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TRENCH EFFECTS ON BLAST-INDUCED PIPELINE STRESSES

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ABSTRACT: An experimental program was conducted to obtain data from model tests to evaluate the effects of open trenches on blast-induced circumferential and longitudinal stresses on an underground pipeline. A model pipe was instrumented with five sets of orthogonal strain gages at two longitudinal locations. Five sets of experiments were performed. (2) The first set of experiments, in which the blast-induced stresses covered the range of a stress-predictive equation derived previously, consisted of tests without a trench. Similar blasting tests were then conducted using four different trench geometries. The trenches were all the same width and located the same distance from the model pipe. Two different lengths and depths were used on the four trenches. (3) The measured strains and ground motions from the no-trench experiments showed that the new data compared very well with values obtained using the predictive equations developed on a previous program. In general, the trenches were more effective in reducing the circumferential pipe stresses than the longitudinal pipe stresses. However, different depths and lengths of the trench affected the pipe stress amplitude variations. The longer and deeper trench was the most effective.

INTRODUCTION AND BACKGROUND

Blasting near buried gas pipelines is a common occurrence which can cause the combined pipe stresses to exceed allowable limits. Explosives are used frequently for pipeline construction, including parallel pipelines adjacent to earlier ones, for strip mining, highway construction, artificial lake construction, seismic exploration, utility line construction in the expanding suburbs, etc., in the vicinity of natural gas pipelines. Prior to 1975, no valid criteria existed for determining safe charge-distance limits in blasting situations near buried pipelines. Many states had, and some still have a ground motion criterion which limits maximum ground vertical particle velocity to either 1 or 2 in./sec at the surface. This soil particle velocity criterion evolved from work published by Crandell (2) for the effects of ground shock on buildings. More recent experimental work investigating the effects of buried charges on buildings, such as that of Dvorak (3) in Czechoslovakia, and Nicholls, Johnson and Duvall (11), using data obtained by Thoenen and Winds (13), and Edwards and Northwood (4) basically show that threshold soil particle velocity criteria are reasonable when applied to above-ground structures. However, a steel pipe is a strong structure relative to a building, and, when buried, also has a large mass of earth providing additional inertial resistance to any ground shock from a buried detonation.

In 1964, McClure, Atterbury and Frazier (9) developed pipeline stress prediction equations at the Battelle Memorial Institute under contract for

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the Pipeline Research Committee (PRC) of the American Gas Association (A.G.A.). These equations were theoretical elasticity solutions based upon Morris' equation (10) for ground motion, and the assumptions that: (1) A pipeline movement equals exactly that of the surrounding soil; and (2) no diffraction of shock fronts occurs. No experimental data were available to compare to the Battelle equations when they were developed. The method was recommended for use only for explosive-to-pipe distances greater than 100 ft. Because of the limitations on surface ground motion criteria and on the Battelle equations, a better method was needed to estimate pipeline stresses induced by nearby blasting.

In 1975, the Pipeline Research Committee initiated a blasting research program with Southwest Research Institute (SwRI) for the purpose of developing engineering procedures for predicting pipeline stresses induced by nearby buried explosive detonations, particularly those within 100 ft of a natural gas pipeline. Two consecutive projects were funded by the PRC. In the first project, Westine, Esparza, and Wenzel (14) 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 data to define empirically the functions for point and parallel line explosive sources buried in a homogeneous soil. In 1979, a follow-on project was funded by PRC for SwRI to refine the empirical equations and to expand their application to other explosive geometries and field situations. 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. The final form of the empirical pipe response equations developed by Esparza, Westine and Wenzel (5) for estimating maximum pipe stresses from point and parallel line explosive sources, respectively, detonated in soil were:

$$\frac{\sigma_c}{E} = \frac{\sigma_l}{E} = 4.44\left(\frac{nW}{\sqrt{Eh}\,R^{2.5}}\right)^{0.77} \quad \text{..............................} \quad (1)$$

$$\frac{\sigma_c}{E} = \frac{\sigma_l}{E} = 4.44\left(\frac{1.4\,n\,\dfrac{W}{L}}{\sqrt{Eh}\,R^{1.5}}\right)^{0.77} \quad \text{..............................} \quad (2)$$

where σ_c = maximum blast-induced circumferential stress, in pounds per square inch; σ_l = maximum blast-induced longitudinal stress, in pounds per square inch; n = equivalent energy release constant (nondimensional); W = total charge weight of point or line charge, in pounds; E = modulus of elasticity, in pounds per square inch; h = wall thickness, in inches; R = perpendicular distance between pipe and charge, in feet; and L = total length of explosive line charge, in feet. (Note that 1 psi = 6.89 kPa, 1 lb = 0.454 kg, 1 in. = 25.4 mm, and 1 ft = 0.305 m.)

