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Strength analysis of buried curved pipes due to blast explosions

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Abstract

With the advent of new low-cost and powerful computers and explicit time-integration FEM codes, three-dimensional models are now available for the transient response analysis of buried structures due to blast explosions in their proximity. In the industrial domain, a most interesting issue is to determine the critical distance between the center of the explosion and the buried structure in order to insure its integrity. In the present paper a systematic study is presented on the stresses induced to buried pipelines, focussing on their curved parts such as elbows and tees. In more detail, it was examined whether the curved parts of a pipeline suffer more compared to the straight parts. For the purposes of the present study, the distance from the center of the explosion, the depth from the ground surface and the impulse of the explosion are considered to be fixed. On the contrary, the shape of the pipeline is variable, as well as the relative position of the pipeline with respect to the center of the explosion. The entire analysis was based on a 3D explicit code (LS-DYNA, version 950). The main outcome of the study is that in all cases taken into account, the equivalent von Mises stresses exerted on the curved parts are either smaller or at most equal to those exerted on the straight parts of the structure. The numerical results lead to the conclusion that for fast and safe decision making, the curved parts of a pipeline may be ignored. Nevertheless, a more thorough investigation is required in order to extend this conclusion to other cases where the radius of curvature is different than the one chosen for the needs of the present study. Finally, the influence of other parameters, such as the impulse characteristics, the soil layer characteristics, the depth, the backfill etc, should also be further examined.

1 Introduction

Shock effects on buried structures are of most importance in mechanical and civil engineering. An elementary theory is reviewed by Dowding [1], while the computational approach may be achieved either by decoupling procedures [2,3] or by the Finite Element Method (FEM). In previous FEM studies [4,5] it was found that when implicit codes, such as [6], are applied to three-dimensional models, tremendous computer effort is required (e.g. more than one week), especially when powerful computers are not available. On the contrary, when a usual dual PC (2x128 MB RAM, 400 MHz) is available, explicit FEM codes, such as LS-DYNA version 950 [7], are capable of solving a 3D problem of 60,000 elements and 65,000 nodes within 36 hours, while smaller models can be computed within 15hrs or even 8 hrs.

This paper presents three-dimensional FEM-results concerning a blast explosion taking place at a distance of 20m away from a buried pipeline, which is considered to be suitable for natural gas transmission. In more detail, it is assumed that the explosion takes place on the ground surface, while the pipeline may be straight, T-shaped or with an elbow (the location of the explosion and the orientation of the pipeline are well defined in each case). However, as the main aim is to compare the stresses induced to a straight pipeline with those induced to a curved pipeline (pipeline with an elbow or a Tee), the internal pressure is not taken into account.

Using the previously mentioned 3D FEM code, the peak particle velocities near the exterior wall of the pipeline are calculated, as well as the equivalent von Mises stresses. The ultimate goal of this approach is to state a qualitative relation between the maximum stresses on the straight and on the curved parts of a pipeline. As it will be shown, such a relation can be established and is of most importance for fast and safe decision making.

2 Theoretical background

An explosion on the ground surface initiates the propagation of P-, SH- and SV-waves [4]. Due to these waves, a buried structure, like a pipeline, experiences a dynamic loading, which is added to the static loading of the structure. Without loss of generality, it can be said that the shape of the structure in combination with wave reflection and refraction introduces a severe complexity in obtaining an analytical solution. The quantities of interest in such a study are the peak particle velocity and the equivalent von Mises stresses. It is possible to use either quantity in order to decide whether the structure under examination will not fail.

According to the U.S. Bureau of Mines (RI 8507), for residential structures near explosion sites, the peak particle velocity should be less than

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$\dot{u}_{\max}$ =50mm/sec. This velocity may be calculated by using one of the equations listed in Table 1 (W = amount of explosive). It is emphasized that these equations do not take into account the existence of any buried structure.

Table 1: Analytical equations for the estimation of the peak particle velocity.

All Field solution (Hinnman) [8]	$\dot{u}_{\max} = \chi \cdot 0.47 \cdot \left(\frac{W^{n/3}}{R^n} \right), \quad n = 2.5$
The α-model (Kanarachos and Provatidis) [5]	$\dot{u}_{\max} = \chi \cdot \alpha \cdot \left(\frac{W^{n/3}}{R_\alpha{}^n} \right), \quad n = 1.6$

Another alternative for the calculation of the peak particle velocity is to model the soil layers involved without the structure under examination and to examine the values of the peak particle velocity at the area of interest. In either case, the maximum value should be less than 50mm/sec. Although is has been shown that this value may be exceeded [1], it is suggested that for a first approximation one should use the above-mentioned limiting value.

