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STRAIN ANALYSIS OF BURIED PIPELINES DUE TO BLAST-INDUCED GROUND SHOCK WAVES

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ABSTRACT

The aim of this paper is to introduce a robust analytical methodology for the calculation of strains in flexible buried pipelines due to surface point-source blasts. Following a brief bibliographic overview regarding the characteristics of ground waves produced from surface explosions, emphasis is put on the concept of modeling wave propagation with radial attenuation and spherical front, as well as the basic assumptions of the methodology. The workflow for strain analysis of a 3-D cylindrical thin shell representing the pipeline due the propagation of P- and Rayleigh waves, which dominate the waveform generated by an explosion, is accordingly presented. To simplify the design procedure, a set of easy-to-use relations for the calculation of maximum strains and their position along the pipeline axis is supplied. The derived expressions are evaluated through comparison with field strain measurements in flexible pipelines due to a series of full scale blasts, and state-of-practice design methods. Comparisons show that the proposed methodology provides improved accuracy at no major expense of simplicity, as well as the advantage of properly accounting for the effect of local soil conditions.

Keywords: blast, buried pipelines, safety distance, design

INTRODUCTION

Despite the remarkable expansion in the use of buried pipeline networks over the last few years, limited fresh literature refers to their design against ground shock wave propagation. In fact, seismic design of buried pipelines is still based on the expressions proposed by Newmark (1968) and Kuesel (1969). This, to a certain extent, is due to the fact that earthquake induced ground motion is rarely strong enough to affect steel pipelines, as proven by their in-situ response in various earthquakes. Nevertheless, accidental or intended surface explosions (e.g. an accident in an explosive storage facility or routine quarry blasts) may generate ground waves with significant amplitude in short distance from the source of the explosion, much larger than that originating from a strong earthquake, and prove threatening for the pipeline. The precise calculation of the safety distance from the source of a potentially threatening explosion could be of outmost importance for the rational design of a pipeline, as over-conservative estimates can lead to unnecessary re-routing, and to a disproportionate increase in the cost of the project.

The design of pipelines against blasts is based today either on analytical relations originally proposed for seismic waves with plane front and constant amplitude (Dowding, 1985) or by an empirical relation initially proposed by Esparza et al. (1981) and lately embraced by the ASCE-ALA guidelines

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(2001). It is realized that the first approach is a rather crude approximation, which was merely employed to provide conservative estimates in the absence of any problem-specific solutions. On the contrary, the later approach has been developed specifically for the problem at hand, based on an experimental database for blast-induced strains on instrumented pipe segments. Nevertheless, this approach is purely empirical, and consequently its range of application should be limited to conditions similar to these which prevailed in the relevant experiments.

This paper aims at filling this gap in the modern literature by presenting a new analytical methodology for calculating strains in buried pipelines due to surface point-source blasts. The proposed methodology incorporates 3-D thin shell theory for the accurate modeling of the pipeline response and properly accounts for the spherical front and the radial attenuation of ground vibration induced by blast waves. The methodology is mainly intended for the design of buried steel pipelines, but its assumptions are also valid for flexible pipelines made of other materials such as PVC.

It is acknowledged that the theoretical derivation of pipeline strains with the proposed methodology is rather complex, and difficult to follow during this, necessarily concise, presentation. For this reason, only the basic assumptions and the course of action for the derivation of design strains are presented herein, while emphasis is placed upon the application of the methodology and the comparison of its results to field strain measurements in flexible pipelines due to a series of full scale blasts (Siskind et al., 1994). A comprehensive presentation of the methodology for the analytical calculation of strains can be found in Kouretzis et al. (2006a).

GROUND SHOCK WAVES INDUCED BY A SURFACE EXPLOSION

In a simple way, a surface point-source blast may be modeled as a time-dependent vertical point load acting on the surface of a homogeneous, isotropic, elastic half space (Figure 1a). This is commonly referred as Lamb's problem, after the name of the researcher who first formulated and solved it. Keeping in mind that the load, as well as the geometry, is vertically axisymmetric, the transverse component of ground displacement is neglected and the dynamic equations of motion are solved in the 2-D space, i.e. in the vertical plane through the center of the explosion.

Mooney (1974) provided a series of closed-form solutions for the calculation of the displacements and velocities resulting from the application of a bell-shaped load pulse. Mooney's predictions show that both the radial as well as the vertical component of particle velocity attenuate exponentially with the distance from the source. According to Mooney (1974), the relation between the peak particle velocity V_{max} and the distance R can be written under the general form:

$$V_{\max} = E \cdot R^{-n} \tag{1}$$

Constant E is a function of the load and the medium characteristics, while the attenuation exponent n depends on the properties of the half-space, as well as the radial distance. Namely, n in the near field obtains values between 1.27 and 0.84, and is further reduced between 0.72 and 0.42 at larger radial distances. The predicted response in the near field reflects the attenuation of compressional (P) waves, while in the far field it reflects the slower attenuation of surface Rayleigh (R) waves.

Figure 1b illustrates two typical particle velocity time histories, one for the radial and the other for the vertical component of the ground motion, obtained from the analytical solution of Mooney (1974). It should be noted that both time histories refer to the far-field, a fact that justifies the rather long time lag between the arrival of the two waveforms, and the small amplitude of the P-wave with respect to the amplitude of the Rayleigh wave. By examining both waveforms, it is also observed that S-waves are overshadowed by the practically concurrent arrival of Rayleigh waves with larger amplitude.