In the short literature study concerning the use of trenches to reduce blasting stresses on a pipeline, it was found that Barkan (1) in the USSR had done considerable work in evaluating the effectiveness of trenches and other barriers in reducing ground vibrations. Woods (15) in the U.S. has tested the effectiveness of some trench designs. These two references indicate that a trench of large dimensions relative to the wave length of the surface motions can reduce vertical soil displacements. Unfortunately, buried explosive detonations normally produce seismic waves of lower frequency content than the vibrating sources reported by Barkan (1) and Woods (15). Thus, these vibratory source data indicate that very deep trenches are needed to effectively shield a pipeline from low-frequency (blast-induced) vibrations. However, SwRI analysis of unpublished test data compiled from a limited number of small charge detonations conducted in 1979 indicated reductions in pipe stresses even when using shallow trenches. These explosive detonation tests were bootstrapped as part of a monitoring operation of blasting for the installation of sewer and water lines near two parallel gas pipelines. Consequently, the test conditions could not be planned to yield large variations in all the pertinent parameters. Furthermore, most of the strain data recorded were of very low amplitude (small charges, large distances), making it difficult to obtain accurate data and to ascertain whether a trench would provide similar stress reduction for stronger shocks (larger charges, smaller distances). In addition, no direct data comparisons were possible for a blasting situation with and without a trench. In all cases, the no-trench pipe stress amplitudes were estimated using Eq. 1.

An additional search through the literature yielded no other experimental data from trench experiments. Several investigators, such as Lysmer and Wass (7), Segol, Lee and Abel (12), and May and Bolt (8), used computational models to study the effects of open trenches to seismic waves. Basically, their results agreed with those obtained experimentally by Woods (15): Trench depth is the most important parameter and the effectiveness of a trench is primarily a function of the ratio between its depth and the wavelength of the propagating waves.

In general, none of the computational and experimental data found in the literature model or use an explosive as the source of the seismic waves being affected by an open trench. Furthermore, the effect of a trench in the response of a buried structure is addressed in only one case. This lack of information was the impetus for Esparza (6) to conduct a series of well-planned and well-executed experiments that would generate data on the effect of trenches on blast-induced stresses on a buried pipeline.

EXPERIMENTAL APPROACH

The objective of the research program conducted by Esparza (6) was limited to obtaining some experimental data that would provide insight into the effects of trenches on blast-induced stresses on a buried pipeline. In the experiments from which Eq. 1 was derived, model and full-scale pipes were instrumented with strain gages and buried in soil, and the blast-induced transient strains were recorded. From these strain data, the maximum circumferential and longitudinal pipe stresses were determined. In this study, a model pipe similar to the one used previously was also instrumented with strain gages to generate the data presented in this paper.

The plan followed was to first conduct a series of nine experiments without a trench to tie-in to the previous pipe response and soil motion data, and to check the complete measurement system. In this series of tests, three different explosive charge sizes were to be detonated at three different distances from the model pipe to generate the test matrix of nine experiments listed in Table 1. The explosive charge sizes and locations were originally selected so that the stresses without a trench would cover the whole range of Eq. 1 in five discrete steps. For each charge size, two of the charge locations were selected so that their maximum blasting stresses predicted would be of about the same amplitude as two other values estimated for the next charge size.

The test matrix in Table 1 was followed explicitly. However, one test was added later in the program because it was found in the first trench tests that used the 6-ft (1.8-m) location of the 2-lb (0.907-kg) charge that the trench (even when shored) was completely destroyed, so that no reduction in pipe stress could be expected. Therefore, the charge location was changed to 18 ft (5.5 m), for which a stress of 2,770 psi (19,100 kPa) was predicted with Eq. 1. This new estimated stress was about the same as that predicted for two other charge sizes and locations, as shown in Table 1.

The nine blasting configurations used in the no-trench tests were then implemented using four different trench geometries to determine the effect of each trench on the maximum pipe stresses. Frequency analyses of the data were beyond the scope of this project and were not made. The trenches were all the same width and located the same distance from the model pipe, but of two different lengths and two different depths. Except for the one change on the large charge tests when the trench was destroyed, the trench tests followed the test sequence of the no-trench tests listed in Table 1. The effect of each trench on the free field soil motions was not part of the objective, only on the pipe response. Therefore, no soil motions were measured on the trench tests.

The data generated in these tests were analyzed and evaluated to de-

TABLE 1.—Planned Matrix for No-Trench Tests

Charge weight (lb) (1)	Charge distance (ft) (2)	Estimated pipe stress[a] (psi) (3)
0.08	7.0	1,430
0.08	5.0	2,730
0.40	9.5	2,740
0.08	3.5	5,430
0.40	6.5	5,700
2.00	12.5	5,590
0.40	4.5	11,560
2.00	8.5	11,740
2.00	6.0	22,950

[a] The estimate of the standard error for the pipe stresses is ±34%.

Note: 1 lb = 0.454 kg, 1 ft = 0.305 m, 1 psi = 6.89 kPa.

termine what effects the different trenches had on the maximum blasting pipe stresses. A similitude analysis was conducted and the data were plotted using the resulting nondimensional groups to determine whether it was possible to develop a simple empirical solution that could be applied to any blasting situation in which a trench would be used to reduce pipe stress amplitudes. The description of the tests conducted, and the results of the experiments and the data analysis are presented and discussed in subsequent sections.

DESCRIPTION OF MODEL EXPERIMENTS

A total of 47 experiments were accomplished in this program; 10 were conducted with no trench and 37 were conducted using the four trenches defined in Table 2. In all but two tests, the trench longitudinal centerline was 2 ft (0.61 m) from the pipe longitudinal center. All the tests were conducted in the spring of 1983 at the SwRI explosives range on the same test site used to perform the model experiments used to develop Eq. 1. The site consists of a relatively homogeneous field of sandy loam. Core samples taken in a previous project revealed that the soil in the test area down to 6 ft (1.8 m) in depth was quite uniform. The average soil density measured from the survey cores was 102 lb/ft^3 (1.64 g/cm^3). The soil was classified as SM-ML, and its moisture content during the tests was about 10%. The average *P*-wave velocity near the surface was 775 ft/sec (236 m/s).

