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Strength analysis of buried pipes under explosive loads

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Abstract

Three-dimensional FEM models concerned with the transient response and relevant strength analysis of buried structures due to blast explosions were proven extremely costly using conventional FEM codes. This is due to the required small time-step as well as the considerable extension of the problem domain that has to be chosen so long that no reflection is allowed from the artificial infinite soil boundaries before the maximum displacement (or Von Mises stress) amplitude of the structure is reached. In case of buried pipelines, the complexity increases because the length of the model should at least include the unknown wave length along the pipeline. To overcome this problem, a reduced model taking into consideration the decoupled incident P- SH- and SV-waves, has been developed. The new theory achieves a manageable conservative relationship between the strength of the buried pipeline and the allowable peak particle velocity. The proposed relationship is based on the criterion of either the hoop or Von-Mises stresses and it is given in terms of the allowable stress as a percentage of the Specified Minimum Yield Stress (SMYS) of the pipeline. An example is given for a buried high-pressured natural gas pipeline.

1 Introduction

Transient response and relevant strength analysis of buried structures due to blast explosions is usually carried out through complicated and costly three-dimensional soil-structure interaction FEM models using well known nonlinear oriented and general-purpose FEM codes, such as ABAQUS [1], LS-DYNA3D [2], e.t.c. or specific two-dimensional FDM codes, such as FLAC [3], e.t.c. Generally, in order to obtain reliable results, it is necessary to choose a small time-step as well as to define a significant problem domain, so that no reflection is allowed from the artificial infinite soil boundaries before the maximum displacement (or Von Mises stress) amplitude of the structure is reached. For the case of buried pipelines, the complexity increases because the length of the model should at least include the unknown wave length along the pipeline.

As a result, full models using conventional FEM codes are extremely costly to analyse a large number of test cases and determine critical safety distances far from high pressured buried pipelines transporting natural gas in several types of soil conditions. Under these circumstances, a simple conservative model is required for fast decision making, upon request.

To the best of our knowledge, some basic formulas may be found in classical textbooks, such as Dowding [4], but the general case of an arbitrarily directed incident wave towards a pipeline is not covered. In that book it is pointed out that, the frequency, type of structure, and materials justify both higher and lower limits than the traditional vibration criterion of $\dot{u}_{max} = 50\,\text{mm/sec}$ peak particle velocity that has been suggested by the U.S. Bureau of Mines (RI 8507) for residential structures near explosion sites. For instance, Siskind and Stagg [5] have carried out experiments on a Grade B pipeline and found that peak particle velocity of 127 mm/sec produced strains about one-fourth of pressurization and 10% to 18% of the ultimate strength.

In this paper, a conservative model is proposed for the efficient determination of the allowable peak particle velocity, so that the integrity of the structure is reserved. This model is based on the decoupling of reduced models (of a few degrees of freedom) taking into consideration the incident P- SH- and SV-waves. It is much easier to define firstly the peak particle critical velocity and then the distance from the explosion where it appears [10], instead of carrying out a full soil-structure interaction calculation.

2 Soil structure interaction - critical wall thickness

The hardest case to apply an analytical procedure for the strength analysis of a pipeline under explosive loads is when the pipeline is relatively thin and therefore follows the soil motion. So, it is necessary to establish the critical pipe wall thicknesses, for typical nominal pipe sizes.

According to Burns and Richards [7], on account of the interaction between the soil and the structure, the resulting thrusts and moments are affected by:

- the Compressibility Ratio "C", which is a measure of the extensional stiffness of the medium relative to that of the liner,
- the Flexibility Ratio "J", which is a measure of the flexural stiffness of the medium (K_{soil}) relative to that of the liner $\left(K_{pipe}\right)$, and
- the Slippage which takes place at the interface between the structural liner and the medium.

The most important parameter for the soil structure interaction is, certainly, the Flexibility Ratio J:

$$J = K_{soil} / K_{pipe} \tag{1}$$

where

$$K_{soil} = \frac{E_{soil}}{1 + \nu_{soil}} \qquad K_{pipe} = 6 \cdot \frac{E_{pipe} \cdot I_{pipe}}{1 - \nu_{pipe}^2} \cdot \frac{1}{r_{pipe}} \tag{2}$$

with E_{soil} and E_{pipe} denoting the moduli of elasticity, ν_{soil} and ν_{pipe} the Poisson's ratios, r_{pipe} the nominal pipe radius, and I_{pipe} the moment of inertia:

$$I_{pipe} = t^3 / 12 \tag{3}$$

It has been shown that if $J > 10$, the pipe is adequately flexible and follows the soil movement.

