserve the remaining funds by not analyzing the low amplitude data further, but instead to use these funds to help make a return visit to install new strain gages and record more useable data. However, shortly thereafter, all work was halted at the site by the NJDOT. Consequently, the relocation of the AGTC lines ‘again was postponed, and the pipeline relocation work was finally completed in early November 1989. During the relocation work, AGTC decided that sections of the out-of-service lines could not be left in the ground for use in the blasting research project due to environmental concerns. As an alternative, AGTC agreed to obtain an 80-ft length of 30-inch pipe and to bury it in the same ditch from which the relocated 30-inch line was removed. In addition, Texas Eastern Pipeline Company agreed to allow use of their relocated 12-inch line adjacent to the highway R.O.W.

A new highway construction contract was finally signed at the end of December 1989, and blasting work at the site of interest was resumed early in April 1990. On April 16,1990, the SwRI crew departed San Antonio and arrived at the test site. Work was begun immediately on the 30-inch pipe section. Six sets of strain gages were installed including three redundant sets in case of malfunction, and cables attached and routed to the recording instruments located in an office trailer

adjacent to the highway R.O.W. The 12-inch operational line was then uncovered by Texas Eastern personnel, and the SwrI crew prepared the surface areas and mounted a similar set of strain gages. In the meantime, the highway construction blasting work had progressed at a slowerpace than had been anticipated so that the tit explosive shot monitored was at a distance of 140 ft from the 30-inch pipe and 180 ft from the 12-inch pipeline. At these distances the blasting stresses on the pipes were barely up to 100 psi. After monitoring three additional shots, a decision was made to return the SwRI crew to San Antonio and wait until the blasting contractor was blasting within 80 ft of the 30-inch line and expected to progress in two weeks to within a few feet of the pipe section so that the largest possible strain amplitude range would be recorded. On May 6,1990, SwRI personnel returned to the site and recorded data for 17 additional shots with the nearest explosive hole located from 4 to 81 ft to the strain gages on the 30-inch pipe section. Unfortunately, due to the grade and nature of the geology towards the 12 inch line (and, residential area), the blasting contractor decided that it would be unsafe to continue blasting in that direction. Consequently, the closest shot to the 12-inch line was 81 ft from the strain gage location and, consequently, only low amplitude data were recorded on this pipeline.

Description of Experiments

As stated previously, it was not possible to use on this project the two existing sections of pipeline that were relocated for the highway construction. Instead, an 80-ft section of pipe was placed by AGTC in the trench that had contained the 26-inch line. In addition, a new section of an operational 12-inch line belonging to Texas Eastern Pipeline Company was also instrument& for this project. Figure 1 shows a plan view sketch of the physical layout of the test area as it existed prior to the relocation of AGTC lines. Figure 2 shows in greater detail the specific area that was blasted and the location of the instrumented pipes finally to obtain the data included in this report. Figure 3 is a series of photographs of the test site during different stages in the highway construction blasting work.

A total of 21 firings were monitored to obtain the test data presented in this report. Most of the larger pipe strain levels recorded came from the 30-inch pipe section. This 80-ft section of 30-inch O.D. by 0.469 W.T., API-5LX-60 pipe was supplied by' AGTC and buried with a ground cover approximately three feet deep. This pipe section was placed in a ditch originally used for the 26-inch line relocated for the highway construction. The existing ditch had been cut through the

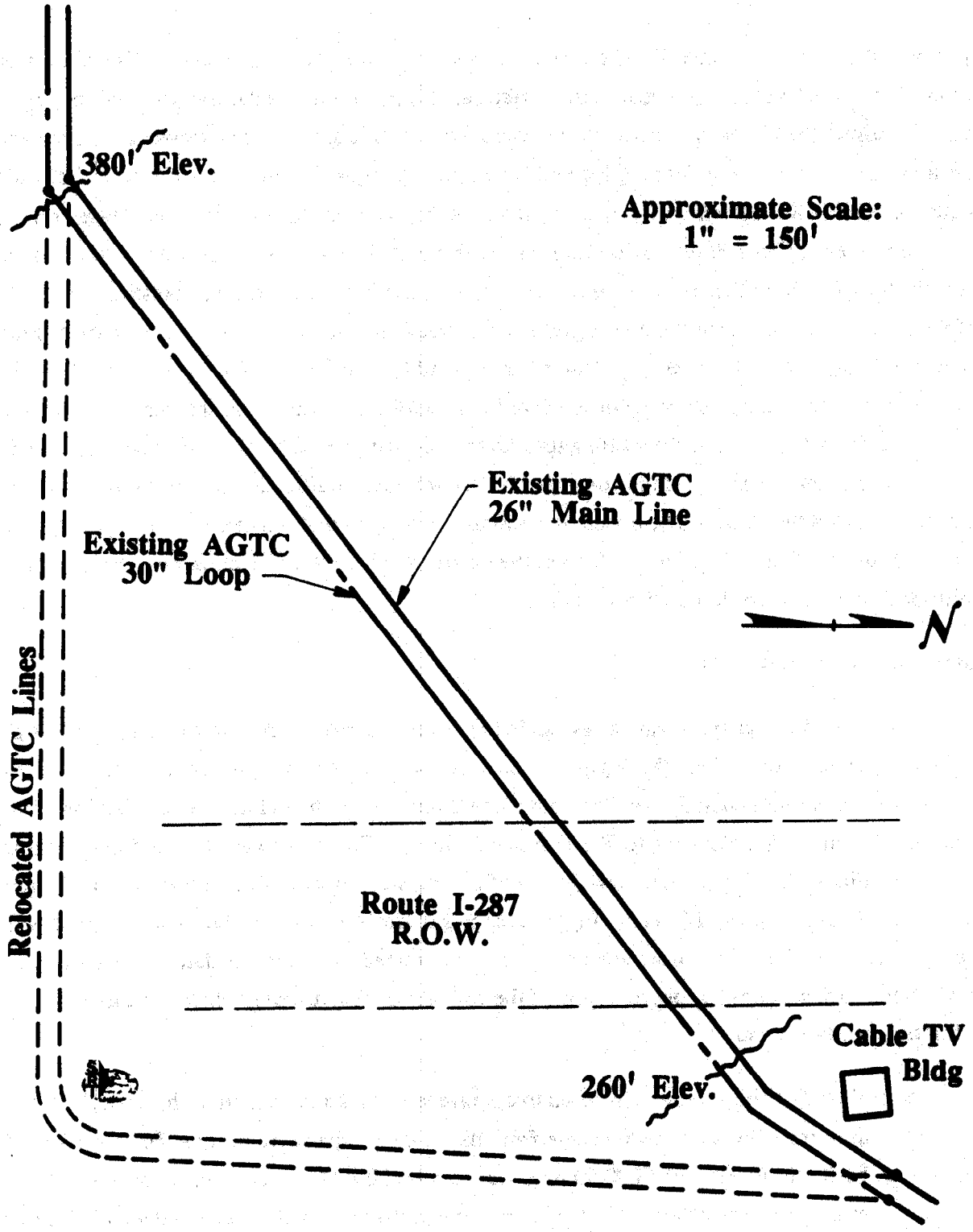


Figure 1. Plan View of Test Site Prior to Relocation

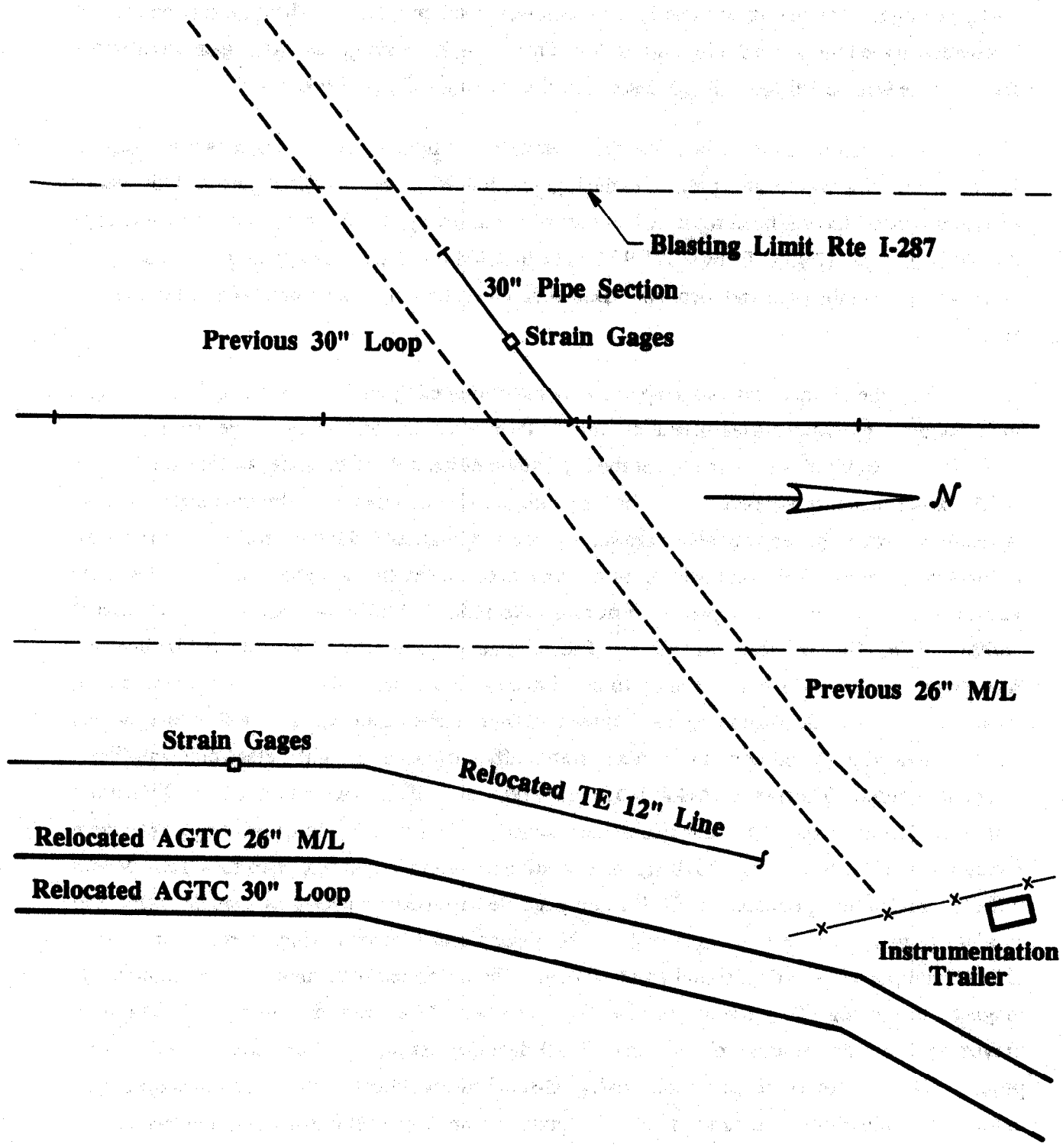


Figure 2. Test Site After Relocation

rocky geology, and existing soil and broken rock were used to backfill. The pipe section was left uncovered at the longitudinal midpoint for SwRI to mount the strain gages. After gage installation, the bell hole was backfilled with sand, some of the existing soil, and broken rock.

A 12-inch operational line was also instrumented in an effort to obtain as much data as possible. This line was located parallel to the highway R.O.W., as indicated in Figure 2. This section of line was new, having been relocated as part of the highway construction. This new line is an API-5LX-52 pipe, 12.75 O.D. by 0.375 W.T. The trench through the rocky geology was backfilled with sand around the pipe and local soil. Burial depth to the top of the pipe was a minimum of 3 feet.

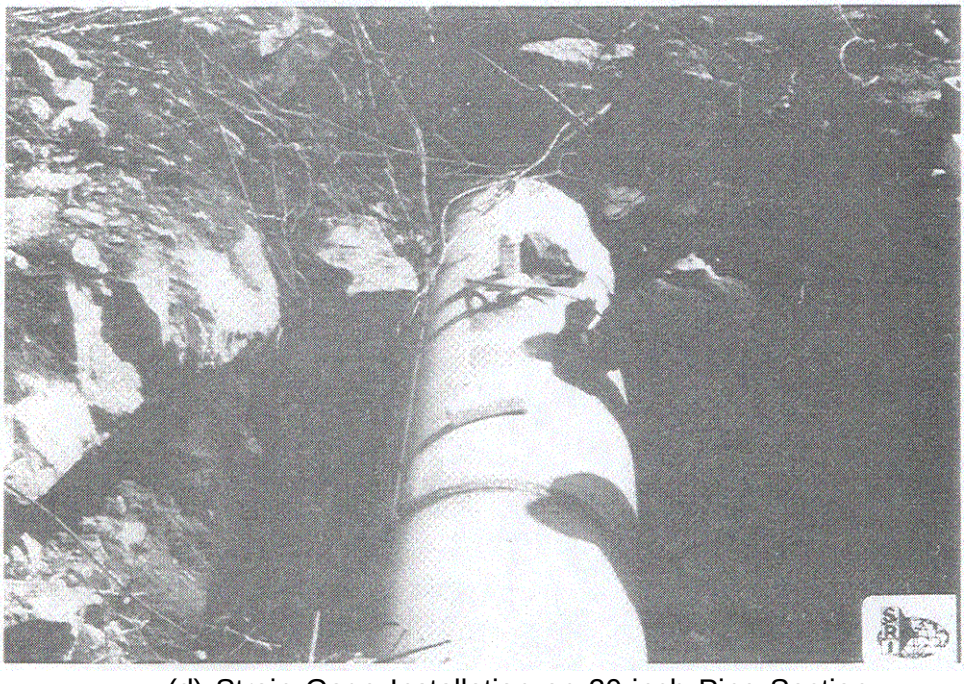
Both the 30-inch and 12-inch pipes were instrumented by SwRI with weldable strain gages manufactured by Micro-Measurements Inc. Two element, 90° strain gage rosettes type LWK-06-W250D-350 were mounted at the' top and on either side of the pipe, as shown in Figure 4. The strain elements were oriented in the circumferential and longitudinal directions of each pipe. A redundant set of gages was also installed to insure operational elements throughout the blast monitoring periods. After connecting three conductor cables to each element, the strain gage installations were covered and protected from the elements with Micro-Measurements M-Coat D and M-Coat F. The six cables for each set of these strain gage rosettes were protected by flexible, water-tight conduit, which was routed to an above-ground junction-box. At the junction-box, connections were made to above-ground, three conductor cables approximately 400 ft long, which were terminated at the other end within a portable office trailer housing the electronic amplifiers and data recorders. The trailer was located in the parking area of the UA Columbia cable TV station situated adjacent to the test site.- Each strain sensing element and interconnecting cable were connected to a Vishay Model 2310 signal conditioner/amplifier unit and then to a Teac Model XR-5000 magnetic tape recorder. Each strain gage element was connected as a single active arm in a bridge using a three-wire connection. The Vishay unit provided bridge completion, bridge balance and power, and data signal amplification. The amplified data signals were recorded on magnetic tape using FM electronics in the Teac recorder. At the test site, quick-look data were played back into an oscillograph recorder. Final data processing was done later at SwRI. This process consisted of digitizing each analog channel using Nicolet 2094 digital scopes and manipulating the digitized data via a CAMAC crate into an Apple McIntosh computer system.

(a) Test Site Prior to Relocation Work Looking NE Down Algonquin's Old R.O.W.

(b) Test Site After Relocation Work and Before Test Data Were Recorded, Looking NW

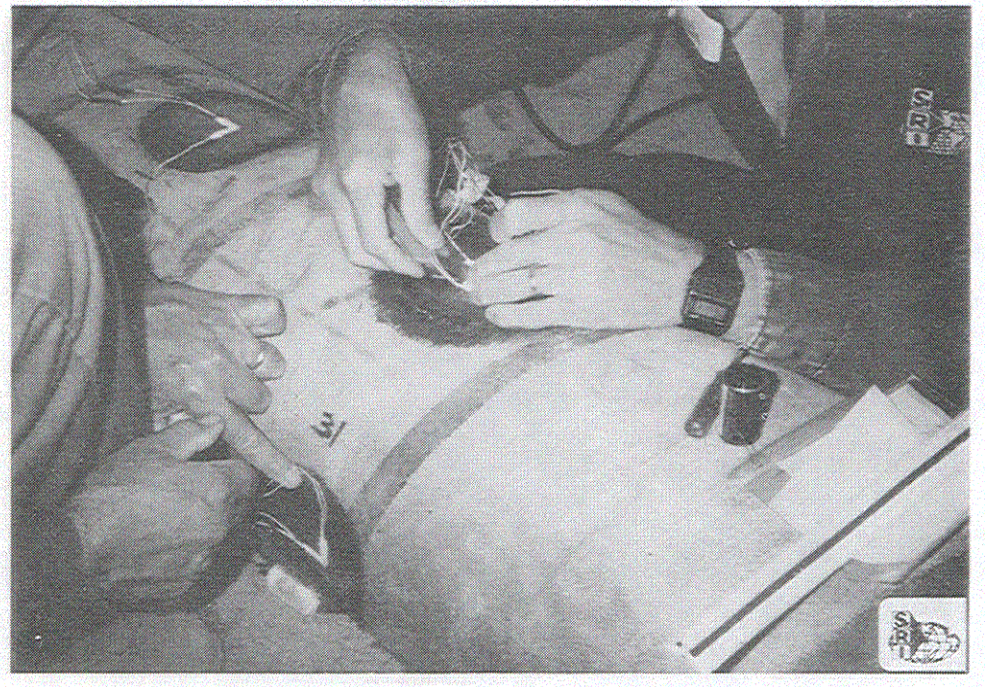
Figure 3. Photographs of Highway Blasting Test Site

(c) 30-inch Pipe Section Exposed for Strain Gage Installation
Looking NE from Center of Highway R.O.W.



(d) Strain Gage Installation on 30-inch Pipe Section

Figure 3. Photographs of Highway Blasting Test Site (continued)



(e) Strain Gage Installation on 12-inch Pipeline

(f) Loading of Explosives in Hole Array

Figure 3. Photographs of Highway Blasting Test Site (continued)

(g) Rock Face as Blasting Approaches 30-inch Pipe, Looking NE

(h) Rock Face and Removal of Muck, Looking NW

Figure 3. Photographs of Highway Blasting Test Site (continued)

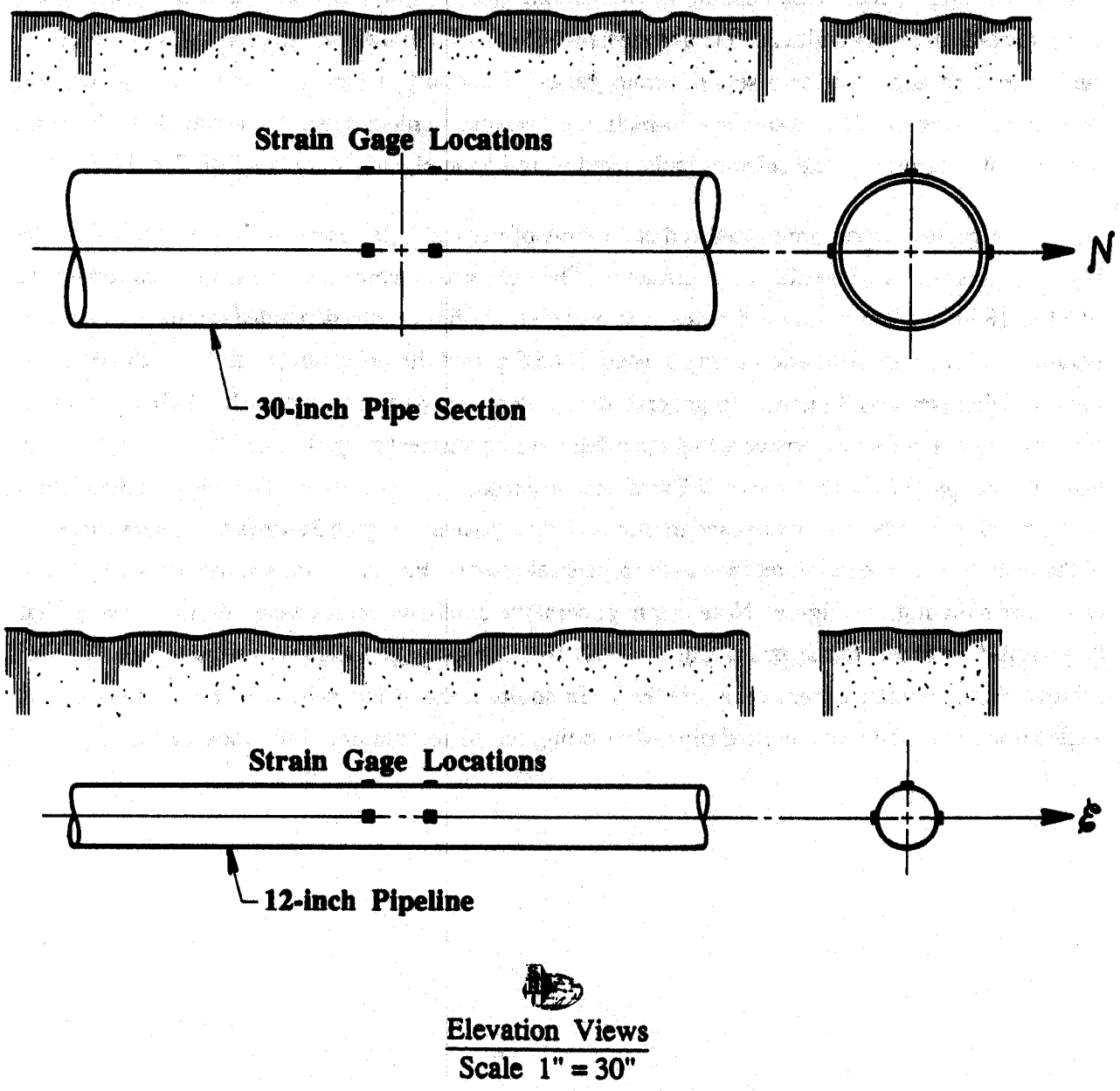


Figure 4. Location of Strain Gages on Pipes

In addition to the pipe strain data recorded, ground motion data were also recorded by Haley & Aldrich, Inc. This consulting firm monitored ground vibrations for AGTC during the highway blasting work and at AGTC's request provided additional seismographs to record vibrations on the ground above the two sets of strain gages. Generally, when only one seismograph was available, it was installed above the 30-inch line, because in most cases it was the closer location to the explosive array. The seismographs used were Instantel, Inc. Models DS-677 and DS-200.