Finally, as a third option, in order to check the integrity of the structure, one may calculate the maximum equivalent von Mises stress, by using FEA, and compare it with the allowable stress.

With respect to closed formulas, for the case where wave propagation occurs perpendicular to the long axis of the pipe, there are analytical equations only for the calculation of the hoop stresses, although a *conservative* approach of the axial stresses can also be achieved [4]. According to Dowding [1], it holds:

$$\sigma_{hoop} = 1.15 \cdot K \cdot \rho \cdot c_L \cdot \dot{u}_{\max} \qquad [1]$$

where K is the longitudinal stress magnification factor, ρ is the soil density, c_L is the P-wave velocity and $\dot{u}_{\max}$ is the maximum peak velocity.

3 Numerical Model

The FEA models used for the purposes of this paper consist of the first layer of the ground (SOIL-1), the second layer of the ground (SOIL-2) and the pipe itself. Both soil layers were modeled with (1x1x1) brick elements (units in meters), while the mesh was finer for the sections of the soil surrounding the curved parts of the pipe. The pipe wall was divided in two layers along the radial direction and in sixteen segments along its circumference. The data for the soil layers are given in Table 2, where the data for the pipe are given in Table 3.

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Table 2: Material and geometrical data for the soil layers.

Quantity	Soil-1	Soil-2
Young's Modulus E (MPa)	1,153	3,050
Poisson's ratio ν	0.25	0.3
Density ρ (Kg/m^3)	2,100	2,300
Yield stress σ_{yield} (MPa)	0.64	6.5
Velocity c_L (m/sec)	796	1,378
Depth (m)	7	17

Table 3: Material and geometrical data for the pipe.

Quantity	Value
Nominal Diameter (mm)	762
Wall thickness (mm)	12.7
Young's modulus E (MPa)	210,000
Density ρ (Kg/m^3)	7,800
Poisson's ratio (ν)	0.25
Yield stress σ_{yield} (MPa)	448
Radius of curvature [only for elbow] (m)	3
Distance from explosion (m)	20
Depth (m)	2

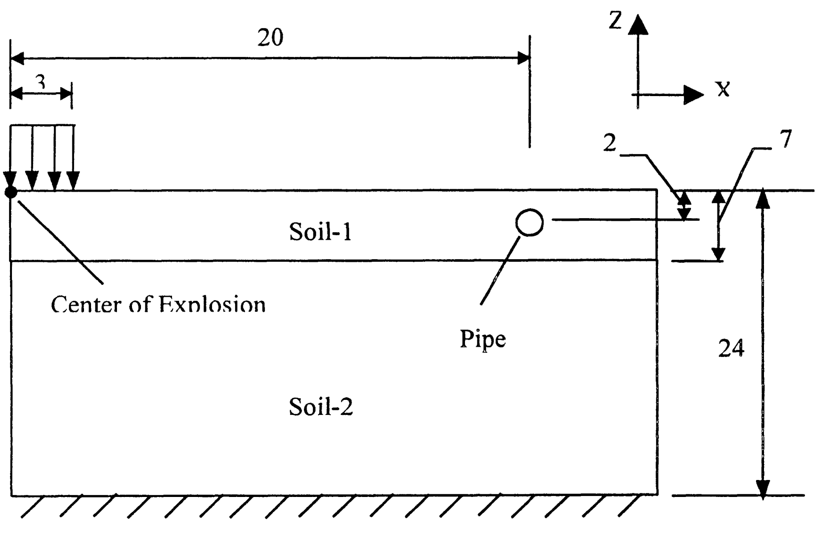

Figure 1: Basic geometry of soil layers, pipe and center of explosion.

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It is clarified that the "distance from the explosion" is measured from the center of the explosion to the centerline of the pipe, while the depth equals the distance of the centerline of the pipe from the ground surface (see Figure1).

The explosion was simulated as a triangular pressure impulse, which was applied on a circular area of radius R=3m. The maximum value of 400MPa occurred at t=1msec, while the duration of the impulse was 5msec. This gave a total impulse of 1000MPasec. It is noted that such an impulse corresponds to the explosion of 20,000Kg of smokeless gunpowder, which corresponds to W=36,600lbs TNT equivalent. As far as the boundary conditions are concerned, the nodes on the bottom of the second soil were fixed, while the nodes on the x-plane through the center of the explosion had the x-degree of freedom restrained. On the other surfaces (the ground surface excluded) non-reflecting 3D boundaries were used. It is also noted that the values for the stresses were calculated at the center of the elements. Finally, the time interval under examination was 120msec.