The model pipe was made from three lengths of drawn-over-mandrel, SAE-1026, carbon steel round tubing with a specified minimum yield strength of 68,000 psi (469 MPa). These lengths of ASTM-A-513-80, Type 5 tubing were butt-welded together to form a length of 53.5 ft (16.3 m), which included a continuous section 20 ft (6.1 m) long in the center. The 6-in. (152-mm) outside diameter by 0.125-in. (3.18-mm) wall thickness model pipe was instrumented with five sets of orthogonal strain gages at two longitudinal locations on the pipe. Two longitudinal locations were used to insure that the maximum strains were recorded. Fig. 1 shows the test layout for the trench experiments.

Two-element, 90° strain gage rosettes (Micro-Measurements Type CEA-06-125UT-350) were bonded to the model pipe with a room temperature cure epoxy (Micro-Measurements M-BOND 10) after proper surface preparation. The orthogonal strain elements of the rosettes were oriented in the circumferential and longitudinal directions of the model pipe.

TABLE 2.—Description of Trenches Tested

Trench number (1)	Width (ft) (2)	Length (ft) (3)	Depth (ft) (4)
1	0.5	6	2
2	0.5	12	2
3	0.5	6	4
4	0.5	12	4

Note: 1 ft = 0.305 m.

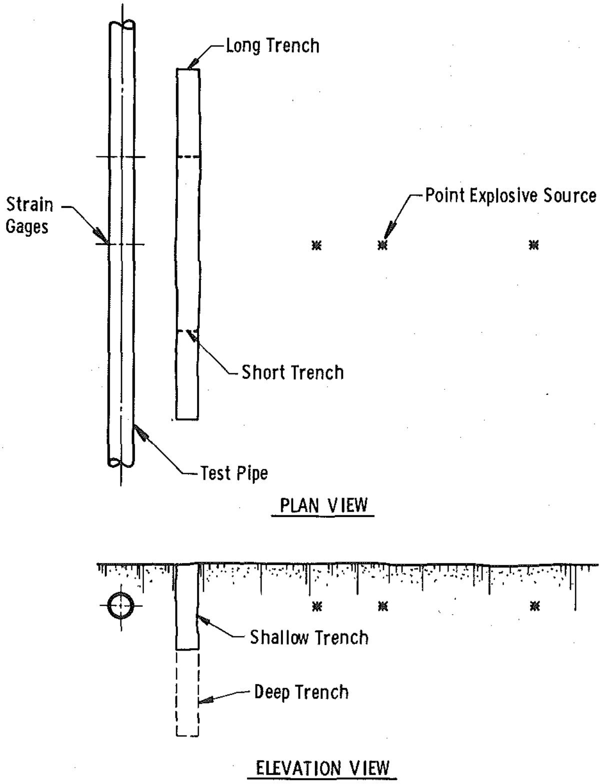

FIG. 1.—Test Layout for Point Source Experiments with Trenches

Each strain element was connected using a three-wire system as a one active arm of a constant-voltage-powered Wheatstone bridge. The strain elements sensing circumferentially were numbered 1 through 5, while those sensing longitudinally were numbered 6 through 10. Strain elements 1 and 6 were on the front of the pipe (side closest to the explosive charge), 2 and 7 were on the top, and 3 and 8 were on the back. Locations 4 and 9 were labeled "front-top" (up 45° from the front locations) while locations 5 and 10 were labeled "back-top" (up 45° from the back locations). In all strain data traces presented, a positive strain amplitude is a tensile strain, while a negative strain amplitude is a compressive strain.

To tie into the data of the previous experiments and insure that the test site responded similarly to the blasting, radial soil velocity measurements were also made in the 10 no-trench experiments only. For these soil motion measurements, Bell & Howell Type 4-155 piezoelectric velocity transducers were used. This transducer is a small, rugged vibration transducer with a high natural frequency. The velocity range for this sensor is 0.2–100 in./sec (5–2,540 mm/s), with a frequency bandwidth of 1–2,000 Hz. The output signals from the strain channels and the velocity transducers were recorded on magnetic tape.

Both trench and no-trench experiments were set up in a similar fashion, as shown in the sketches in Fig. 1. The model pipe was first instrumented and then buried at the test site. The depth of the model pipe was two pipe diam., 12 in. (0.3 m) from the surface of the ground to the longitudinal centerline of the pipe. The soil was backfilled carefully, particularly in the vicinity of the strain gage installations, and tamped to approximately the "in-situ" density. The model pipe was in the ground about one month prior to the beginning of testing.

Each trench was excavated with a trenching machine after backfilling the previous trench. To minimize trench damage from each series of tests, the trench walls were shored up with two pieces of plywood braced at the four corners. In all but two tests, the trench was located so that its longitudinal centerline was 2 ft from the centerline of the model pipe.

A typical experiment was conducted by first machine-excavating the required trench (or reconditioning a trench from the preceding test). The hole for the explosive spherical charge made from C-4, a plastic explosive, was then located along a perpendicular line bisecting the longitudinal centerline of the model pipe. Using a post hole digger, the hole for the explosive charge was made deep enough so that the center of the spherical charge was buried a distance of 1 ft (0.3 m), the same depth as the center of the model pipe. The hole with the charge was then carefully backfilled and the soil was hand tamped. To provide maximum confinement, a steel plate was placed on the ground centered on the charge and then covered with sandbags, as in the previous experiments performed for the A.G.A. Explosive bridgewire (EBW) detonators were used to detonate the high-explosive charges.