A typical experiment consisted of an array of vertical holes being drilled and loaded by the highway construction and blasting contractor. The hole arrays were production patterns consisting of 11 to 18 holes. The number of holes used and their configurations depended on the geology and geometry of the rock formation being blasted. The depth of the holes ranged from 16 to 20 ft, and the hole diameter was 3 inches. In general, the burden and spacing between shot holes was about 6 ft, and the maximum explosive weight per delay on a given test ranged from 15 to 20 lb of Austin Powder Company 2x16 shells of 60% Extra Gelatin explosive. AustinRock Star electric detonators with 25 millisecond delays were used to initiate the explosives. Figure 5 shows the layout for some of the tests and their location relative to the pipe strain gages. For clarity only some of the explosive arrays are shown in this figure. Note that in general the explosive arrays were not located such that they would be at 90° to the strain gages. With fixed strain gage locations it was not possible to achieve that geometry except on a few tests. In addition the arrays were oriented & a variety of angles relative to the instrumented pipes depending on the orientation of the rock free face.

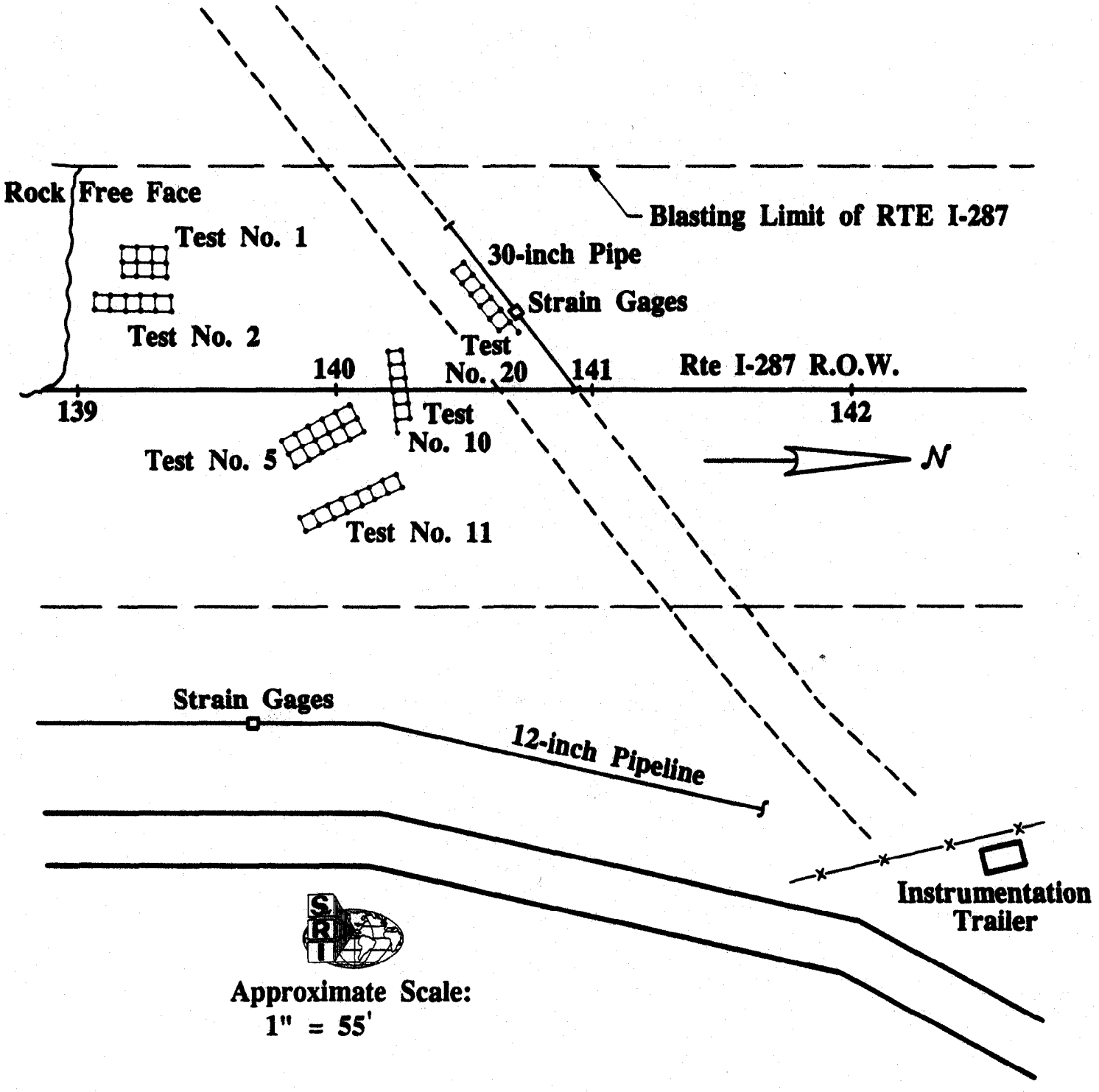


Figure 5. Typical Explosive Charge Arrays

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III. EXPERIMENTAL RESULTS

Strain Data

The maximum peak strains measured on the 30-inch pipe in the circumferential and longitudinal direction are listed in Table 1. This table identifies each test by test number and provides other information related to the explosive charge used per delay, the delay time, and the distance from the neatest explosive hole to the strain gage locations. For each test, the absolute values of the maximum circumferential and longitudinal strains measured are listed. The corresponding biaxial stresses computed from the measured strains are also included on this table.

Note that many of the peak strains listed in Table 1 are quite small. All measured values were rounded off to the nearest microinch/inch ($\mu\varepsilon$). If the measured strain was less than 1 $\mu\varepsilon$, it is listed as being 1 $\mu\varepsilon$. The stresses listed were computed using the measured maximum strains, a nominal modulus of elasticity of $E = 29.5 \times 10^6$ psi, and a Poisson's ratio $\mu = 0.3$. All computed stresses were rounded off to the nearest 1 psi or to three significant figures.

A similar listing of the data measured on the 12-inch pipeline is presented in Table 2. As indicated on this table, the shortest distance to the 12-inch line monitored was 82 ft, and only one other shot was closer than 100 ft. Originally, blasting had been expected to take place to within 45 ft of the 12-inch line, which was why it had been instrumented. However, the blasting contractor changed plans primarily due to the closeness of residences adjacent to the highway R.0.W just east of the pipeline (see Figure 5). Consequently, the skin levels recorded were generally quite low. The strain values listed were rounded-off to the nearest one micro strain ($\mu\varepsilon$), and any peak values recorded that were less than one are listed as one. The computed stresses were rounded-off to the nearest 1 psi or to three significant figures. As can be seen, the majority of the blasts produced very miniscule pipe stresses with a considerable number being 42 psi (or more correctly, equal to or less than 42 psi).

Examples of the maximum strain datarecorded on the 30-inch pipe are presented in Figures 6 to 8. Figure 8 shows the data traces recorded with the largest strains from the 30-inch pipe. A similar set of traces for the 12-inch line is shown in Figure 9 for Test No. 11.

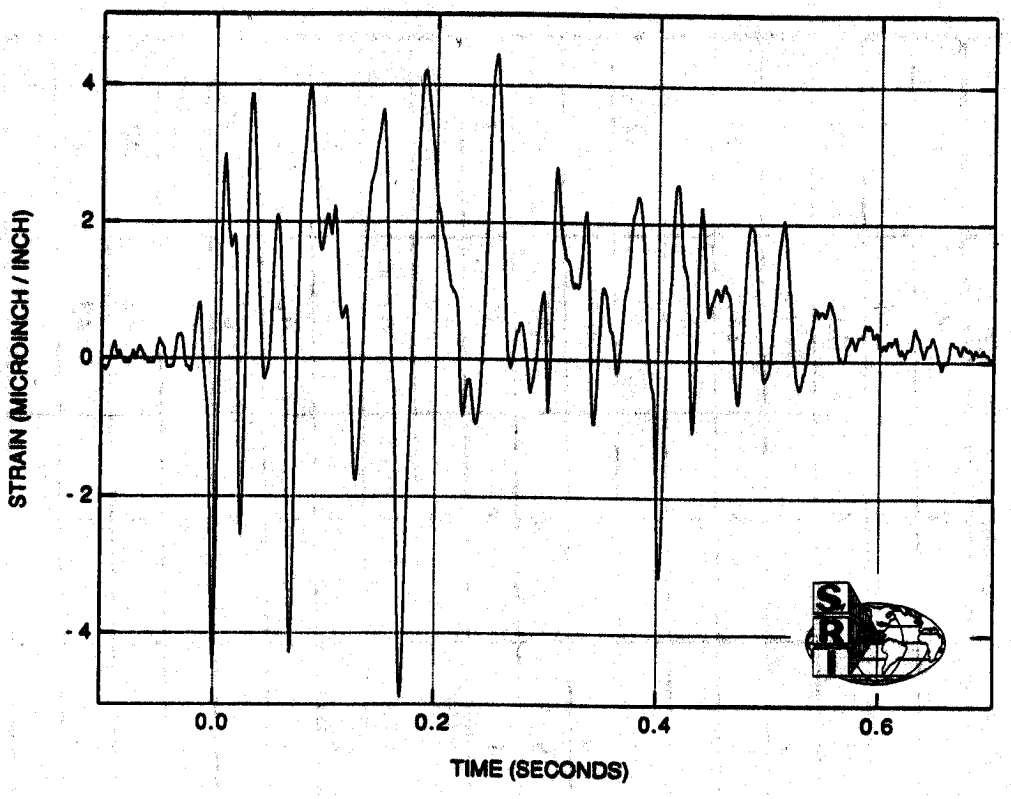
Table 1. Recorded Maximum Strains on 30-inch Pipe

Test No.	Max. Charge Wt/Delay (lb)	Delay Time (ms)	No. of Holes in Array	Distance to Nearest Hole (ft)	Max. Circumf. Strain($\mu\varepsilon$)	Max. Long. Strain ($\mu\varepsilon$)	Circumf. Stress (psi)	Long. Stress (psi)
1	17.5	25	12	140	3	1	107	62
2	17.5	25	12	136	2	1	75	52
3	17.5	25	12	131	2	1	75	52
4	17.5	25	12	125	2	2	84	84
5	15	25	18	76	3	3	126	126
6	15	25	12	64	5	4	201	178
7	15	25	16	58	5	5	211	211
8	15	25	16	75	6	4	233	188
9	15	25	16	76	4	3	159	136
10	15	25	13	54	10	6	383	292
11	15	25	16	81	6	3	224	156
12	15	25	15	40	11	5	405	269
13	15	25	13	50	10	6	383	292
14	15	25	15	25	15	11	593	470
15	15	25	17	47	4	4	168	168
16	10	25	14	17.5	32	23	1260	1060
17	20	25	17	44	6	7	263	285
18	10	25	14	20.5	22	18	888	797
19	15	25	15	12	84	272	5370	9640
20	15	25	11	4	468	454	19600	19300
21	15	25	16	28	50	130	2890	4700

Table 2. Recorded Maximum Strains on 12-inch Pipe

Test No.	Max. Charge Wt/Delay (lb)	Delay Time (ms)	No. of Holes in Array	Distance to Nearest Hole (ft)	Max. Circumf. Strain(με)	Max. Long. Strain (με)	Circumf. Stress (psi)	Long. Stress (psi)
1	17.5	25	12	180	2	2	84	84
2	17.5	25	12	165	2	2	84	84
3	17.5	25	12	152	3	4	136	159
4	17.5	25	12	142	2	1	75	52
5	15	25	18	101	3	4	136	159
6	15	25	12	146	1	1	42	42
7	15	25	16	177	1	1	42	42
8	15	25	16	100	6	7	263	263
9	15	25	16	91	9	6	350	282
10	15	25	13	136	1	1	42	42
11	15	25	16	82	9	8	370	347
12	15	25	15	169	1	1	42	42
13	15	25	13	117	2	1	75	52
14	15	25	15	159	1	1	42	42
15	15	25	17	115	2	2	84	84
16	10	25	14	149	2	1	75	52
17	20	25	17	131	1	1	42	42
18	10	25	14	156	1	1	42	42
19	15	25	15	172	1	1	42	42
20	15	25	11	179	1	1	42	42
21	15	25	16	192	1	1	42	42

TEST NO. 06 CIRCUMFERENTIAL STRAIN



TEST NO. 06 LONGITUDINAL STRAIN

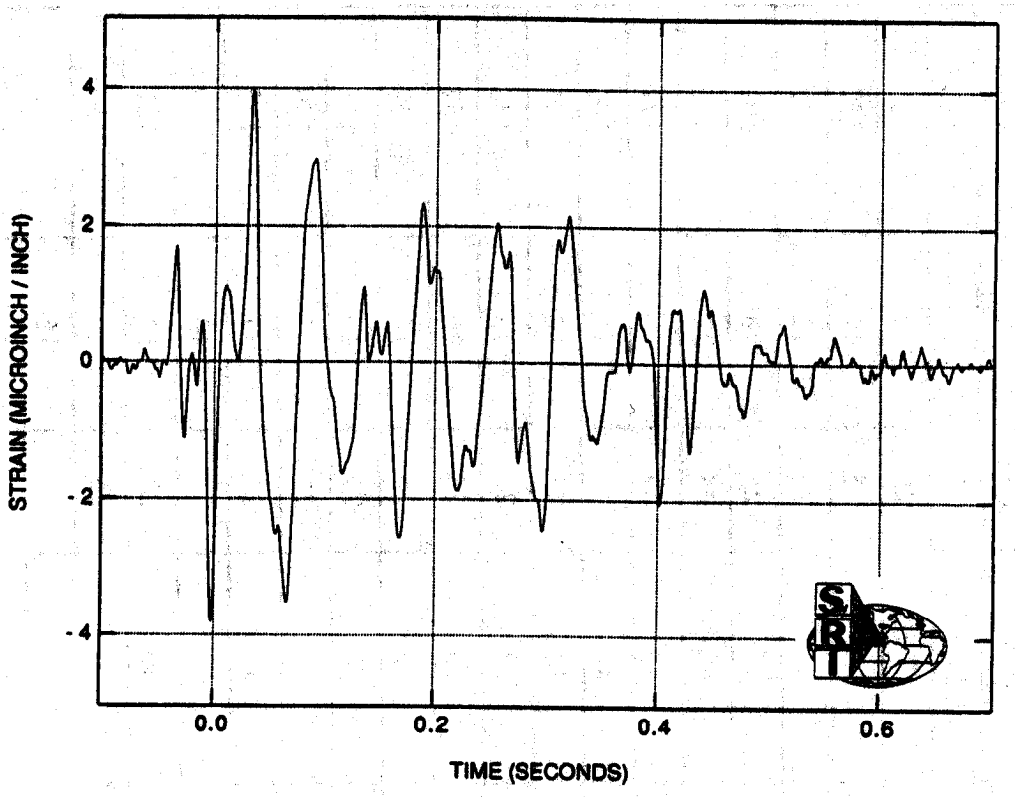
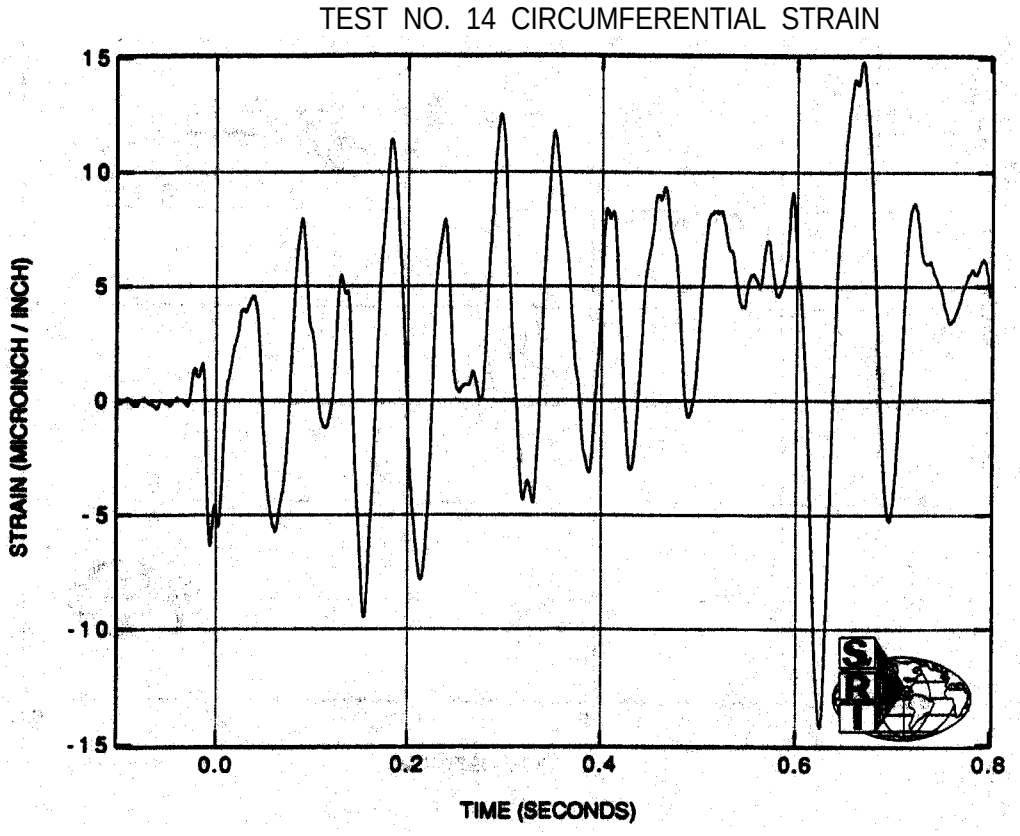


Figure 6. Maximum Circumferential and Longitudinal Strains on 30-inch Pipe, Test No. 6