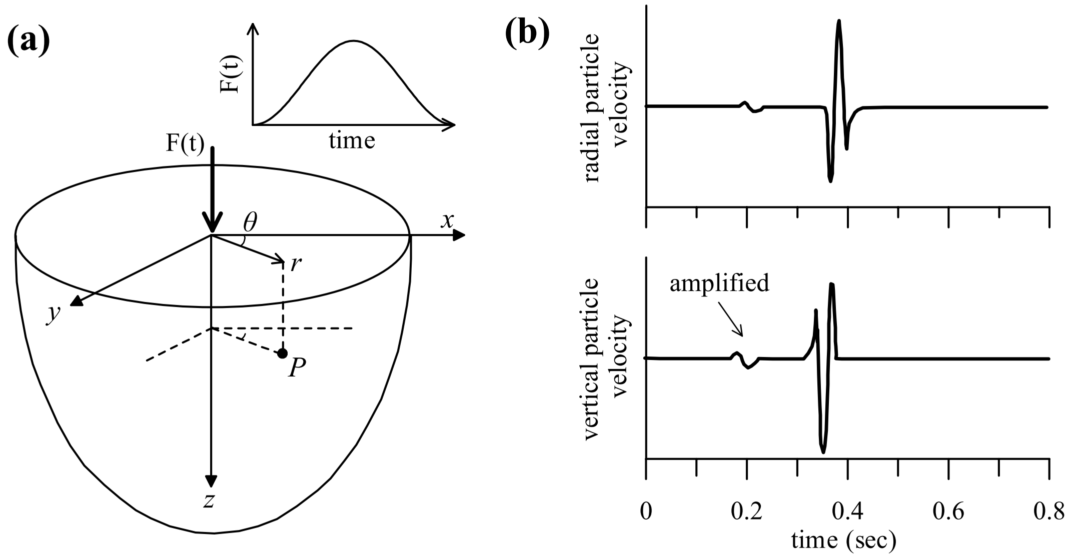

Figure 1. Analytical model for the evaluation of the response of an elastic half-space to the concentrated bell-shaped dynamic load. Typical resulting peak particle velocity time histories are also illustrated (after Mooney, 1974).

It should be pointed out that all the above are valid for an elastic medium. In fact, actual soil behavior is elasto-plastic and its hysteretic damping cannot be considered in an analytical solution, hence the quantative estimates of the attenuation exponent proposed by Mooney (1974) are of little practical interest. For the approximate calculation of the peak particle velocity in real-world problems, a number of empirical attenuation relations with the general form of Eq. 1 have been proposed in the literature. However, most of them concern deep underground explosions at purely rock sites, and are not directly applicable to the problem studied herein. Only a few publications (e.g. Siskind et al., 1994, TM5-855-1, 1998) refer to wave propagation from surface or near-surface blasts and propose relations which are applicable to soil and rock formations alike.

METHODOLOGY OUTLINE AND ASSUMPTIONS

As mentioned above, the proposed methodology applies to long and flexible buried pipelines. In more detail, the following assumptions are adopted with regard to the pipeline behavior:

- The inertia and kinematic interaction effects between the buried pipeline and the surrounding soil can be ignored. Theoretical arguments and numerical simulations plead for the general validity of the former statement regarding inertia effects (EC-8, 2003), while the importance of kinematic interaction effects can be checked on a case-by-case basis via the flexibility index:

$$F = \frac{2E_m\left(1-\nu_l^2\right)\left(D/2\right)^3}{E_l\left(1+\nu_m\right)t_s^{\,3}} \tag{2}$$

where E_m is the Young's modulus of the surrounding soil, E_l is the Young's modulus of the pipe material, ν_m is the Poisson's ratio of the surrounding soil, ν_l is the Poisson's ratio of the pipe material, t_s is the thickness of the cross-section, and D is the pipe diameter. The flexibility index is related to the ability of the lining to resist distortion from the ground (Hoeg, 1968). Values of the flexibility index higher than 20 are obtained for most common pipelines, indicating that ignoring overall the soil-structure interaction is a sound engineering approach (Siskind et al., 1994, O' Rourke and Liu, 1999). Moreover, keeping in mind that, even in very stiff soil or rock

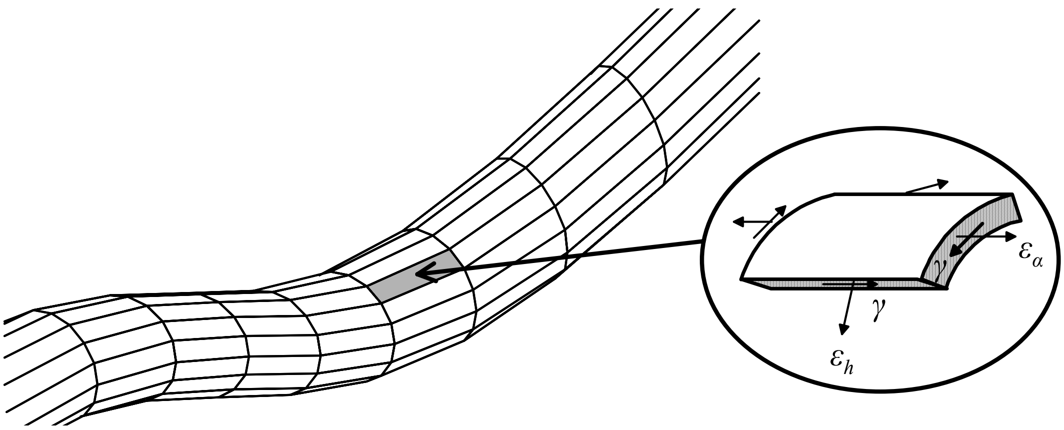

Figure 2. Strain notation for thin-walled cylindrical shells.

