UNILATERAL SOIL-PIPELINE INTERACTION ANALYSIS UNDER SEISMIC EXCITATION

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SUMMARY

The seismic behaviour of buried pipelines is studied numerically taking into consideration some unilateral effects. These effects are due to the possible creation of gaps around the pipeline because of the soil elastoplastic and tensionless behaviour.

The formulation and the solution of the problem is obtained by a numerical procedure based on the Finite Element Method and a step by step time integration. The presented procedure is then applied to an example problem. It is shown that the unilateral soil-pipeline interaction may produce stress concentrations because of the soil-pressure rearrangements.

INTRODUCTION

Classical analytical approaches to the problem of the seismic analysis of buried pipelines are based on the assumption of strain compatibility (Refer. 1). By this postulate, the pipe moves with the surrounding soil in such a way as to have nearly the same curvature and the same longitudinal strain as the ground. So the strain in the ground is trasmitted to the piping without any attenuation, amplification or difference of any kind. This method of analysis is sometimes very conservative, especially for stiff tunnels near the ground surface. For this reason, methods for computing stresses due to longitudinal bending and to transverse loading have been presented (Ref. 2).

On the other hand, recent experimental dynamic tests (Ref. 3) prove the existence of important differences of soil and pipe displacement amplitudes especially in the case of dynamic excitation perpendicular to the pipe axis.

The possible appearence of such gapping and separation phenomena is the starting point of the present study. In spite of using the classical spring configuration of the soil-pipe axial and transversal interaction model (Ref. 4), a unilateral, Winkler-type spring modelization as in Ref. 5 has been adopted. So, the contact behaviour between pipe and soil is described by equality as well as inequality conditions. When the soil and the pipe come

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in contact during a seismic excitation, a soil pressure-reaction is developped; otherwise a separation appears due to tensionless soil behaviour. Then the soil reaction is zero. By repeated contacts the gap width increases because of the growing permanent elastoplastic soil deformations.

The aim of this paper is to present a numerical procedure, which examines whether or not these gaps appear during a horizontal seismic excitation perpendicular to the axis of buried pipeline. In the case of a positive answer, the further aim is to determine the redistribution of the soil pressures along the pipe. The procedure takes no consideration of unilateral behaviour due to friction effects (slipping).

METHOD OF ANALYSIS

For the numerical formulation and solution of the problem a double discretization, in space and time, is applied using the Finite Element Method and a step by step time integration scheme (Ref. 5,6,7).

First a spatial discretization is used for the soil-pipeline system. So, the pipeline is discretized into beam finite elements. Each pipeline node is connected to the soil through two discrete soil-elements, one on each side of the pipeline. It is assumed that each soil-element consists of an elastoplastic spring and a dashpot, connected in parallel (Fig. 1). These soil-elements activate a compressive force r(t) only when they are in contact with the corresponding pipeline nodes (t is the time). Let y(t) denote the relative approach (the soil element shortening deformation) and g(t) the existing gap between pipeline node and soil. Thus the unilateral behaviour of the soil-pipeline interaction is described by the following conditions :

$$\text{If} \quad y \leq g \quad \text{then} \quad r = 0. \tag{1a}$$

$$\text{If} \quad y > g \quad \text{then} \quad r > 0. \tag{1b}$$

Further, the soil pressure is

$$r = C_s . \dot{y} + p(y), \tag{2}$$

where: C_s denotes the soil damping coefficient,

$\dot{y} = \partial y / \partial t$, and

p(y) the elastoplastic spring force.

This force is given either by the nonlinear, exponential expression

$$p(y) = p_u(x,n) . [1 - \exp(-b|y-g_o|)] \tag{3a}$$

for the virgin loading or the reloading curved paths, or by the linear expression

$$p(y) = a(x,n) . [y-g] \tag{3b}$$

for the unloading or reloading straight paths in the (p-y) diagram of Fig. 2. In the last relationships denote:

g_o and g	the initial and the current gap, respectively,
x	the distance along the pipeline,
n	the current number of cyclic loading
p_u	the ultimate soil capacity
a,b	coefficients.

A detailed discussion of the above mentioned soil modelization has been presented elsewhere (Ref. 5).

Now the problem relations for the assembled soil-pipeline system are written in matrix form :

$$\underline{M}\,\underline{\ddot{u}} + \underline{C}\,\underline{\dot{u}} + \underline{K}\,\underline{u} = \underline{f} + \underline{A}^T\,\underline{r}, \qquad (4)$$

$$\underline{y} = \underline{A}\,\underline{u}, \qquad (5)$$

$$\underline{u}(t=0) = \underline{u}_o, \quad \underline{\dot{u}}(t=0) = \underline{\dot{u}}_o, \quad \underline{g}(t=0) = \underline{g}_o, \qquad (6)$$

where:

$\underline{M}$, $\underline{C}$, $\underline{K}$ are the mass, damping and stiffness matrix, respectively;

$\underline{g}$, $\underline{r}$, $\underline{y}$ are the gap, force and deformation vectors of the soil elements, respectively;

$\underline{f}$, $\underline{u}$ are the force and the relative displacement vectors of the pipeline nodes,

$\underline{A}$ is a kinematic transformation matrix, and

$\underline{u}_o$, $\underline{\dot{u}}_o$, $\underline{g}_o$ are the known vectors for the initial conditions (6).