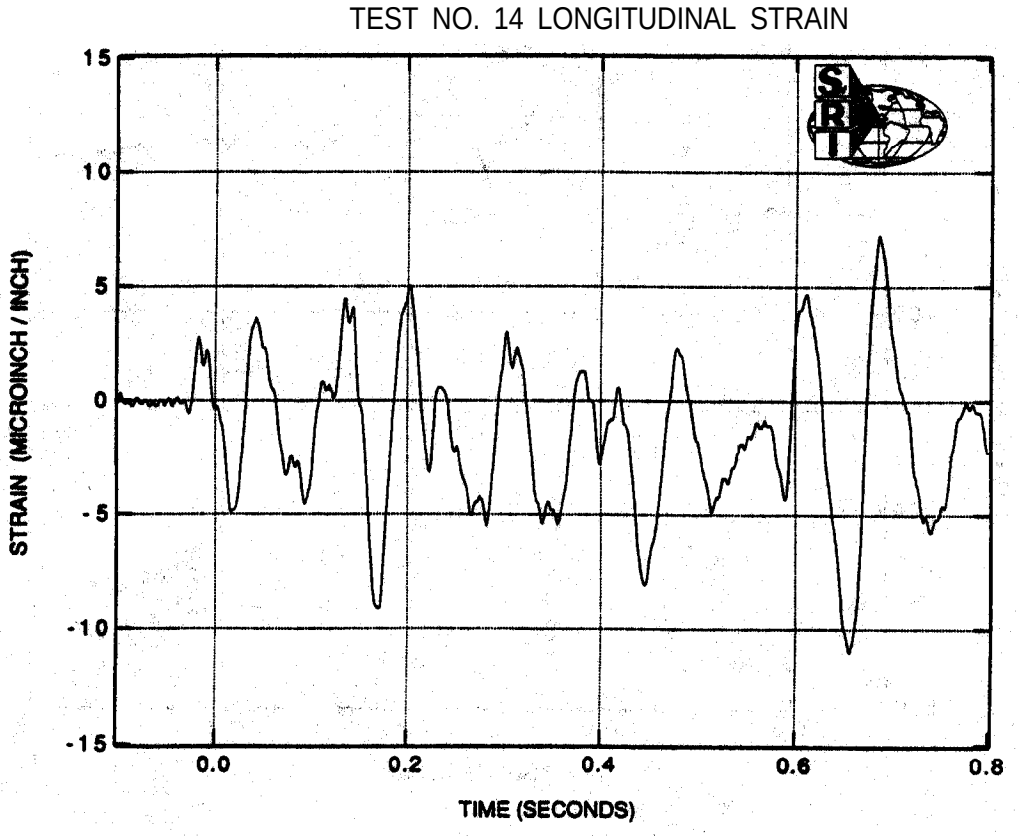
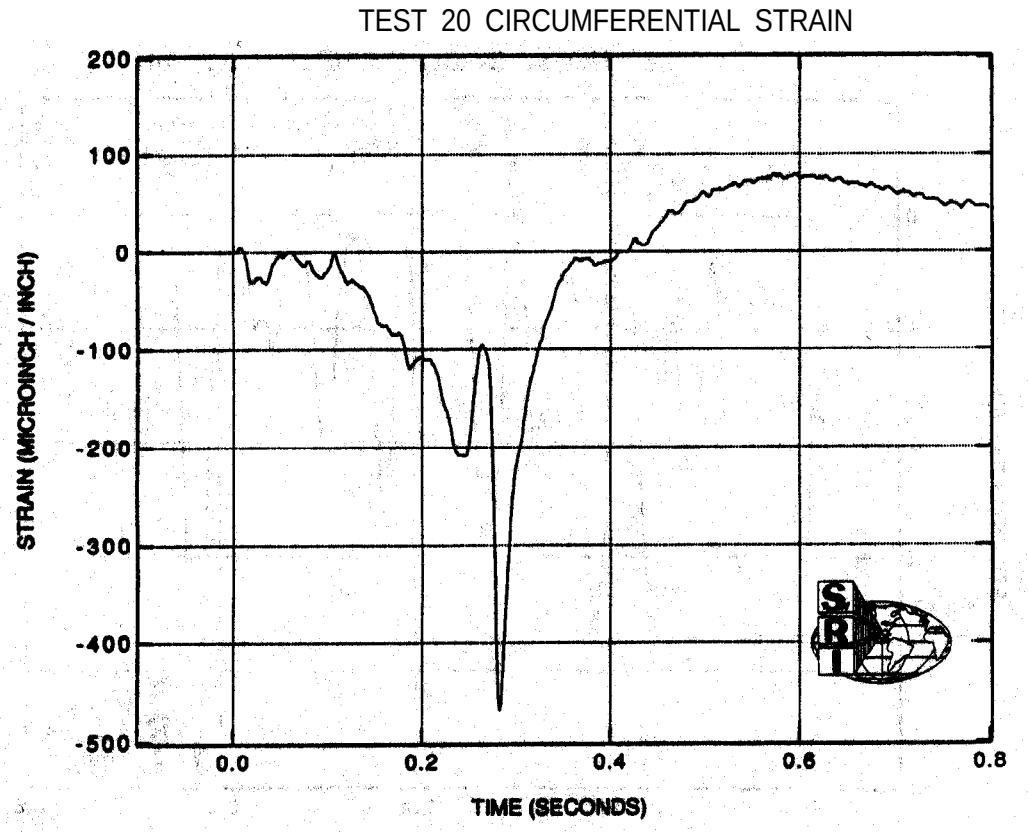


Figure 7. Maximum Circumferential and Longitudinal Strains on 30-inch Pipe, Test NO. 14



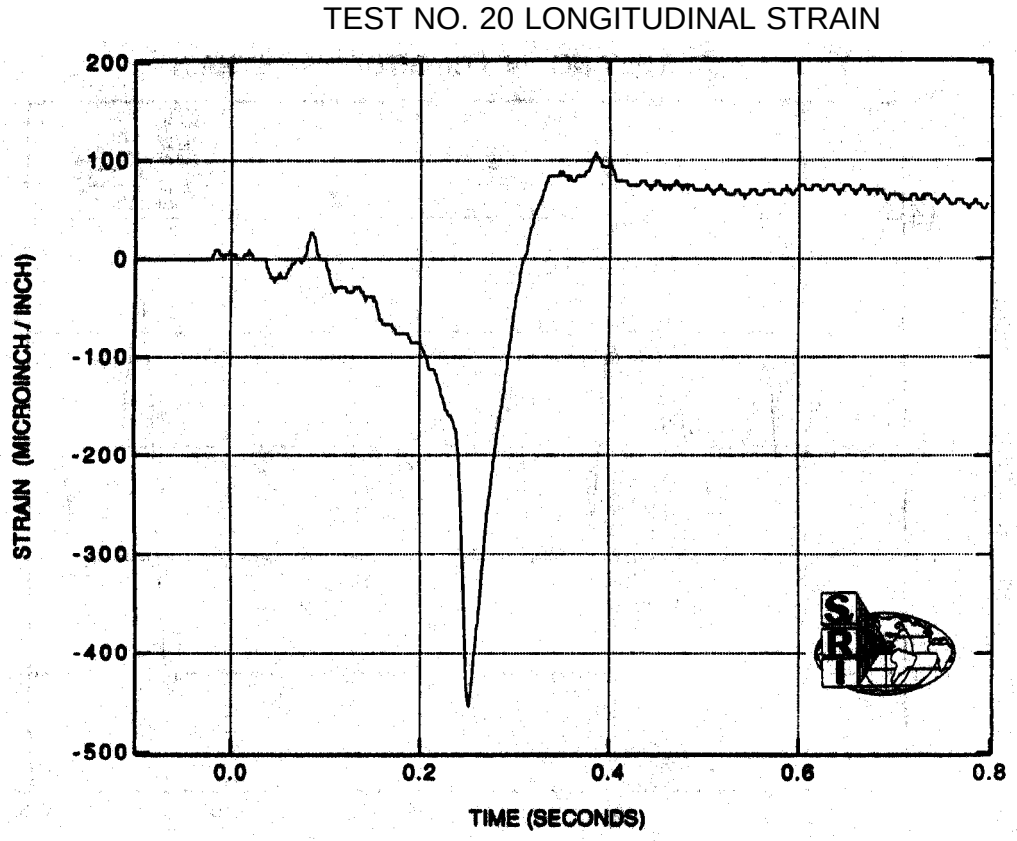


Figure 8. Maximum Circumferential and Longitudinal Strains on 30-inch Pipe, Test NO. 20

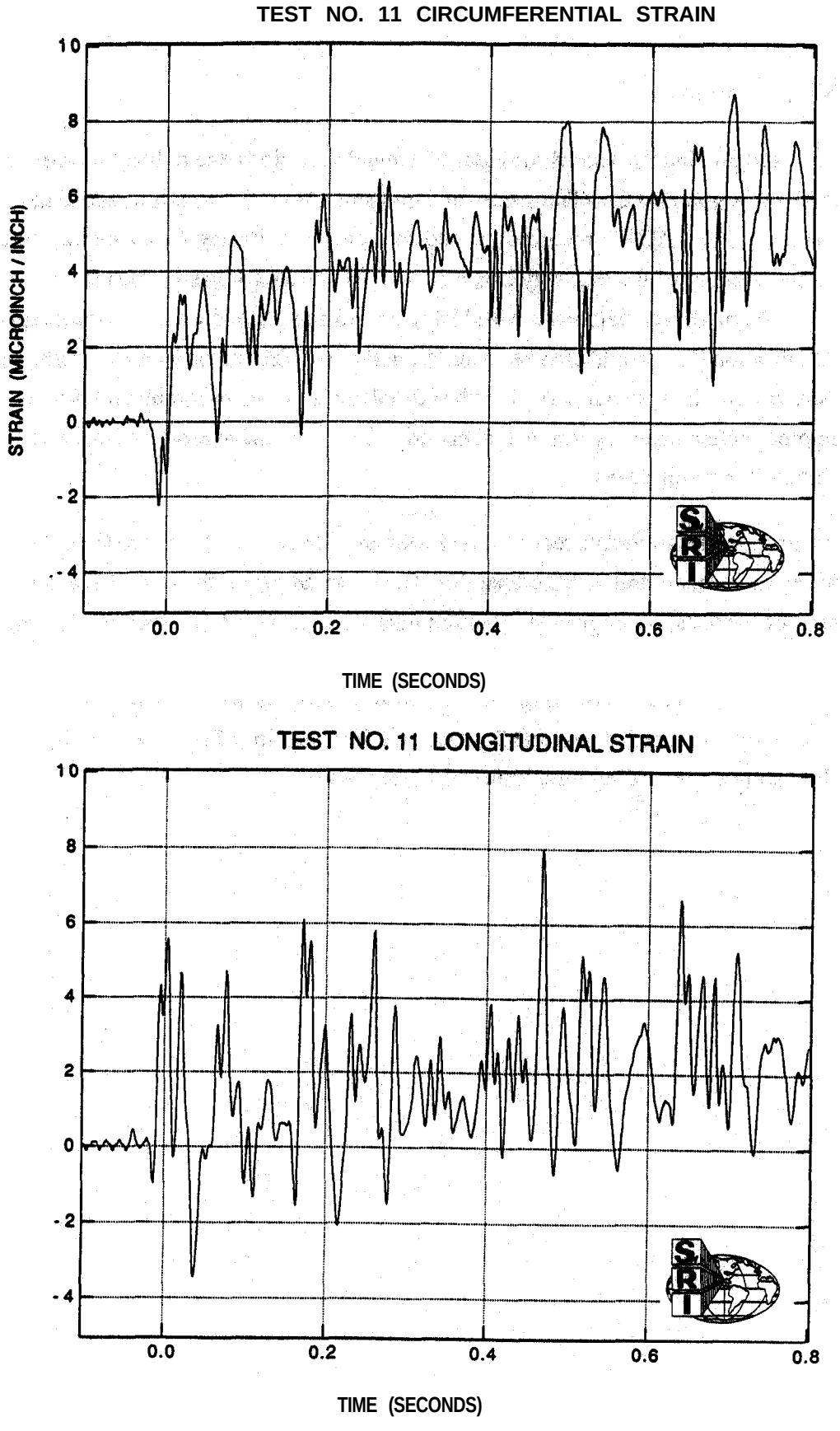


Figure 9. Maximum Circumferential and Longitudinal Strains on 12-inch Pipe, Test No. 11

Ground Vibration Data

As stated previously, records of induced ground vibrations due to blasting were also made at the test site by Algonquin Gas Transmission Company (AGTC) through its blasting consultant, Haley & Aldrich, Inc. AGTC required ground vibration monitoring to insure the safety of its pipelines in the vicinity of the highway construction. While SwRI was recording pipe strain data at the site, AGTC made arrangements with Haley & Aldrich for additional seismograph units so that ground vibration data would also be recorded in the backfill, slightly below grade, just above where the strain gages had been mounted on the buried pipes. A seismograph unit was located over the 30-inch pipe section on every test, and a second unit was available most of the time for use over the 12-inch pipeline strain gages.

The ground vibration data recorded by Haley & Aldrich included the peak particle velocity in the transverse, vertical, and longitudinal directions. In addition, for one of the seismographs used on some of the tests, other ground vibration data were provided to SwRI, which included the peak vector sum of the three velocity components and the three total peak displacements for each sensing direction. The ground vibration data provided to SwRI is presented in Table 3. A sample of three velocity traces recorded over the 30-inch pipe for Test No. 15 is shown in Figure 10. This data recording shows a recording tune frame of 1.5 seconds.

Table 3. Ground Motion Data

Test No.	30-inch Pipe Section							12-inch Pipeline		
	Peak Particle Velocity			Peak Vector	Peak Displacement			Peak Particle Velocity		
	T (ips)	V (ips)	L (ips)	Sum (ips)	T (in)	V (in)	L (in)	T (ips)	V (ips)	L (ips)
1	0.23	0.19	0.22	0.31	0.003	0.001	0.003	NA	NA	NA
2	0.30	0.37	0.30	0.40	0.003	0.001	0.004	NA	NA	NA
3	0.24	0.37	0.17	0.37	0.003	0.002	0.003	0.32	0.33	0.89
4	0.22	0.25	0.24	0.28	0.003	0.002	0.004	0.27	0.32	0.55
5	0.26	0.28	0.33	NA	NA	NA	NA	NA	NA	NA
6	0.58	0.56	0.52	NA	NA	NA	NA	NA	NA	NA
7	0.33	0.53	0.60	0.66	0.006	0.004	0.006	0.15	0.18	0.15
8	0.37	0.49	0.53	0.60	0.004	0.003	0.005	0.28	0.56	0.47
9	0.27	0.34	0.43	NA	NA	NA	NA	0.34	0.49	0.59
10	0.56	0.52	0.74	0.84	0.006	0.005	0.009	0.19	0.26	0.21
11	0.29	0.39	0.35	0.45	0.004	0.004	0.004	0.33	0.66	0.55
12	0.79	0.54	0.83	0.90	0.008	0.007	0.010	0.18	0.18	0.19
13	0.47	0.74	0.79	NA	NA	NA	NA	0.19	0.16	0.17
14	1.08	1.24	2.20	NA	NA	NA	NA	NA	NA	NA
15	0.41	0.34	0.91	0.96	0.007	0.003	0.009	0.15	0.30	0.25
16	1.10	1.37	3.45	3.6	0.026	0.035	0.061	0.19	0.20	0.23
17	0.26	0.35	0.33	0.45	0.005	0.004	0.006	0.14	0.16	0.20
18	1.19	1.32	1.62	NA	NA	NA	NA	0.15	0.13	0.13
19	5.04	4.75	3.31	NA	NA	NA	NA	0.14	0.17	0.24
20	4.83	OR	OR	NA	NA	NA	NA	0.11	0.15	0.19
21	1.43	2.69	1.95	NA	NA	NA	NA	0.12	0.15	0.20

NA = Not Available
OR = Geophone over ranged

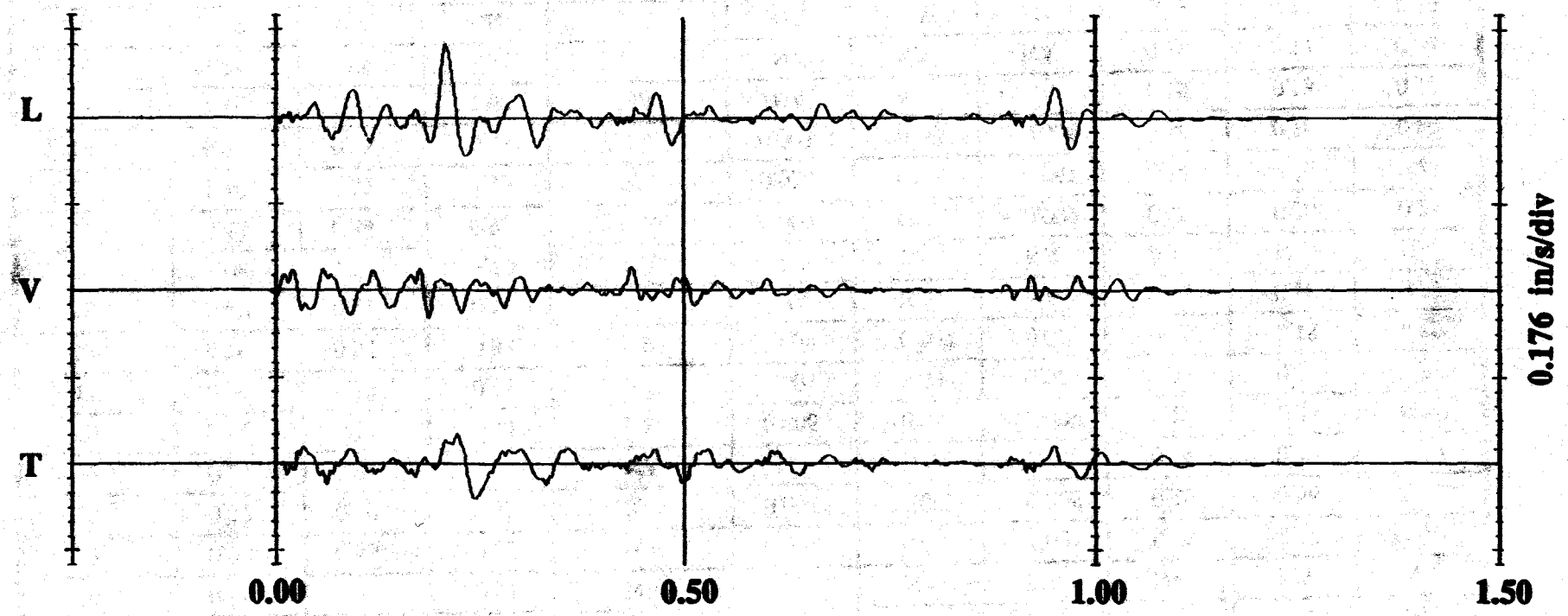


Figure 10. Particle Velocity Traces from Seismograph at 30-inch Pipe for Test No. 15

IV. DISCUSSION OF RESULTS

After recording the pipe strain data at the test site, the primary objective of this investigation Was to analyze the rock blasting data and to compare the results with the previously derived soil equations. This section of the report begins with a short discussion of the rock blasting data analysis and comparisons with the previous results for experiments in soil. This will lead into a brief description on the use of delays in blasting, their purpose, and their effect on ground vibrations. A short discussion follows about ground motion prediction equations the amount of scatter that is commonly found in measurement of particle velocities at actual blast sites, Finally, this section concludes with some remarks about the, correlation between peak particle velocity and pipe stress considering the amount of scatter that is possible in these parameters at actual blast sites.

For a single charge detonated in soil in the vicinity of a buried pipeline, Esparza, et al. (1981), developed the following equation to estimate the stresses induced on a pipeline;

$$\frac{\sigma}{E} = 4.44\left(\frac{nW}{\sqrt{Eh}\,R^{2.5}}\right)^{0.77} \qquad (s = \pm\ 34\%) \tag{1}$$

Similarly, for a line of charges parallel to a pipeline detonated simultaneously in soil:

$$\frac{\sigma}{E} = 4.44\left(\frac{1.4nW/L}{\sqrt{Eh}\,R^{1.5}}\right)^{0.77} \qquad (s = \pm\ 34\%) \tag{1a}$$

where

σ	=	maximum blast-induced circumferential or longitudinal stress (psi)
n	=	equivalent energy release of the explosive (nondimensional)
w	=	total weight of single or line charge (lb)
L	=	total length of explosive line (ft)
E	=	pipe modulus of elasticity (psi)
h	=	pipe wall thickness (in.)
R	=	distance between pipe and charge (ft)
S	=	estimate of the standard error (%)

In addition, techniques for handling a line of charges at an angle to the pipeline and multi-row grid patterns of explosive holes parallel and angled to a pipeline were, developed. These techniques essentially reduced these more complex explosive sources into equivalent point or parallel line sources depending on their distance from the pipeline.

The pipe blasting data presented in Tables 1 and 2 were analyzed and compared to Equations (1) and (1a) and to the methods developed for simplifying the more complex explosive source geometries. The results of 'these analyses indicated that the most realistic comparison was that between the stresses predicted with Equation (1) and rock blasting stresses computed from the experimentally measured strains when the maximum charge per delay used by the blaster was used as the single charge weight in Equation (1):

The parameters in this equation were defined for both the 30-inch pipe section and the 12-inch pipeline as follows:

Pipe	E (psi)	h (in)	R (ft)	n	W (1b)
30 - inch	29.5×10^6	0.469	**Measure distance to nearest blast hole listed in Tables 1 or 2**	1.01	Maximum charge per **delay used by blaster**
12-inch	29.5×10^6	0.375		1.01	

A handbook value for the modulus of elasticity E was used, while the wall thickness h specified for the pipe and confirmed in the field, is listed above.

