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PIPELINE RESPONSE TO BURIED EXPLOSIVE DETONATIONS

VOLUME I - SUMMARY REPORT

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FINAL REPORT
A.G.A. Project PR-15-109
SwRI Project 02-5567

for
THE PIPELINE RESEARCH COMMITTEE
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SUMMARY

This report describes a blasting research program conducted to develop simple procedures for predicting the maximum stresses in steel pipeline induced by nearby, buried, explosive detonations, This extensive experimental and analytical study was funded by the Pipeline research Committee of the American Gas Association and performed by Southwest Research Institute from 1975 to 1981.

In this program, the general problem of a buried explosive detonating near a pipeline was divided into two parts. In the-first part, similitude theory;, empirical analyses and test data were used to derive equations for estimating maximum ground displacement and particle velocity. The ground motions., provided the forcing function imparted to a buried pipeline. In the second part, similitude theory, conservation of mass and momentum, and approximate energy methods were used to derive functional relationships for the maximum pipe strains and stresses. Experimental data from more than 60 tests, primarily in model scale, were then used to develop equations for estimating maximum pipe stresses induced by point and parallel line explosive sources buried in a homogeneous soil ‘media. The large amount of data used and the wide range of these data make the solutions applicable to most soil blasting situations near pipelines.

Subsequently,’ the applicability of these prediction equations was extended to estimate pipe stresses from other more complex geometries. Test data were obtained from 38 model scale experiments using angled-line, parallel grid, and angled-grid explosive sources also buried in soil. These data were then used to develop empirical methods by which complex explosive geometries could be simplified into equivalent point or parallel line sources, depending on their proximity to the pipeline. Using the simplifying methods developed, the test data from the complex geometry source compared quite well with the point and parallel linesource equations.

As part of the blasting research program, three other limited tasks were also performed. In the first, a correction factor to the point source solution was derived empirically for situations in which-a pipeline is between a relatively near free surface and the explosive source. In this case, the lack of earth behind the pipe enhances the pipe stresses because of the lack of inertial resistance. In the second limited task, a literature study was conducted to determine the effects of barriers between an explosive source and a pipeline. Strain measurements from one specific set of field tests were used to develop an equation to predict the effects of a trench on strain levels on a pipe as a function of scaled distances. Because of the limited data base, this equation should be valid only within the range of the dimensionless parameters involved. Finally, four model experiments were also conducted in a study to determine the feasibility of simulating the problem of blasting in a rock mass adjacent to a pipeline buried in soil. The pipe stress and ground motion data from these experiments were used to develop an equation for computing an effective standoff distance so that the point source soil equations could be used to approximate the pipe response.

Because no test data were obtained in rock/soil media application of the effective standoff equation is tentative at this time.

This final engineering report was, prepared in two volumes. Volume I is a summary of the prediction equations and methods developed. Definitions of parameters and symbols are included, as well application information. Volume II is a complete technical report which describes in detail the background of this research effort, the experimental program and results, the development of the ground motion and pipe stress solutions, the use of some of these equations and methods in example problems, and the three smaller tasks performed. In addition, discussions are presented on assumptions and limitations of the solutions developed, the sensitivity of the point and parallel line stress equations, alternative forms for these equations, the total, state of, stress on a pipe and yield theories factors of safety, and other procedures which are in some blasting codes, and have been used to limit blasting near pipelines.

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Mr. H. R. Wortman, Chairman, 1975-1976, Consumers Power Company
Mr. O. Lucas, Chairman, 1976-1978, Columbia Gas Transmission Corporation
Mr. J. S. Taylor, Chairman, 1978- 1981, Consumers Power Company

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

I. INTRODUCTION

This summary report is Volume I of the final engineering. report which describes an extensive research program conducted to develop procedures for predicting the stresses in buried pipelines caused by nearby buried detonations. The research effort was perform&l during the period 1975 through 1980 by by Southwest Research Institute (SwRI) for the Pipeline Research Committee (PRCI) of the American Gas Association (A.G.A.).

Prior to 1975, no valid criteria existed for determining the charge-distance limits in blasting situations near buried pipelines. In many instances, ground motion limitations applicable for above ground structures have been and are still applied to underground gas pipelines. In other cases, the Battelle, equations, published in 1964, have been used to estimate pipe stresses. These equations, developed without the benefit of experimental pipe response data, were recommended for use only for explosive-to-pipe distances greater than 100 feet.

Because of the limitations on surface ground motion criteria and the Battelle equations, better prediction methods were needed to handle blastings at close distances, within 100 feet, to pipelines. In 1975, the PRCI initiated a research program with SwRI for the purpose of developing procedures for predicting pipeline stresses induced by nearby buried explosive detonations, particularly those within 100 feet. The Blasting Research Supervisory Committee was formed by the PRCI to guide and monitor this research program.

Two consecutive projects were funded by the PRCI. In the first project begun in 1975, Project No. PR-15-76, SwRI reviewed the literature and developed functional relationships using similitude theory for the forcing function and pipe response. Then, 43 model and full-scale tests were conducted to obtain the data necessary to develop the stress solutions for point and parallel line explosive sources buried in a homogeneous soil. A complete engineering report was prepared and published. That report is replaced by this one and should no longer be used. In 1978, a seminar on blasting effects was presented to acquaint the gas pipeline industry with the background, development, use, and limitations of the newly developed pipe stress equations. Later, a videotape report which summarized the first research project was made available to the sponsors.

In 1979, a follow-on project, Project No. PR-15-109, was initiated, to expand the application of the solutions to other explosive geometries and field situations. Five different blasting conditions were investigated experimentally and analytically. Seventy model scale tests were conducted to obtain data from point explosive sources buried deeper than the pipe, line sources oriented at various angles to the pipe, 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 effects of barriers between an explosive source and a pipeline. As a result of this extensive research project, improved prediction equations were derived for estimating pipe stresses from point and parallel line explosive sources detonated in soil. Not only are these new equations more accurate than those developed in the earlier project, but they are also considerably simpler to use. In addition, methods were developed for simplifying the more complex explosive geometries into equivalent parallel line or point sources.

The purpose of Volume I is to provide the user with a summary of the prediction equations and methods he or she can refer to quickly, to look up a particular estimating procedure and corresponding definitions. However, before applying any procedure, the user must first be familiar with the contents of Volume II and understand the assumptions, approximations, and limitations applicable to the various equations and methods. Volume I is organized into six sections and two appendices. In Section II, the equations for estimating radial ground motions and pipe stresses induced by point explosive sources buried in soil are presented. In Section III a similar set of equations for parallel line sources is presented. In Section IV, simplifying methods are summarized for handling angled-line, parallel grid and angled-grid sources. Section V includes the results of three very limited studies concerning the case of a pipeline relatively near a free surface, use of trenches to reduce pipe stresses, and the feasibility of using concrete/soil model tests to obtain two-media data. In Section VI, some general comments are made regarding the total state of stress on the pipe and the use of yield theories. Finally, in the appendices, some additional information is included to assist the reader in applying the prediction equations and methods, The appendices also contain some simple example problems and a consolidated list of the parameters used in this volume.

II. PREDICTION EQUATIONS FOR POINT EXPLOSIVE SOURCE

Radial Ground Motions

From an extensive collection of data from the literature and this research program, new empirical relationships were developed for predicting peak radial ground displacement and particle velocity when buried explosive charges are detonated in a homogeneous ground media such as soil or rock. These relationships define the forcing function applied to a buried pipe from blasting and are as follows:

$$\frac{X}{R}\left(\frac{p_o}{\rho c^2}\right)^{0.5} = \frac{0.0414\left(\frac{W_e}{\rho c^2 R^3}\right)^{1.11}}{\tanh^{1.5}\left[18.2\left(\frac{W_e}{\rho c^2 R^3}\right)^{0.237}\right]} \qquad (1)$$

$$\frac{U}{c}\left(\frac{p_o}{\rho c^2}\right)^{0.5} = \frac{0.00617\left(\frac{W_e}{\rho c^2 R^3}\right)^{0.852}}{\tanh\left[26.0\left(\frac{W_e}{\rho c^2 R^3}\right)^{0.30}\right]} \qquad (2)$$

where
- X = peak radial ground displacement (ft)
- u = peak radial ground particle velocity (ft/sec)
- R = standoff distance (ft)
- w_e = explosive energy release (ft-lb)
- ρ = mass density of the soil or rock (lb-sec^2/ft^4)
- C = seismic P-wave velocity in the soil or rock (ft/sec)
- p_o atmospheric pressure (lb/ft2),

Note that any consistent set of units can be used in these equations and that each term in these relationships is nondimensional.