As usually, dots denote differentiation with respect to time. For an earthquake, the force vector $\underline{f}$ includes also the inertia forces for the pipeline nodes due to the prescribed acceleration history of the supports (Ref. 6).

Thus, the problem is to find that vector set ($\underline{u}$, $\underline{\dot{u}}$, $\underline{\ddot{u}}$, $\underline{r}$, $\underline{y}$) which satisfies the relations (1)-(8) when $\underline{f}$, $\underline{u}_o$, $\underline{\dot{u}}_o$, and $\underline{g}_o$ (usually $\underline{g}_o=\underline{0}$) are given. This problem is solved by a time integration, step by step algorithm, based on the central difference method and discussed in Ref. 6.

EXAMPLE PROBLEM

To demonstrate the effectiveness of the procedure previously presented the example problem depicted in Fig. 1 has been solved. This problem considers an empty steel circular pipeline of length L = 200 m, outside diameter 1 m, thickness 1.5 cm, elastic modulus 21.10^7 KN/m^2 and yield stress 50 KN/cm^2. The pipeline is clamped by the two anchor blocks A and B imbeded into a rock soil (fixed-end conditions).

The joints of the pipeline are at 20 m and are assumed to appear an elastoplastic bending behaviour. The maximum elastic angle of the relative rotation between adjacent sections equals to 4 degrees. To describe the joint behaviour, an elastoplastic rotation spring has been inserted in each joint.

Further, the soil, into which the pipeline is buried, consists of two regions. The first soil region (soft) has a shear modulus $G_I = 5000$ KN/m^2 and the second one (hard) has $G_{II} = 100000$ KN/m^2. For simplicity, soil degradating, cyclic and damping effects are ignored and the parameters in the rels. (3) are taken to be $b = 100$ m^{-1}, $g_o = 0$,

$a = p_u \cdot b$, $p_u = 100$ KN/m^2 for the soil region (I), and

$p_u = 2000$ KN/m^2 for the region (II).

Further, the seismic excitation is assumed to be a sinusoidal horizontal wave propagation parallel to the pipeline axis (Fig. 1). This wave travels with a mean speed $v = 0.4$ Km/sec and has a duration $T = 2\pi/\omega$, where $\omega = 10$ rad/sec. At each pipeline point **x**, the maximum ground displacement is $y_o = 0.05$ m. Thus, the horizontal ground motion, perpendicular to the pipeline axis, is given by the relation

$$y_g(x,t) = \left[H(t-\frac{x}{v}) - H(t-\frac{x}{v}-T) \right] . \, y_o . \sin\left[\omega(t-\frac{x}{v})\right] ,$$

where H(t) is the Heaviside function ($H(t-c) = 0$ for $t<c$, $H(t-c) = 1$ for $t>c$).

Now some indicative results for the example problem are presented.

In Fig. 3 the gaps along the pipeline at the times 0.6 sec and 2.1 sec are shown. The gaps at 2.1 sec are the final ones due to permanent plastic soil deformations. The difference of the gap widths in the soil region (I) and the region (II) is remarkable. Thus, for a subsequent horizontal seismic excitation the part of the pipeline in the soil (I) may not have a behaviour of a beam on elastoplastic foundation because of the existed gaps.

In Fig. 4 it is shown the distribution of the soil-pressures along the pipeline at the time $t = 0.60$ sec. The stresses are smaller in the soft soil (I) than in the hard soil (II). Furthermore, a stress concentration is observed around C, where the soil-quality changes.

CONCLUSIONS

It has been presented a numerical procedure, based on the finite element method and a step by step time integration algorithm, which is suitable for the unilateral seismic analysis of buried pipelines. The unilateral effects are due to gapping and influence the seismic response of the pipelines, as it has been proved in an example problem. Therefore, such effects should be taken into consideration. In the presented study unilateral effects due to friction (slipping) have not been considered. A further parametric study, including these effects, other problem parameters as well as a comparison between the unilateral and the classical - Winkler-spring modelization of the soil-pipeline interaction will be discussed in a forthcomming paper.