4 Results

4.1 Case 1: Two soil layers, no pipeline

The most convenient approach is to ignore the existence of the structure and calculate the peak particle velocities in the soil. On the ground surface, the numerical results from such an effort at (x,y,z)=(20,0,0) are the following (in m/sec):

$$\dot{u}_x = 1.47 \quad \dot{u}_y = 0 \quad \dot{u}_z = 1.81 \quad \dot{u}_{tot} = 2.17$$

It is emphasized that these are the maximum values; they do not occur at the same instant. Since the selected plane is a plane of symmetry, the y-component of the velocity must be zero. A quite interesting conclusion comes out from this simple analysis: the choice between the velocity components as the peak particle velocity for further analysis [4] is of great importance. Another point worth mentioning is that the numerical results acquired are in very good accordance with the All-field equation introduced by Hinman [8] as shown in Figure 2. A typical velocity diagram for nodes along the positive direction of the x-axis is shown in Figure 3. Two details are of importance: the consistency between the changes of the x- and z-velocity components (the z-component increases as the x-component increases) and the influence of the fixed boundary (wave reflection and refraction amplifies the signal after approximately 0.64msec from the detonation).

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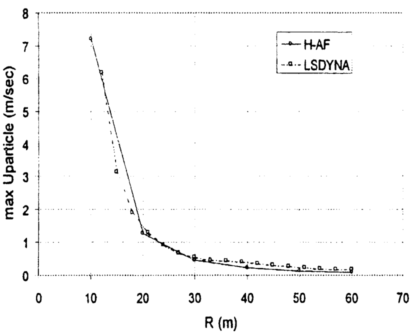

Figure 2: Peak particle velocity versus radial distance from the center of the explosion.

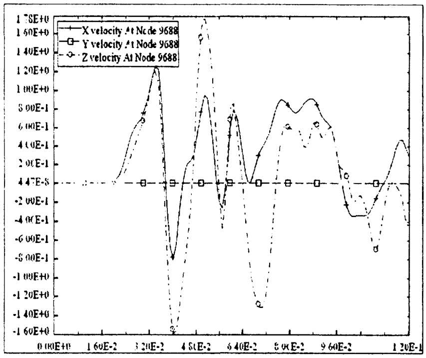

Figure 3: Velocity versus time diagram for nodes on the positive x-axis.

4.2 Case 2: Two soils, straight pipe

Having in mind the previous case, it is interesting to examine how the presence of a straight pipe alters the results.

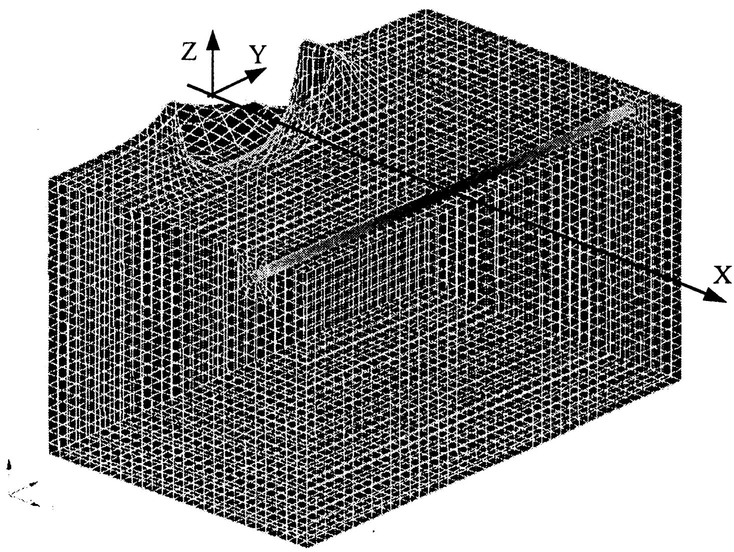

Figure 4: Two soils with a buried straight pipe: principal stress distribution.

It can be easily verified from Figure 4 that the maximum stresses appear on the section of the pipe which lies on the y=0 plane. For this specific section, the maximum equivalent von Mises stresses (for both element layers of the pipe wall) are recorded (Figure 5), as well as the components of the velocity on the outer surface of the pipe (Figure 6).