Major differences separate these empirical equations from others that predict ground motions. The new equations are not log linear; test results cover more orders of magnitude, and a coupling term $(\rho c^2/p_o)^{0.5}$ is divided into the scaled displacement and velocity. The presence of atmospheric pressure in the prediction relationships does not mean atmospheric pressure is a physical phenomenon influencing the results. The quantity pc^2 is a measure of the compressibility of the shock propagation media. Hence, the quantity p_o is a reference standard (compressibility of air) and empirically introduces relative compressibilitiesfor different media such as soil and rock. This point, as well as how these equations were derived, is elaborated on in Volume II. The test data used in fitting the curves and substantiating the validity of these equations cover almost ten orders of magnitude in scaled energy release $W_e/\rho c^2R^3$, a range of $10^{-11} < W_e/\rho c^2R^3 < 10^{-1}$.

The ground motion data obtained by SwRI in the model and full-scale experiments were for values of W_e/pc^2R^3 greater than 6.4×10^{-5}. For this range of scaled charge weights typically encountered in blasting situations near pipelines, log-linear curves were fitted to all of the SwRI point source data. The resulting radial soil displacement and particle velocity equations for point explosive sources are:

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

$$\frac{U}{c}\left(\frac{p_o}{\rho c^2}\right)^{0.5} = 0.00489\left(\frac{W_e}{\rho c^2 R^3}\right)^{0.790} \tag{4}$$

for $6 \times 10^{-5} < W_e/pc^2R^3 < 6 \times 10^{-2}$

As was the case with the general equations, each parameter group is dimensionless and, therefore, any consistent set of units can be used. These simplified point source equations, as well as the general equations, predict the radial ground motions at a point below the ground surface corresponding to the depth for the center of the pipe. In our tests, this depth was usually two pipe diameters. The equations should be applicable over reasonable range in scaled depths up to almost the ground surface. These simplified equations give essentially the same predictions for radial ground motions as the more general ones, Equations (1) and (2). Therefore, the simpler Equations (3) and (4) are recommended to estimate ground motions from point sources in soil within the applicable range. An example using Equations (3) and (4) is included in Appendix A.

Pipe Stresses

Functional relationships were developed for the maximum strain and stresses on a buried pipeline using similitude theory, relationships for conservation of mass and momentum, and approximate energy methods. Subsequently, these functions were defined empirically from the point source test data obtained in the model and full-scale experiments.

The resulting equations for predicting the maximum elastic pipe strains from a point source detonated in soil and buried to about the same depth as the pipe are:

$$\epsilon_{cir} = 4.78 \left(\frac{n\ W}{\sqrt{Eh}\ R^{2.5}} \right)^{0.805} \tag{5}$$

and

$$\epsilon_{long} = 1.98 \left(\frac{n\ W}{\sqrt{Eh}\ R^{2.5}} \right)^{0.735} \tag{6}$$

For these strain prediction equations

ϵ_{cir} = maximum circumferential strain (in./in.)
ϵ_{long} = maximum longitudinal strain (in/in.)
n = equivalent energy release(nondimensional)
W = total charge weight of point source (lb)
E = modulus of elasticity (psi)
h = pipe wall thickness (in.)
R = distance between pipe and charge (ft)

In these equations, the parameters must be entered with the units shown. The strain data used to develop, these solutions ranged from 10 to 1500 µin./in. This range should cover most blasting situations using point sources buried in soil near gas pipelines. The estimate of the standard error of the strain data about the two solution curves was 44 and 36% for the circumferential and longitudinal strains, respectively.

As these strain solutions evolved in this research program, they provided realistic estimates of strain for subsequent test series. For similar applications, Equations (5) and (6) are most useful. However, in pipeline blasting situations the estimated blast strains need to be converted to stresses so they can be combined with other stresses on the pipe to determine the total state of stress. This conversion procedure may be dictated by company policy or be decided upon by the engineer in charge.

To eliminate the step of converting strains to stresses by the user, maximum biaxial stresses were computed in this program for each test using the maximum measured strains and a biaxial conversion procedure. This conversion conservatively assumes that the maximum peak strains occur at the same point on the pipe, arc of, the same algebraic sign, and peak simultaneously. Additional details on this procedure are found in Volume II. Using the biaxial stresses and similar data analyses as used on the strain data, equations were derived for circumferential and longitudinal stresses which almost coincided with each other. Therefore, all of the stress data, regardless of orientation, were used to derive a single function. This prediction procedure makes the stresses equal in both the circumferential and longitudinal direction.

The resulting equation for predicting the maximum pipe stresses for a point explosive source detonated in soil is

$$\sigma_{cir} = \sigma_{long} = 4.44\ E \left(\frac{n\ W}{\sqrt{Eh}\ R^{2.5}} \right)^{0.77} \tag{7}$$

where
σ_{cir} = maximum circumferential stress (psi)
σ_{long} = maximum longitudinal stress (psi)
n = equivalent energy release (nondimensional)*
W = total charge weight of point or line (lb)
E = modulus of elasticity (psi)
h = wall thickness (in.)
R = distance between pipe and charge (ft)

In this equation, the parameters must be entered with the units shown. The range in line pipe stress data varied in excess of the yield down to 600 psi. This range covers most soil blasting situations near pipelines. The estimate of the standard error of the stress data was 34%. This implies that,, assuming a normal distribution, 68% of the data points were within ±34% of the prediction curve and 95% of the data points were within ± 68%. The application of Equation (7) is also limited to distances R greater than 2 pipe diameters.

To illustrate how Equation (7) can be applied to point explosive source blasting situations, some additional information and a simple example problem are included in the appendix. For details on the derivation of this. equation, additional application information, and the determination of the total state of stress on the pipe, refer to Volume II of this report.

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*n = 1 .O for ANFO

III. PREDICTION EQUATIONS FOR PARALLEL LINE EXPLOSIVE SOURCE

Radial Ground Motions

When a number of equally spaced explosive charges of the same weight are in line and detonated simultaneously, the radial ground motions generated differ from those for a point source. Using ground motion data from this project and from the literature, relationships were derived for predicting radial soil ground. motions from parallel line explosive sources. A series of point charges can be treated as a parallel line source when a transducer has a standoff distance smaller than the length of the explosive line, the charge spacing is smaller than the standoff distance and the transducer sensing axis is perpendicular to the explosive line. All of our test data meeting these requirements were used to curve fit log-linear equations for estimating soil displacement and particle velocities for parallel explosive lines. The equations for predicting ground motion near a parallel line source are:

$$\frac{X}{R}\left(\frac{p_o}{\rho c^2}\right)^{0.5} = 0.0746\left(\frac{W_e/L}{\rho c^2 R^2}\right)^{1.073} \tag{8}$$

$$\frac{U}{c}\left(\frac{p_o}{\rho c^2}\right)^{0.5} = 0.00465\left(\frac{W_e/L}{\rho c^2 R^2}\right)^{0.734} \tag{9}$$

where
X = peak radial soil displacement (ft)
u = peak radial soil particle velocity (ft/sec)
R = standoff distance (ft)
w_e = explosive energy release (ft-lb)
L = effective length of explosive line (ft) (See Appendix B)
P = mass density of soil (lb-sec^2/ft^4)
c = seismic P-wave velocity in soil (ft/sec)
P_O = atmospheric pressure (lb/ft^2)
R $\leq$ L

Any consistent set of units can be used to evaluate each nondimensional term in these equations.

The range of the test data on which these parallel line source equations are based is smaller than that of the data used to derive the general point source equations. Ideally, more data over a wider range in scaled charge weights and from several test sites (different ground media) would increase the confidence of Equations (8) and (9). These parallel line prediction relationships, are not as general as the Equations (1) and (2) for point sources.