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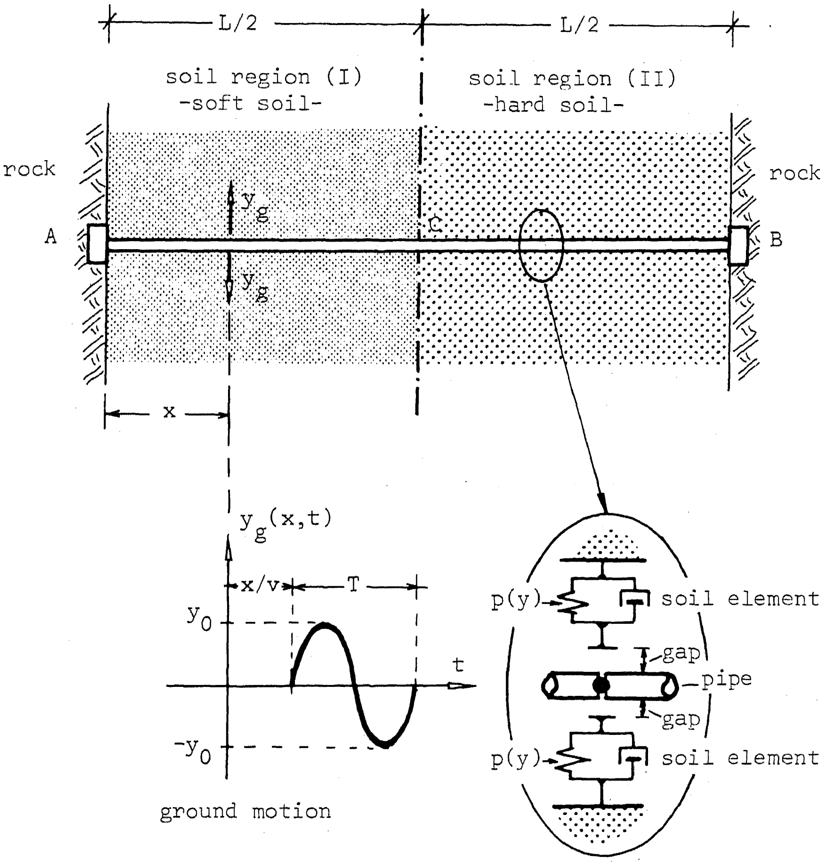

Fig. 1 Soil-pipeline system, horizontal seismic ground motion for the example problem and soil-pipeline interaction modelization.

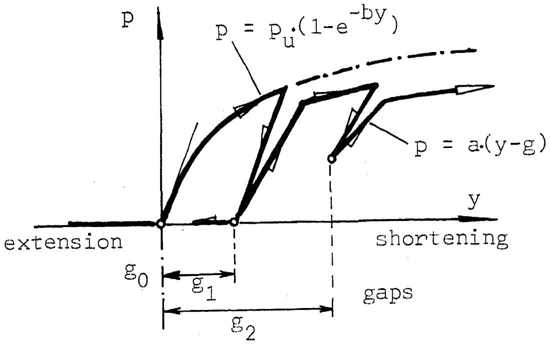

Fig. 2 Unilateral, degradating soil behaviour in loading-unloading with remaining gaps.

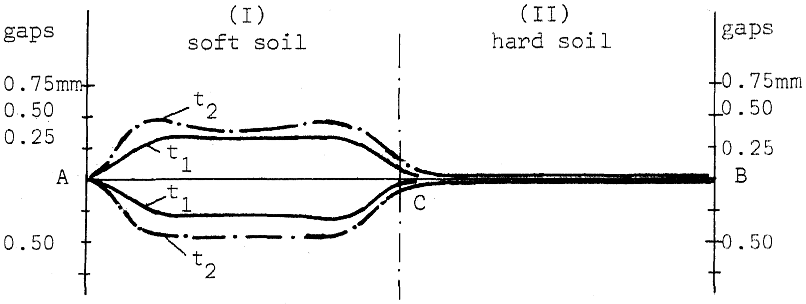

Fig. 3 Gaps along the pipeline at the times $t_1 = 0.6$ sec and $t_2 = 2.1$ sec.

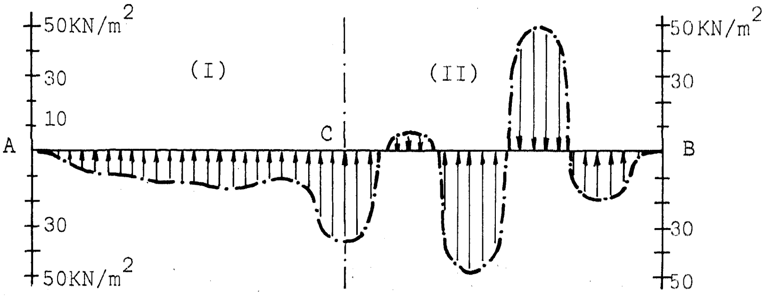

Fig. 4 Soil-pressure distribution at the time $t_1 = 0.6$ sec.