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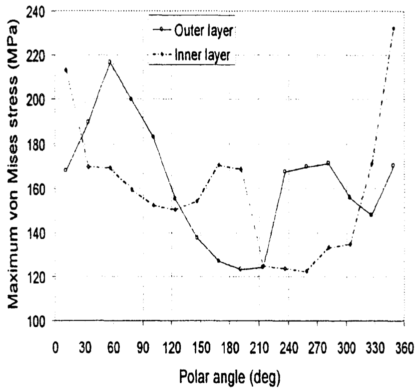

Figure 5: Polar distribution of the maximum von Mises stresses.

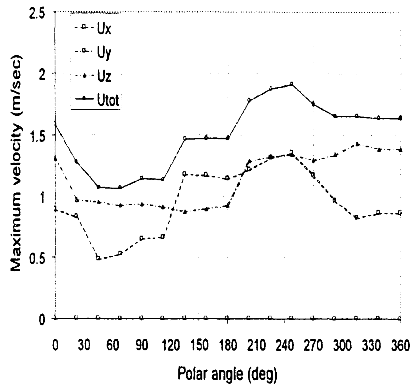

Figure 6: Polar distribution of the particle velocities on the surface of the pipe wall.

It is clarified that the convention used in the previous charts suggests the polar angle be measured by starting from the 'north' position and moving clockwise. Strictly speaking, the maximum value is 233MPa. Furthermore, the maximum velocity on the outer surface of the pipe is (in m/sec):

$$\dot{u}_x = 1.35 \quad \dot{u}_y = 0 \quad \dot{u}_z = 1.43 \quad \dot{u}_{tot} = 1.91$$

The velocity on the ground surface at *(x,y,z)*=(20,0,0) is (in m/sec):

$$\dot{u}_x = 1.48 \quad \dot{u}_y = 0 \quad \dot{u}_z = 1.72 \quad \dot{u}_{tot} = 2.27$$

Therefore, the presence of the straight pipe leaves the maximum *x*-velocity on the ground surface practically unchanged (increment of 0.6%), while it causes a 5% decrease of the maximum *z*-velocity. The maximum total velocity is also increased by almost 5%. In addition, the maximum total velocity on the ground surface is almost 19% larger than the maximum total velocity on the pipe wall.

Substitution of the quantities in eqn.(1) and for the positions at 0°, 90 °, 180 ° and 270 °, gives results with considerable dispersion in *K* as shown in Table 4.

Table 4: Calculation of the longitudinal stress magnification factor *K*.

	0°	90 °	180 °	270 °
x-velocity	41	35	28	41
z-velocity	35	31	24	35
Total velocity	27	23	18	27

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4.3 Case 3: Two soil layers, pipe with curved part (elbow & Tee)

Now, it is interesting to investigate the case of a pipe with a curved part (radius of curvature: 3m) and see how the buried structure behaves with respect to the location of the center of the explosion. For this purpose, three characteristic scenarios (A, B, C) will be examined, as shown in Figure 7. For each case, the same procedure, as previously, will be followed.

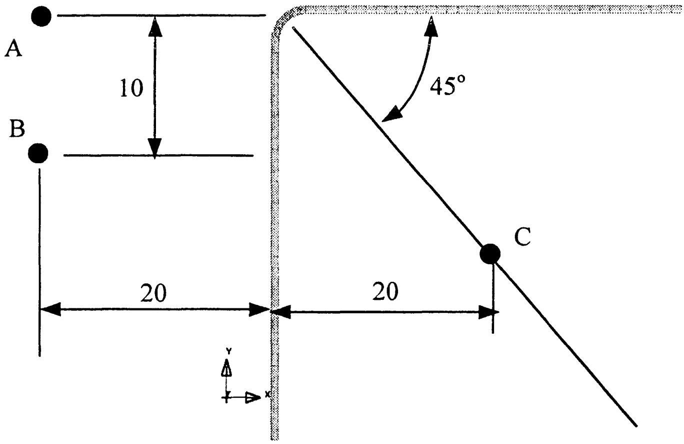
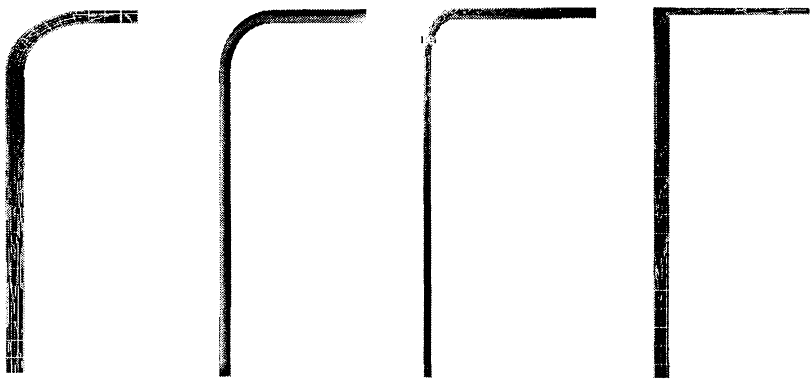


Figure 7: Locations of the center of explosion (cases A, B and C).