However, in a soil environment similar to that in the SwRI model tests, Equations (8) and (9) should provide reasonable ground motion predictions for scaled charge densities within the range of

$$10^{-4} < W_e/L/\rho c^2 R^2 < 10^{-1}$$

Pipe Stresses

Functional relationships for the maximum strain and stresses on a buried pipeline were also developed empirically from model test data for parallel line sources. The resulting equations for predicting the maximum circumferential and longitudinal elastic pipe strains from a parallel line source detonated in soil and buried to about the same depth as the pipe are:

$$\epsilon_{cir} = 4.78 \left(\frac{1.3n\ W/L}{\sqrt{Eh}\ R^{1.5}} \right)^{0.805} \qquad (10)$$

and

$$\epsilon_{long} = 1.98 \left(\frac{1.3n\ W/L}{\sqrt{Eh}\ R^{1.5}} \right)^{0.735} \qquad (11)$$

where ϵ_{cir} = maximum circumferential strain (in./in.)
ϵ_{long} = maximum longitudinal strain (in./in.)
n = equivalent energy release (nondimensional)
w = total charge weight of line source (lb)
E = modulus of elasticity (psi)
h = pipe wall thickness (in.)
R = distance between pipe and explosive line (ft)
L = total length of explosive line (ft) (See Appendix B)

The range of the maximum measured strains from parallel line sources was 43 to 1,780 μin./in., making these solutions valid for most parallel line source blasting in soil near gas pipelines. The estimate of the standard error applicable to Equations (10) and (11) is 44 and 36% respectively.

The measured pipe strains for parallel line sources were used to compute conservative biaxial pipe stresses in the same manner as was done for the point source data. Because the parallel line and point source pipe response data were curve fit together, one stress equation also resulted for estimating parallel line circumferential and longitudinal stresses. The resulting circumferential and longitudinal stress equation is:

$$\sigma_{cir} = \sigma_{long} = 4.44\ E \left(\frac{1.4n\ \ W/L}{\sqrt{Eh}\ \ R^{1.5}} \right)^{0.77} \tag{12}$$

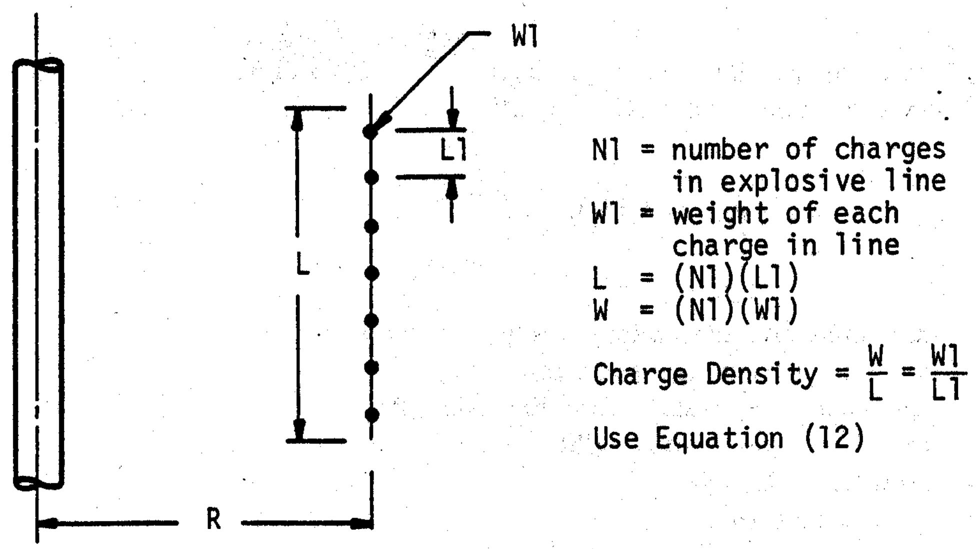
where σ_{cir} = maximum circumferential stress (psi)
σ_{long} = maximum longitudinal stress (psi)
n = equivalent energy release (nondimensional)
w = total charge weight of line (lb)
E = modulus of elasticity (psi)
h = wall thickness (in.)
R = distance between pipe and explosive line (ft)
L = total length of explosive line (ft) (See Appendix B)

The maximum blasting pipe stresses measured in this program ranged from 1828 psi up to stress values larger than the specified minimum yield stress of most pipeline steels. Therefore, use of Equation (12) should be limited to this range of stress values. The range is broad enough to be useable for most soil blasting situations using parallel line sources near gas pipelines. The estimate of the standard error for this equation is 34%.

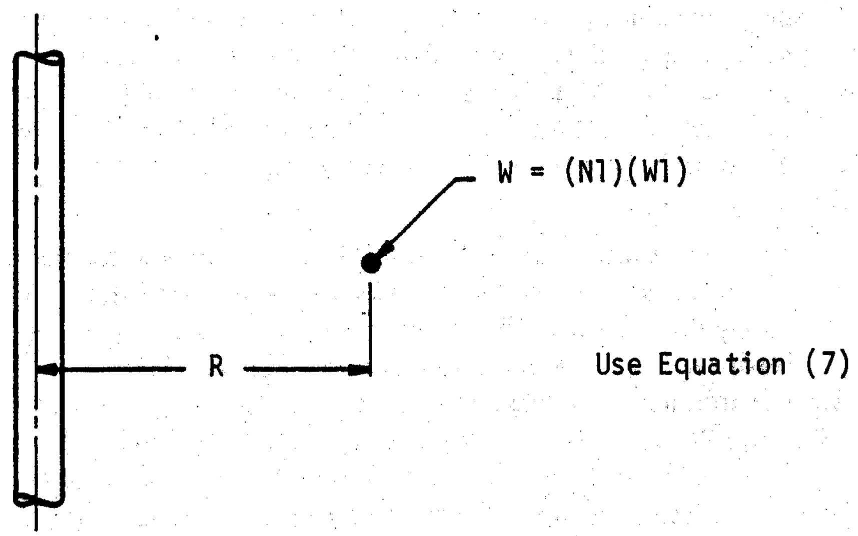
All of the parallel line sources which generated the data used in developing Equation (12) were treated as continuous explosive lines because the spacing between charges was smaller than the standoff distance, the standoff distance was smaller than the length of the explosive line, and all the charges making up the line were detonated simultaneously. If the spacing between charges is larger than the standoff distance, each charge should also be analyzed as a point source. And, if the standoff distance between the pipe and the explosive line source is greater than the length of the explosive line, the entire explosive array can be approximated by a point source.

The prediction equations for a point source and for a parallel line indicate that the transition point between a line and a point source occurs at a value of standoff distance R somewhat smaller than the explosive line length L. However, for simplicity in application of the predictive equations, a transition value of R equal to L is recommended. This value is conservative, yet accurate and easy to remember. Thus, for values of $R/L \leq 1.0$, a series of equal charges in a straight line parallel to a pipe is treated as a parallel explosive line to estimate the pipe stresses. For values of $R/L > 1.0$, the explosive line is treated as an equivalent point source. Figure 1 summarizes how to estimate pipe stresses from parallel line explosive sources.

For additional details on the derivations of the parallel line source equations, other limitations, application information, and discussions on the total state of stress on a pipeline exposed to blasting, please refer to volume II of this final report.



(a) Explosive Line Parallel to Pipeline for R ≤ L



(b) Parallel Line as Equivalent Point Source for R > L

Figure 1. Methodology for Estimating Pipe Stresses from Parallel Line Explosive Sources

IV. PREDICTION METHODS FOR COMPLEX EXPLOSIVE SOURCES

General

In addition to the point and parallel line source equations presented in the two preceding sections, methods were developed by which angled-line, parallel grid and angled-grid sources could be simplified into equivalent parallel line or point sources. Thus, the appropriate point or parallel line equation could then be applied to obtain reasonable stress estimates from these complex explosive geometries:

Angled-Line Source

In general, an angled-line source is simplified into an equivalent parallel line source if R, its equivalent standoff distance, is equal to or less than L, the effective length of the line. The equivalent value of R is defined as follows:

$$R = R_{gcl} / \cos B \qquad \text{(line)} \tag{13}$$

where

$$R_{gcl} = A + \frac{(Nl - 1)Ll \sin B}{2} \tag{14}$$

The effective explosive line length is:

$$L = (Nl)(Ll) \tag{15}$$

For these equations

- R_{gcl} = distance between the geometric center of the explosive line and a pipeline (ft)
- A = distance of nearest charge (ft)
- B = angle between pipe and explosive line

N1 = number of charges in explosive line
L1 = spacing of charges (ft)

The explosive density of the equivalent parallel line is

$$\frac{W}{L} = \frac{(Nl)Wl)}{(Nl)(Ll)} \quad \frac{Wl}{Ll} \tag{16}$$

where Wl is the explosive weight (lb) of one of the point charges making up the angled-line source. With the values of R and W/L as defined by Equations (13) and (16), the stresses are estimated using the parallel line source solution, Equation (12).