The equivalent energy release n of the explosive used in these tests was determined from the weight strength specified by the manufacturer as compared to that of ANFO 94/6, which was used as the reference value in the previous blasting research investigations. A typical value for ANFO is 900 cal/gm, while the value for the Austin 60% Extra Gelatin used on the highway construction work is specified as 913 cal/gm.

Equation (1) appears to be an upper bound' for the rock data, as shown in Figure 11, for both circumferential and longitudinal stresses. Therefore, all the results fall below the line for the equation except for two data points. The solid curve in Figure 11 shows the range of the soil data

used to develop Equation (1). The scatter in the data is larger than was experienced in the soil experiments, particularly as compared with the model tests conducted in a “laboratory” environment. For example, Figure 12 shows the data obtained by Esparza (1984) under very controlled conditions, as opposed to the rock data obtained in a variable geology and topography, with charge weights that were difficult to verify, variable burden and spacing even though nominal values were supposed to be used, with the open face of the bench changing directions from being parallel to the pipe to being perpendicular, and charge locations that in general were not perpendicular to the strain gage locations varying from 0° to almost 90° from the perpendicular. In addition to all these real world obstacles to obtaining useable and repeatable data, most of the strain levels measured and their corresponding stresses were of relatively small amplitude, some as small as the steady state noise levels present in the measurement channels. Consequently, it was at times much more difficult to obtain accurate peak strain data in the rock tests than in the previous soil tests,, thus adding to the scatter of the rock data.

One primary reason for the low stress levels in the rock tests, which was anticipated, was the relatively large distances between the pipe and the blast holes, particularly for the 12-inch pipeline. Another reason is the fact that in rock, a large portion of the explosive energy is used to fragment the rock so that for a given charge, a smaller amount of energy is transmitted as a seismic wave than if the same charge is detonated in soil. Additionally, since the blast hole array was typically parallel to a free face in the rock, lack of confinement would contribute to lower s&s levels. Note that when blasting is done in a rock geology, the pipeline would normally be a trench with **soil** backfill. **Therefore, the seismic wave transmitted in the trench soil the forcing function acting on the pipeline and not the seismic wave transmitted in the rock.** Finally, the experiments in soil using multiplecharges were conducted without any delays (a few were conducted with very short delays) between explosive holes. Consequently, the stress prediction equations and methods developed with soil data used the total charge of the arrays as a single detonation at the larger distances from the pipe, or as a simultaneous line of charges at the closer distances. The tests monitored in this research study all used 25 millisecond delays between charges. When blasting in rock, such as in highway construction, it is common practice to use delays to enhance fragmentation of the rock and reduce ground vibration.

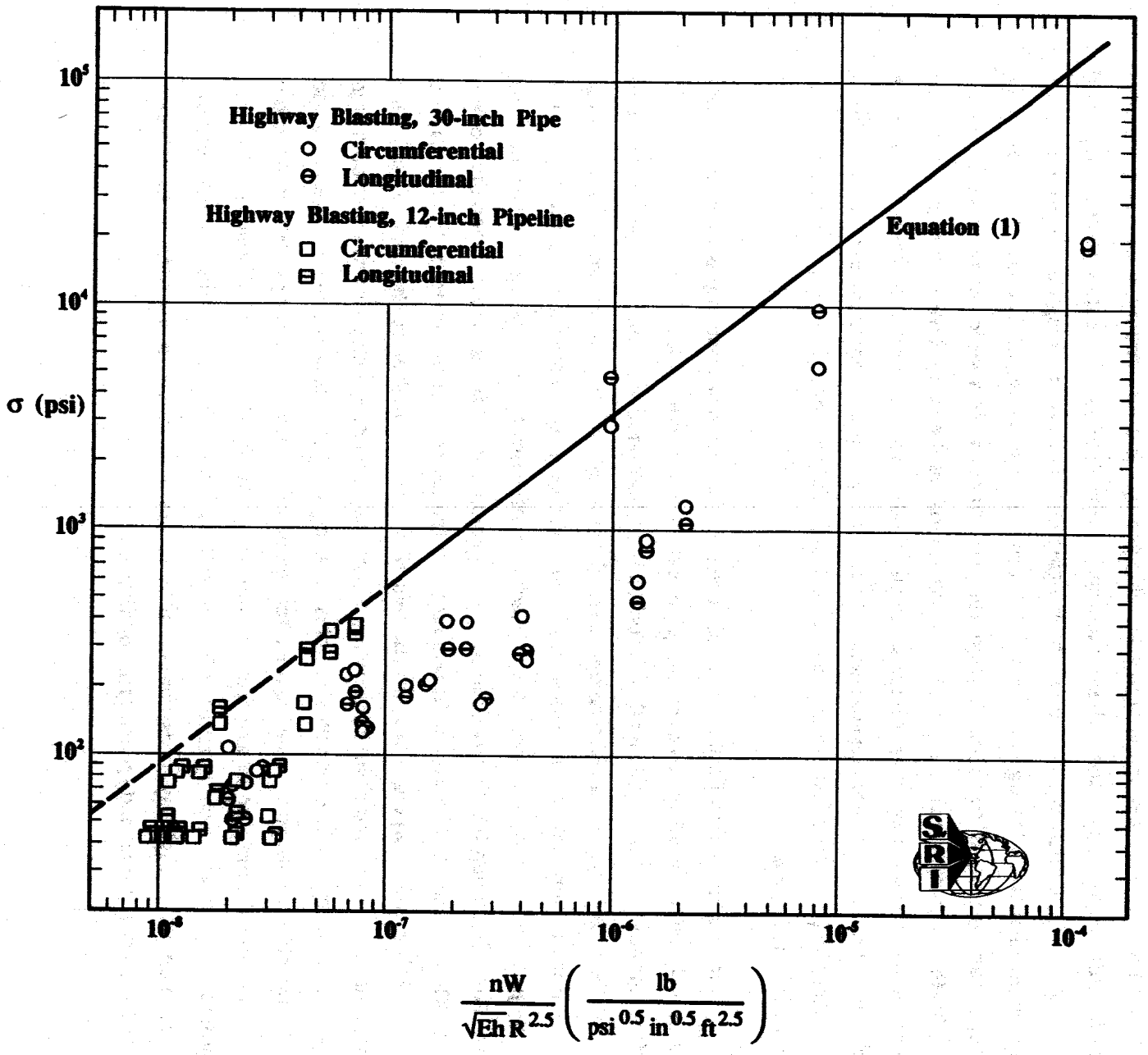


Figure 11. Comparison of Rock Blasting Pipe Stress Data with Soil Blasting Equation

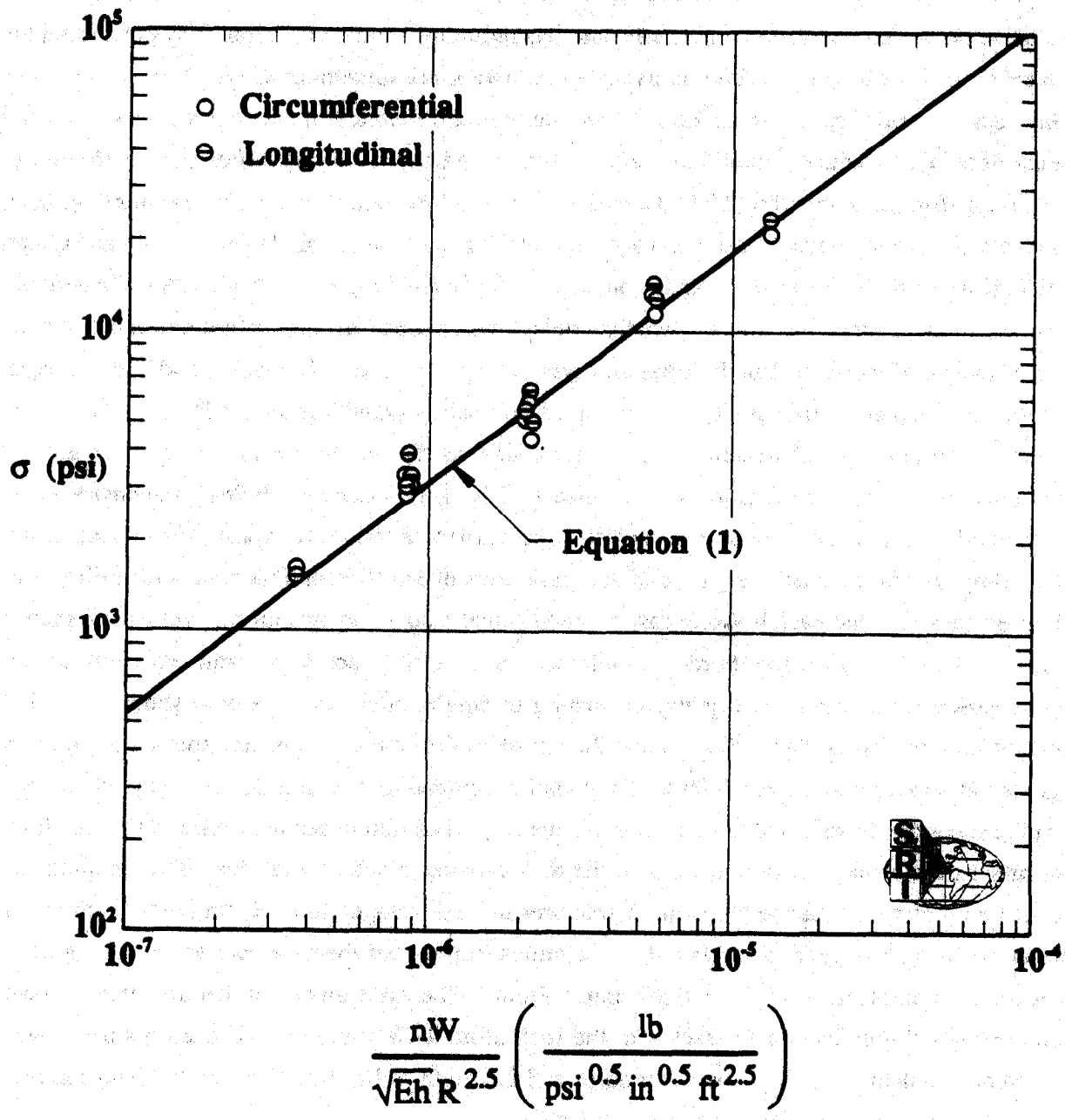


Figure 12. Comparison of Soil Pipe Stress Data from Laboratory Tests with Stress Prediction Equation (Esparza, 1984)

The amount of ground vibration caused by blasting is related to the amount of explosives detonated at any one time. For multiple hole arrays, the use of delays will reduce the amount of explosive being detonated at one given instant thus reducing ground vibrations. By permitting the movement of rock at various time intervals and allowing reinforcement of waves between holes, delay caps also aid rock fragmentation. There are several references that discuss blast design and the use of delays to reduce ground vibrations and enhance fragmentation (Dupont, 1980; Hemphill, 1981; Langefors and Kihlström, 1978; Dowding, 1985). In addition, many investigations have been made related to using delay blasting in rock such as those by Lang, et al., (1986), Green and Green (1986), Kopp and Siskind (1986), Anderson, et al., (1985), and Stagg and Rholl (1987). In general, there are many factors that dictate whether delays will reduce ground vibrations and enhance fragmentation. These factors include the rock type and its structure, hole spacing and burden, depth of holes and decking, explosive type, and explosive loading density (powder factor). Thus, it is inconceivable that a standard delay can be established as the one to use for minimizing ground vibrations. In the past, a minimum of a 9 millisecond delay between blast holes was considered as the standard for each to be an independent blast with regard to vibration (Hemphill, 1981). According to Dowding (1985), it is customary to consider a minimum of 8 milliseconds per delay to be effective. However, he states that each blasting case should be analyzed on its own merits, but delays should be at least 1 ms/ft of effective burden. Anderson, et al., (1985) conducted f&scale production fragmentation experiments in a quarry consisting of single, dual, and five-hole shots on a 45-ft bench of granite. Their data indicated that the optimum delay was 20 ms, and that fragmentation degraded at shorter and longer delays. They also concluded that with a 20 ms delay the energy from the second hole shot was expended in further fragmentation of the rock around the first hole shot rather than being transmitted through the rock causing ground vibrations. Their hypothesis was that enough time must be allowed for fractures to be developed to a certain point for the next hole in the firing sequence to activate those fractures further, but the time cannot be so long as to allow the rock mass already fractured to separate from the bench to an extent that the seismic wave from the second hole cannot interact with the rock around the first hole. The 20 ms delay was equivalent to a delay of 2 ms/ft between holes and 2.5 ms/ft of burden. Stating the delays in this manner takes into account the explosive hole layout.

According to Lang, et al., (1986), fragmentation of rock by blasting takes place in space and in time, and the latter controls the degree of breakage. The seismic wave generated by an explosive in rock travels at the velocity of sound in material The fractures and cracks created by the explosion travel with a velocity that is only 38% of the velocity of sound. Their analysis of

the fragmentation process by the seismic wave and the “subsequent expansion of gases generated by the explosion to minimize ground vibration caused by blast looks at the fragmentation efficiency in terms of the ground particle velocity with ‘and without the use of time delays. The optimum delay times for three groups of rocks were determined to be:

15-45 msec for hard rock (13,000 ft/sec sound velocity)

20-50 msec for softer rock (9,800 ft/sec sound velocity)

35-75 msec for weak rock (6,600 ft/sec sound velocity)

It is evident from these times that the optimum delay time is shorter in rocks having high sonic velocities (fracture occurs faster). Also, one can estimate that for blasts in soil, such as those conducted by Esparza, et al., (1981), the optimum, delay would be estimated to be an order of magnitude longer, or 200 to 750 msec, to be effective in reducing vibration levels. This confirms the experimental results of the earlier blasting research project in which the few tests fired in soil with short delays between rows of an explosive grid pattern produced ground vibrations and pipe response data that were of similar amplitude as the rest of the tests that used simultaneous initiation of all the explosive holes..

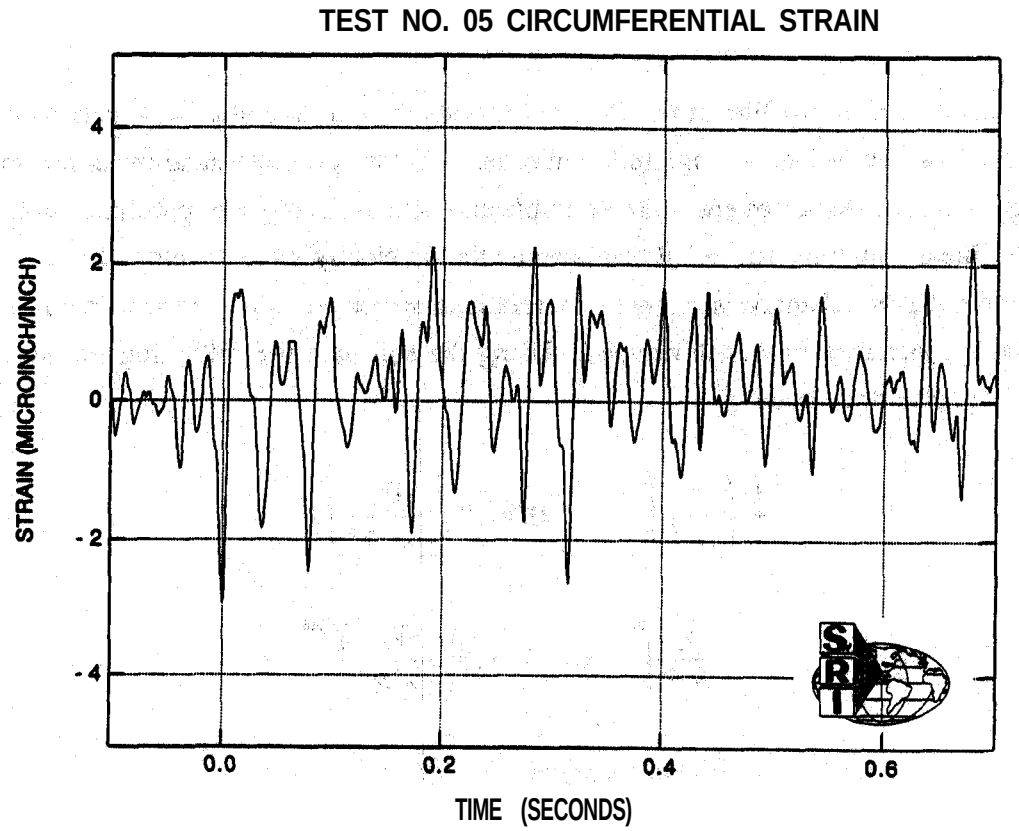
Kopp and Siskind (1986) looked at the use of millisecond delays in blast design and their effect on the resulting ground vibrations and airblast. Delay intervals within rows were 17 and 42 ms, which were equivalent to 0.5 and 1.3 ms/ft respectively. Their analysis of the data showed no significant difference in the ground vibration levels from these two delays, However, spectral analysis did show a difference in the predominate frequencies of the ground vibrations measured. The 17 ms delays produced predominant frequencies around 10 Hz while the 42 ms delays had a broader scatter of predominate frequencies. Delay intervals between rows were 30 to 100ms. Their investigation found that the longer delays between rows gave the lowest vibration levels. Kopp and Siakind recommend further work to better understand the complex interactions between spacing, burden and delay intervals within and between rows of blast holes and their influence on ground vibrations.

The question of whether the use of delays can decrease the stresses induced on a buried pipeline by blasting is not only dependent on the strength of the seismic wave and its wave length (frequency content), but also on the response time of the pipeline together with the surrounding soil, and on the different response modes and frequencies of the pipe. In the earlier report, Esparza,

et al., (198l), assumed a simplified sinusoidal seismic wave and pipe response in both the circumferential and longitudinal direction. Thus, any uniform series of seismic waves that arrive at the pipe under l/4 of the response period apart would be considered to load the pipe as if no delays were present. Seismic waves spaced between l/4 and 2 periods apart would be in a regime where the pipe stresses may or may not be reduced due to the delays used. Finally, the seismic waves arriving more than 2 response periods apart would be expected not to enhance the pipe stress and thus the charge weight per delay would be responsible for the maximum stress. Obviously, the main difficulty in determining how a time delay will affect the pipe is quantifying accurately the response time of the pipeline. For example, the strain data. from Test No. 5 shown in Figure 13 shows a predominant response frequency in the circumferential direction of about 40 Hz and in the longitudinal direction of about 30 Hz. For a similar explosive grid, but at a closer distance, the corresponding frequencies were 14 and 18 Hz in Test 14, (Figure 7). This observation indicates that when the explosive array is at larger distances, the pipe responds to the blast loading at higher frequencies (shorter response time); Therefore, at these distances, one would expect a given delay time to be more effective in reducing stress levels in comparison to simultaneous detonations. As the distance from a given charge array to the pipeline decreases (a stronger seismic wave results), the response time of the pipeline/soil increases so that a given delay would probably become less effective. Furthermore, seismic energy loads the pipe from different angles when the array is in close proximity to the pipeline. How these different loading directions interact is difficult to predict. Additional experimental data are needed to determine what delay times can decrease the blast-induced stresses on a buried pipeline.

Since the use of charge weight per delay is common practice in predicting and establishing ground vibration limits, the same parameter was used for comparing (in Figure 11) the pipe stress data to the soil prediction equation. As stated previously, when the data are plotted in this manner, the point source soil prediction equation appears to be an upper bound for the rock data. Thus, assuming that effective delay intervals are used between explosive holes in an array that is similar to those monitored in this investigation, Equation (1) should provide a realistic maximum pipe stress estimate when blasting in rock next to an open face near a pipeline in a trench backfilled with soil.