formations, the wavelength of blast-induced strong motion does not exceed 10m (Dowding 1985), i.e. it is much smaller than typical pipeline diameters, wave scattering effects in the soil-pipeline boundary are considered negligible, and are ignored herein. As a result from the above, the pipeline here is assumed to fully conform to the ground motion, and its displacements are considered equal to those of the surrounding soil. The validity of this assumption is also verified experimentally, via blast-induced displacement time history measurements on flexible pipelines and in the surrounding soil, presented by Siskind et al. (1994).

- The pipe is modeled as a 3-D thin elastic shell (Figure 2), where normal (axial ε_a and hoop ε_h) as well as shear (γ) strains develop along the axis and the perimeter, but not along the radius of the pipeline. Not accounting for material non-linearity is common in such analytical solutions, as steel pipelines constructed with in-situ welds are considered to fail at their joints for relatively low strain levels (i.e. 0.5%), well below the yield limit of the pipeline material.
- There is no slippage at the soil-pipe interface. It can be shown (Kouretzis et al., 2006b) that this is a conservative assumption, as it leads to larger overall strains compared to the condition of a "smooth" interface, where the pipeline is free to slip relatively to the surrounding soil. In addition, the presence of the cavity formed in the ground by the construction of the pipeline is also ignored, thus a non-perforated ground model is adopted for the calculation of pipeline strains due to transversely propagating waves. Although this assumption does not affect the calculation of axial strains, it provides upper bound estimates of hoop strains for a wide range of pipelines with flexibility ratios 20<F<10,000.

As structural inertia is neglected, the number of significant circles of the excitation does not affect the response of the pipeline. Thus, the pulse-like ground motion induced by the blast can be replaced by a train of harmonic waves with constant amplitude, which is simpler to treat analytically by solving the equivalent steady-state problem. Harmonic ground waves are assumed to propagate from the center of the point-source explosion with a spherical wave front. The attenuation of the peak particle velocity with the distance from the source, regardless of the wave type that it is attributed to, is quantitatively described by Eq. 1. For harmonic waves, Eq. 1 can be re-written in terms of displacement as:

$$A_{\max} = A\left(R/d\right)^{-n} \tag{3}$$

where $A=(E/2\pi\nu)d^{-n}$ is the maximum ground displacement at the projection of the explosion source on the pipe (Point O in Figure 3a), ν is the frequency of the harmonic wave, d is the distance of the explosion source from the pipe axis (Figure 3), and $R=\sqrt{z^2+d^2}$. If the elevation of the pipeline axis relatively to the source of the explosion is equal to H, distance d is expressed as $d=\sqrt{d_h^2+H^2}$, where d_h is the horizontal distance between the pipeline and the point source. However, for the case of near-surface blasts examined here, H is considered much smaller than d_h and will be neglected hereafter.

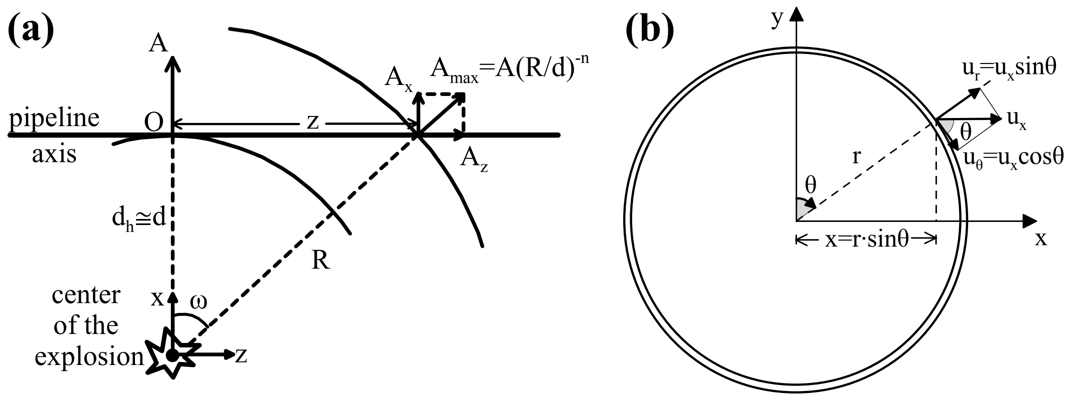

Figure 3. (a) Definition of the peak particle displacement A_{max} applied to the pipeline, as a result of the radial propagation of a blast-induced P wave in the horizontal plane, and (b) The cylindrical coordinate system employed in the strain analysis of the 3-D shell.