While preparations were being completed at the test site, the tape recorder and instrumentation were set to record the strain signals. After the charge was ready for testing, the tape recorder was started and a calibration signal recorded on cue from a prerecorded countdown sequence. The charge was then detonated using a Reynolds Model FS-10 Portable Firing System to fire the RP-83 EBW. This system also provided a fiducial or time-zero signal for recording on tape for subsequent use in the data digitizing process.

EXPERIMENTAL RESULTS

This section presents the data obtained in the 47 experiments. For the no-trench experiments, the maximum circumferential and longitudinal strains measured will be listed with their corresponding biaxial stresses, and compared with the predicted stresses computed from Eq. 1. In addition, the soil motion data from the no-trench tests will be compared to previous results. For the trench tests, similar listings of measured strains and corresponding stresses will be presented. In addition, examples of the no-trench and trench time histories of measured strains are provided.

Testing was begun with the no-trench experiments. As indicated in Table 1, three different charge weights buried at three different distances from the pipe comprised the nine planned experiments without a trench. Another test was added later. The description of these 10 no-trench ex-

TABLE 3.—Maximum Measured Strains with No Trench

Test number (1)	Charge weight (lb) (2)	Charge distance (ft) (3)	Circumferential strain (μ in./in.) (4)	Longitudinal strain (μ in./in.) (5)
1	0.08	3.5	119	125
2	0.08	5.0	77	77
3	0.08	7.0	38	37
4	0.40	9.5	65	73
5	0.40	6.5	97	126
6	0.40	4.5	315	340
7	2.00	12.5	137	156
8	2.00	3.5	249	337
9	2.00	6.0	478	571
43	2.00	18.0	62	102

Note: 1 lb = 0.454 kg, 1 ft = 0.305 m, 1 μ in./in. = 1 μ m/m.

periments, and the maximum measured strains and corresponding stresses are summarized in Table 3. For each test, this table lists the charge weight (*W*), the perpendicular distance (*R*) between the charge and the pipe, and the maximum peak strains measured in the circumferential (ϵ_c) and longitudinal (ϵ_l) directions.

Observation of the circumferential and longitudinal stresses (σ_c and σ_l) computed from the measured strains listed in Table 3, and their comparisons with the pretest predicted values (σ_p) showed that the new data tie in very well with the previous data. The graphical comparison provided in Fig. 2 of the new stress data to Eq. 1 emphasizes the excellent agreement. In this figure the five discrete stress steps selected to cover

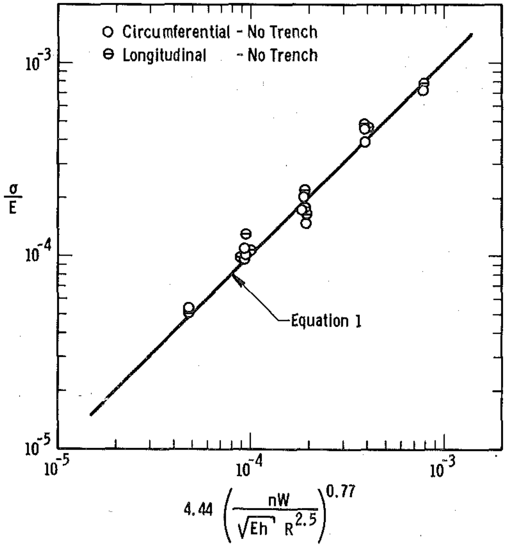

FIG. 2.—Comparison of New Stress Data to Predictive Equation

the range of Eq. 1 can be seen for each set of experimental data.

In addition to strain measurements, ground motion data were recorded only in the no-trench experiments. These data were also obtained to tie in with the previous work and to show that a valid comparison was possible. The radial horizontal soil velocity was measured at three locations, one of which was approximately the same distance from the explosive charge as the model pipe. Each velocity-time trace was integrated in the data processing so that both peak radial soil velocity and displacement could be compared to the previous results.

Esparza, Westine and Wenzel (5) fitted nondimensional log-linear equations to a large number of explosive point source, soil motion data that extended over four orders of magnitude of the nondimensional energy term. These empirical equations for predicting radial soil motions produced by an underground explosion are:

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

$$\frac{X}{R}\left(\frac{p_o}{\rho c^2}\right)^{0.5} = 0.0373\left(\frac{W_e}{\rho c^2 R^3}\right)^{1.060} \quad \ldots\ldots\ldots\ldots \quad (4)$$

in which U = peak radial ground particle velocity; X = peak radial ground displacement; R = standoff distance; W_e = explosive energy release; ρ = mass density of the soil; c = seismic P-wave velocity in the soil; and p_o = atmospheric pressure. Each parameter group in Eqs. 3 and 4 is dimensionless and, therefore, any consistent set of units can be used in applying these equations to a particular problem. The new soil motion data were nondimensionalized and are compared to Eqs. 3 and 4 in the graph shown in Fig. 3. For both soil velocities and displacements, the new data compare very well with the equations.

The trench experiments were originally planned to be conducted in groups of nine tests similar to the no-trench experiments. However, minor changes to the test plan for each trench resulted in slightly different numbers of tests for each condition. The results of the trench experiments are summarized in Tables 4–7, with the charge size and location. These tables list the actual maximum strains measured on the pipe in the circumferential (ϵ_c) and longitudinal (ϵ_l) direction, regardless of gage location or amplitude sign.

