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# Research on Analytic Calculation Method of The Dynamic Response of Buried Pipelines under Indirect Ground Shock

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**Abstract:** Buried pipelines are important lifeline engineering. During war conventional weapons blasting in the air would induce indirect ground shock, and the shock to the buried pipeline can lead to the paralyzed of urban economic and social function. And the numerical simulation of the dynamic damage of buried pipeline is complicated and time consuming, so this article using the equivalent static load method proposes analytic solution method of stress calculation of buried pipeline under ground shock. Through comparing the results calculated by analytic solution method and numerical solution, it shows that the analytical solution is feasible in engineering application.

## Intruduction

When conventional weapons blast in the air they would produce air shock wave which compresses soil to generate indirect ground shock. The shock may cause damage to the sewer line, fire pipelines, oil pipelines, gas pipelines and power cables pipeline buried in soil. Newmark's studies show that the anti-seismic design of the pipeline is generally determined by the maximum axial strain[1]. There are two common methods of research on the transmission of shock in soil and the interaction with underground structure. One is analytical solution[2], the other is numerical solution[3]. Numerical solution is usually used to solve many complex issues. But the process of numerical solution is complicated and time-consuming, and it's extremely inconvenient in engineering applications[4]. Analytical solution is simple and practical, so this article uses the equivalent static load, that is using the structure static analysis mode instead of dynamic analysis[5], and proposes the analytic solution method of stress calculation of buried pipeline under indirect ground shock. Through comparing the results calculated by the analytic solution and the numerical solution, the conclusion verifies the validity and accuracy of the analytic solution.

## Analytic solution of the dynamic stress of buried pipelines

**Calculation of the peak pressure of compression wave.** Assumed that the compression wave generated by explosion in soil is one dimension plane strain wave. And the soil mechanics model is considered as two polylines loaded elastic-plastic model (Prandtl model). Based on the one-dimensional plane wave theory and solution of characteristic line, Fang Qin got the amended formulas of compression wave parameters in soil as follows [5]:

$$P_{ch} = \Delta P_{ch}\left[1-(1-\delta)\frac{h}{2\eta \upsilon_1 \tau}\right] \tag{1}$$

$$t_r = \frac{h}{c_1} - \frac{h}{c_0} = \frac{h}{c_0}(\gamma_c - 1) \tag{2}$$

$$t_d = t_r + (1+0.4h)\tau \tag{3}$$

Where $P_{ch}$ is peak pressure of the soil compression wave(MPa). $t_r$ and $t_d$ are the boost time of compression wave and buck time of ground shock wave(s). $\Delta P_m$ is overpressure peak value of the ground shock wave(MPa).$\tau$ is buck time of air shock wave(s). $\delta$ is the strain recovery ratio of soil medium. $c_0$ and $c_2$ are the elastic wave velocity and uninstalling wave velocity(m/s). $\gamma_c$ is wave velocity ratio of the elastic wave and plastic wave. $\eta$ is modified coefficient.

**Calculation of the dynamic stress of buried pipelines.** It is necessary to do dynamic analysis due to the impact load on buried pipelines changing over time. Actually the load to pipeline is on the upper part of cylindrical surface. So to simplify the calculation, the pipeline is viewed as a beam element, and transforms the surface load into line load. The calculation method is shown in Eq. 4.

$$P_l(t) = \frac{P(t)}{L} = \frac{2p(t)}{\pi \mathrm{D}} \tag{4}$$

Where $P_l(t)$ is line load on the beam, P(t) is surface load, L is perimeter of the pipeline semicircle. The load on pipeline can be simplified as shown in Figure1(a).

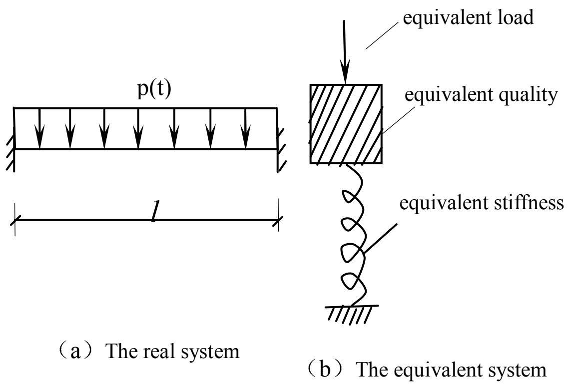


Figure 1. Equivalent-degree-of-freedom system of the beam

Studies have shown that [5], though deflection line of beam changing up and down under indirect ground shock, it remained the same shape substantially as static deflection curve at different time. That is as long as there is one parameter (such as mid-span-displacement) displacements of all particles in the beam can be marked. Such system is single degree of freedom system. The dynamic load on the buried pipeline in the paper changes over time according to the same principles essentially and the deformation shape is the same as the static deflection curve. Therefore, the pipeline can be simplified to single degree of freedom system. Then use the simple mass-spring system instead of the component of distributed mass of single degree of freedom, which called the equivalent system of actual component as shown in Figure 1 (b).