OVERVIEW OF THE ANALYTICAL CALCULATION OF STRAINS

To preserve the limits of the presentation, the analytical calculation of strains is presented indicatively for a harmonic P wave propagating with spherical front in the horizontal plane and a pipeline constructed at horizontal distance d from the center of the explosion (Figure 3a). Referring to a polar coordinate system originating from the center of the explosion, the corresponding ground motion can be expressed analytically as:

$$u_R = A_{\max} \sin\left[\frac{2\pi}{L}\left(R - C_p t\right)\right] \tag{4}$$

where C_p is the propagation velocity of P waves, $L=C_p \cdot T$ is the wavelength, T is the wave period, A_{max} is the maximum ground displacement at radial distance R from the source, and t stands for time. To aid the analytical computation of strains, ground displacement is vectorially decomposed into two components (Figure 3a): one with motion parallel to the undeformed pipe axis (A_x) and the other with motion perpendicular to it (A_z). As the deformation of the surrounding soil is transferred unaltered to the buried structure, the displacements induced on each point of a 3-D cylindrical shell with radius r equal to the radius of the pipeline will be:

$$u_x = A_{\max} \cos\omega \cdot \sin\left[\frac{2\pi}{L}\left(R' - C_p t\right)\right] \tag{5}$$

$$u_z = A_{\max} \sin\omega \cdot \sin\left[\frac{2\pi}{L}\left(R' - C_p t\right)\right] \tag{6}$$

where

$$\omega = \arctan\left(\frac{z}{d + r\sin\theta}\right) \text{ and } R' = \sqrt{z^2 + \left(d + r\sin\theta\right)^2} \tag{7}$$

In Eq 7, z is the distance of any given cross-section from the projection of the center of the explosion on the pipe axis (Point O in Figure 3a) and r, θ define the location of each point on the shell in cylindrical coordinates (Figure 3b).

Total strains on the 3-D shell result from the superposition of strains due each component of displacement defined in Eqs 5 and 6. For example, strains due to the perpendicular to the pipeline axis component of displacement u_x may be computed with the aid of a cylindrical coordinate system fitted to the axis of the structure (Figure 3b), where u_x can be decomposed into the following radial and tangential components:

$$u_r = A \cdot \left(\frac{R}{d + r\sin\theta} \right)^{-n} \cdot \sin\theta \cdot \cos\omega \cdot \sin\left[\frac{2\pi}{L} \left(R' - C_p t \right) \right] \tag{8}$$

$$u_\theta = A \cdot \left(\frac{R}{d + r\sin\theta} \right)^{-n} \cdot \cos\theta \cdot \cos\omega \cdot \sin\left[\frac{2\pi}{L} \left(R' - C_p t \right) \right] \tag{9}$$

According to the "elastic thin shell" assumption adopted herein, the corresponding strains in the structure are calculated from the strain-displacement equations in cylindrical coordinates as:

$$\varepsilon_a = \varepsilon_{zz} = \frac{\partial u_z}{\partial z} = 0 \tag{10}$$

$$\varepsilon_h = \varepsilon_{\theta\theta} = \frac{1}{r} \cdot \frac{\partial u_\theta}{\partial \theta} + \frac{u_r}{r} = \frac{A}{LR^3} \left({}^{R}\!/\!{}_{d} \right)^{-n} \cdot \cos^2\theta \cdot \begin{pmatrix} 2d^2 \pi R \cos\left[\frac{2\pi}{L} \left(R - C_p t \right) \right] - \\ Lz^2 \left(1 + n \right) \sin\left[\frac{2\pi}{L} \left(R - C_p t \right) \right] \end{pmatrix} \tag{11}$$

$$\gamma = \gamma_{\theta z} = \frac{1}{r} \cdot \frac{\partial u_z}{\partial \theta} + \frac{\partial u_\theta}{\partial z} = \frac{Azd}{LR^3} \left({}^{R}\!/\!{}_{d} \right)^{-n} \cdot \cos\theta \cdot \left(2\pi R \cos\left[\frac{2\pi}{L} \left(R - C_p t \right) \right] - L(1+n) \sin\left[\frac{2\pi}{L} \left(R - C_p t \right) \right] \right) \tag{12}$$

The resulting Eqs 11 and 12 that provide the strains on the shell have been simplified by assuming that the radius of the pipeline r is small compared to the distance from the explosion d:

$$d + r\sin\theta \approx d \text{ or } R' \approx R \tag{13}$$

Pipeline strains due to the parallel to the pipeline axis component of displacement, u_z can be computed accordingly, and superimposed to strains of Eqs 11-12 to provide the actual strain field of the pipeline, which is presented in Table 1.

Strains due to the propagation of Rayleigh waves, which dominate the strong motion waveform at relatively large distances from the explosion are computed accordingly, and are also presented in Table 1. According to basic wave propagation theory, a Rayleigh wave is equivalent to a P wave and an SV wave propagating simultaneously along the same path, with velocity C_R and a phase difference of $\pi/2$. The amplitude ratio of these two Rayleigh wave components is constant, depending solely on the distance from the ground surface and the Poisson's ratio of the elastic half-space (Ewing et al., 1957). For example, close to the free surface of an elastic half space with Poisson's ratio v_m=0.25, the amplitude ratio is equal to $A_{max,V}/A_{max,H}$=k=1.4677, where $A_{max,V}$ is the amplitude of the SV wave component and $A_{max,H}$ is the amplitude of the P-wave component.