The maximum peak circumferential strain (ϵ_c) for each of the no-trench experiments was usually found to be the one sensed by the back strain gage. However, the variations among the peak strains at the front, top and back locations were normally small. On the other hand, with a trench between the pipe and the charge, the maximum circumferential strain occurred mostly at the back location, but also at the front, top, and top-back locations.

The maximum peak longitudinal strain (ϵ_l) for each of the no-trench experiments usually occurred at the back-top location, and, in a few cases, at the back location. In either case the peak amplitudes for these two locations were almost identical. With a trench between the pipe and the charge, the maximum longitudinal strain was obtained mostly at the back

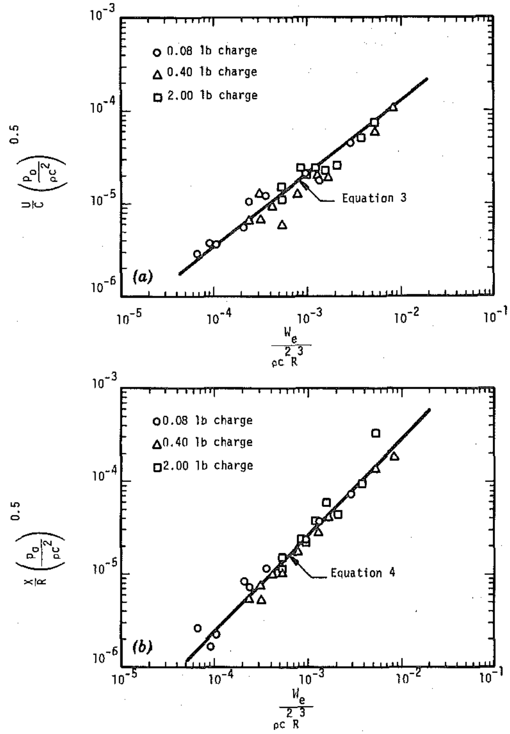

FIG. 3.—Comparison of Soil Motion Data to Predictive Equation: (*a*) Eq. 3; (*b*) Eq. 4

location. In some tests, the maximum ϵ_l was also found at the front, back-top and top locations on the pipe.

Fig. 4 compares strain-time histories for similar experiments in which data were recorded without a trench and one of the four trench geome-

TABLE 4.—Maximum Measured Strains for Trench No. 1 Tests

Test number (1)	Charge weight (lb) (2)	Charge distance (ft) (3)	Circumferential strain (μ in./in.) (4)	Longitudinal strain (μ in./in.) (5)
10	0.08	3.5	13	27
11	0.08	5.0	29	53
12	0.08	7.0	15	32
13	0.40	9.5	26	65
14	0.40	6.5	60	123
15	0.40	4.5	45	99
16	2.00	12.5	100	182
17	2.00	8.50	235	299
18	2.00	6.0	536	644
44	2.00	18.0	20	80

Note: 1 lb = 0.454 kg, 1 ft = 0.305 m, 1 μ in./in. = 1 μ m/m.

TABLE 5.—Maximum Measured Strains for Trench No. 2 Tests

Test number (1)	Charge weight (lb) (2)	Charge distance (ft) (3)	Circumferential strain (μ in./in.) (4)	Longitudinal strain (μ in./in.) (5)
19	0.08	3.5	38	68
20	0.08	5.0	38	62
21	0.08	7.0	17	31
22	0.40	9.5	53	99
23	0.40	6.5	98	176
24	0.40	4.5	150	226
25	2.00	12.5	100	180
26	2.00	8.5	409	500

Note: 1 lb = 0.454 kg, 1 ft = 0.305 m, 1 μ in./in. = 1 μ m/m.

TABLE 6.—Maximum Measured Strains for Trench No. 3 Tests

Test number (1)	Charge weight (lb) (2)	Charge distance (ft) (3)	Circumferential strain (μ in./in.) (4)	Longitudinal strain (μ in./in.) (5)
27	0.08	3.5	22	23
28	0.08	5.0	20	38
29	0.08	7.0	14	27
30	0.40	9.5	29	76
31	0.40	6.5	55	117
32	0.40	4.5	162	216
33	2.00	12.5	60	157
34	2.00	8.5	144	254
45	2.00	18.0	22	79
46[a]	0.40	9.5	31	79
47[a]	0.40	6.5	41	84

[a] Spacing between pipe and trench was 4 ft instead of 2 ft.
Note: 1 lb = 0.454 kg, 1 ft = 0.305 m, 1 μ in./in. = 1 μ m/m.

TABLE 7.—Maximum Measured Strains for Trench No. 4 Tests

Test number (1)	Charge weight (lb) (2)	Charge distance (ft) (3)	Circumferential strain (μ in./in.) (4)	Longitudinal strain (μ in./in.) (5)
35	0.08	3.5	32	51
36	0.08	5.0	14	38
37	0.08	7.0	9	24
38	0.40	9.5	22	61
39	0.40	6.5	45	95
40	0.40	4.5	117	156
41	2.00	12.5	97	148
42	2.00	8.5	96	200

Note: 1 lb = 0.454 kg, 1 ft = 0.305 m, 1 μ in./in. = 1 μ m/m.