If R, as defined by Equation (13), is greater than L, the angled-line source is collapsed into an equivalent point source. The equivalent charge weight then becomes

$$W = (Nl)(Wl) \tag{17}$$

and its location becomes the geometric center of the angled-line, namely

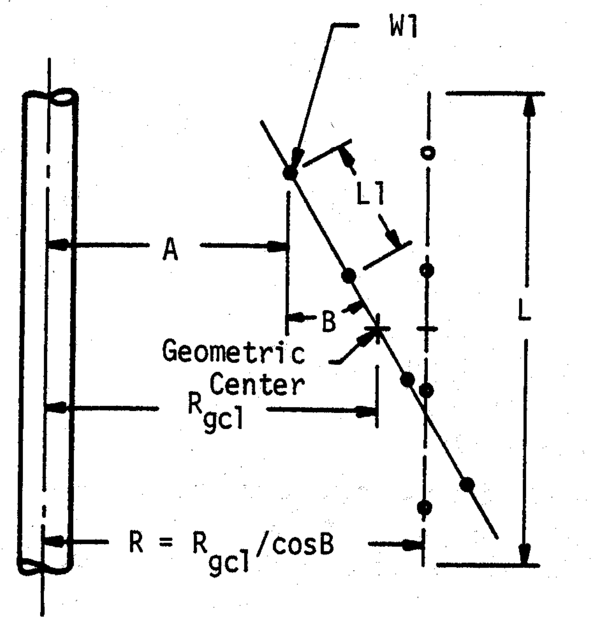
$$R = R_{gcl} \qquad \text{(point)} \tag{18}$$

With these values for W and R, the pipe stresses are estimated using the point source solution, Equation (7). Figure 2 summarizes the simplifying methods for an angled-line source.

Parallel Grid Source

An empirical method was also developed for simplifying a rectangular grid of explosives buried in soil into an equivalent parallel line or point source. Analyses of the test data indicated that the grid can be treated as a parallel line equivalent in location, length and charge density as the first explosive row making up the array. Because of this observation, the standoff distance R, length of the equivalent parallel line source L, and equivalent charge density W/L are defined for a parallel grid similar to that for a parallel line, namely:

$$R = A \qquad \text{(line)} \tag{19}$$

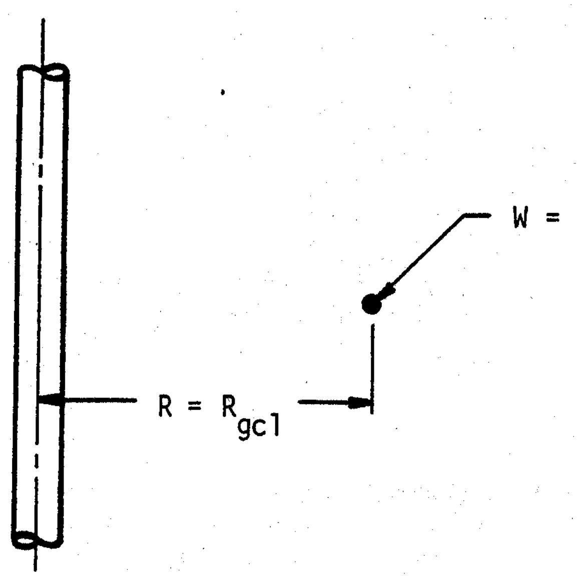


A = distance to nearest charge
NI = number of charges in explosive line
WI = weight of each charge in line
L = (N1)(L1)
= (N1)(W1)
B = angle between pipe and explosive line

Charge Density $\frac{W}{L} = \frac{W1}{L1}$

Use Equation (12)

(a) Angled-Line as Equivalent Parallel Line for $R \leq L$



Use Equation (7)

(b) Angled-Line as Equivalent Point Source for $R > L$

Figure 2. Methodology for Estimating Pipe Stresses from an Angled-Line Explosive Source

$$L = (N1)(L1) \qquad (20)$$

$$\frac{w}{L} \quad \frac{W1}{L \quad 1} \qquad (21)$$

where A =i distance of nearest row making up the grid (ft)
N1 = number of equally spaced charges in the front row
L1 = spacing of charges in the front row (ft)
W1 = explosive weight of one charge in grid (lb)

Analyses of the data indicated that as long as $\underline{R} < 1.5L$, good agreement occurred with the parallel line source solution. Therefore, for these values of R, Equation (12) is used to estimate the pipe stresses from a grid source simplified into an equivalent parallel line source.

As indicated in Figure 3, at values of R greater than 1.5L, the grid is approximated by a single charge equal in weight to that in the entire array and located at the geometric center of the grid. In other words, when the front row of the grid was located at distance greater than 1.5L, R and W were defined as:

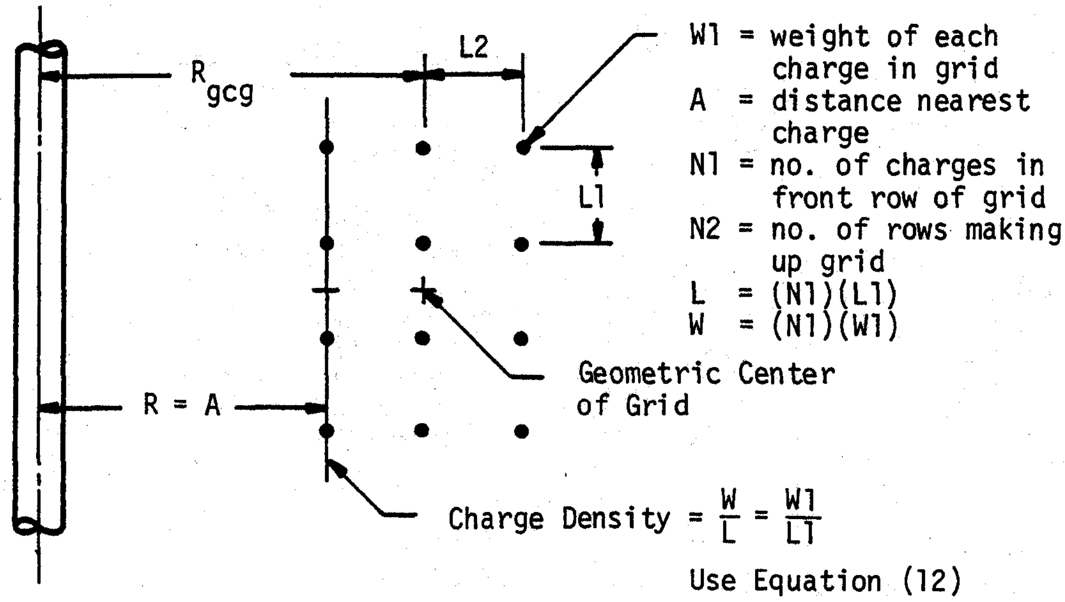
$$R = R_{gcg} = A + \frac{(N2-1)\ L2}{2} \qquad (22)$$