DERIVATION OF DESIGN STRAINS

The analytical expressions for the pipe strains are quite complicated, providing the distribution of strains along each cross-section for the whole length of the pipeline, and for the entire duration of the harmonic wave excitation. For design purposes, the evaluation of the overall maximum value of each strain component, and the position where this appears along the pipeline is sufficient. To conclude to a set of easy-to-use relations, we employ the procedure described briefly in the following:

Table 1. Analytical expressions of pipeline strains due to P- and Rayleigh waves

strain	P wave
axial	$\frac{A}{LR^3}\left(R/d\right)^{-n}\left(2\pi z^2 R\cos\left[\frac{2\pi}{L}\left(R-C_p t\right)\right]+L\left(d^2-nz^2\right)\sin\left[\frac{2\pi}{L}\left(R-C_p t\right)\right]\right)$
shear	$\frac{Az}{dLR^3}\left(R/d\right)^{-n}\cdot\cos\theta\cdot\left(4d^2\pi R\cos\left[\frac{2\pi}{L}\left(R-C_p t\right)\right]+L\left(-d^2\left(2+n\right)+nz^2\right)\sin\left[\frac{2\pi}{L}\left(R-C_p t\right)\right]\right)$
hoop	$\frac{A}{LR^3}\left(R/d\right)^{-n}\cdot\cos^2\theta\cdot\left(2d^2\pi R\cos\left[\frac{2\pi}{L}\left(R-C_p t\right)\right]-Lz^2\left(1+n\right)\sin\left[\frac{2\pi}{L}\left(R-C_p t\right)\right]\right)$
strain	**Rayleigh wave**
axial	$\frac{A_{max,H}}{LR^3}\left(R/d\right)^{-n}\left(2\pi z^2 R\cos\left[\frac{2\pi}{L}\left(R-C_R t\right)\right]+L\left(d^2-nz^2\right)\sin\left[\frac{2\pi}{L}\left(R-C_R t\right)\right]\right)$
shear	$\frac{A_{max,V}z}{LR^2}\left(R/d\right)^{-n}\left(\left\{\left(1/k\right)\cdot 4d\pi\cdot\cos\theta-L\cdot n\cdot\sin\theta\right\}\cdot\cos\left[\frac{2\pi}{L}\left(R-C_R t\right)\right]+\left\{\frac{\left(1/k\right)\cdot L\left(-d^2\left(2+n\right)+nz^2\right)\cdot\cos\theta-2\pi dR^2\cdot\sin\theta}{dR}\right\}\cdot\sin\left[\frac{2\pi}{L}\left(R-C_R t\right)\right]\right)$
hoop	$\frac{A_{max,V}}{LR^2}\left(R/d\right)^{-n}\left(\left\{\frac{\left(1/k\right)\cdot 4d^3\pi\cdot\cos^2\theta+L\cdot n\cdot z^2\sin2\theta}{2d}\right\}\cdot\cos\left[\frac{2\pi}{L}\left(R-C_R t\right)\right]+\left\{\frac{\left(1/k\right)\cdot Lz^2\left(1+n\right)\cdot\cos^2\theta-\pi dR^2\cdot\sin2\theta}{R}\right\}\cdot\sin\left[\frac{2\pi}{L}\left(R-C_R t\right)\right]\right)$

- To begin with, axial, hoop and shear strains of Table 1 are normalized against the V_{max}/C ratio, which is found to be the "reference" strain in many publications and guidelines referring to the design of buried pipelines against ground shock (e.g. Dowding, 1985, ASCE-ALA, 2001, EC8, 2003). The resulting normalized strains are mathematical expressions that quantitatively account for the effect of the spherical wave front, the attenuation of the peak particle velocity with the distance from the source, and the spatial and temporal superposition of strains (e.g. the innovations introduced by the presented methodology to account for the special characteristics of blast waves). Accordingly, to eliminate the independent variable θ -that is the polar angle in the cross-section- values of the normalized strains ε_i^* are computed at 8 characteristic points of the cross-section that differ by π/4.
- The differential equations $\partial\varepsilon_i^*/\partial t=0$ are solved symbolically to evaluate the time instant when the maximum values of ε_i^* appear. By replacing these values of time at the equations of Table 1, the distribution of the maximum (over time) value of ε_i^* along the pipeline is calculated, as a function of the attenuation exponent n and $z^*=z/L$, $d^*=d/L$. For example, the maximum axial strain due to a P wave is:

$$\varepsilon^*_{\alpha,\max}=\frac{\left(R^*/d^*\right)^{-n}\left(4\pi^2 z^{*4}R^{*2}+\left(d^{*2}-nz^{*2}\right)\sqrt{\left(d^{*2}-nz^{*2}\right)^2}\right)}{2\pi R^{*3}\sqrt{4\pi^2 z^{*4}R^{*2}+\left(d^{*2}-nz^{*2}\right)^2}} \tag{14}$$

  and it is drawn in Figure 4 as a function of the, normalized over the wavelength, distance along the pipeline axis z^*, for different values of the independent variables n, d^*. Similar nomograms can be produced for all strain components, and for all 8 characteristic points of the cross-section.
- From the nomograms drawing the distribution of all strain components along the pipeline, it emerges that the maximum normalized strain is not a function of the normalized distance d^*, and that the position z^*_{max} along the axis of the pipeline where this maximum occurs appears to be independent, or in other cases, linearly dependent to the normalized distance d^*. Thus, we can

"graphically" estimate the overall maximum value of the normalized strain, along the whole length of the pipeline, which we call "Correction Factor" (or CF[ε_i]), and the position of this maximum from the ratio z_{max}/d. The variation of these values with the attenuation exponent n shows that linear semi-logarithmic expressions can be established for each correction factor. These relations, for values of the attenuation exponent 1.5<n<3 that correspond to common ground conditions (TM5-885-1, 1998), are presented in Table 2, and are proposed for the design of the pipeline.