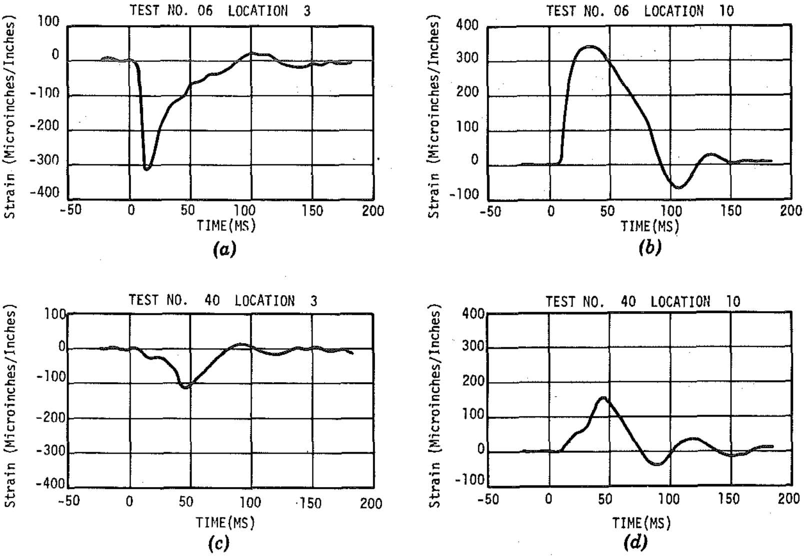

FIG. 4.—Comparison of No-Trench and Trench Tests Strain Data: (*a*) Circumferential Strain, No Trench; (*b*) Longitudinal Strain, No Trench; (*c*) Circumferential Strain, Trench No. 4; (*d*) Longitudinal Strain, Trench No. 4 (1 μ in./in. = 1 μ m/m)

tries. In this example a 0.4-lb (0.18-kg) charge was located 4.5 ft (1.37 m) from the model pipe, and the traces shown are from the strain gages that experienced the maximum circumferential and longitudinal strains in each test. All the traces were plotted using similar scales so that the effect of the trench is readily apparent. Fig. 4 shows that trench 4 is quite effective in reducing the blast-induced strain amplitudes. For trench 4, the corresponding maximum stresses show reduction factors of 2.5 and 2.3 in the circumferential and longitudinal stresses, respectively.

For each test, the corresponding biaxial pipe stresses (σ_c and σ_l) were computed using the following equations:

$$\sigma_c = \frac{E}{1 - \nu^2} (\epsilon_c + \nu \, \epsilon_l) \qquad (5)$$

$$\sigma_l = \frac{E}{1 - \nu^2} (\epsilon_l + \nu \, \epsilon_c) \qquad (6)$$

where σ_c = circumferential pipe stress; σ_l = longitudinal pipe stress; ϵ_c = circumferential pipe strain; ϵ_l = longitudinal pipe strain; E = pipe modulus of elasticity; and ν = Poisson's ratio. These stresses were computed as in the previous work by combining the maximum peak strains measured along each orthogonal direction regardless of location, and assuming both strains to be of the same sign and occurring at the same time. In this way the trench stresses could be compared to the no-trench stresses obtained in this program, as well as the predictive Eq. 1 derived from the previous results.

A comparison of how each trench affected the maximum pipe stresses is seen in Fig. 5 for the circumferential stresses, and in Fig. 6 for the longitudinal stresses. In these two figures the measured stresses for the trench tests are divided by the predicted stresses (σ_p) from Eq. 1 for similar test conditions to determine the effect of the trench. The data points are grouped by trench geometry. Observation of Figs. 5 and 6 indicates that trench 4 was generally the most effective and trench 2 the least effective for the test conditions used in these experiments. However, depending on charge size and location, the reduction factors can vary widely even for the same trench. In some instances the stresses from the trench tests exceeded those from the corresponding no-trench tests. In Fig. 5, the ratios of the circumferential stresses for trench 1 ranged from 0.13–0.9, for trench 2 from 0.35–1.54, for trench 3 from 0.17–0.64, and for trench 4 from 0.28–0.82. In Fig. 6, the ratios of the longitudinal stresses for trench 1 ranged from 0.18–1.23, for trench 2 from 0.47–1.72, for trench 3 from 0.52–1, and for trench 4 from 0.36–1.

A comparison of Figs. 5 and 6 shows that the trenches were more effective in reducing the circumferential stresses than the longitudinal stresses. In only one test did the circumferential stress with the trench exceed the no-trench value. However, in five tests involving mainly trench 2, the longitudinal stresses with a trench exceed the no-trench stresses.

In general, the trenches were most effective when the explosive charge was located at distances closer to the trench. Both depth and length of the trench affected the variations in stress reductions. For the shallower trenches (1 and 2), the shorter trench 1 was more effective in reducing stresses. For the deeper trenches (3 and 4) the opposite effect was observed: The longer trench 4 was generally more effective. For trenches of the same length (1 and 3, and 2 and 4), the deeper trenches were usually more effective. The long and deep trench 4 was the most effective, while the long and shallow one (trench 2) was the least effective. The other two trenches were in between in their stress reduction capability.