Some analysis of the ground vibration data presented in Table 3 was also performed in this investigation. In the previous research effort, Esparza, et al. (1981), reported on radial (longitudinal) particle velocity measurements made in soil. Equations for peak radial velocity and displacement for single charge explosions were developed empirically using the soil test data and some large



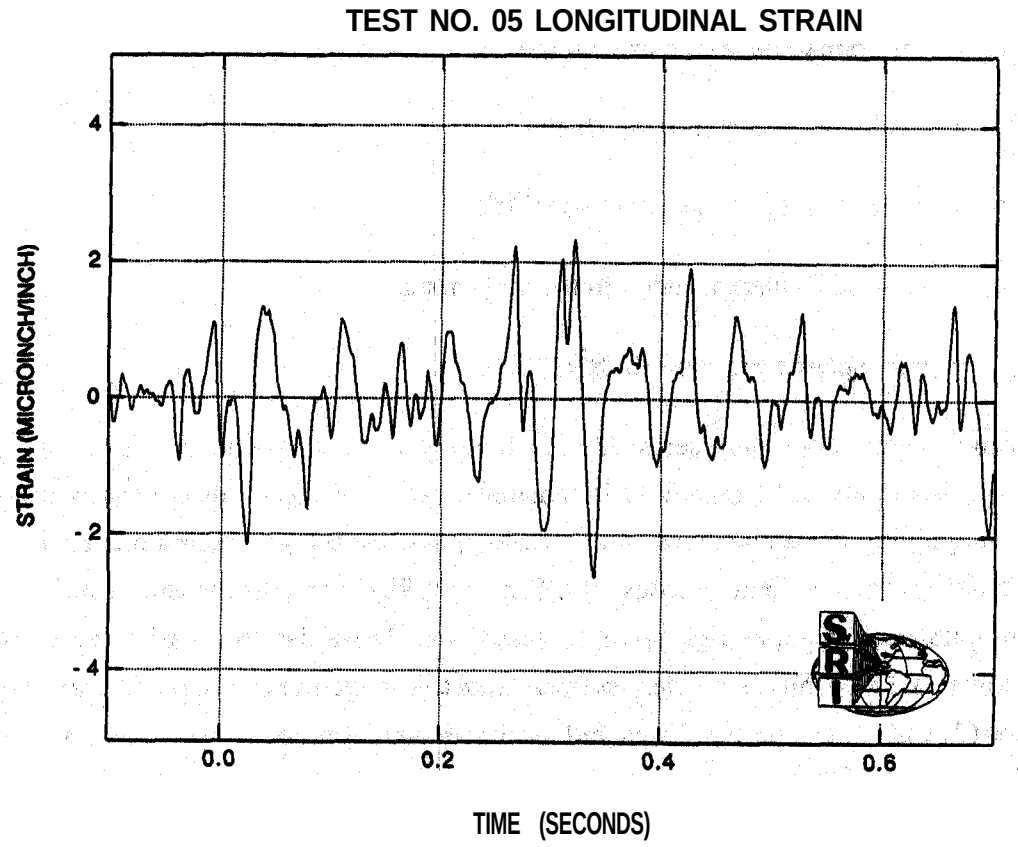


Figure 13. Pipe Response Data in the Circumferential and Longitudinal Direction, Test No. 5

scale rock test data from the literature. These equations were nondimensional, general equations that extended over ten orders of magnitude. In order to obtain simpler equations, more applicable to the range of scaled distances encountered in blasting situations 'close to pipelines (within about 100 ft), log-linear equations for radial displacement and velocity were developed from the SwRI soil data. From the model analysis, a functional relationship between the ground motion parameters and the blasting parameters was developed. Using the soil data the following simpler, general equations were also developed:

$$\frac{U}{c}\left(\frac{p_o}{\rho c^2}\right)^{0.5} = 0.00489\left(\frac{W_e}{\rho c^2 R^3}\right)^{0.790} \tag{2}$$

$$\frac{X}{R}\left(\frac{p_o}{\rho c^2}\right)^{0.5} = 0.0373\left(\frac{W_e}{\rho c^2 R^2}\right)^{1.060} \tag{3}$$

in which U = peak radial ground particle velocity (ft/sec)

X = peak radial ground displacement (ft)

R = distance to the explosive charge (ft)

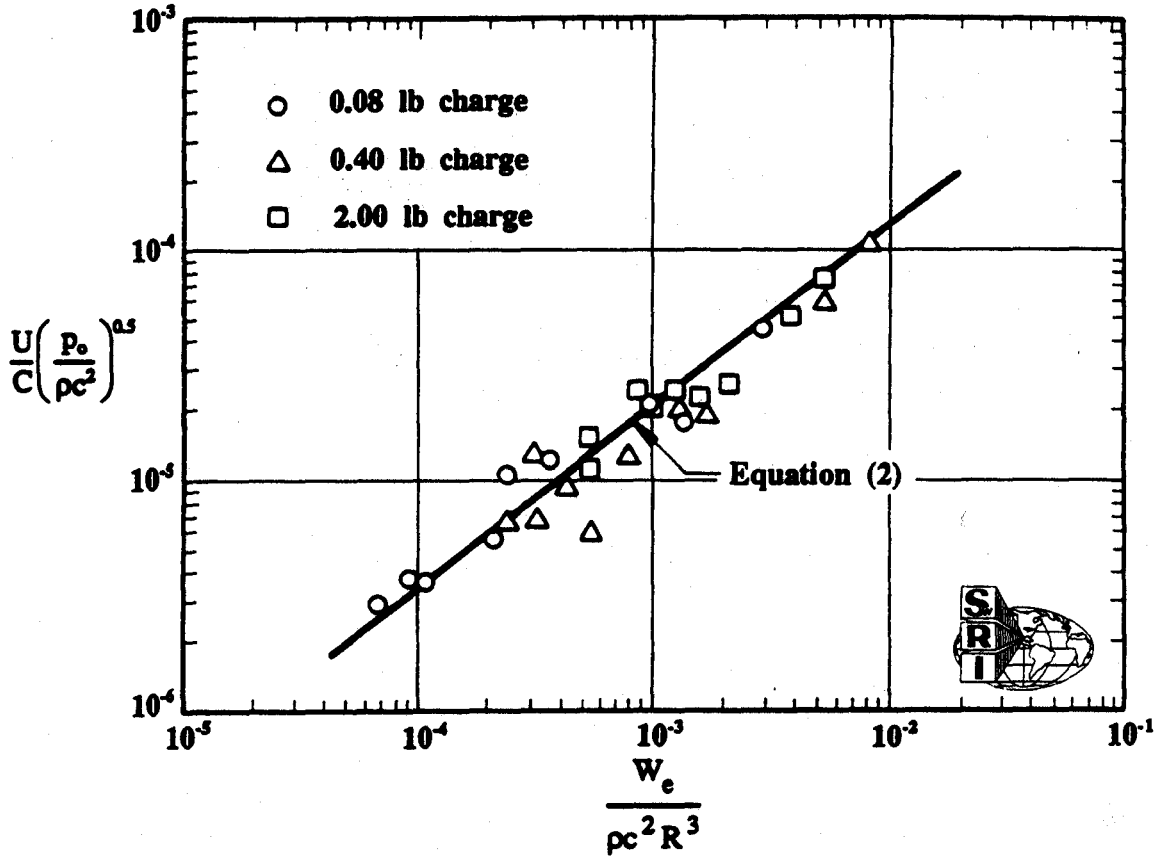
W_e = explosive energy release (ft-lb)

ρ = mass density of the soil (lb-sec^2/ft^4)

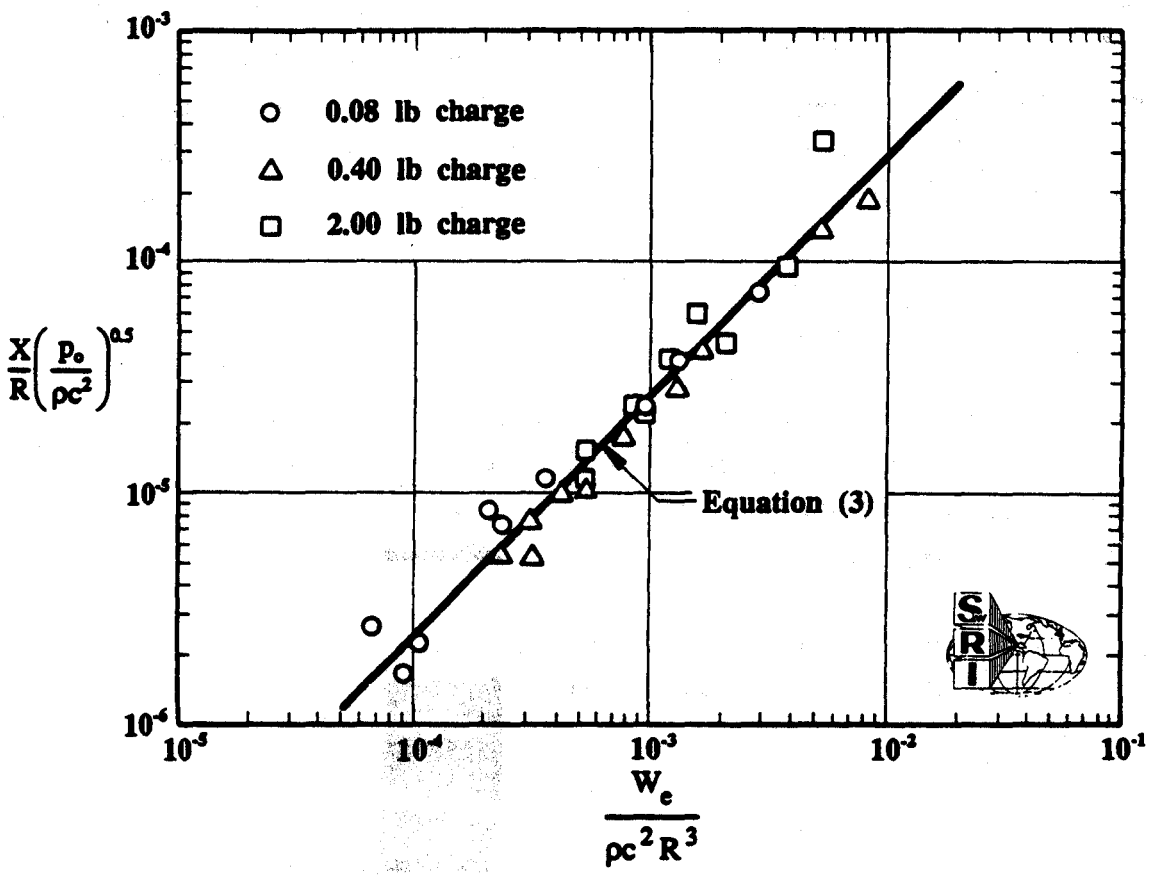
C = seismic P-wave velocity in the soil (ft/sec)

p_o = atmospheric pressure (lb/ft)

Note that even though a consistent set of U.S. customary units is shown for the variables, each parameter group in Equations (2) and (3) is dimensionless and, therefore, any consistent set of units can be used in applying these equations. For example, in comparing experimental data obtained from single charge tests in a homogeneous soil, Esparza (1984) used the measured soil parameter ρ and c to compute each parameter group in the equations. These data comparisons are shown in Figure 14. However, since those tests were performed in a homogeneous soil, ρ and c are constants, and Equations (2) and (3) can be simplified and used with common units. For a "typical" soil with ρ := 100 lb/ft^3 and c = 1,000 ft/sec, the velocity equation becomes:



(a) Peak Radial Velocity



(b) Peak Radial Displacement

Figure 14. Comparison of Ground Motions for Soil Tests (Esparza, 1984)

$$U = 1280\left(\frac{W}{R^3}\right)^{0.79} \qquad (4)$$

where

U = peak radial soil velocity (in/sec)

W = equivalent explosive weight compared to 94/6 ANFO (lb)

R = distance to the explosive charge (ft)

Note that this equation can be easily expressed in terms of a scaled distance, defined as $R/W^{1/3}$, as follows:

$$U = 1280\left(\frac{R}{W^{1/3}}\right)^{-2.37} \text{ (soil)} \qquad (5)$$

Peak particle velocity data can be found in the literature plotted in terms of this cube-root scaled distance because it is a consequence of the model analyses and is therefore dimensionally correct; e.g., the data from Esparza (1981 and 1985) and Dowding (1985). As stated by Dowding (1985), plotting peak particle velocity as a function of $R/W^{1/2}$, or square root scaling, is more traditional. Consequently, a number of equations have been derived empirically using square root scaling, even though this type of scaling is not dimensionally correct. For instance, DuPont (1980) presents one developed by the U.S. Bureau of Mines for surface blasting in rock and is as follows:

$$U = 160\left(\frac{R}{W^{1/2}}\right)^{-1.6} \qquad (6)$$

According to DuPont (1980) this equation is for use only for planning blasting projects. Modifications may be required when a blasting job is started and actual seismic data are recorded. Also, note that according to DuPont (1980), the charge weight-perdelay is used in this equation providing the delay interval is eight milliseconds or longer.

Another approach used to handle peak particle velocity data and develop prediction equations is to begin with a propagation equation of the form

$$U = K W^{\beta_1} R^{\beta_2} \qquad (7)$$

where K is a constant coefficient sometimes related to the geology, and B_1 and B_2 are empirical exponents. This coefficient and the exponents are then evaluated from the test data. Various investigations have, obtained different results depending on the range of the data and the properties of the specific test site. The problem with this approach is that resulting equations are dimensionally illogical.

Regardless of which approach is used to relate particle velocity to charge weight and distance, data obtained at actual blast sites exhibit considerable scatter primarily because of the nonuniform geology normally present. Unlike the data presented in Figure 14, which was obtained in a homogeneous soil test bed in the "laboratory," real world data looks more like that in Figure 15 for the longitudinal velocities from Table 3 obtained in this investigation. Note that these data points were measured with a seismograph which was sensing in the "soil" backfill above the pipeline while the blasting took place in rock. An examination of blasting studies by Walter and Carroll (1980) showed large variability in vibration data. Data from four types of blasting operations (trenching, road construction, quarrying, and strip mining) showed variations in the order off 60% around the mean. They point out that significant variations will occur regularly and should be normally expected. This variability seems inherent in blasting vibrations and is probably due to geological, physical and operational factors that are not directly observable or controllable. An example of vector sum velocity data with even more scatter from construction blasting in Illinois compiled by Lucole and Dowding (1979) is presented in Figure 16 using square root scaling. One can see the large scatter in the data that is possible in many real world blastings. Because of this large scatter, many blasting criteria for above ground structures require that blasts be designed based on maximum probable velocities rather than average values. The three lines shown in this last figure denote the upper limits below which fall 50,84, and 95% of the data at a given scaled distance. Thus, the 95% line would provide the most conservative peak velocity estimate.

For blasting in a uniform rocky geology, Equations (2) and (3) developed by Esparza, et al., (1981), can provide ground motion estimates of average amplitudes by using appropriate values for p and c. For example, for a rock with p = 150 lb/ft^3 and c = 10,000 ft/sec, the peak velocity equation transforms into

$$U = 2990\left(\frac{R}{W^{1/3}}\right)^{-2.37} \quad \text{(rock)} \quad \text{for} \quad R/W^{1/3} < 20$$

which is similar to Equation (5), except for the coefficient.

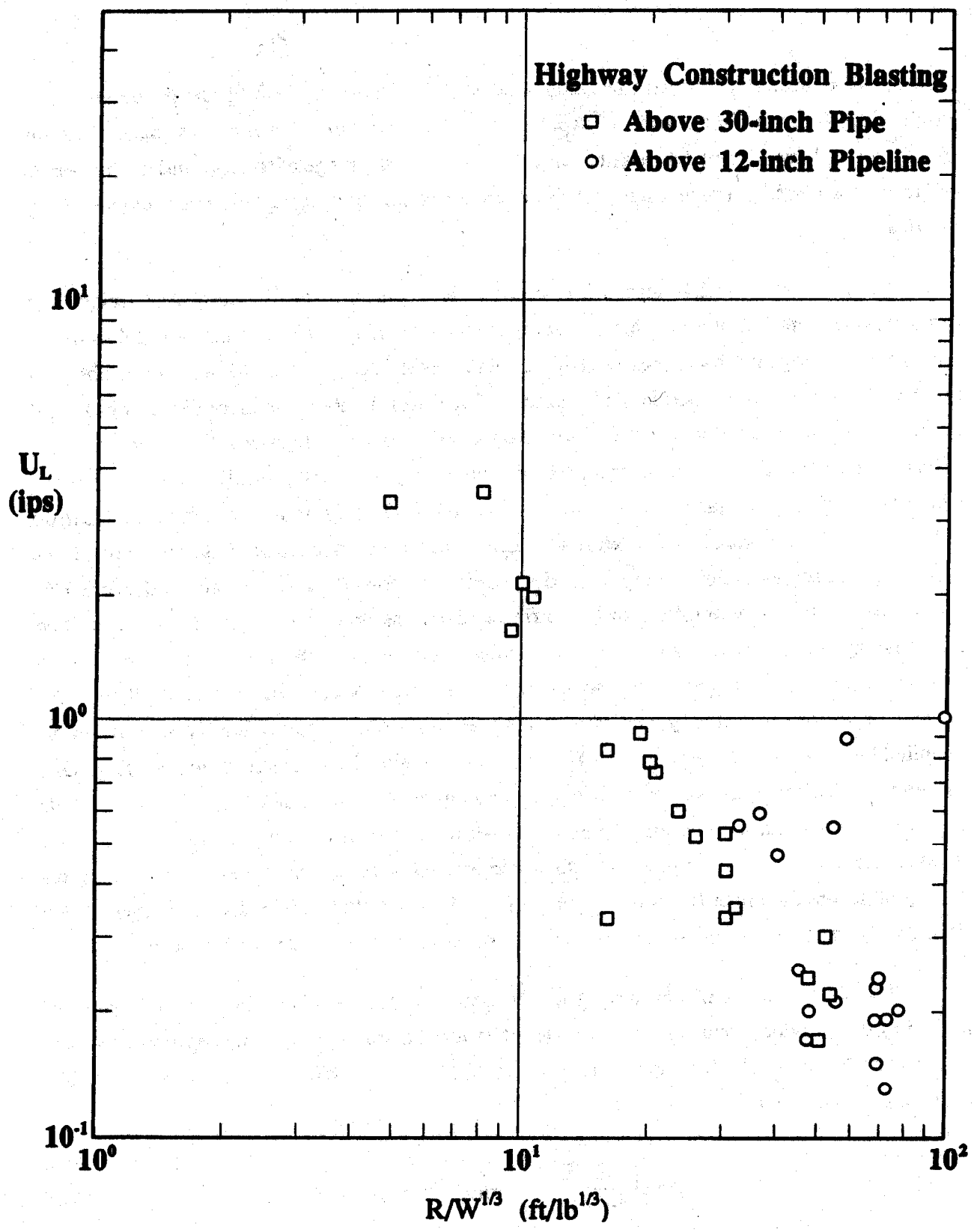


Figure 15. Longitudinal Particle Velocities Above Pipelines

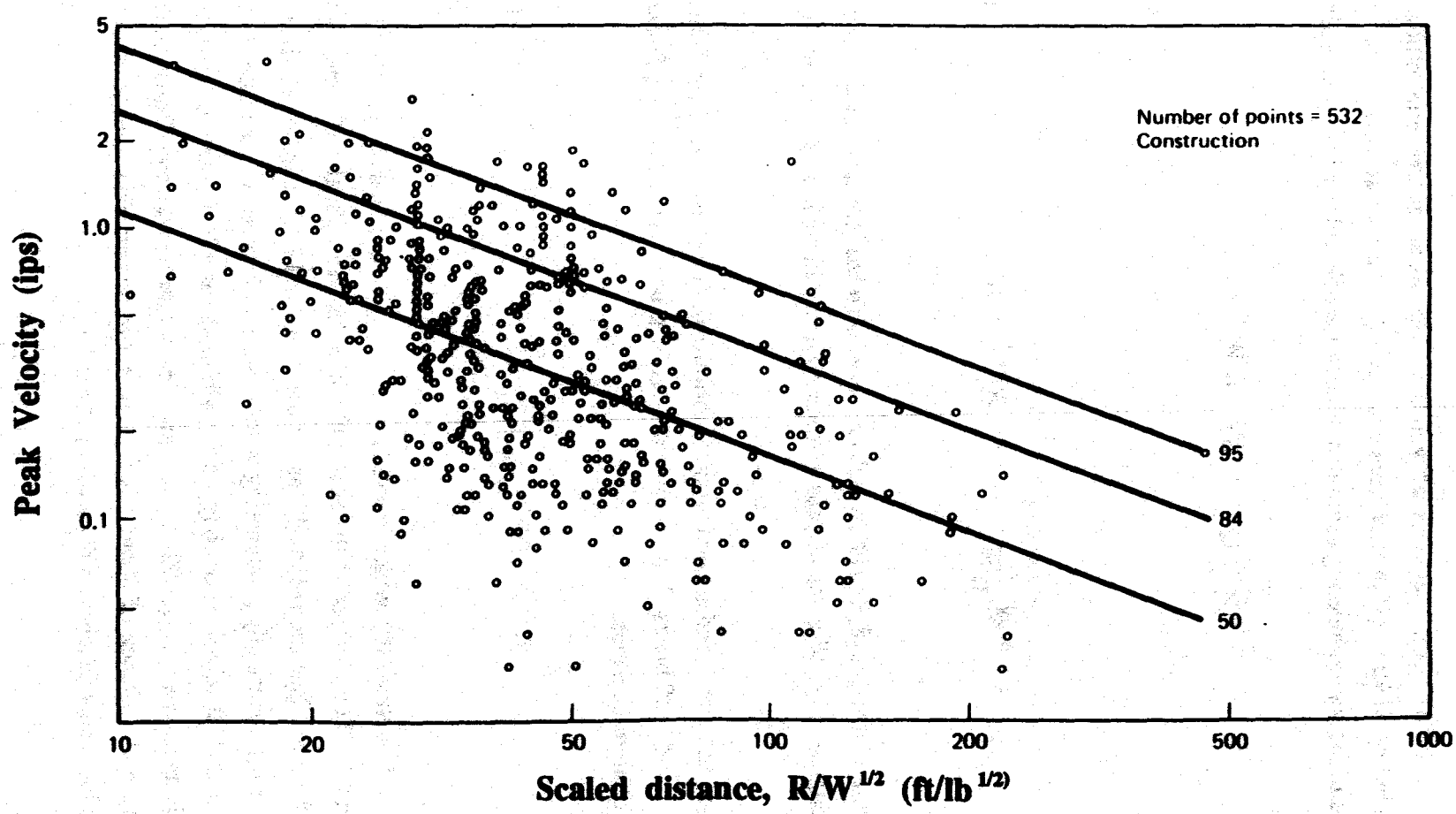


Figure 16. Peak Particle Velocity From Construction Blasting (Lucole and Dowding, 1979)

In Dowding's (1985) book, peak radial velocity data from quarry and other high explosive tests compiled by Hedran (1968) are presented using cube root scaling. From these data, upper-bound equations for engineering estimates of peak particle velocity are presented as

$$U = 6{,}000\left(\frac{R}{W^{1/3}}\right)^{-2.8} \quad for \quad R/W^{1/3} < 10 \tag{9}$$

and

$$U = 360\left(\frac{R}{W^{1/3}}\right)^{-1.6} \quad for \quad R/W^{1/3} > 10$$

It is interesting to note that Equations (8) and (9), which are based on relatively close-in detonations, produce very similar engineering estimates of peak particle velocity in rock, as shown in Figure 17.