$$W = (N1)(N2)(W1) \qquad (23)$$

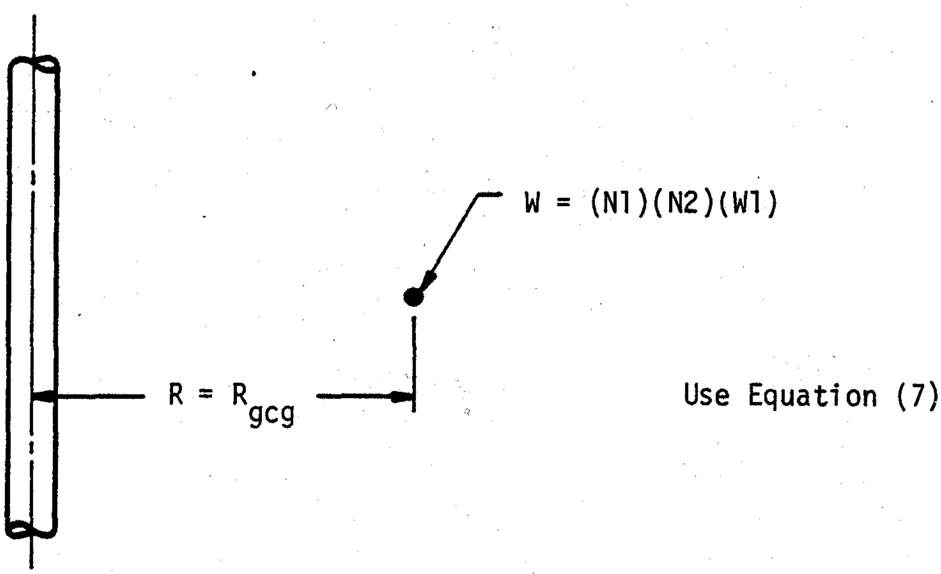
where N2 is the number of equally spaced rows making up a grid. With these values for the standoff distance and charge weight, Equation (7) is used to estimate the pipe stresses from a grid explosive source simplified into an equivalent point charge.

Angled-Grid Source

The method developed for simplifying rectangular explosive arrays located at an angle to a pipeline combines the procedures for the parallel grid and angled-line sources. As indicated in Figure 4a, the front row of the angled-grid first becomes an equivalent angled-line. This equivalent angled-line, with its geometric center located a distance R, away from the pipe centerline, is further simplified into an equivalent parallel line if $R = R_{gcl}/\cos B$ is less than or equal to 1.5 times the length L of the equivalent angled-line (the first row making up the grid). As was the case with a parallel grid, the charge density W/L becomes that

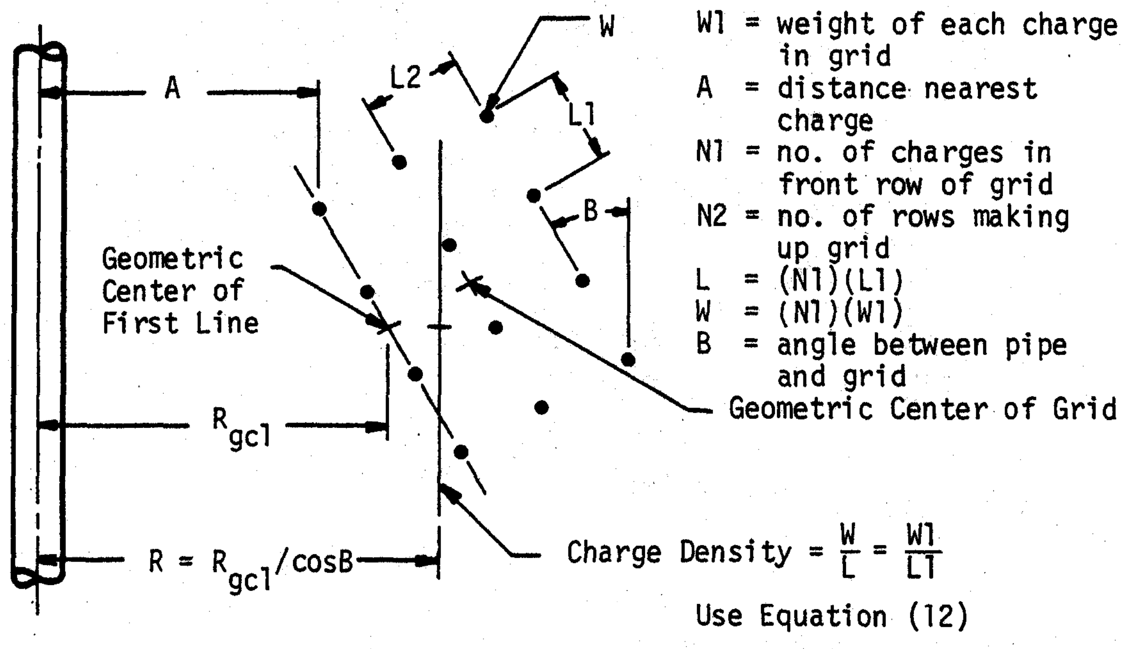


(a) Parallel Grid as Equivalent Parallel Line for $R \leq 1.5$ L

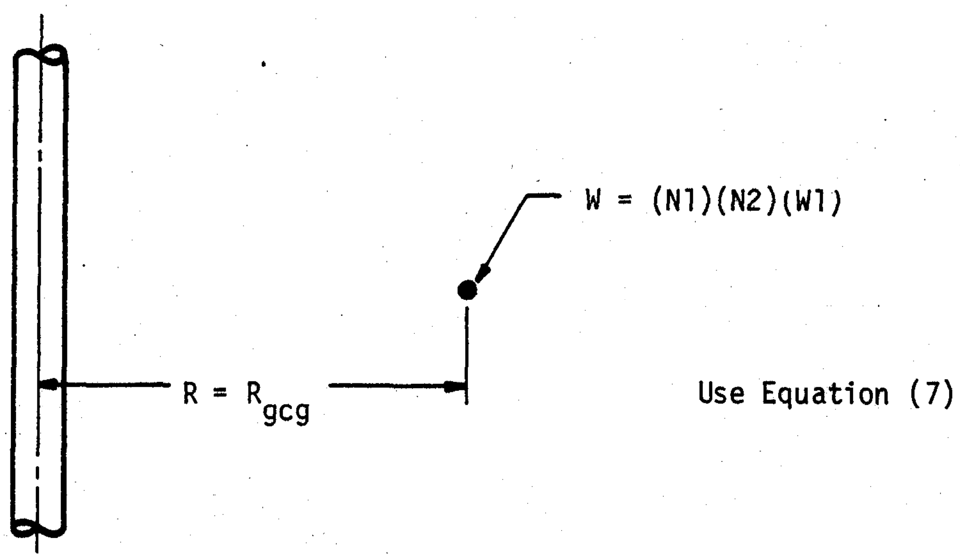


(b) Parallel Grid as Equivalent Point Source for $R > 1.5$ L

Figure 3. Methodology for Estimating Pipe Stresses from a Parallel Grid Explosive Source



(a) Angled-Grid as Equivalent Parallel Line for R $\leq$ 1.5 L



(b) Angled-Grid as Equivalent Point Source for R > 1.5 L

Figure 4. Methodology for Estimating Pipe Stresses from an Angled-Grid Explosive Source

of the first row of the grid. With R and W/L defined, the pipe stresses for an angled-grid can be estimated using the parallel line solution, Equation (12).

As was the case for the parallel grid, if the standoff distance [as defined by Equation (13)] of the equivalent parallel line representing an angled-grid is such that $R = R_{gcl}/\cos B > 1.5L$, the grid is collapsed into an equivalent point source. As indicated in Figure 4(b), the equivalent point charge W would equal the total explosive weight of the angled-grid and its standoff distance would be R_{gcg}, the distance between the pipe centerline and the geometric center of the angled-grid. This distance can be computed as follows:

Note that this equation can be used not only for calculating the standoff distance of the equivalent point charge for an angled-grid, but also for the equivalent point source for any grid or line source, parallel or at an angle to a pipe.

With W and R as defined in Figure 4b, the pipe stresses can be estimated using Equation (7) for any angled-grid that has been simplified into an equivalent point source.

Exceptions to Simplifying Methods

Two significant exceptions to the simplifying methods for the complex explosive geometries were observed in analyzing the experimental data. The first one concerns angled-line sources. The largest angle possible between an explosive line and a pipeline is 90°. At this angle, such an angled-line source is treated as a point source with a charge weight equal to the total weight in the line and located at the geometric center.