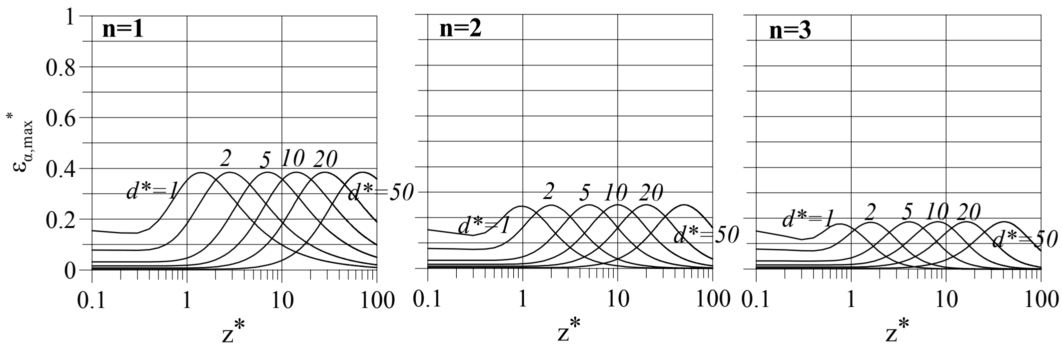

Figure 4. Distribution of maximum (over time) normalized axial strain along the pipeline axis, for different ground attenuation exponents and distances from the explosion.

Table 2. Simplified design relations

	P-wave	
strain component	CF[ε_i]	z_{max}/d
axial	-0.195lnn+0.392	-0.66lnn+1.489
shear	-0.162lnn+0.758	-0.177lnn+0.7
hoop	1	0
	Rayleigh wave (for k=1.1677)	
strain component	CF[ε_i]	z_{max}/d
axial	-0.133lnn+0.267	-0.661lnn+1.489
shear	-0.11lnn+0.516	-0.176lnn+0.697
hoop	0.694	0

COMPARISON WITH FIELD TESTS AND CURRENT PRACTICE

Validation of the proposed methodology is attempted through comparison to actual pipeline strain measurements due to full scale blasts, performed by Siskind et al. (1994) to monitor the effects of coal mine overburden blasting on nearby pipelines. Results from 29 blasts of up to 950kg per delay are shown in Figures 5a & 5b, in terms of measured axial and hoop strains in 2 of the tested buried pipelines: one 50.8cm diameter, 6.63mm wall thickness steel pipeline and one 21.9cm PVC pipeline with 8.43mm wall thickness, located at distances from 20m to 1064m from the nearest blast source of each test. These 2 pipelines were selected out of a total of 5 pipelines installed during the test blasts, since they are the only ones for which the flexibility criterion (Eq 2) is met, as noted by Siskind et al. (1994). Local soil conditions consist of a 12-m deep shale layer, covered with a 2-m layer of clayley soil. The pipelines were buried under 1m of excavated clayley soil, while the depth of detonation varied from 13m to 20m.

The proposed analytical expressions for the calculation of axial and hoop strains due to Rayleigh waves (Table 1) were employed for each blast test, as more appropriate for the distances considered. The case-specific attenuation relation derived by Siskind et al. (1994) was used for the calculation of the peak particle velocity at the position of the pipeline, namely:

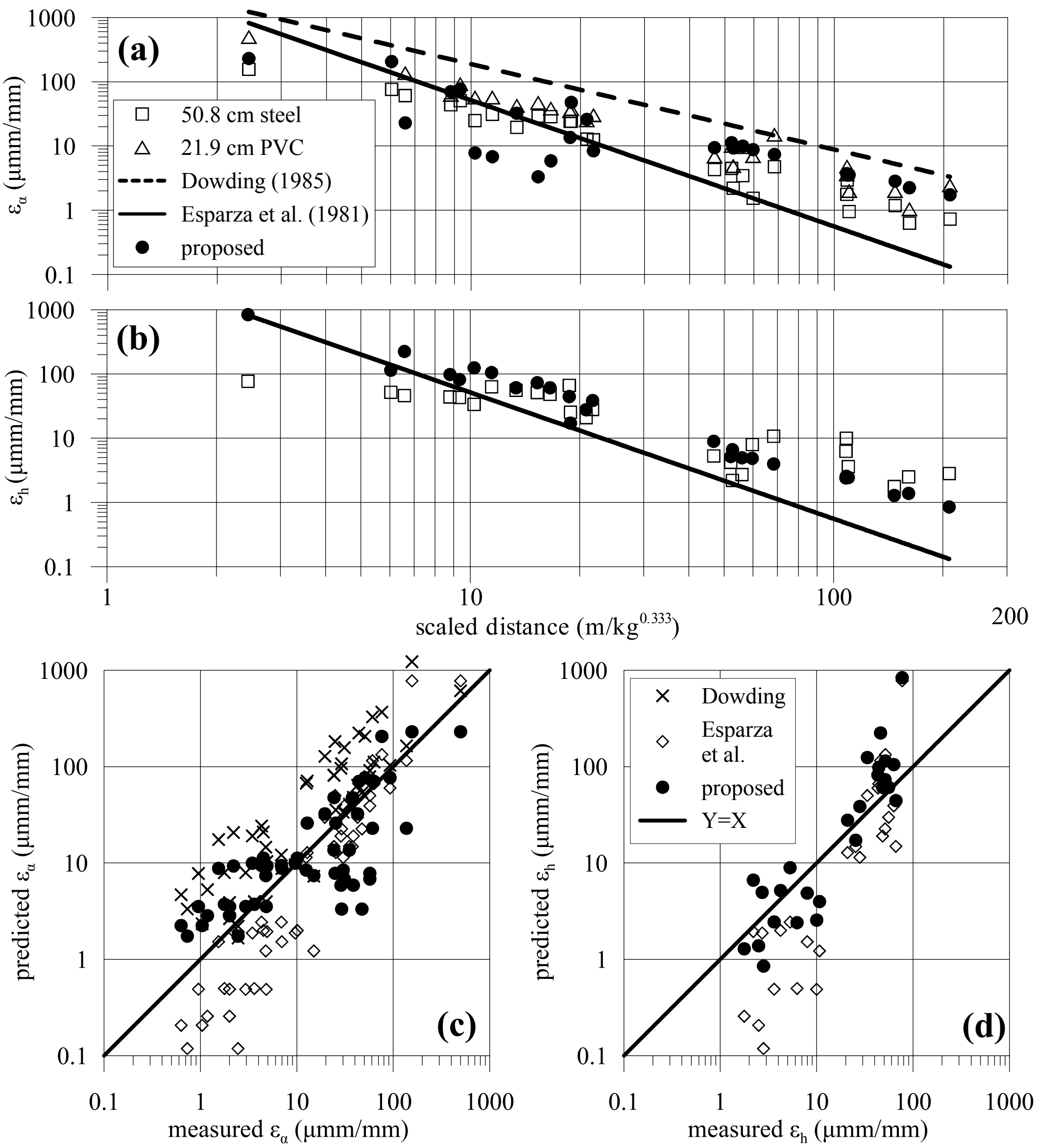

Figure 5. Comparison of the results of the proposed methodology and of the current state-of-practice, with field strain measurements presented by Siskind et al. (1994).

$$V_{\max}(m/\sec) = 3.22 \cdot \left(\frac{R}{W^{0.333}}\right)^{-1.33} \tag{15}$$

where R is the distance from the nearest blast hole (in m) and W is the charge per delay (in kg). The peak particle displacement A_{max} was calculated from the peak particle velocity using the following expression, valid for harmonic waves:

$$A_{\max} = \frac{L_R}{2\pi} \cdot \left(\frac{V_{\max}}{C_R}\right) \tag{16}$$

where the Rayleigh wave propagation velocity in shale, C_R, was taken to be equal to 800m/sec, while the wavelength L_R, was considered equal to 40m, based on the mean frequency content of the strong motion recordings reported by Sisking et al. (1994).

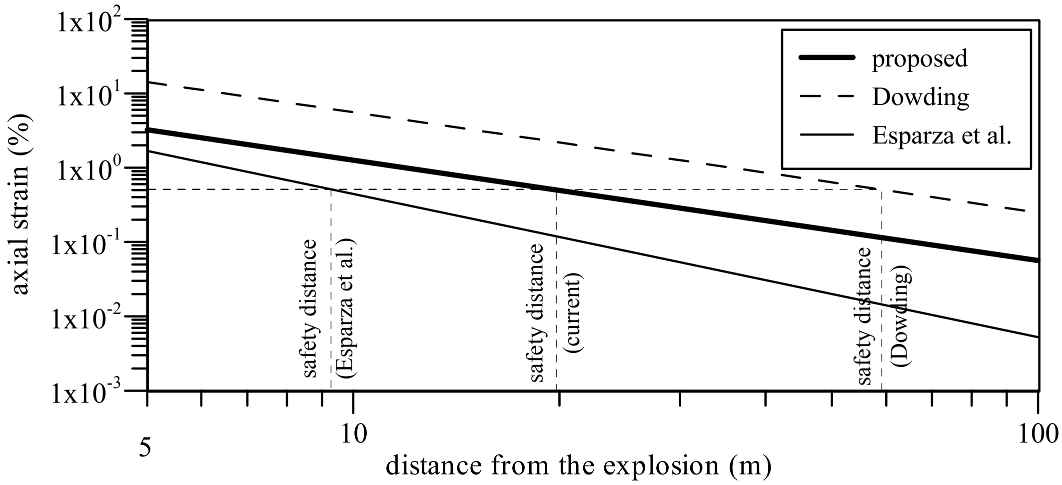

Figure 6. Comparison of the results of the proposed methodology and of the current state-of-practice for the fictitious case of a 50.8 cm steel pipeline constructed in wet clay.

Axial and hoop strains measured in the field and calculated by the proposed methodology are drawn in Figures 5a & 5b respectively, against the scaled distance of the pipeline from the nearest source blast, while their correlation is illustrated in Figures 5c & 5d, in an one-on-one comparison. In addition to the proposed methodology, strains on the pipelines are computed using the empirical relation proposed by Esparza et al. (1981) for single-point source, as well as the simplified expression adopted by Dowding (1985). The exact relations and the input data used for these parallel predictions are given in the Appendix. From Figure 5 it is observed that results of the proposed methodology are in general compatible with the experimental measurements. On the other hand, the expression adopted by Dowding (1985) provides an upper bound of measured axial strains, while the empirical expression of Esparza et al. (1981) provides reasonably accurate results for relatively small scaled distances ($<20\text{m/kg}^{0.333}$), but underestimates axial and hoop strains thereafter.