Combining the above eqns (1) to (3) in conjunction with typical soil properties:

$E_{soil} = 1153 MPa$ and $\nu_{soil} = 0.25$

and the well known material properties of steel pipelines:

$E_{pipe} = 210000 MPa$ and $\nu_{pipe} = 0.30$

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one receives:

$$t_{pipe} = \sqrt[3]{8{\cdot}10^{-4} \cdot r_{pipe}} \tag{4}$$

By applying eqn (4) for several nominal diameters (pipe sizes) one may obtain the following Table 1.

Table 1. Critical wall thicknesses according to eqn (4)

Pipe size (inches)	Critical Wall Thickness (mm)
36	71.5
30	67.3
24	62.5
18	56.8
16	54.6
10	46.7

3 Pipe Stresses

For conservative purposes the following assumptions are made:

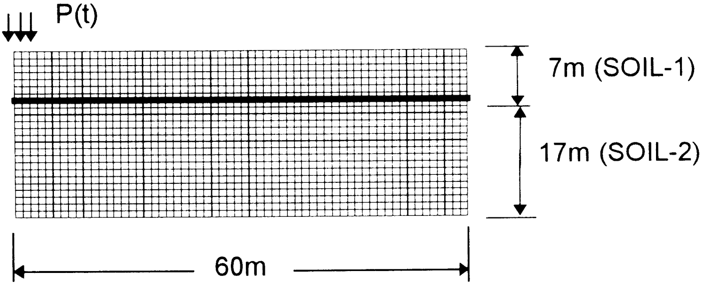
- The pipe follows the soil motion.
- The incident P- and SV/SH-waves are assumed to operate simultaneously. This is sustained by numerous FEM results that lead to soil velocities in phase as, for example, it is shown in Figure 1.

3.1 Hoop stress

Hoop stresses on the pipe consist of the following three terms:

- Internal Pressure action [6]: $F \cdot \sigma_{yield}$ (5)
- P-wave action [4]: $1.15 K \rho c_L \dot{u}_{max}$ (6)
- SV-wave action [4]: $E_{pipe} \dot{u}_{max} / 2c_S$ (7)

where F is the construction type Design Factor varying between 0.40 and 0.72 [6], σ_{yield} is the Specified Minimum Yield Stress (SMYS) of the pipe, K is the longitudinal stress magnification factor, ρ is the soil density, c_L is the P-wave velocity, $\dot{u}_{max}$ is the maximum peak particle velocity, c_S is the S-wave velocity and E_{pipe} is the elastic modulus of the pipe.