In an effort to derive a simple empirical solution that would be used to predict the effect on blasting stresses for a given geometry, further analyses of the data were performed using nondimensional parameters obtained using similitude methods. To estimate blast-induced stresses on a buried pipeline from an explosive point source using Eq. 1 required definition of four parameters: W, E, h and R. To develop a functional relationship between the stress on the pipe when a trench is present (σ_t) and the stress when no trench is present (σ) requires additional parameters to define the trench and its relationship to the pipe and the explosive source. For the case in which the stresses on a pipe at a given site with and without a trench are of interest, the pipe and soil parameters can be considered invariant. Using similitude theory, a functional relationship for the stress ratio then becomes

$$\frac{\sigma_t}{\sigma} = f\left(\frac{D_t}{R}, \frac{L_t}{R}, \frac{Y}{R}, \frac{Z}{R}, \frac{W_c}{\sigma R^3}\right) \quad \text{(7)}$$

where σ_t = maximum pipe stress using a trench; σ = maximum pipe stress without a trench; R = distance between explosive and pipe; D_t =

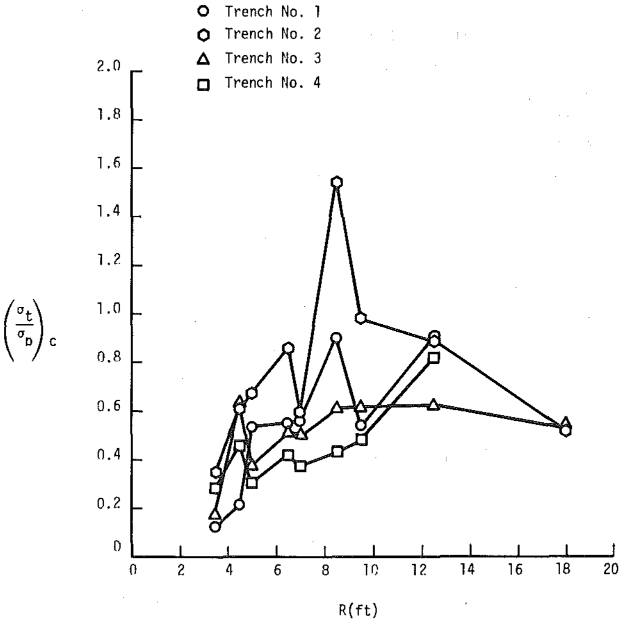

FIG. 5.—Effect of Trenches on Circumferential Pipe Stresses (1 ft = 0.305 m)

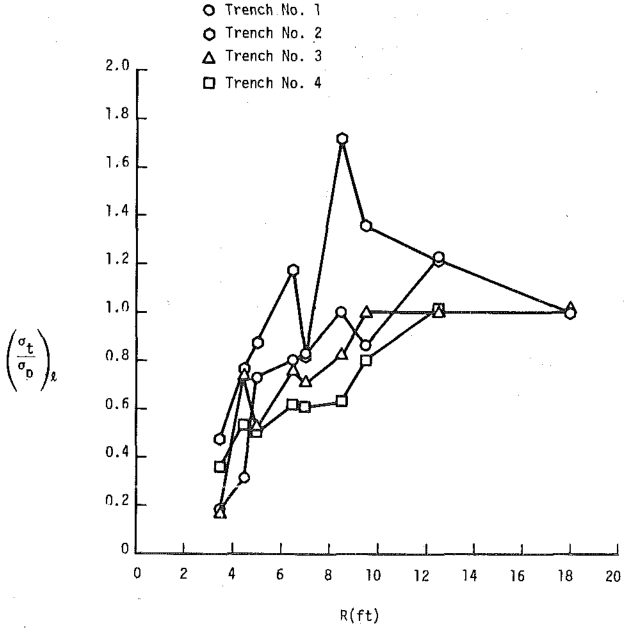

FIG. 6.—Effect of Trenches on Longitudinal Pipe Stresses (1 ft = 0.305 m)

depth of trench; L_t = length of trench; Y = distance between the pipe and the trench; Z = depth of the pipeline; and W_c = explosive charge energy. Any self-consistent set of units makes each of the six terms dimensionless.

Even though the parameter space is reduced from eight dimensional parameters to six nondimensional ratios (or pi-terms) using similitude analysis, the space is still too large for developing an empirical solution unless the dependent variable is a weak function of some of the dimensionless terms. Plots of σ_t/σ versus each of the other five pi-terms in Eq. 7 were made to determine if a significant trend would be apparent that would show the stress ratio more dependent on one pi-term than the others. No simple relationship was found that would predict the stress reduction for a given trench and blasting situation. This indicates that considerably more work, both experimental and analytical, is required to better understand and predict the effect of trenches on blast-induced pipeline stresses. However, the present data do have a limited application for predicting the effects of a trench. Since the experiments can be considered replica models of actual blasting situations, the results can be used to predict the effects of a trench which is geometrically similar to one of those used in the model experiments, provided the charge size and location scale up approximately the same by the corresponding scale factor.

For example, a 24-in. (610-mm) diam line pipe with a 0.5-in. (12.7-mm) wall thickness is geometrically four times the size of the model pipe. If a blasting situation near this pipe is geometrically similar to one listed in Tables 4–7, the effect of the trench can be estimated. For instance, a model charge of 0.4 lb (0.18 kg) is similar to that of 25.6 lb (11.6 kg) in this example. At a charge distance of 38 ft (11.6 m) from the 24-in. (610-mm) pipe, the stresses would be about the same as on the 6-in. (152-mm) model pipe with a charge distance of 9.5 ft (2.9 m). If the trench used is geometrically similar to trench 1 [2 ft (0.6 m) wide, 24 ft (7.3 m) long and 8 ft (2.4 m) deep], then from Figs. 5 and 6 the circumferential stress ratio would be about 0.5 and the longitudinal stress ratio would be about 0.8. From Table 1, the estimated stresses without a trench are both 2,740 psi. Using this trench, the circumferential stress would be reduced to about 1,370 psi, and the longitudinal stress to about 2,190 psi.