Dowding (1985) also developed general ground motion equations based on 12 field studies involving quarry, tunnel, and shaft blasts. For a rock with p and c as used above to derive Equation (8), his peak velocity equation becomes:

$$U = 198\left(\frac{R}{W^{1/3}}\right)^{-1.45} \tag{11}$$

This equation is similar to Equation (10), which is valid for scaled distances greater than 10 ft/lb$^{1/3}$. Therefore, Equation (11) would underpredict the peak velocities for closer scaled distance when compared to the values for either Equation (8) or (9), as shown in Figure 17. Elastic theory, through the equations of motion for a spherically propagating wave from a point source in an infinite and homogeneous body, predicts that velocities of body waves will decay as $1/R^2$ for near disturbances and as 1/R for greater distances (Dowding, 1985). The close-in data used to develop Equations (8) and (9) indicate a decay with distance of about $1/R^{2.6}$. The more distant data used to develop Equations (10) and (11) indicate a decay with distance of about $1/R^{1.5}$.

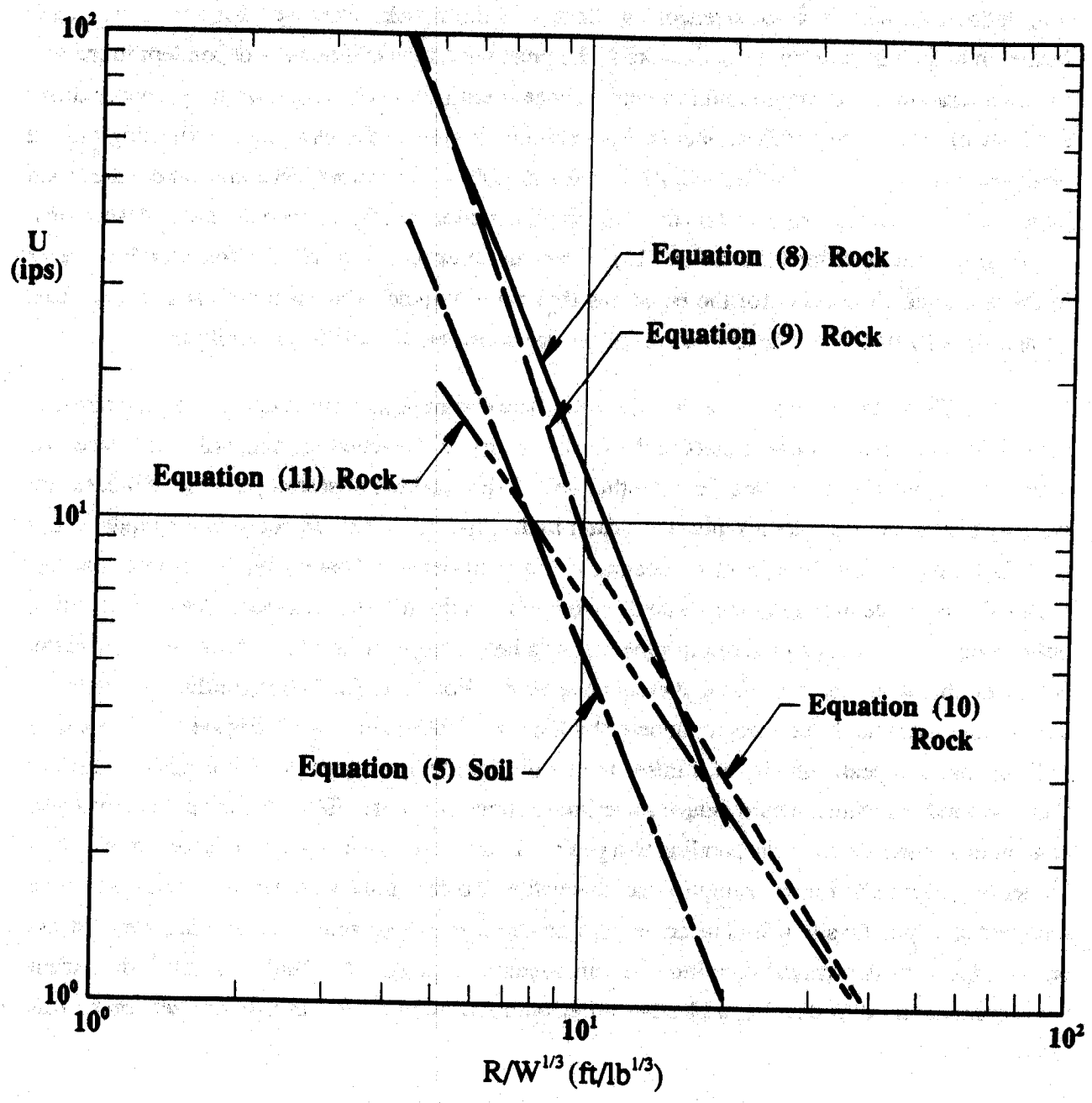


Figure 17. Ground Particle Velocity Equation Comparisons

Equations (2) and (3) will provide realistic engineering estimates of the average peak longitudinal velocity in a homogeneous geology of soil or rock. However, for a pipeline that is buried in a ditch in rock with a soil backfill, the peak velocities will be very dependent in the two media interaction, and the ground motions estimated with these equations would probably differ significantly from actual measurements. For example, Figure 18 shows a graph of the longitudinal peak velocities measured by Haley & Aldrich for AGTC on the ground just above where the strain gages had been installed by SwRI on the 30-inch pipe section and the 12-inch pipeline. Also shown in this graph are Equations (5) and (8- 11), One can observe, first of all, the considerable scatter in the test data. Secondly, for the equations that were derived using data with scaled distances greater than 10 ft/lb$^{1/3}$, the measured data peaks are considerably smaller in amplitude.

In field blasting situations, a correlation between peak particle velocity and pipe stress is sometimes attempted with test shots in the same vicinity as the actual blasting will take place. At other times a correlation is used from another site. With the kind of scatter possible in measuring velocity in real world geologies, plus the scatter in the pipe stress data, any correlation made would probably have a very low level of accuracy and confidence. Obviously, in some instances, reasonably accurate stress predictions could be made using this technique. In such a case, monitoring only velocity as a means of limiting pipe blasting below a given safe level may be appropriate. However, this would be very site and medium specific. For example, the longitudinal velocity vs. pipe stress data from the soil tests conducted by Esparza (1985) are shown in Figure 19. These data indicate that at a peak velocity of 2 in/sec in this uniform soil, a common limit used by many for above ground structures, would induce a maximum stress of about 2,500 psi on the pipe. However, at another site the stress corresponding to a peak velocity of 2 in/sec can certainly be significantly higher (see Figure 24 for an example) than this value. To determine whether the stress magnitude recorded at a specific site would be an acceptable stress amplitude requires the total state of stress on the pipe and its physical condition be considered and analyzed. Additional blast data from measurements used to develop a blasting criterion are presented later in the next section of this report.

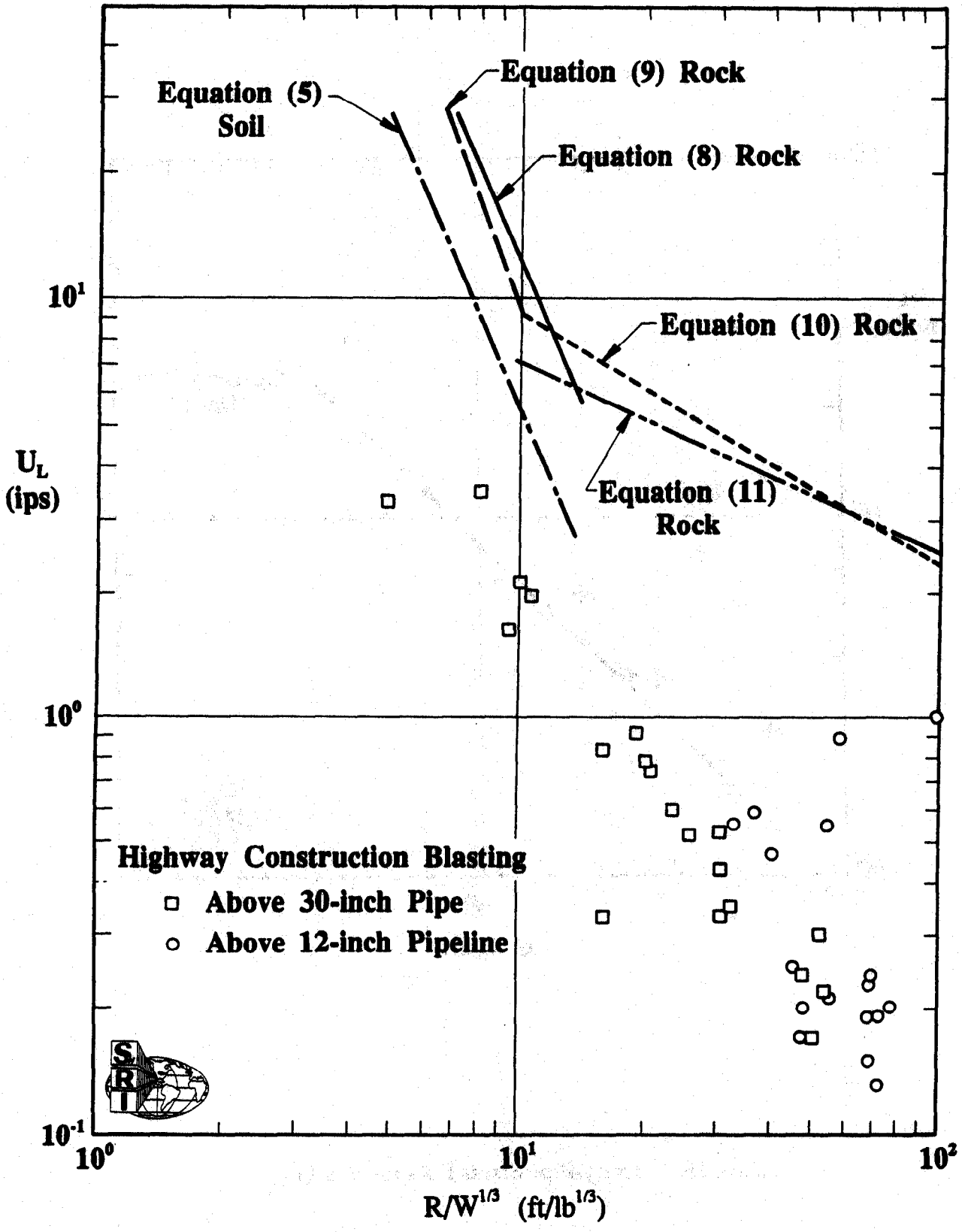


Figure 18. Comparison of Rock Blasting Data Measured in Soil with Various Equations

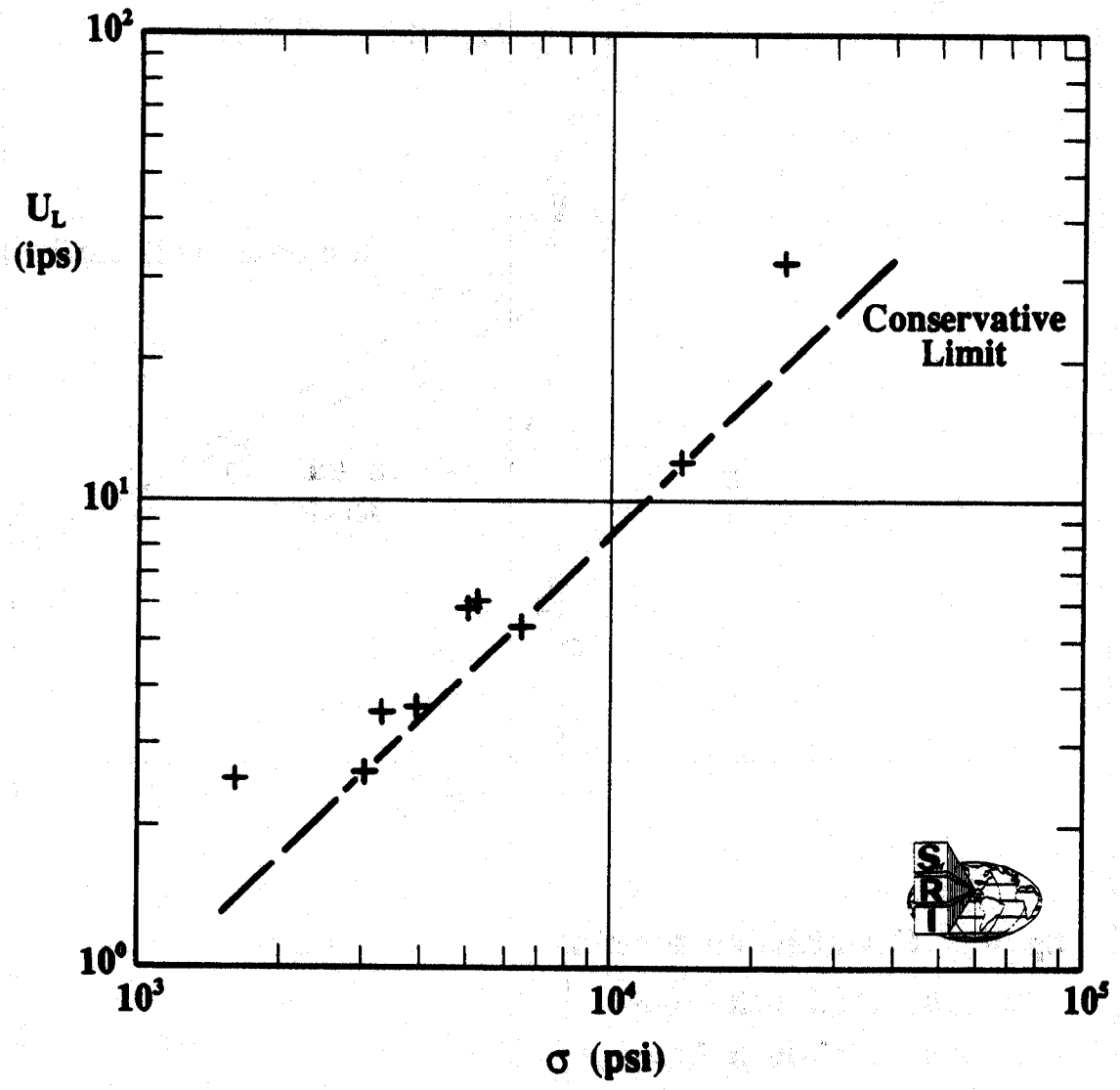


Figure 19. Velocity-Pipe Stress Data for Soil Tests

V. OTHER ROCK BLASTING DATA

Objective and Scope

During 1989, SwRI recorded pipe strain data on a pipe construction project adjacent to an existing operating pipeline. These data were recorded as part of an investigation to develop a safe criteria by a pipeline company for trench blasting when significant rock formations are encountered. Prior to this investigation, and like many other pipeline companies presently use, this client had used for several years blasting criteria based on vibrations at the in-service pipeline not to exceed the 2 in/sec criterion for residential structures based on compiled data by Nicholls, et al. (1971). However; due to this limitation, in many cases contractors had problems with fragmenting rock consistently during trench construction requiring blasting at close proximity to anexisting pipeline. Furthermore, as discussed earlier in this report, correlation attempts between charge weight and peak velocity are sometimes inconsistent and vary from site to site. Finally, the new criterion was to be based on the magnitude of the blasting pipe stress, taking into consideration the pipeline operating conditions. Therefore, a series of preliminary experiments was conducted to obtain the pipe stress data for developing the criterion. Then, during actual construction 'blasting, another series of shots was monitored and pipe strain data recorded to evaluate the criterion and modify it as needed for use on the rest of the construction project. In this section of the report the pipe stress and ground vibration data obtained are presented to provide additional insight and information concerning rock blasting near pipelines. The actual criterion developed by this particular pipeline company will not 'be presented:" However, some additional analysis of the data Was performed on this PRCI project, and these results are included in this section.