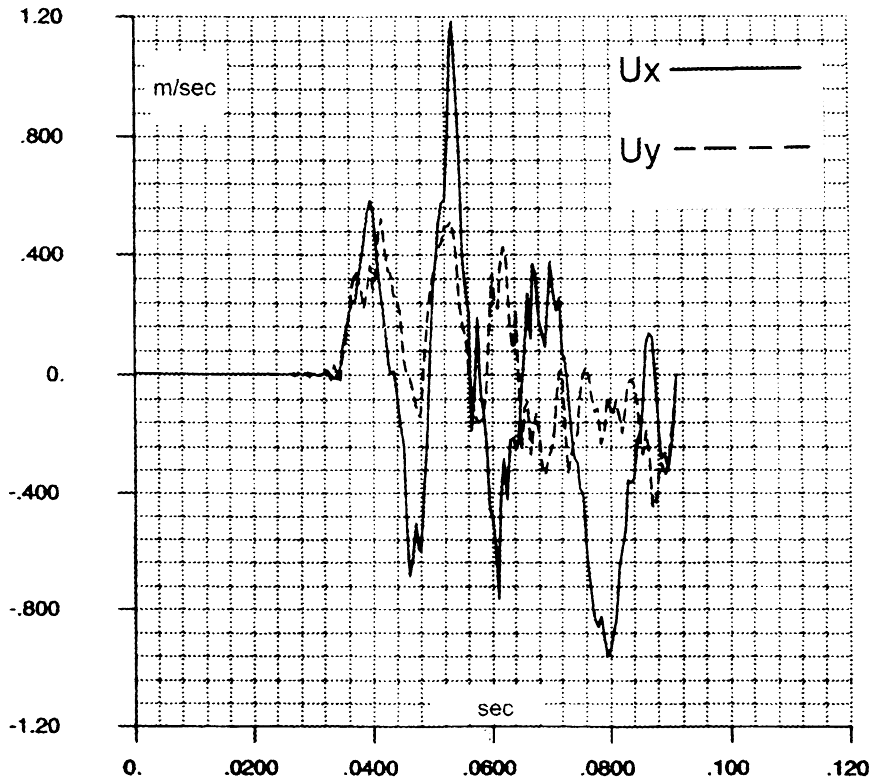


Figure 1: Particle velocity components for a distance of R=40m from the center of the explosion (Ux: horizontal, Uy: vertical). Results were obtained using an ABAQUS-FEM axisymmetric soil model (1440 quadratic and 25 infinite elements) of two layers with properties: SOIL-1 $(c_L = 796 m/sec, c_S = 463 m/sec)$ SOIL-2 $(c_L = 1378 m/sec, c_S = 713 m/sec)$.

3.1.1 The longitudinal stress magnification factor K

The factor K in eqn (6) expresses the maximim stress on the pipe that is produced by the uniform static pressure $p_L = \rho c_L \dot{u}_{max}$ due to incident longitudinal or, in other words, P-waves. For example, to only give an idea about its probable magnitudes, it is well known from basic engineering mechanics, that for the extreme case of a uniform external pressure directed perpendicularly to the boundary of the pipe, the factor K equals to the ratio of pipe diameter D to twice the wall thickness t $\left(K = D/2t\right)$.

Of course, the above mentioned factor is not our case, because the external pressure is not perpendicular but it is approximately parallel to a specific direction, such as the ground surface or otherwise. In our case, when the wave length of the incident longitudinal P-wave is of the order of the pipe diameter, then it creates some instantaneous supports on the pipe. Numerous FEM calculations have shown that the factor K is dependent on both the position and the type of these boundary conditions as well as on the relation between D and t [9]. For example, for a typical natural gas transmission pipe the diameter of which is less than 1m (i.e., close to the one-fourth of the wave-length that corresponds to the period of Figure 1), with a factor $\left(K = D/2t\right)$ around 30, it was found that two symmetrical simple pipe supports behind the wave front may increase that as follows:

- For simple supports at $\pm 45^\circ$ to approximately $K=1000$
- For simple supports at $\pm 90^\circ$ to approximately $K=500$

3.2 Axial stress

Moreover, axial stresses of the pipe consist of the following two terms:

- Internal Pressure action: $F\sigma_{yield}/2$ (8)
- SH-wave action: $\pm E_{pipe}\dot{u}_{max}/2c_S$ (9)

The above axial stresses do not include bending stresses because, after a certain distance from the explosion, these become negligible compared with the rest ones [8]. At this point it should be noted that the action of the SH-wave may be additive, negative or neglective to the action of the internal pressure. Generally, it depends on the phase difference between the incident waves.

By comparison of eqns (5-7) with eqns (8,9) it becomes evident that the resultant hoop stress always exceeds the resultant axial stress.

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4 Criteria for establishing the maximum allowable peak particle velocity

This study is based on two alternative criteria concerning the strength of the pipe. The first refers to the resultant *hoop* stress and the second to the *Von Mises* stress. In both cases the maximum induced stress should not exceed the allowable stress $\sigma_{allowable}$ that may be defined as a percentage ξ of the yield stress, that is:

$$\sigma_{allowable} = \xi . \sigma_{yield} \tag{10}$$

4.1 Hoop stress criterion

Starting from the assumption that the resultant hoop stress should not exceed the allowable stress $\sigma_{allowable}$ of eqn (10), one receives the following critical value:

$$\dot{u}_{max} = \frac{(\xi - F)\sigma_{yield}}{\dfrac{E_{pipe}}{2c_s} + 1.15 K \rho c_L} \tag{11}$$

4.2 Von Mises stress criterion

Since the high-pressured natural gas pipeline is made of a ductile material (e.g., X65, X60, X52), the Von Mises criterion is applicable for its strength. It is well known that for a two-dimensional (bi-axial) state the Von Mises stress is given by the formula:

$$\sigma_{VonMises} = \sqrt{\sigma_{axial}^{2} + \sigma_{hoop}^{2} - \sigma_{axial}\sigma_{hoop}} \leq \sigma_{allowable} \tag{12}$$

which should be applied for three different cases with respect to the phase difference of the incident SH-wave in eqn (9) that affects the axial stress component σ_{axial}. Eqn (12) should be also combined with eqns (5-9) and finally the critical peak particle velocity $\dot{u}_{max}$ is calculated as the positive root of the binomial:

$$A\dot{u}_{max}^{2} + B\dot{u}_{max} + G = 0 \tag{13}$$

with

$$A = a_2^2 + a_3^2 - a_2 a_3 \quad , \quad B = \frac{3}{2} a_1 a_3 \quad , \quad G = \frac{3}{4} a_1^2 - \sigma_{allowable}^2 \tag{14}$$

where the above constants are given by:

$$a_1 = F \cdot \sigma_{yield} \quad , \quad a_2 = \pm \frac{E_{pipe}}{2c_s} (or\, 0) \quad , \quad a_3 = \frac{E_{pipe}}{2c_s} + 1.15 K \rho c_L \tag{15}$$