In addition to the tests summarized in Tables 4–7, two other tests were conducted using trench 3. In these experiments, the distance between the trench and the model pipe was 4 ft (1.22 m), instead of 2 ft (0.61

TABLE 8.—Comparison of Stress Data for Trench No. 3

		Trench No. 3, 4-ft Distance		Trench No. 3, 2-ft Distance	
W (lb) (1)	R (ft) (2)	σ_c (psi) (3)	σ_l (psi) (4)	σ_c (psi) (5)	σ_l (psi) (6)
0.4	9.5	1,770	2,860	1,680	2,750
0.4	6.5	2,150	3,120	2,920	4,330

Note: 1 lb = 0.454 kg, 1 ft = 0.305 m, 1 psi = 6.89 kPa.

m). Both of these tests used 0.4-lb (0.18-kg) charges, one located 9.5 ft (2.9 m) and the second 6.5 ft (2 m) from the pipe. The results are shown in Table 8. Comparing stresses from the 4-ft (1.22-m) spacing tests with those using 2-ft (0.61-m) spacing between the trench and the model show that for a standoff distance *R* of 9.5 ft (2.9 m), the results are almost identical (see Table 8). However, for an *R* equal to 6.5 ft (2.0 m), the stresses are reduced more with a 4-ft (1.22-m) spacing. Note that in this layout the trench was actually closer to the charge than to the model pipe.

OBSERVATIONS AND CONCLUSIONS

The measured strains and ground motions from the no-trench experiments showed that the new data compared very well with values obtained using the predictive equations developed on a previous program. This indicated that the pipe was responding as expected, the measurement system was performing well, and the pipe stress prediction equation derived previously could be applied with confidence. The maximum circumferential strains measured usually occurred at the strain gage located at the back side of the pipe, the side opposite the charge. However, in most tests the peak strains at the front, top and back locations were almost the same amplitude. The maximum longitudinal strains in the no-trench tests usually occurred at the strain gage located between the top and back of the pipe and, in a few cases, at the back strain gage. In either case the peak strain amplitudes for these two strain gage locations were almost identical, as was the case in previous experiments.

For the four sets of trench experiments, the maximum circumferential strains occurred mostly at the back strain gage location, but also at the gages located at the front, top, and between the back and the top of the pipe. The maximum longitudinal strains occurred primarily at the back strain gage location, but also at the gages located at the front, top, and between the back and the top of the pipe. Thus, depending on the trench, the maximum strains were not necessarily measured at the same location on the pipe as the no-trench maximum values. Also, the general shape of the strain traces were affected by the trenches.

The measured maximum strains were used to compute the circumferential and longitudinal stresses for each test. Stresses from the 37 trench experiments were compared to those from the no-trench tests, as well as to the stresses predicted from the previous no-trench stress equation. In all but one test, the effect of the trench was to reduce the circumferential stresses by as much as 87% of the value without a trench. In one test the circumferential stress was enhanced by about 50% of the no-trench stress. The longitudinal stresses were reduced by the trenches as much as 82%. However, on five of the 37 trench tests, the maximum longitudinal stress was increased by as much as 72%. Thus, in most tests, the four trenches were effective in reducing the blasting stresses significantly. However, enhancement of the stresses did occur, mostly with the long and shallow trenches.

In all trench tests, the maximum longitudinal stresses were always greater than their circumferential counterpart. Since the no-trench stresses are essentially the same in both orthogonal directions, the trenches were more effective in reducing the circumferential stresses than the longitudinal stresses.

Both depth and length of the trench affected the stress amplitude variations. For the shallower trenches, the shorter trench was more effective in reducing the stresses. For the deeper trench the opposite effect was observed; the longer trench was generally more effective. For trenches of the same length, the deeper trenches were usually more effective. The long and deep trench was the most effective, while the long and shallow was the least effective. The other two were in between.

In two of the trench experiments, the distance between the pipe and the trench was double that of two other similar tests. In one case, the stresses were essentially the same, regardless of the distance between the pipe and the trench. In the second case, the stresses were reduced more with the longer distance between the pipe and the trench.

Additional analysis of the test data using nondimensional parameters obtained using similitude methods did not yield an empirical solution that would predict the effect of a given trench on blasting pipeline stresses. Even though the parameter space was reduced by using similitude analysis, the number of significant parameters is still too large for developing an empirical solution. This shows that further experimental and analytical investigations are required to better understand and predict the effect of trenches on blast-induced pipeline stresses. However, for blasting situations similar to those presented in this report, a scale factor can be determined and used to estimate the stress reduction for trenches which are replica models of those used in this program. An alternative for a blasting condition which is not similar to those presented here would be to conduct model experiments of that particular blasting configuration to determine trench effectiveness.

The data presented appear to be the first set of blast-induced pipe response measurements for which direct comparisons can be made between trench and no-trench situations. These results definitely show that open trenches can be effective in reducing pipeline stresses from nearby underground blasting. However, because of the complexity of the problem, no simple empirical solution or method for predicting the effect of trenches on blasting pipeline stresses is presently possible.

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