Description of Experiments

The preliminary test series consisted of ten tests planned to provide data from a variety of charge weights and two charge distances from the pipeline so that none of the test conditions was duplicated, Due to a partial misfire on one test, an eleventh test was shot. Some of the tests were configured to obtain results for the most severe conditions that would be expected during the actual construction. However, the staggered hole pattern, typical of designs used in ditch blasting, used for these preliminary tests was basically the same on all tests and similar to the one the blasting contractor was planning on using during construction. The layout of a typical preliminary test is shown in Figure 20. For all these tests the distance from the center of the pipe to the centerline of the ditch being excavated was either 15 or 25ft. These tests were conducted adjacent to an operational

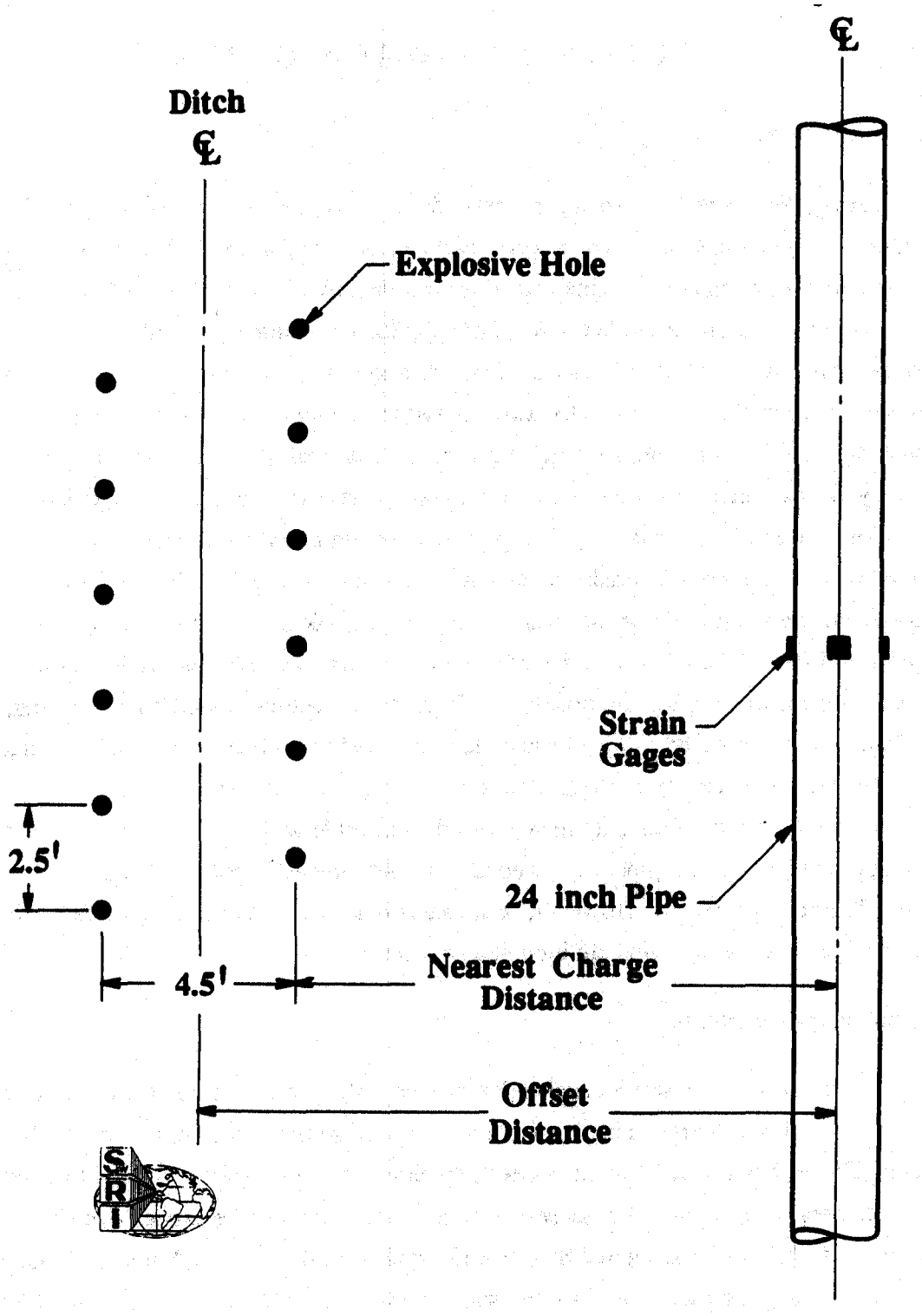


Figure 20. Plan View Layout for Ditch Blasting Tests

pipeline, 24-inch O.D. by 0.375 W.T., Grade B which was temporarily out of service. IRECO Unigel dynamite cartridges, 2 x 8 inches, were used by the blasting contractor. According to the manufacturer, this explosive has an energy of 1000 cal/gm making it 1.14 times more energetic than 94/6 ANFO., Several delay patterns were used ranging from one hole per delay to six holes per delay. In all cases, a delay of 17 milliseconds was used.

The preliminary tests were performed during a time period that coincided with the 24-inch line being temporarily out of service. Weldable, 90° strain gage rosettes were installed on the front (side facing the blast), the top, and the back of pipeline to measure orthogonal sets of circumferential and longitudinal strains. One set of six strain gage elements was installed opposite each explosive hole pattern. In addition to strain measurements, seismographs were used including two above the pipe where the gages were mounted, one two inches above the pipe, and the second one foot below grade.

The construction test serjes consisted of seven shots for which the operational. 24-inch pipeline was instrumented in the same manner & for the preliminary tests.' The explosive used was the same and the hole pattern similar. However; the charge weight per delay was limited by the preliminary criterion, and the total number of holes used on each test was varied according to what was required by the blasting contractor to fracture the particular rock formation of interest.

Experimental Results

The data from the ditch blast tests are presented in Table 4. The data are identified by test number for both test series, preliminary and constuction. For each test the following information is given: the distance to the nearest explosive hole; the equivalent weight. charge nW per delay (n = 1.14 relative to ANFO and W is the actual weight); the powder factor in pounds of explosive per cubic yard of rock, the peak radial (longitudinal), particle velocity measured in the soil backfill one foot below grade, above the strain gages; and the pipe stresses due to blasting computed using the biaxial stress equations and the maximum circumferential and longitutdinal strains measured on each test. A typical set of strain data traces is shown in Figures 21 and 22.

In addition to the strain data, some ground motion data were recorded in the preliminary and construction tests and are presented in Table 4. These data are plotted in Figure 23 along with the highway construction data and the velocity equations. An attempt was made to correlate the ditch blasting peak particle velocity data and the pipe stresses. As shown in Figure 24, which plots

Table 4. Ditch Construction Blasting Data

PRELIMINARY TESTS

Test No.	Centerline Offset Distance (ft)	Distance to Nearest Hole (ft)	nW per Delay (lb)	Powder Factor (lb/yd^3)	Radial Part. Velocity (ips)	Circumf. Stress (psi)	Long. Stress (psi)
1	15	12.75	9.20	2.83	4.5	11,800	11,200
2	15	12.75	9.20	2.93	3.9	8,780	7,440
3	25	22.75	27.60	3.20	2.7	8,950	6,050
4	25	22.75	27.60	3.20	4.4	11,010	7,700
5	25	22.75	20.70	2.20	5.0	8,900	5,860
6A	15	12.75	5.75	2.05	3.5	7,280	7,430
6B	15	12.75	5.75	1.64	2.7	2,520	3,380
7	15	12.75	6.90	2.40	4.8	19,400	16,900
8	15	12.75	27.60	3.65	5.2	27,400	23,300
9	15	12.75	4.60	3.20	4.5	7,150	4,150
10	15	12.75	4.60	3.20	3.2	6,560	5,240

CONSTRUCTION TESTS

Test No.	Centerline Offset Distance (ft)	Distance to Nearest Hole (ft)	nW per Delay (lb)	Powder Factor (lb/yd^3)	Radial Part. Velocity (ips)	Circumf. Stress (psi)	Long. Stress (psi)
1	21	19.5	4.60	3.30	1.1	1,150	880
2	22	20.5	13.80	2.73	5+	4,610	5,040
3	22	20.5	9.20	2.98	5.6	6,500	7,790
4	25	23.5	14.95	2.66	2.6	710	980
5	15	13.5	3.45	1.77	3.2	3,900	4,240
6	19	17.5	4.60	1.85	--	2,710	2,350
7	11	9.5	3.45	1.92	5.9	4,860	6,543

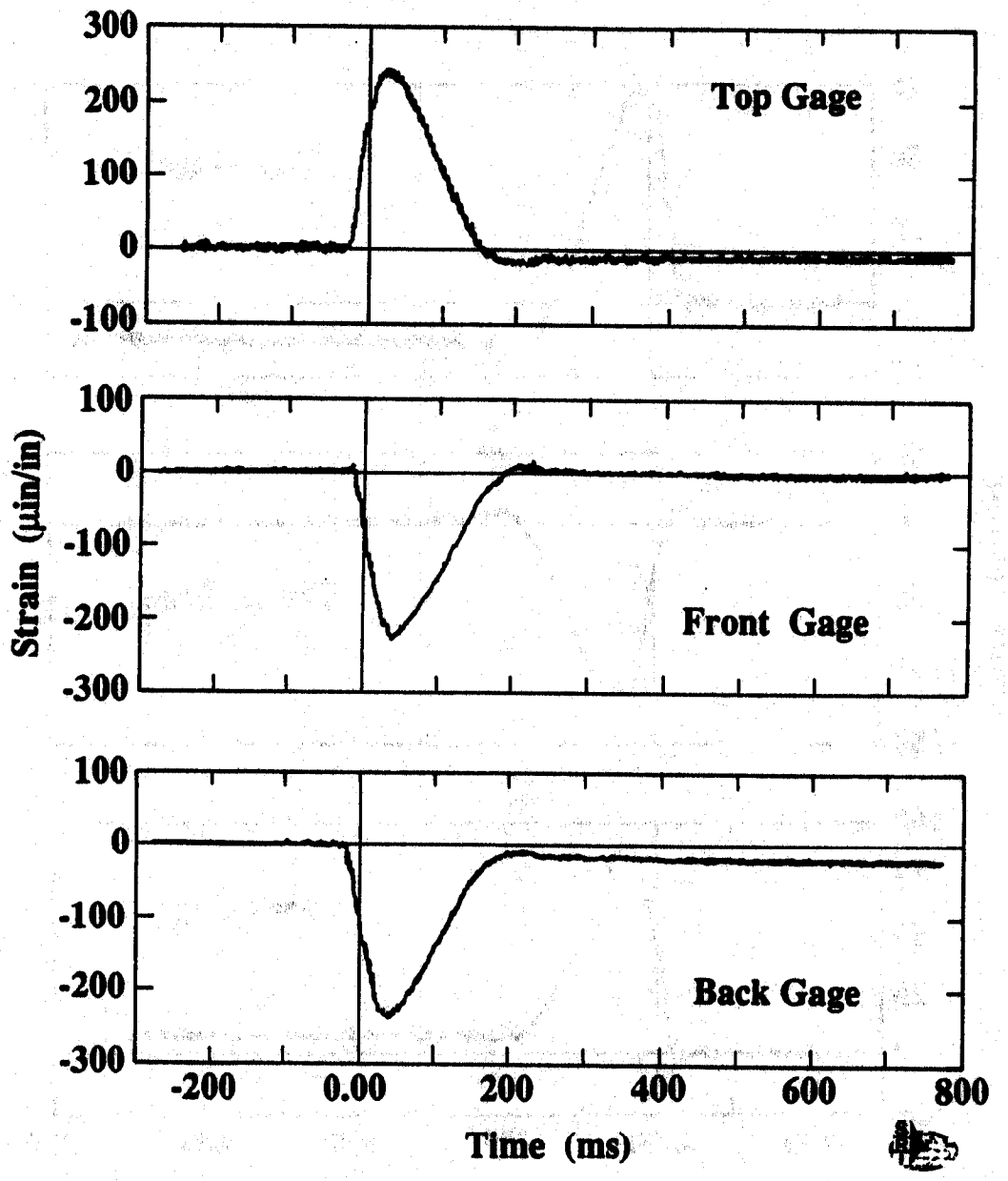


Figure 21, Circumferential Strain Data for Ditch Rock Blasting Test

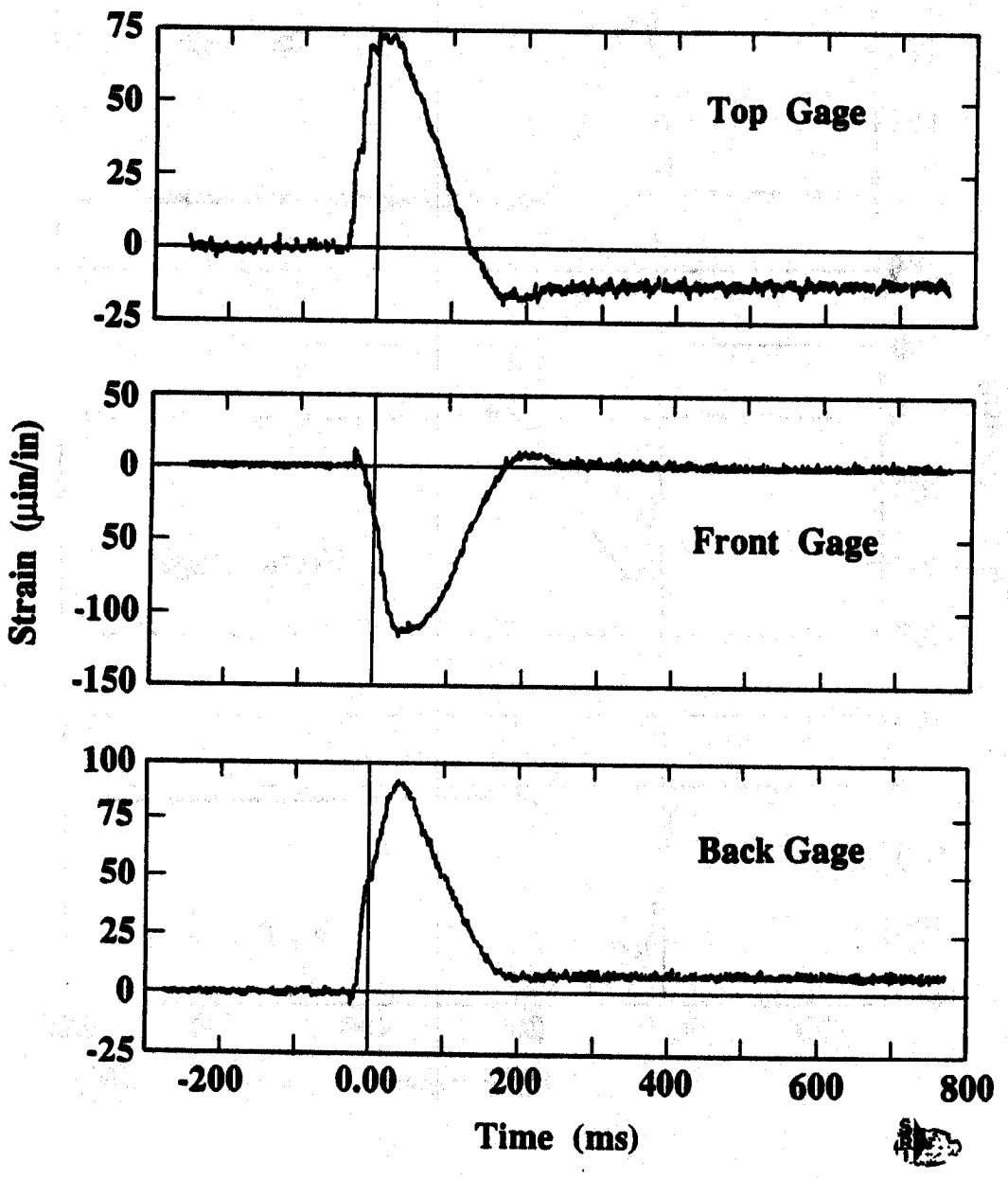


Figure 22. Longitudinal Strain Data for Ditch Rock Blasting Test

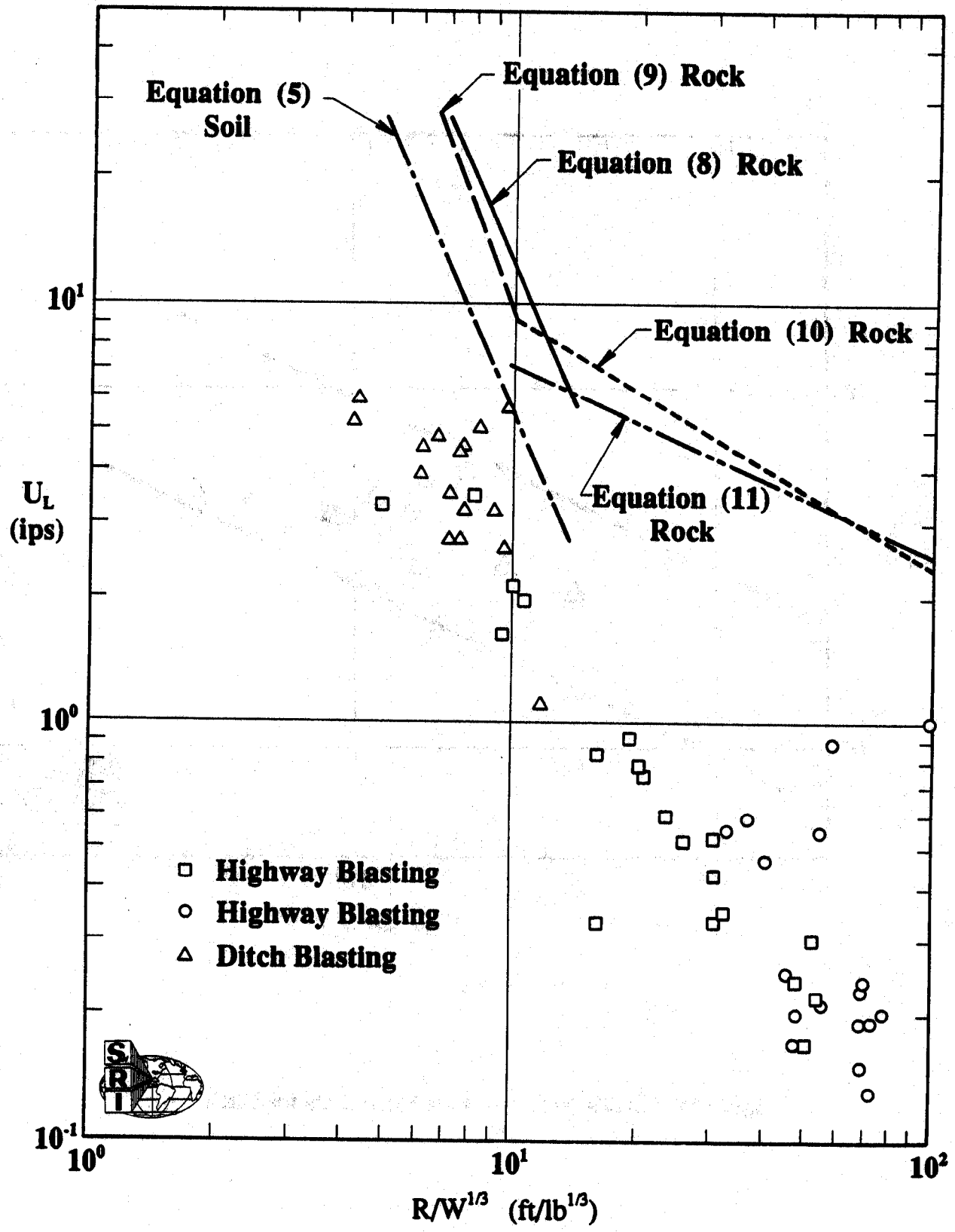


Figure 23. Ditch Blasting Velocity Data Compared with Highway Data

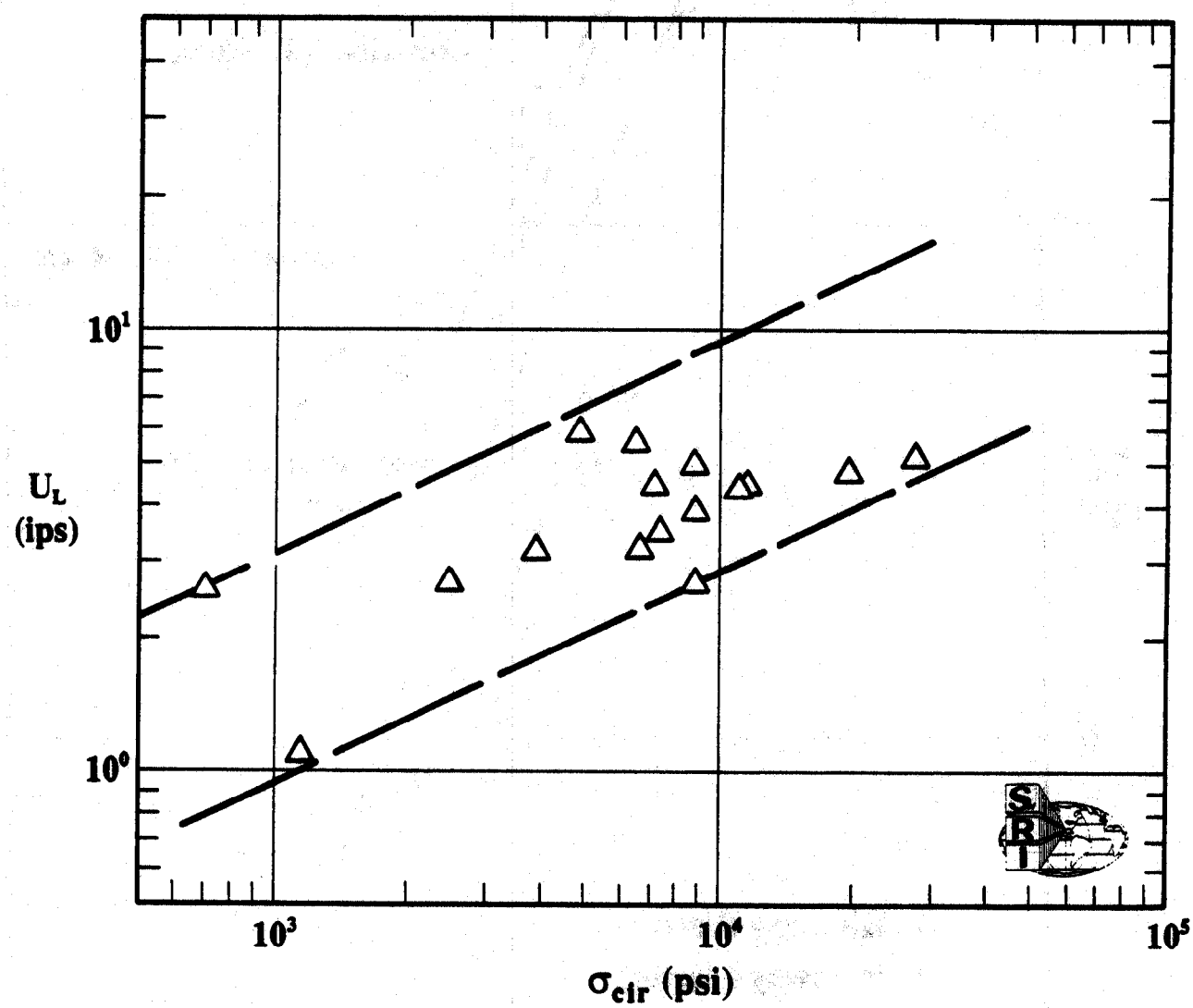


Figure 24. Particle Velocity - Pipe Stress Data for Ditch Tests

peak radial (longitudinal) velocity versus circumferential stress, considerable scatter is present. Upper and lower bounds on the data show that a velocity range of about 2.5 to 8.5 ips would correspond to the desired limit of 8,000-psi. Another way of looking at this scatter 'would be that if a blasting criterion was to specify a peak velocity such as 3 in/set, according to these data, the pipe circumferential stress would be expected to range from 950 to almost 12,000 psi. This large variability and inconsistency in pipe stress and velocity data made it difficult to use particle velocity as a criterion for this particular ditch blasting project.

