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Analytical solution of the dynamic response of buried pipelines under blast wave

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ABSTRACT

Several studies have addressed the effect of blasting on buried pipelines, but none of them has used an analytical method to find the beam deflection under the effect of the blast wave. In this study, the pipeline is modeled as beam, and its displacements are calculated under a blast wave equivalent dynamic load. Mathematical modeling of the problem results in a fourth-order inhomogeneous partial differential equation, which has to be solved so that the pipe displacements and the peak particle velocity could be found. Since it is not possible to solve the problem in the time domain, the problem is converted to the frequency domain by a Fourier transform, and then the differential equation is solved. Finally, the solution is transformed back to the time domain, and the maximum particle velocity is calculated using a computer code.

1. Introduction

Despite the significant growth in the use of buried pipeline networks over the last years, limited literature refers to their design against ground shock wave propagation. Today, the design of pipelines against blasts is based on either analytical relations originally proposed for seismic waves with plane front and constant amplitude,[1] or an empirical relation initially proposed by Esparza et al.[2] and lately embraced by the ASCE-ALA guidelines.[3] There are also recent researches using the analytical approach.

In fact, the seismic design of buried pipelines is still based on the expressions proposed by Newmark[4] and Kuesel[5]. This 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, thereby threatening the pipeline.

Empirical study of the ground vibrations due to blasting and its effect upon structures was first undertaken by Crandell[6]. His research was not only about pipelines, but also all structures located above the ground. To assess the response of pipelines to ground waves, most pipeline companies follow the common surface ground motion criterion of 50 mm/s (2 in/s) for peak particle velocity, which has been adopted in many governmental regulations to determine explosive quantity – safety distance limits for blasts near buried pipelines. However, a steel pipe is a strong structure compared to a building; there is also the additive effect of the earth, providing inertial resistance to any ground shock from an explosion.[7] Siskind and Stagg suggested that the criterion of a peak particle velocity less than 127 mm/s should be used for strong pipelines, instead of the 50 mm/s criterion.[8] Actually, none of these researches succeeded in formulating a mathematical model that could be used to predict safety distances of pipelines from the explosion source.

Most recent researches have also used finite element programs to make a model of the effect of explosion waves on buried pipelines, because of its simplicity and efficiency. Some effort has also been made to find analytic solutions for explosion problems, but, as it is clear, analytic methods are so difficult and complicated and several simplifying assumptions should be considered.

An analytical methodology to calculate blast-induced strains in buried pipelines has been presented by employing 3-D thin elastic shell theory in the analysis of the structure, as reported by George[9]. The aim of that research was to introduce a methodology for the analytical calculation of strains in flexible buried pipelines due to surface point-source blasts. Although an analytical method was employed, its results were adequate only when the stiffness of pipes was remarkably less than that of soil. So the results of this study may not be authentic when pipe lines are buried in soft rock, because the stiffness of gas pipes is usually more than that soft rock and soil. In addition, both linear and nonlinear behavior of buried pipelines under blast pressures induced by external explosions has been discussed analytically by Nourzadeh[10] and two

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direct formulas have been derived for primary analysis and the design of buried pipelines subject to underground explosions. These formulas were derived from the closed form solution of the quasi-static equation of the motion of the pipeline modeled as a beam; therefore, pipelines of greater diameters may act somehow differently and should be modeled by shell elements.[10] Although it was one of the most recent research leading to the analytical solution, it still did not consider the dynamic load of blasting. So it was not a complete dynamic solution for explosion problems. In addition, the blast load was directly applied to pipe, but, usually, blasts occurring in construction projects are not adjacent to gas pipes. So blast wave effects should be considered instead of direct blast load.

Lately, the analytic solution of the dynamic response of buried pipelines under indirect ground shock of nuclear blast was studied by Guofu[11]. He assumed that nuclear explosion ground shock wave was simplified as sudden loading triangular waveform, and the compression wave in soil was one dimension plane strain wave. Actually, the blast wave load was simplified to a static load multiplied by a coefficient.

The aim of the current research was to the find displacement of pipe caused by blast wave propagation analytically. Therefore, a mathematical model consisting of modeling blast-induced pressure wave propagation and the equivalent load which acting on the pipe and modeling it and its adjacent soil was generated. Wave propagation was considered planar, since both explosion and pipe could be located near the earth. Pipe could also be modeled as a beam, but the results of this modeling might not be valid for pipes with a large diameter.