5 Results for straight pipelines

Let us assume a natural gas transmission pipeline of nominal diameter 36″ (D=762mm), made of X65, in Class location 2 that corresponds to a design factor $F = 0.60$ [6], with nominal wall thickness $t = 12.7mm$, under design pressure $p = 70bar\,(7MPa)$. According to the ASME/ANSI Code B31.8 [6], the Specified Minimum Yield Stress (SMYS) equals to $\sigma_{yield} = 65{,}000psi \cong 448MPa$.

First of all, one can notice that the nominal wall thickness (12.7mm) is 5.6 times smaller than the critical value in Table 1. So, it is sure that the pipeline follows the motion of the soil.

In this case, a static FEM analysis of a cross section under uniform pressure $p_0 = 1MPa$ using 384 elements arranged in three layers along wall thickness (Figure 2), provides a stress magnification factor $K = 553$. Using eqns (11) and (13) in conjunction with typical soil properties $\left(\rho = 2100kg / m^3, c_L = 796m / sec, c_s = 463m / sec\right)$ for a variety of allowable stress in terms of SMYS, the following Table 2 is obtained.

Table 2. Maximum Peak particle velocity $\dot{u}_{max}(mm / sec)$

Percentage (ξ) of SMYS	Based on Hoop stress	Based on Von Mises stress	
		Minimum	Maximum
67%	24.3	56.7	59.4
80%	69.5	102.5	109.8
90%	104.2	136.5	148.3
100%	138.9	170.1	186.6

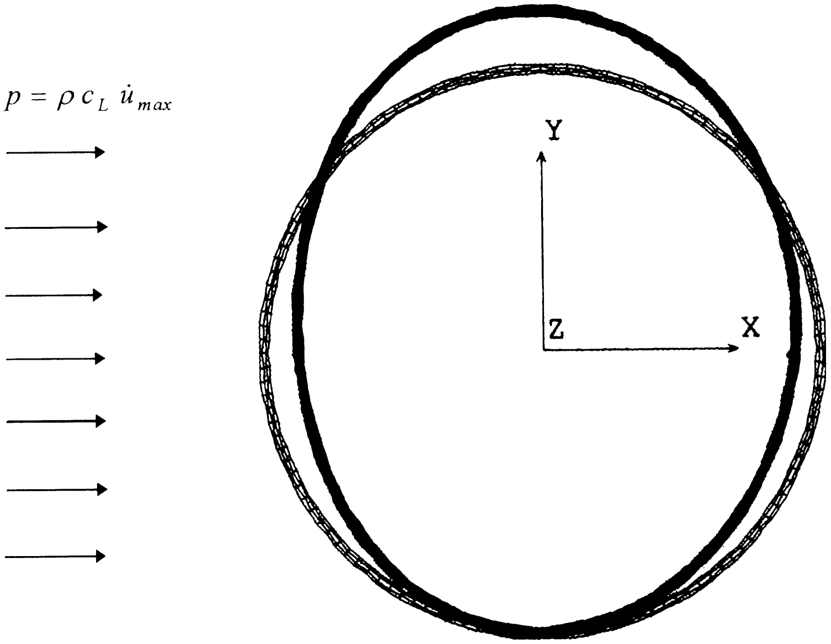

Figure 2: Finite element mesh and deformation of a pipe cross section for the case of an incident longitudinal P-wave.

6 Conclusions

A conservative reduced model was developed for the efficient determination of the maximum allowable peak particle velocity on a buried pipeline under explosive loads. The model was based on the fact that:

(a) the pipeline follows the soil motion

(b) incident waves operate simultaneously

(c) the total maximum hoop or Von Mises stresses (including pressurisation) should be lower than the allowable stress, that was expressed as a percentage of the Specified Minimum Yield Stress (SMYS).

The method was applied for the case of a high-pressured natural gas transmission pipeline of size 36 inches, where maximum allowable peak particle velocities were found to vary between 24 and 187mm/sec, depending on both the stress criterion and the allowable percentage of SMYS.

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