The second exception to the general procedures is in reality an additional step that should be included whenever stress estimates are made on explosive line and grid sources. It is possible for one of these complex geometries to have a charge spacing and location relative to a pipeline such that the nearest individual charge making up the line or grid when analyzed by itself as a point source would result in higher stress predictions than if the total array is analyzed as an equivalent point or parallel line source. Therefore, in estimating pipe stresses for a particular field situation in which an explosive line or grid is to be used, the stress magnitudes should be checked for the closest single charge. If the single charge values are higher than those from the total geometry, those higher stress estimates should be the ones used in deciding whether a blasting situation will be permitted without modifications to charge weights or standoff distances.

To assist the reader in the mechanics of applying the simplifying methods presented in this section, some additional information and an example problem are included in the Appendix. Additional details on these methods, their limitations and additional application information are included in Volume II of this final report,

V. RESULTS OF OTHER STUDIES

Pipeline Near A Free Surface

From a very limited data base, a correction factor was derived for the point source stress prediction equation for cases in which a pipeline is buried relatively close to a free surface as shown in Figure 5. In such cases, the amount of soil backing the pipe can be so small that higher stresses result than would be predicted by the, point source equation. To account for the missing inertial resistance, the point source solution is modified by introducing the following expression for a correction factor F:

(25)

where H = effective thickness of soil backing up the p&line (ft)
R = distance between centers of pipe and charge (ft)
h = pipe wall thickness (ft)
ρ_s = soil mass density (lb-sec^2/ft^4)
ρ_p = pipe material density (lb-sec^2/ft^4

Equation (25) is dimensionless and any self-consistent set of units can be used to compute a numerical value for F.

From a limited amount of data, we determined that the correction factor defined by Equation (25) should be used whenever the ratio of R/H exceeds a value of 4. Thus, for situations in which very deep charges are used or the pipeline is relatively close to a free surface, the point source solutions should be modified by the correction factor F as follows:

where F = 1 for $R/H \leq 4$
F = Equation (25) for $R/H > 4$

Note that this equation was derived empirically from only a few data points and the largest stress measured was only 3,452 psi. However, use of the correction factor F as defined in Equation (25) for larger stress values will result in conservative stress estimates.

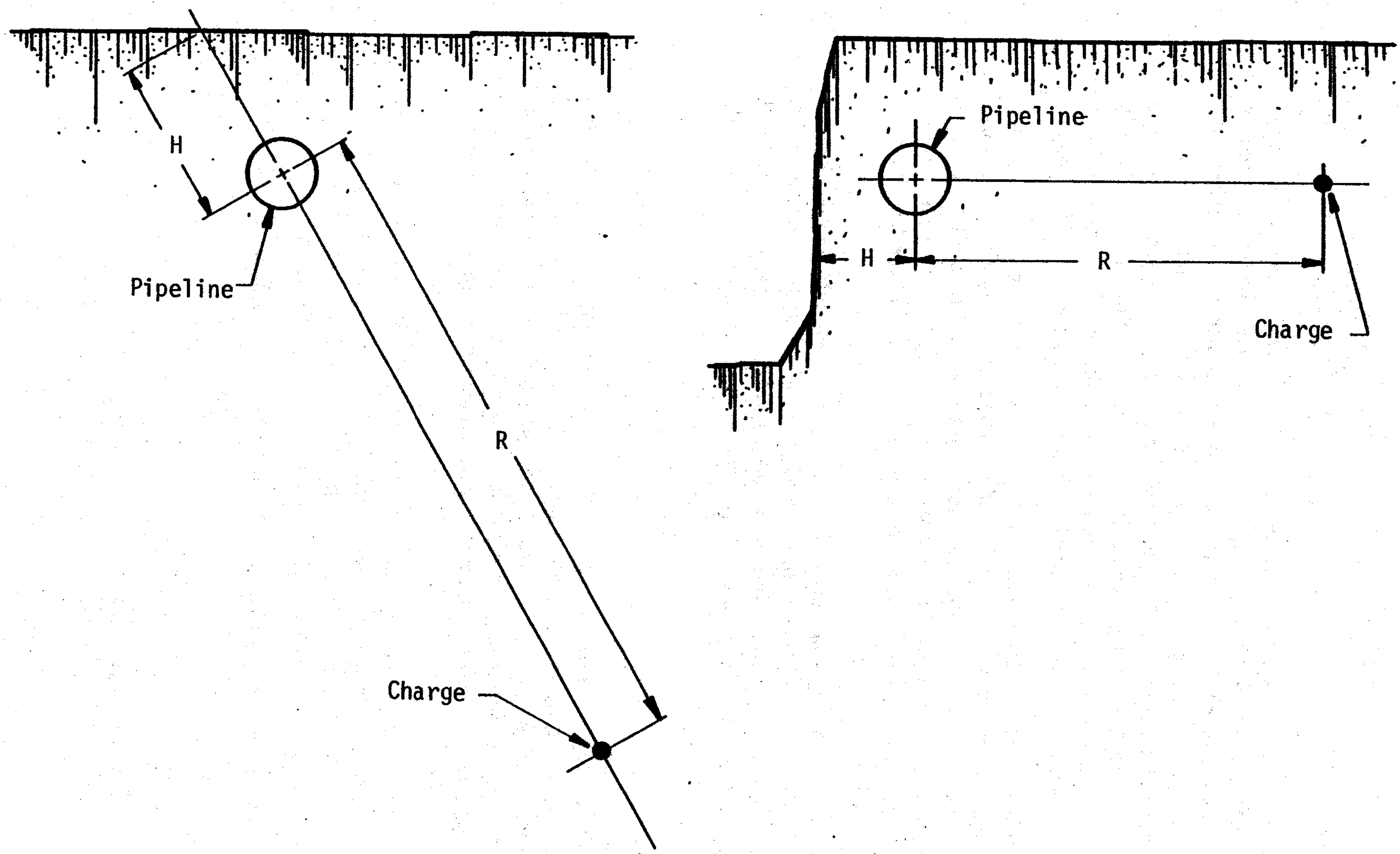


Figure 5. Examples of a Pipeline Near a Free Surface

Pipeline Shielding Study

From the literature study on the effect of an open trench between a pipeline and an explosive charge, we concluded that given the right conditions a trench can certainly reduce the blast effects on a pipe. Most of the information available on trench effects concerns the transmission of waves from vibrating sources. For low frequency vibrations with corresponding long wave lengths, the data in the literature indicate that a trench would have to be very deep to be very effective. Buried explosive detonations, although not vibratory sources, normally produce seismic waves which are relatively long, thus indicating that very deep trenches are needed to shield a section of a pipeline from a buried detonation effectively.

However, unpublished test data from a limited number of small charge buried detonations indicate significant reductions in pipe strains under certain trench conditions. A function was developed in this study to relate the reduction in pipe strain due to a trench. This function relates the strain reduction to the standoff distance, depth of the trench, strain magnitude without a trench, the location of a pipe behind a trench, and the length of the trench.

Analysis of the test data showed that the strain reduction ratio was a function primarily of the scaled standoff distance and that the other terms were of secondary importance in this case. An equation was curve fitted to the strain reduction ratio versus scaled standoff distance. Because of the limited data base, this equation and its limitations are only presented in Section X of Volume II.

Two-Media Problem

All of the results presented earlier in this volume concerned. pipeline response and radial ground motions from explosive charges buried in soil. Because blasting is often used to excavate or fracture rock masses near pipelines which are buried in soil, a very limited study was conducted using a concrete block/soil model test layout to observe what happens when the charge is detonated in a hard medium and the seismic waves generated then load a pipe buried in a softer medium.

From the four concrete/soil tests performed, an approximate equation for computing an effective standoff distance for soil was developed from the ground motion and pipe stress data recorded. This effective standoff distance permits the soil point source prediction equations to be used to estimate pipe stress in this two-media blasting situation.