Additional Analysis of Ditch Blasting Data

All data recorded in the preliminary and construction tests were from tests ,with offset distances ranging only from 15 to 25 ft. Taking the previous discussions one step further and in an effort to generalize these results, all stresses listed in Table 4 have been plotted in Figure 25 and compared to the stress prediction equation discussed in Section IV. As was done with the highway construction data, the abscissafor the ditch b&sting data was computed using the equivalent charge weight nW per delay. One small adjustment was made in this analysis. Instead of the centerline offset distance, the distance to the nearest charge hole is used as in all the previous analyses, Although the ditch blasting data cover a narrow range in scaled distances, they do scatter rather evenly above and below the line for Equation (1). Recall that the highway blasting data, as shown in Figure 11, plotted mostly below the line for Equation (1). Thefore, if one were to use Equation (1) to predict maximum stress when blasting a ditch similar to the one described here, one would need a safety factor of about 2 to account for those stress values that are greater than predicted. This safety factor would make Equation (1) more conservative, but would probably extend its applicability over a broader range of distances and charge weights. Such a line, as shown in Figure 25, would represent about a 95% upper bound line for the data. Thus, the data presented in Table 4 from ditch blasting tests indicate that a simple adjustment to the coefficient in Equation (1) could provide maximum stress prediction equation for apipeline buried in soil backfill near rock formations blasted in ditch excavation. Thus, for ditch blasting in rock, the point source equation for estimating pipeline stresses would be as follows:

$$\frac{\sigma}{E} = 8.88 \left(\frac{nW}{\sqrt{Eh} \quad R^{2.5}} \right)^{0.77} \qquad (12)$$

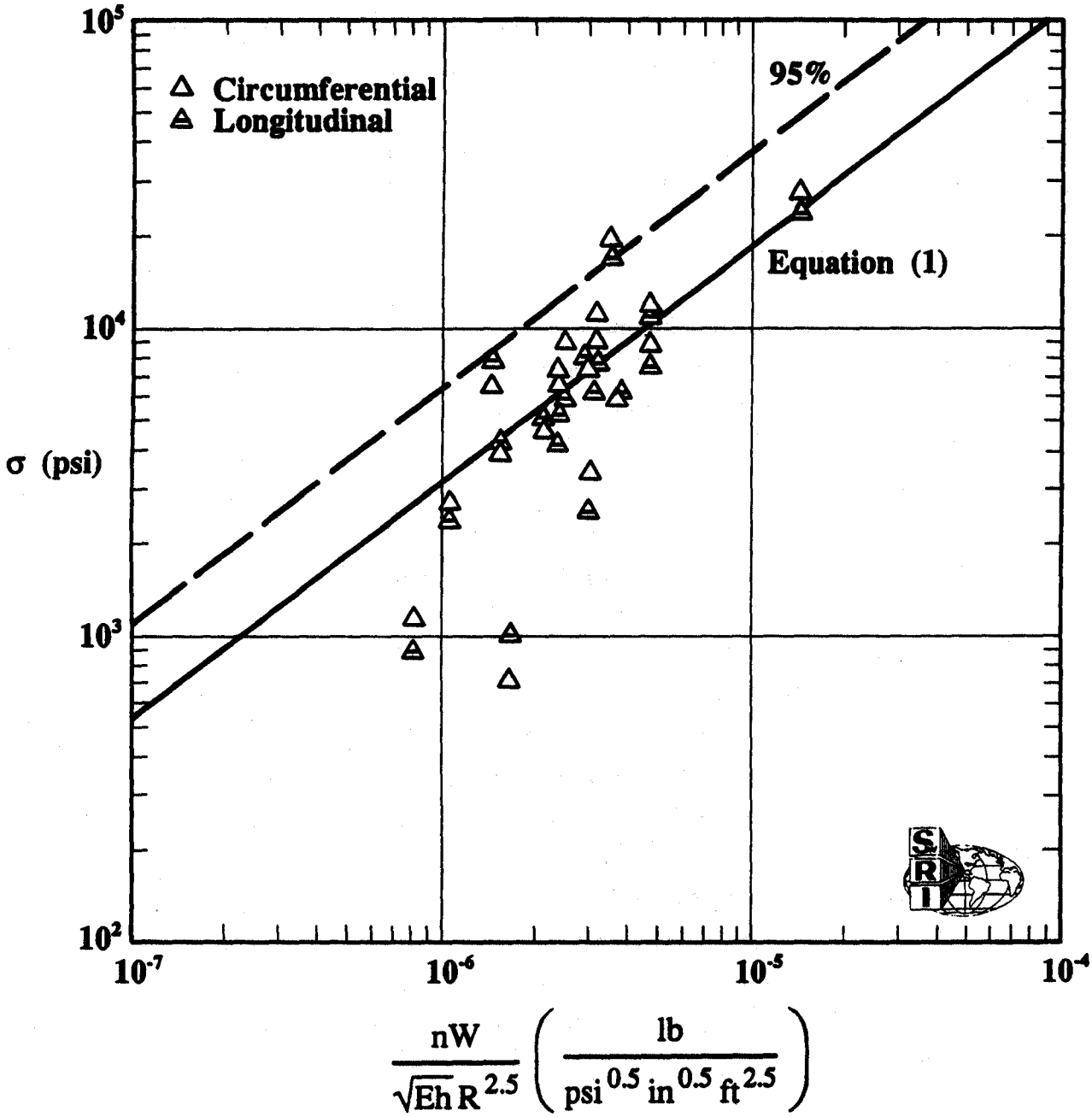


Figure 25. Ditch Blasting Pipe Stresses Compared to Soil Blasting Equations

However, additional data are needed to verify this modification before this equation may be applied in general.

Comparing the ditch blasting data to the previously discussed highway construction data in Figure 11 shows that the ditch tests produced higher stresses at a given scaled distance, even though the arrays used were of similar geometry and explosive loading. However, one big difference was the degree of confinement. While the construction blasts always were fired against an open face parallel to the long dimension of the array, the opposite was true for the ditch construction tests. This difference in confinement appears to account for the majority of the difference in the pipe stresses. This conclusion is similar to that obtained from ground motion data. For example, in a plot of particle velocity versus square root scaled distance presented by Dowding (1985), a multiplying factor of 2.5 is used on the upper limit of the data scatter to account for unusual confinement, such as in pre-split blasting, as opposed to more “typical” blasting situations. DuPont (1980) states that for charges fired with a high degree of confinement, peak particle velocity may be five times greater than with a free face to provide relief.

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VI. CONCLUSIONS, OBSERVATIONS & RECOMMENDATIONS

An investigation, was conducted' to record and analyze pipeline strain data from highway construction blasting in rock., The construction of an interstate highway section and the availability of two pipelines, to be relocated provided an opportunity to obtain pipe strain data not available in previous PRCI blasting research projects conducted with underground blasting in soil. After many delays and obstacles were encountered in performing this study, SwRI was finally able to monitor rock blasting for 21 firings, which provided important pipe strain data from a section of 30-inch pipe and from a 12-inch operational pipeline adjacent to the highway construction project.

In the previous PRCI blasting research program, several equations and techniques were formulated to predict pipeline stresses from nearby blasting using data from an extensive set of tests conducted in uniform soil. These equations and techniques, developed by Esparza, et. al., (1981), were applicable to a variety of explosive configuration such as a single point source, a parallel or angled-line source, and a parallel or angle-grid source, all detonated simultaneously. In the present PRCI blasting research program, a beginning has been made, to address blasting situations in rock adjacent to a pipeline that is in a trench cut in the rock, but backfilled. with soil and broken rock. A limited number of actual highway construction blasts were monitored. The explosive arrays for the blasts consisted of small grids (i.e., 2 x 8 holes or 3 x 6 holes maximum) detonated with a delay between holes. After the strain data from these limited number of rock blasting tests wereprocessed, the corresponding maximum circumferential and longitudinal pipe stresses were computed. These resulting stresses were then analyzed and compared with the previously derived soil' blasting equations. The best results were found, by using the previous, single-point source equation, which is

and using the explosive weight per delay as the single explosive source.. The results of this analysis indicated that for bench type construction blasting where there is an open face, the previous, soil blasting equation provides an upper bound for about 95% of the stress data when the explosive weight per delay is used in the equation. Therefore, this equation can be used to predict pipeline stresses for other similar rock blasting situations. However, because only one delay period (25 ms) was used on all the rock blasting tests, additional discussions on delays are also presented in this

report as a result of reviews of several references found in the literature on this subject. It was concluded that additional data are needed to determine what delay times do decrease blast-induced stresses on a buried pipeline. Because of the limited type and number of rock blasting tests that were part of this research project,' it is not possible at this time to determine if, besides the point source equation, all the other equations and techniques developed for blasting in soil can be modified or adapted and made applicable to similar blasting geometries in rock. Therefore, blasting research should continue, and a recommendation for using model experiments is provided later in this section.

In addition to the analysis of the pipe stress results, some analysis of ground vibration data recorded by others at the pipe strain gage locations was also performed. After a review of several particle velocity equations in the literature, it is shown that the velocity data from actual blast sites, such as that recorded in this study and in many others, exhibit considerable scatter. Consequently, with the kind of scatterthat is possible in peak velocity and pipe stress data, any correlation attempted between these two parameters would have a low level of accuracy and confidence. Even for those instances where reasonable data are obtained, the resulting correlation would be very site specific. If measurement of pipe strains are to be made for a specific blasting situation, it is recommended that these strain data be used to develop a blasting criteria for that specific application based on the blasting pipeline stresses, rather than on a correlation with peak particle velocity.

Experimental pipe stress data were also presented from another blasting investigation concerned with blasting rock for ditch construction parallel to an existing operational pipeline. These additional data were used by a particular pipeline company to develop and evaluate a blasting criterion for cross-country ditch blasting. Some additional analysis of the ditch blasting data was performed and presented in this report in an attempt to generalize the previous stress prediction equation developed from soil blasting data for application to ditch blastings in rock. By making a more conservative change of increasing the coefficient by a factor of two, the soil blasting equation was modified, and can be used to estimate stresses from ditch blasting in rock. However, because of the narrow range of the test parameters, the modified equation is not recommended at this time to develop blasting criteria based solely on this equation. Additional data are needed to reach that stage in critical situations or with very different blasting configurations.

In recording the data for this PRCI program at an actual blasting operation, it became obvious very quickly that it is extremely difficult to plan and perform a systematic set of tests as one can do in a laboratory environment. Many of the problems encountered would also be present in obtaining data for developing a blasting criterion or in monitoring blasting operations with or without

data recording. These problems can range from schedule changes, weather delays, irregular hole patterns and depths due to geological configuration, blasting “rules of thumb,” inaccurate or nominal charge loading of holes, lack of coordination between the driller and blaster, inaccurate or lack of distance measurement between explosive holes and pipeline, to uncertainty in calculating the powder factor.

All of these problems and others can make compliance to any blasting criterion difficult to ascertain and can add to the scatter of the data when making pipe strain measurements. Consequently, the data presented in this report has limited applications, as pointed out in the body of this report. The new rock data do provide additional insight to the level of pipe stress to be expected for a pipe located in a ditch with “soil” backfill as blasting occurs in rock adjacent to it. However, additional experimentation is definitely needed and highly recommended. To obtain more data at a lower cost, model experiments using a variety of blasting configurations commonly found in rock blasting and with different delay periods near pipelines are recommended. Using a concrete slab as a rock simulant, tests can be performed in the laboratory using six-inch pipe as a l/4 or l/5 scale of pipe commonly used in gas transmission lines. In addition, model experiments are recommended to investigate other aspects of pipeline response to blasting that have not been tested experimentally such as the analytical result that diameter does not affect the stress level induced in a pipeline. The results of these investigations using model tests will provide considerably more data and help increase confidence in the ability to estimate realistically pipeline stresses from blasting in rock. The data recorded from the model tests would be compared to the previous soil data and the rock data presented in this report. The modification made to the point source equation for soil blasting would be validated. If possible, adjustments to the other equation and methods developed for soil blasting would be made to extend their use to rock blasting. Finally, the additional research will attempt to correlate ground displacement to pipe stress to determine if this parameter is more useful than particle velocity to predict pipeline stresses.

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VII. REFERENCES

Ambraseys, N. R. and Hendron, A. J., "Dynamic Behavior of Rock Masses," **Rock Mechanics Engineering Practice,** pp. 203-227, (KG. Stagg and O.C. Zienkiewicz, Eds.), John Wiley & Sons, Inc., London., 1968.

Anderson, D. A., Winzer, S. R., and Ritter, A. P., 'The Relationship Between Rock Structure and Delay Timing, Fragment Size, and Distribution in Explosively Loaded Rock," **Fragmentation by Blasting,** First Edition, Society of Experimental Mechanics, Brookfield Center, Connecticut, 1985.

Austin, "Extra Gelatins," Product Information Bulletin EG861, Austin Powder Company, Cleveland, Ohio, 1990.

Barkan, D. D., **Dynamics of Bases and Foundations,** McGraw-Hill Book Company, New York, 1962.

Crandell, F. J., "Ground Vibrations Due to Blasting and Its Effect Upon Structures," Journal Boston **Society of Civil Engineering,** Volume 36, pp. 245,1949.

DuPont, Blasters' Handbook, Explosive Products Division, E.I. DuPont de Nemours & Co., Inc., Wilmington, Delaware, 1980.

Dvorak, A., "Seismic Effects of Blasting on Brick Houses," **Proce Geofyrikeniha Ustance Ceskoslavenski Akademic,** Volume 169, Geofysikalni Sbornik, pp. 189-202,1962.

Edwards, A. T., and Northwood, T. D., "Experimental Studies of the Effects of Blasting on Structures," **The Engineer,** Volume 210, pp. 538-546, September 30,1960.

Esparza, E. D., Westine, P. S., and Wenzel, A. B., "Pipeline Response to Nearby Explosive Detonations," 1980 Interim Annual Report, Project No. 02-5567, Southwest Research Institute, San Antonio, Texas, December 1980.

Esparza, E. D., Westine, P. S., and Wenzel, A. B., "Pipeline Response to Buried Explosive Detonations," Final Technical Report, Project No. 02-5567, Southwest Research Institute, San Antonio, Texas, August 1981.

Esparza, E. D., 'Trench Effects on Blast-Induced Pipeline Stresses," Final Report, Project No. 06-9348, Southwest Research Institute, San Antonio, Texas, April 1984, Journal of Geotechnical Engineering, ASCE, Volume III, No. 10, pp. 1193-1210, October 1985.

Esparza, E. D. and Westine, P. S., "Well Casing Response to Buried Explosive Detonations," Final Report, Project No. 06-7926, Southwest Research Institute, San Antonio, Texas, July 1985.

Green, R. H. and Green, M. W., 'The Effect of Precise Millisecond Delays on Fragmentation at the Rock of Ages Quarry,"Proceeding of the Twelfth Conference on Explosives and Blasting" Technique, Society of Explosives Engineers, Atlanta, Georgia, February 1986.

Hemphill, G. B., Blasting Operations, McGraw-Hill Book Company, New York, 1981.

Hendron, A. J. and Oriard, L. L., "Specifications for Controlled Blasting in Civil Engineering Projects,"Proceeding of the First American Rapid Excavation and Tunneling Conference, Society of Mining Engineers, AIME, Littleton, Colorado, 1972.

IRECO, '*Explosives Engineers' Guide," IRECO Incorporated, Salt Lake City, Utah, 1989.

Kopp, J.W. and Siskind, D.E., "Effects of Millisecond-Delay Intervals on Vibration and Airblast From Surface Coal Mine Blasting," U.S. Bureau of Mines Report of Investigations 9026, 1986.

Lang, L. C., Bohus, G., Foldesi, J., and Benedek, D., 'The Optimum Delay," Proceedings of the Second Mini-Symposium on Explosives and Blasting Research, Society of Explosives Engineers, Atlanta, Georgia, February 1986.

Langefors, U. and Kihlström, B., The Modern Technique of Rock Blasting, Third Edition, John Wiley & Sons, Inc., New York, 1979.

Lucole, S. W. and Dowding, C. H., "Statistical Analysis of Blast Emission Records from Quarrying, Mining and Construction Operations in the State of Illinois," Illinois Institute of Natural Resources, Document 79/02, 1979.

Lysmer, J. and Waas, G., "Shear Waves in Plane Infinite Structures," Journal of the Engineers Mechanics Division, ASCE, Volume 98, pp. 85-105, February 1972.

May, T. W. and Bolt, B. A., 'The Effectiveness of Trenches in Reducing Seismic Motion,"' **Earthquake Engineering and Structural Dynamics,** Volume 10, pp. 195-210,1982.

McClure, G. M., Atterbury, T. V., and Frazier, N. A., "Analysis of Blast Effects on Pipelines," **Journal of the Pipelines Division, Proceeding of the American Society of Civil Engineers,** November 1964.

Nicholls, A. W., Johnson, C. F., and Duvall, W. I., "Blasting Vibrations and Their Effects on Structures," U.S. Bureau of Mines Bulletin 656, 1971.

Northwood, T. D., Crawford, R., and Edwards, A. T., "Blasting Vibrations and Building Damage," **The Engineer,** Vol. 215, No. 5601, May 1963.

Segol, G., Lee, P. C. Y., and Abel, J. F., "Amplitude Reduction of Surface Waves by Trenches," **Journal of the Engineering Mechanics Division,** ASCE, Volume 104, pp. 621-641, June 1978.

Siskind, D. E., Stachura, V. J., and Raddiffee, K. S., "Noise and Vibrations in Residential Structures from Quarry Production Blasting," U.S. Bureau of Mines Report of Investigations 8168, 1976.

Siskind, D. E., Stagg, M. S., Kopp, J. W., and Dowding, C. H., "Structure Response and Damage Produced by Ground Vibrations from Surface Blasting," U.S. Bureau of Mines Report of Investigations 8507, 1980.

Thoenen, J. R. and Windes, S. L., "Seismic Effects of Quarry Blasting," U.S. Bureau of Mines Bulletin 442, 1942.

Stagg, M. S. and Rholl, S. A., "Effects of Accurate Delays on Fragmentation for Single-Row Blasting in a 6.7m Bench," Second International Symposium on Rock Fragmentation by Blasting, Society for Experimental Mechanics, Bethel, Connecticut, August 1987.

Walter, E. J. and Carroll, J., "Natural Variation of Vibration Level Associated with Blasting," **Proceeding of the Sixth Conference on Explosive and Blasting Techniques,** Society of Explosives Engineers, Tampa, Florida, February 1980.

Westine, P. S., Esparza, E. D., and Wenzel, A. B., "Analysis and Testing of Pipe Response to Buried Explosive Detonations," Final Report, Project No. 02-4300, Southwest Research Institute, San Antonio, Texas, July 1978.

Wilson, W. H.' and Holloway, D. C., "Instrumentation Techniques for Model Rock Blasting," **Fracture of Concrete and Rock** SEM-RILEM International Conference, Houston, Texas, June 1987.

Woods, R. D., "Screening of Surface Waves in Sob," **Journal of Soil Mechanics and Foundations** Division, ASCE, Volume 94, pp. 951-979; July 1968.