The fourth case (case D) is when the pipe has a Tee instead of an elbow and the center of the explosion is located at A. For the four cases under examination, the principle stresses σ_{11} on the pipe are shown in Figure 8.



Case (A) Case (B) Case (C) Case (D)

Figure 8: Distribution of principal stresses (σ_{11}) (cases A through D).

The locations where the stresses are higher are marked with darker contour lines. In the first case, it is clear that the higher stresses do not appear on the elbow. On

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the contrary, the most dangerous for failure section lies near the joint of the elbow with the vertical branch. In the second case, large stresses are developed at the elbow but they do not exceed the stresses which are developed on the section which lies on a plane perpendicular to the centerline of a vertical branch and goes through the center of the explosion. In the third case, clearly smaller stresses are exerted on the elbow while in the fourth case the external part of the Tee (the one facing the explosion) undertakes high stresses. In the following figures, representative charts from the numerical results and for the middle of the curved parts are listed.

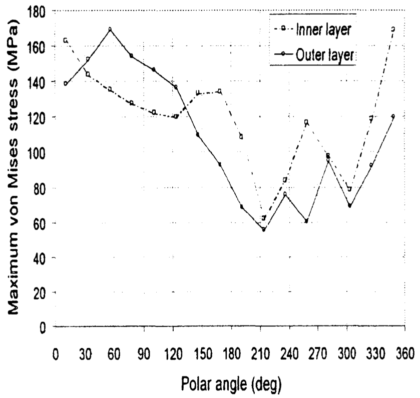

Figure 9: Polar stress distribution (Case A)

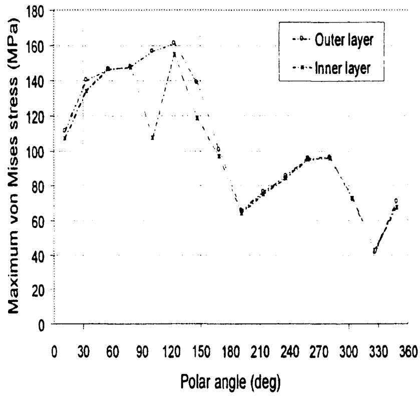

Figure 10: Polar stress distribution (Case B)

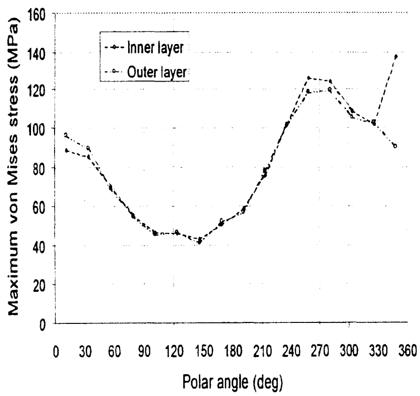

Figure 11: Polar stress distribution (Case C)

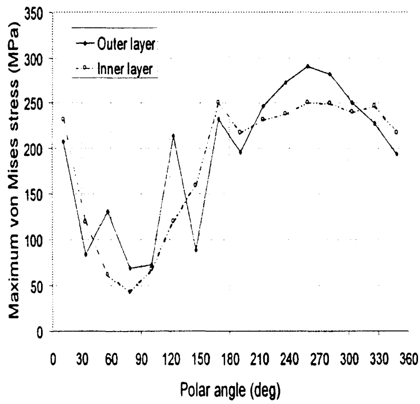

Figure 12: Polar stress distribution (Case D)

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5 Conclusions

The main conclusions of the current study are the following:
1. The curved parts (elbow & Tee) of the pipe do not experience larger stresses than the straight branches. Nevertheless, it is noted that there are cases where the curved parts experience large stresses but not larger than the straight parts.
2. Apart from case A, the most dangerous sections for failure are perpendicular to the centerline of the pipe and lie on planes, which pass through the center of the explosion.
3. The presence of a buried structure alters the peak particle velocity on the ground surface but not dramatically.
4. The maximum equivalent von Mises stress exerted on the structure due to the explosion is quite large.
5. The reflection and the refraction of the propagating waves do play a significant role, because they amplify the oscillating motion of the soil, thus leading to the appearance of even larger stresses.
6. The phenomenon is quite complex and a parametric investigation could probably establish relationships on the basis of regression analysis.

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