From dynamic analysis of the equivalent system of the actual structure, the maximum normal stress under dynamic load is numerically equal to the normal stress under static load (which is equal to dynamic load Maximum) multiplied by the corresponding dynamic coefficient [5]. In this way, the dynamic problem can be dealt as a static problem.

Now calculate the axial normal stress of the pipeline under static load which is equal to the maximum of dynamic load. By simplification, the line load on the pipeline is viewed as linear distribution as shown in Figure 1(a). Then the bending moment of mid-span can be obtained using mechanical knowledge as shown in Equation 5.

$$M = \frac{P_{l\max} l^2}{24} \tag{5}$$

where M is bending moment of mid-span, $P_{lmax}$ is line load of pressure, l is the length of pipeline. According to the formula of normal stress of any point in the cross-section of straight beam in pure bending, the axial normal stress of the back of mid-span can be obtained as shown in Equation 6,

$$\sigma = \frac{MD}{2I} \tag{6}$$

Where σ is axial normal stress of the back of mid-span, I is the inertia moment of cross-section of beam to neutral axis, $I=\pi(D^4-d^4)/64$. Then the axial strain of pipeline can be obtained as follows:

$$\varepsilon=\begin{cases} \dfrac{\sigma}{E} & \sigma < \sigma_e \\ \dfrac{\sigma-\sigma_e}{E_t}+\dfrac{\sigma_e}{E} & \sigma \ge \sigma_e \end{cases} \tag{7}$$

Where ε is the axial strain of pipeline, E, $E_t$ are elastic modulus and tangent modulus of the pipeline, $\sigma_e$ is yield stress of the pipeline.

**Numerical simulation of the dynamic stress of buried pipelines**

**The model.** The model is established as shown in Figure 2 using LS-DYNA. The upper part of model is air, and volume is 20×20×40cm. The lower part is soil, and volume is 100×45.35×90.7cm. The length of pipeline is 100cm, the depth is 40cm, the diameter is 10.7cm, and the thickness is 0.35cm. The pipeline is filled with air. Because the model is axisymmetric, this paper choose 1/4 part for study. The soil, air and pipeline are meshed by the SOLID164 element in LS-DYNA.

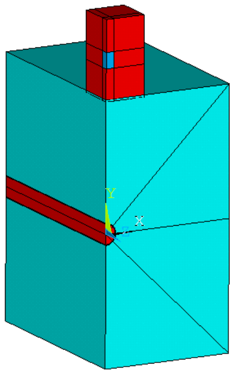

Figure 2. Description of the model

The numerical calculation chooses ALE algorithm for explosive, soil and air, and chooses Lagrange algorithm for pipe. By the keywords CONSTRAINED-LAGRANGE-IN-SOLID the study couples soil with the air and explosive. By co-node algorithm the pipeline is dealt with the air in it and the surrounding soil. the air and explosive are dealt by co-node algorithm too.

**Results comparison of analytical solution and numerical simulation.** For different explosive quantity, pressure values of the direct surface in the midpoint of pipeline and axial strain of the back are shown in Table.3.Pressure values of the direct surface of pipeline and axial strain of the back are calculated by Eq.1-7(all parameters of calculation are same to that of numerical simulation). And then compare with results of numerical simulation as shown in Table.1.

Table 1. Results comparison

| explosive quantity (kg) | Results of analytical solution | | Results of numerical simulation | |
|---|---|---|---|---|
| | pressure of the direct surface (MPa) | axial strain of the back ($10^{-6}$) | pressure of the direct surface (MPa) | axial strain of the back ($10^{-6}$) |
| 1.0 | 0.17 | 15.4 | 0.15 | 14.5 |
| 1.5 | 0.26 | 23.74 | 0.23 | 22.04 |
| 2.0 | 0.35 | 33.46 | 0.33 | 31.26 |
| 2.5 | 0.45 | 42.91 | 0.41 | 39.57 |
| 3.0 | 0.58 | 54.36 | 0.52 | 51.19 |

As can be seen from Table 1, the values of surface pressure and axial strain of analytical solution are greater than the results of the numerical solution, and the deviation is less than 12%. So the results of analytical solution is basically coincident with numerical solution.

## Conclusion

Analytic solution of the dynamic response of buried pipelines under indirect ground shock can meet the actual needs in engineering application. And using this method could do dynamic analysis and estimation of buried pipelines for different explosive quantity. Moreover the method is more efficient and convenient than numerical solution. Through comparing the results calculated by the analytic solution method and the numerical solution, the deviation is less than 12%, and the results of analytical solution is basically coincident with numerical solution. The paper provides theoretical guidance for protective measures and safety design of buried pipeline in engineering application.

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