2. Blast pressure equation

Blasting generates additional pressure in soil, as shown as Fig. 1. Almost immediately after the blast, the pressure within the blast radius rises to a peak pressure, P_{so}, (side on pressure or incident pressure). The side on pressure is decayed to ambient following the positive phase duration, after which negative phase duration occurs when pressure falls below ambient to a minimum value. The negative pressure phase of a blast wave is usually significantly smaller and longer in duration than the positive phase and is consequently, generally ignored.[12]

Nevertheless, a typical design blast load can be represented by an exponential loading with side-on overpressure, P_s, and duration, t_d, as shown in Fig. 2. t_d is considered as the time in which Blast pressure becomes significantly smaller than P_s and so, it can be neglected. In this research, it was considered as the time in which Blast pressure fell below 0.001 P_s.

So blast pressure can be calculated using

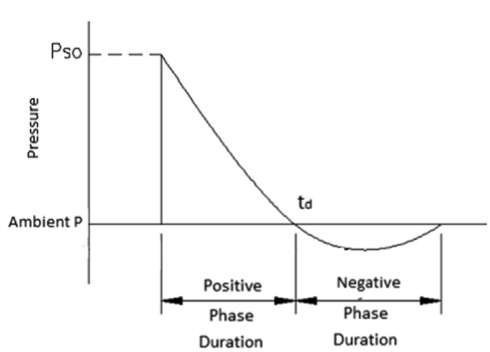

Fig. 1. Ideal blast wave resulting from explosion[10].

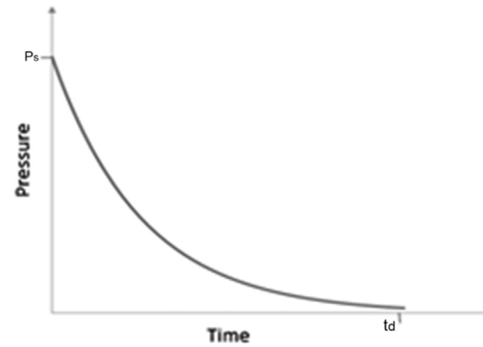

Fig. 2. Blast equivalent load.

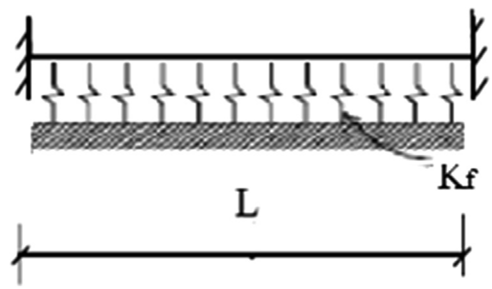

Fig. 3. Pipe equivalent fixed end beam.

$$p(t) = p_s e^{-\alpha t} \tag{1}$$

where $p(t)$ is the blast pressure, α is the constant related to the decay of blast pressure per time and p_s is the peak blast pressure (incident pressure).

3. Mathematical model of structure and loading

3.1. Pipeline model

The discussed structure was a continuous pipeline, so the joints and bents were not considered in the model. The buried pipeline was modeled as a beam on elastic foundation, as shown in Fig. 3.

Actually the load which acted on the pipeline was on one half of cylindrical surface. So, to simplify the calculation, the pipeline was considered as a beam element, and the surface load was transformed to line load. It would not be right if the pipe diameter were too large.

It was also assumed that if the distance were far enough from the source, blast wave would not affect the pipe. So the length of the beam could be limited to *L*. Therefore, the pipe was assumed to be a beam with fixed ends, like the one shown in Fig. 3. Pipe length could also take an infinite value, but it was obvious that the displacement of pipe ends might be negligible when their distance from blast became far enough.

3.2. Soil-structure interaction

Here soil was modeled as a series of independent springs located on one side of the beam. k_f in Fig. 3 is the soil spring stiffness per unit length of the pipe. This parameter depends on the stiffness of the surrounding soil and the depth of burial. The equations used to derive the soil spring stiffness (K_f) are based on[3]:

$$K_f = \frac{\left(N_{ch} cD + N_{qh} \gamma' HD\right)}{\Delta_h} \tag{2}$$