The resulting equation for estimating the effective standoff distances for the concrete/soil tests is:

$$\frac{R_{eff}}{R} = 0.746\left(\frac{W_e}{\rho_s c_s^2 R_c^3}\right)^{0.028}\left(\frac{\rho_s c_s^2}{\rho_c c_c^2}\right)^{0.014} \tag{27}$$

where R_{eff} = effective standoff distance in soil (ft)
R = standoff distance (ft)
W_e = explosive energy release (ft-lb)
ρ_s = mass density of soil (lb-sec^2/ft^4)
c_s = seismic velocity of soil (ft/sec)
R_c = part of R in concrete (ft)
ρ_c = mass density of concrete (lb-sec ^{2}/ft 4)
c_c = seismic velocity of concrete (ft/sec)

Equation (27) shows that model scale experiments can generate data useful in formulating a method for predicting pipe stresses in this two-media blasting situation. Because similar tests using rock instead of concrete have mot been conducted, it is not possible at this time to determine whether this equation can be applied directly to rock/soil blasting situations. However, for rock/soil situations geometrically similar to those in this study, Equation (27) should provide rough estimates of the effective standoff distance. In such a case the mass density and seismic velocity of the rock in question would be used in place of the values for concrete. Because of the many parameters in two-media problems, considerable more data would be required to develop solutions as general as the ones for one medium (soil), For other rock/soil geometries, tests at the actual test site are recommended for placing the concrete/soil results on a firmer basis.

VI. CLOSURE

In this Volume I of the final engineering report, the ground motion and pipe stress results have been summarized for the blasting research program conducted by SwRI on behalf of the PRCI of the A.G.A. This volume provides the reader a quick reference source with equations and methods developed for estimating ground motion and pipe stresses from buried detonations near pipelines. Before applying any procedure presented, the user must be familiar with the contents of Volume II and understand the assumptions, approximations and limitations inherent in any of the new prediction equations and methods for determining blast induced pipe stresses.

Furthermore, an estimate of the maximum blasting stress is necessary but not sufficient information to determine if a buried pipeline will yield or exceed its maximum allowable stress. Other stresses, such as from internal pipe pressurization, must be combined with the blasting stresses and a suitable yield criteria used to determine the total stress conditions in a pipe. The reader is referred to Volume II for additional discussions on yield criteria, factors of safety, and other related topics.

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APPENDIX A

Illustrative Problems

Ground Motions

Most chemical explosives have close to the same energy release per unit weight (W,). This observation implies that if the explosive being used in a blasting situation is not known, the prediction equations can be used substituting a “typical” value for W_e . Average energy release values for a number of commercial explosives are as follows:

Explosive	W_e (ft-lb$_f$/lb$_m$)
ANFO (94/6)	1.52×10^6
AN Low Density Dynamite	1.50×10^6
Comp B (60/40)	1.70×10^6
Comp C-4	1.70×10^6
HBX-1	1.30×10^6
NG Dynamite (40%)	1.59×10^6
NG Dynamite (60%)	1.70×10^6
Pentolite (50/50)	1.68×10^6
RDX	1.76×10^6
TNT	1.49×10^6

Consult explosive manufacturers for explosives not listed here.

To demonstrate the direct use of the simple log-linear ground motion equations, Example Problem No. A-l follows:

Example Problem No. A-l

Given: A point charge of 2.5 lb of 60 percent NG Dynamite will be detonated buried 4 ft in a soil with a density of 120 lb/ft^3 and a seismic propagation velocity of 1,000 ft/sec.

Find: The horizontal ground motions at a standoff distance of 15 ft.

Solution: (a) Put parameters in Equations (3) and (4) in consistent units

$$W_e = (2.5\ \mathrm{lb_m})\left(1.7 \times 10^6 \frac{\mathrm{ft\text{-}lb_f}}{\mathrm{lb_m}}\right) = 4.25 \times 10^6\ \mathrm{ft\text{-}lb_f}$$

$$\rho = \frac{120\ \mathrm{lb_m/ft^3}}{32.2 \frac{\mathrm{lb_m\text{-}ft}}{\mathrm{lb_f\text{-}sec^2}}} = 3.73 \frac{\mathrm{lb_f\text{-}sec^2}}{\mathrm{ft^4}}$$

c = 1,000 ft/sec

R= 15 ft

$$p_o = \left(14.7 \frac{\mathrm{lb_f}}{\mathrm{in^2}}\right)\left(144 \frac{\mathrm{in^2}}{\mathrm{ft^2}}\right) = 2{,}117 \frac{\mathrm{lb_f}}{\mathrm{ft^2}}$$

(b) Calculate each dimensionless group

$$\left(\frac{p_o}{\rho c^2}\right)^{0.5} = \left[\frac{2117}{(3.73)(1{,}000)^2}\right]^{0.5} = 2.38 \times 10^{-2}$$

$$\left(\frac{W_e}{\rho c^2 R^3}\right) = \left[\frac{4.25 \times 10^6}{(3.73)(1{,}000)^2(15)^3}\right] = 3.376 \times 10^{-4}$$

Note that the value for the scaled charge is within the limits of applicability given in Section II.

(c) Substitute into Equation (3) and solve for X

$$\frac{X}{15}(2.38 \times 10^{-2}) = 0.0373(3.376 \times 10^{-4})^{1.060}$$

$$X = 0.00491\ \mathrm{ft}$$

X = 0.059 in.

(d) Substitute into Equation (4) and solve for U

$$\frac{U}{1{,}000}(2.38 \times 10^{-2}) = 0.00489(3.376 \times 10^{-4})^{0.79}$$

U = 0.372 ft/sec

U = 4.46 in./sec

Note that the values computed for X and U would be the average value for a large number pf similar tests. For any one test, the ground motions would fall within the scatter of the large sample.

Pipe Stresses

In deriving the point and parallel line stress prediction equations, substitutions were made to have the various parameters in the units most used in the field. Thus, the energy release (W,) which had been used in the ground motions discussions was replaced by nW. The quantity *n* is a measure of the relative energy among the explosives. Using the energy release of ANFO (94/6) as the base, all explosive energies were normalized to determine the value of n. Thus, ‘for ANFO (94/6), n equals 1.00. Those explosives more energetic have a value of n greater than 1.00 and those less energetic have a value of n less than 1.00. A list of equivalent energy releases is as follows:

Explosive	n
ANFO (94/6)	1.00
AN Low Density Dynamite	0.99
Comp B (60/40)	1.12
Comp C-4	1.12
HBX-1	0.83
NG Dynamite (40%)	1.05

NG Dynamite (60%)
Pentolite (50/50)
R D X
TNT

Consult explosive manufacturers for values not listed here. Note that since relative explosive energy does not vary much, one can always assume a conservative value of n.

To demonstrate the use of Equation (7) to predict stresses from a point source, Example Problem No. A-2 follows:

Example Problem No. A-2

Given: A 2.5lb point charge of 60 percent NG dynamite will be detonated buried 4 ft in soil adjacent to a 24-inch O. D. by 0.312 W. T., API-5L, Grade "B" pipeline. In this area, the pipeline has a 3-ft cover of soil.

Find: Estimate the blast-induced circumferential and longitudinal pipe stresses if the charge is 15 ft from the pipe,

Solution: (a) List parameters required in Equation (7) in proper units

$E = 29.5 \times 10^6$ psi
$h = 0.312$ in.
$n = 1.12$
$W = 2.5$ lb
$R = 15$ ft

(b) Substitute into Equation (7) and solve for the pipe stresses

$$\sigma = \sigma_{cir} = \sigma_{long} = 4.44\ E\left(\frac{n\ W}{\sqrt{Eh}\ R^{2.5}}\right)^{0.77}$$

$$\sigma = (4.44)(29.5 \times 10^6)\left[\frac{(1.12)\ (2.5)}{\sqrt{(29.5 \times 10^6)\ (0.312)}\ (15)^{2.5}}\right]^{0.77}$$

$$\sigma = (4.44)\ (29.5 \times 10^{6})\ (1.059 \times 10^{-6})^{0.77}$$

$$\sigma = 3{,}284 \text{ psi}$$

$$\underline{\sigma_{cir} = \sigma_{long} = 3{,}284 \text{ psi}} \qquad (S = \pm 1{,}117 \text{ psi})$$

To assist in the application of the parallel line solution, Equation (12), the example problem that follows will be solved:

Example Problem No. A-3

Given: Seven 60 percent NG dynamite point charges weighing 2.5 lb each and spaced 3 ft apart are buried 4 ft in a soil media. The line of charges is parallel to a 24-inch O.D. by 0.312 W. T., API-5L, Grade "B" pipeline which has 3 ft of soil cover,