To further investigate the potential effect of local soil conditions on pipeline strains, let us consider the fictitious case where the 50.8cm steel pipeline considered in Siskind et al. (1994) experiments is constructed near the surface of a wet clay layer, with C_s=250m/sec, and is subjected to a series of point source detonations of 1000 kg TNT in distances of 5, 10, 20 and 100m from the pipeline. Calculation of pipeline strains with all three methodologies follows the same workflow as described above. However, attenuation of the peak particle ground velocity in this case is much slower compared to the soft rock formation encountered in Siskind et al. experiments. Namely, for detonation of 1000kg of TNT in wet clay the peak particle velocity is computed as (TM5-855-1, 1998):

$$V_{\max}(m/\sec) = 16.08 \cdot \left(\frac{R(m)}{730^{0.333}} \right)^{-1.35} \tag{17}$$

The comparison of predicted axial pipeline strains is shown in Figure 6. Observe that the expression proposed by Esparza et al. (1981) underestimates the maximum strains, for the whole range of distances of the pipeline from the explosion source. This is expectable, as the measurements on which the Esparza et al. empirical methodology is based on were conducted in a rock site, similar to that of the Siskind et al. (1994) experiments, where the ground shock amplitude levels are considerably lower than in the wet clay. For example, at 20m from the explosion source the peak particle velocity would reach 1.11m/sec in the soft rock site (Eq 15) and 5.45m/sec in the wet clay (Eq 17), exhibiting a five-fold increase.

On the contrary, Dowding's (1985) approximate method provides, as in the comparison with real field data, over-conservative results. For example, axial strains computed with the proposed methodology are about 4.4 times smaller than these computed according to Dowding (1985). Taking into account that the peak particle velocity in both sets of predictions is calculated by the same expression (Eq. 17), it may be concluded that the observed divergences are attributed to the fact that Dowding's analytical expression for axial strain does not account for the wave spherical front.

A feeling of how important such differences may become is obtained when the different methodologies are used to back-calculate the safety distance of the pipeline from the presumed explosion (Figure 6). Supposing that the steel pipeline under consideration is constructed with peripheral in-situ welds, the maximum axial strain on the cross-section should not exceed 0.5%. For that strain limit, the safety distance to meet this requirement according to the results of the proposed methodology is 20m, while it increases to 60m, i.e. a three-fold increase, when Dowding's expression is adopted (Figure 6).

SUMMARY AND CONCLUSIONS

An analytical methodology to calculate blast-induced strains in buried pipelines has been presented, employing 3-D thin elastic shell theory in the analysis of the structure. Compared to existing analytical and empirical methods, the proposed one takes consistently into account the special characteristics of blast-induced ground shock waves i.e. the spherical front and the soil-dependant exponential attenuation of their amplitude with the distance from the source. Simple design relations are provided to aid the practical application of the method.

The proposed relations have been evaluated against field measurements of blast-induced axial and hoop pipeline strains reported in the literature. In addition, a thorough comparison was made with two methods frequently used in current practice: these of Dowding (1985) and Esparza et al. (1981). In conclusion, it was found that the proposed method has achieved improved accuracy at no major expense of simplicity. In comparison, Dowding's methodology, which was originally developed for seismic waves with a plane instead of a spherical front, provides consistently higher estimates of axial pipeline strains. On the other hand, the empirical methodology of Esparza et al. provides comparable predictions for relatively short distances from the blast and stiff-dry ground conditions, simulating the conditions prevailed in the field experiments which were used to calibrate the method. Nevertheless, it may considerably underestimate pipeline strains for longer distances, or wet soil conditions where the ground shock attenuation becomes slower.

APPENDIX - CALCULATION OF STRAINS WITH THE CURRENT DESIGN PRACTICE

Calculation of strains using the methodology proposed by Esparza et al. (1981)

Esparza et al. (1981) suggest that axial and hoop stresses on steel pipelines due to nearby blasts can be computed using the following empirical relation, derived from the statistical evaluation of a series of field tests for single and multi-shot blasts:

$$\sigma = 4.44 \cdot \mathrm{E}_l \left(\frac{\mathrm{K}_4 W_{eff}}{\sqrt{E_l \cdot t_s} R^{K_5}} \right)^{K_6} \tag{Ia}$$

where E_l is the Young's modulus of steel (in psf), t_s is pipe wall thickness (in ft), W_{eff} is the effective weight of the explosives (in pounds), accounting for the orientation of the explosives relatively to the pipeline, R the distance between the pipe and the explosives, greater than 2 pipe diameters and K_i empirical coefficients. The problem examined herein, due to the delayed-type blasts, corresponds to the single-point source case of Esparza et al.'s relation, as also remarked by Siskind et al. (1994), so Eq Ia becomes:

$$\sigma = 4.44 \cdot 4.393 \cdot 10^9\, psf \left(\frac{1 \cdot \left(0.98 \cdot 2207.5\, pounds\right)}{\sqrt{4.393 \cdot 10^9\, psf \cdot 0.0328 ft} \left[R\left(ft\right) \right]^{2.5}} \right)^{0.77} \tag{Ib}$$

The strains corresponding to the stresses computed from Eq Ib are presented in Figures 5a & 5b, and are correlated to measured strains in Figures 5c & 5d, next to results of the proposed methodology.

Calculation of strains using the methodology proposed by Dowding (1985)

For the calculation of blast-induced axial strains Dowding (1985) adopts the following approximate expression, originally proposed for the seismic verification of buried pipelines and tunnels (Newmark, 1968):

$$\varepsilon_{\alpha} = {V_{\max}}\big/{C} \qquad \text{(Ic)}$$

where V_{max} is calculated from Eq 15 and C=800m/sec. Axial strains calculated from Eq Ic are presented in Figure 5a and compared to the field measurements in Figure 5c.

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