Find: The estimated blast-induced pipe stresses if the line of charges is 15 ft from the pipe,

Solution: (a) List parameters required in Equation (12) in proper units

E = 29.5 x 10^{6} psi
h = 0.312in.
= 1.12
N1 = 7 charges
L l = 3 ft
L = (7)(3) = 21 ft
W l = 2.5 lb
W = (7)(2.5) = 17.5 lb
R = 15 ft

(b) Since R c L, substitute in Equation (12) and solve for the pipe stresses

$$\sigma = \sigma_{cir} = \sigma_{long} = 4.44\, E \left(\frac{1.4n\ W/L}{\sqrt{Eh}\ R^{1.5}} \right)^{0.77}$$

$$\sigma = (4.44)(29.5 \times 10^6)\left[\frac{(1.4)(1.12)\ (17.5)/(21)}{\sqrt{(29.5 \times 10^6)(0.312)}\ (15)^{1.5}}\right]^{0.77}$$

$$\sigma = (4.44)(29.5 \times 10^6)(7.414 \times 10^{-6})^{0.77}$$

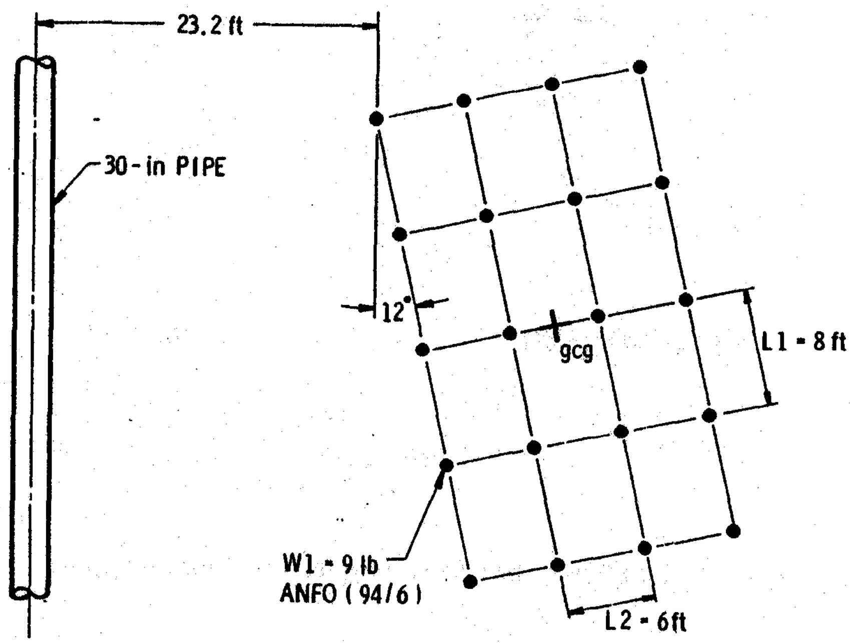
$$\sigma = 14{,}690 \text{ psi}$$

$$\underline{\sigma_{cir} = \sigma_{long} = 14{,}690 \text{ psi}} \quad (S = \pm 4{,}995 \text{ psi})$$

To illustrate the application of the angled-grid simplifying method, the following example problem will be solved:

Example Problem No. A-4

Given: The explosive grid defined in the figure will be used to loosen the soil overburden



A 30-inch O. D. by 0.344 W. T. pipeline is adjacent to the grid as shown in the figure. The centerline of the pipe and the charges are 5 ft below the surface of the ground.

Find: Estimate of the blast-induced stresses.

Solution: (a) List all parameters in proper units

$E = 29.5 \times 10^6$ psi
$h = 0.344$
$n = 1.0$
$N1 = 5$
$Ll = 8$ ft
$Wl = 9$ lb
$B = 12°$
$A = 23.2$ ft
$N2 = 4$
$L2 = 6$ ft

(b) Determine whether the grid is to be an equivalent point or line source

(1) $R = R_{gcl} / \cos B$ (Eq. 13 & 14)

$$R = \frac{\left[A + \frac{(Nl - 1)\, Ll \sin B}{2}\right]}{\cos B}$$

$$= \frac{\left[23.2 + \frac{(4)\ (8)\ \sin 12}{2}\right]}{\cos 12}$$

$\underline{R = 27.12 \text{ ft}}$

(2) $L = (Nl)(Ll) = (5)(8)$ (Figure 4)

$\underline{L = 40 \text{ ft}}$

(3) Is $R > 1.5L$? No, therefore, parallel line solution applies.

(c) Compute Stresses

(1) $$\frac{W}{L} = \frac{W1}{L1} = \frac{9}{8}$$ (Figure 4)

$$\underline{\frac{W}{L} = 1.13 \text{ lb/ft}}$$

(2) $$\sigma_{cir} = \sigma_{long} = 4.44\ E \left(\frac{1.4n\ W/L}{\sqrt{Eh}\ R^{1.5}} \right)^{0.77}$$

$$= (4.44)(29.5 \times 10^6) \left[\frac{(1.4)\ (1.0)\ (1.13)}{\sqrt{(29.5 \times 10^6)(0.344)}\ (27.12)^{1.5}} \right]^{0.77}$$

$$= (4.44)(29.5 \times 10^6)(3.5 \times 10^{-6})^{0.77}$$

$$\underline{\sigma_{cir} = \sigma_{long} = 8{,}240 \text{ psi}} \qquad (S = \pm 2{,}802 \text{ psi})$$

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APPENDIX B

List of Parameters

English Symbols

A	Distance of nearest charge. For point and parallel line sources, A = R (ft)
B	Angle between pipeline and explosive source
c, c_s	Seismic compression wave velocity in soil (ft/sec)
c_c	Seismic compression wave velocity in concrete (ft/sec)
E	Modulus of elasticity for the pipe material (psi)
F	Correction factor for pipeline near a free surface (nondimensional)
g	Acceleration of gravity (32.16 ft/sec^2)
H	Effective thickness of soil backing a pipeline (ft)
h	Pipe wall thickness (in.)
L	Length of an explosive line (for uniform charges spaced equal distances apart, this length is the spacing between charges times the number of charges), L = (Nl)(Ll) (ft)
Ll	Spacing of charges in an explosive line or the front row of a grid (ft)
L2	Spacing of rows making up a grid (ft)
Nl	Number of equally spaced charges in an explosive line or the front row of a grid
N2	Number of equally spaced rows making up a grid
n	Equivalent explosive energy release (nondimensional)
nW	Charge weight equivalent in lb of ANFO
P_0	Atmospheric pressure
P-wave	Compression wave generated by a disturbance in the ground
R, R_{eff}	Standoff distance (actual or effective) from the center of the pipe or ground motion transducer to the center of the charge (ft)
R_{gcl}	Distance between geometric center of explosive line and a pipe (ft)
R_{gcg}	Distance between geometric center of explosive grid and a pipe (ft)
R_c	Part of R in concrete (ft)
R-wave	Surface Raleigh wave generated by a disturbance near the surface of the ground
S	Estimate of the standard error of test data about fitted curve
u	Peak radial soil particle velocity (ft/sec)
U/c	Nondimensional velocity
W	Total charge weight of explosive source (lb)
W_e	Explosive energy released (ft-lb)
W_e/L	Energy released per unit length in an explosive line source (ft-lb/ft)
W/L	Explosive density, charge weight per unit length of an explosive line (lb/ft)
Wl	Explosive weight of individual point charges making up a line or grid source (lb)

X	Peak radial soil displacement (ft)
X / R	Nondimensional displacement

Greek Symbols

ϵ_{cir}	Maximum circumferential pipe strain (in./in.)
ϵ_{long}	Maximum longitudinal pipe strain (in./in.)
$\mu\epsilon$	Microstrain (10^{-6} in./in.)
ρ	Mass density of soil or rock (lb-sec^2/ft^4)
ρ_s	Mass density of soil (lb-sec^2/ft ^{4})
ρ_c	Mass density of concrete (lb-sec^2/ft^4)
σ_{cir}	Maximum circumferential pipe stress (psi)
σ_{long}	Maximum longitudinal pipe stress (psi)

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