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SEISMIC PIPELINE-SOIL INTERACTION UNDER UNCERTAIN-BUT-BOUNDED INPUT PARAMETERS: A STOCHASTIC NUMERICAL APPROACH

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ABSTRACT
The unilateral contact problem of dynamic soil-pipeline interaction under uncertainty concerning input parameters is treated numerically by a computational stochastic approach. Unilateral contact effects due to tensionless soil capacity, soil elastoplastic-fracturing behaviour and gapping are strictly taken into account, as well as environmental effects decreasing the soil resistance. The proposed methodology concerns the treatment of both, the deterministic and the probabilistic problem. The numerical approach concerning the deterministic problem is based on a double discretization, in space by the Finite Element Method combined with Boundary Element Method, and in time, and on nonconvex optimization. Uncertainties concerning the input parameter values are treated as bounded by upper and lower bound estimates using the Monte Carlo method in the probabilistic problem section. Finally, the proposed methodology is applied for a practical case of seismic soil-pipeline interaction.

KEY WORDS: Dynamic soil-pipeline interaction, unilateral contact, uncertain-but-bounded input parameters, numerical and stochastic geotechnical engineering.

INTRODUCTION

As well-known, dynamic soil-structure interaction is a high non-linear problem, mainly due to unilateral contact conditions on the interface and due to non-linear soil constitutive laws [1-4]. Indeed, for the case of the general dynamic soil-structure interaction, see e.g. [1], the interaction stresses in the transmitting interface between the structure and the soil are of compressive type only. Moreover, due to in general nonlinear, elastoplastic, tensionless, fracturing etc. soil behavior, gaps can be created between the soil and the structure. Thus, during strong earthquakes, separation and uplift phenomena are often appeared, as the praxis has shown.

So, the mathematical formulation of the dynamic soil- pipeline problem involves equalities as well as inequalities. Due to above inequality conditions, the pipeline-soil interaction can be considered as one of the so-called inequality problems of structural and geotechnical engineering [5-7]. The mathematical treatment of the so-formulated inequality problems can be obtained by the variational or hemivariational inequality approach [5-9]. Numerical approaches for some inequality problems of structural elastoplasticity and earthquake engineering have been also presented, see e.g. [2, 5-11].

Moreover, uncertainty concerning input parameters in seismic soil-structure interaction is a crucial problem in geotechnical engineering. A stochastic numerical approach treating these aspects has been recently reported [12] concerning the dynamic pile-soil interaction problem.

In the present paper, a stochastic numerical approach for the inequality dynamic problem of pipeline-soil interaction under uncertain input parameters is presented. Environmental degradation for the soil are taken into account. The proposed numerical approach consists of solving first the deterministic problem and next the probabilistic problem. The numerical method for the treatment of the deterministic problem is based on a double discretization and on methods of nonlinear programming. So, in space the finite element method (FEM) coupled with the boundary element method (BEM), and in time a step-by-step method for the treatment of convolutional conditions are used. In each time-step a non-convex linear complementarity problem is solved with reduced number of unknowns. The probabilistic numerical approach uses the Monte Carlo simulation [13-16] for the treatment of uncertain input parameters. Finally, the presented procedure is applied to an example problem of dynamic pipeline -soil interaction.

THE STOCHASTIC COMPUTATIONAL APPROACH

As reported, the probabilistic approach for the dynamic soil- pipeline interaction can be obtained through Monte Carlo simulations. As well-known, see e.g. [13-18], Monte Carlo simulation is simply a repeated process of generating deterministic solutions to a given problem. Each solution corresponds to a set of deterministic input values of the underlying random variables. A statistical analysis of the so obtained simulated solutions is then performed. Thus the computational methodology consists of solving first the deterministic problem for each set of the random input variables and finally realizing a statistical analysis.

Details of the methodology concerning the deterministic problem and the probabilistic aspects for soil-pile dynamic interaction have been reported in [12]. As similar methodology aspects hold herein for the soil-pipeline dynamic interaction, a relevant brief summary is given in the next sections for the completeness of the present paper.

Numerical Treatment of the Deterministic Problem

First, a discretization in space by combining the finite element method (FEM) with the boundary element one (BEM) is used for the soil-pipeline system, see [2,10-12]. The pipeline is discretized into frame-beam finite elements. Each pipeline node is considered as connected to the associate soil nodes on both sides through two *unilateral* (interface) elements. Every such *u-element* consists of an elastoplastic softening spring and a dashpot, connected in parallel (see e.g. the Figure 1a), and appears a compressive force r(t) only at the time-moments t when the pipeline node comes in contact with the corresponding soil node. Let v(t) denote the relative retirement displacement between the soil-node and the pipe-node, g(t) the existing gap and $w_g(t)$ the soil displacement induced by moving sources of the type described in the Introduction. Then the piece-wise linearized unilateral contact behaviour of the soil-pipeline interaction is expressed in the compact form of the following linear complementarity conditions:

$$v+g+w_g \geq 0, \quad r \geq 0, \quad r.(v+g+w_g) = 0. \tag{1}$$

Further, the *u-element* compressive force is in convolutional form [1,11]

$$r = S(t)*y(t), \quad y = w - (g + v), \tag{2a,b}$$

or in form used in Foundation Analysis [19]

$$r = c_s.(dy/dt) + p(y). \tag{2c}$$

Here c_s is the soil damping coefficient, w = w(t) the pile-node lateral displacement, y = y(t) the shortening deformation of the soil-element, and p(y) the spring force. By * is denoted the convolution operation. S(t) is the dynamic stiffness coefficient for the soil and can be computed by the BEM [1]. Function p(y) is mathematically defined by the following, in general nonconvex and nonmonotone constitutive relation:

$$p(y) \in C_g P_g (y), \tag{2d}$$

where C_g is Clarke's generalized gradient and P_g ( ) the symbol of superpotential nonconvex functions [5,6,9]. So, eq. (2d) expresses in general the elastoplastic-softening soil behaviour, where unloading-reloading, gapping, degrading, fracturing etc. effects are included.

For the herein numerical treatment, p(y) is piece-wise linearized in terms of non-negative multipliers as in plasticity [8]. So, the dynamic equilibrium conditions for the assembled soil-pile system are written in matrix form as follows:

$$\underline{M}\,\ddot{\underline{u}}(t) + \underline{C}\,\dot{\underline{u}}(t) + \underline{K}\,\underline{u}(t) = \underline{f}(t) + \underline{A}^T\,\underline{r}(t), \qquad (3)$$

$$\underline{h} = \underline{B}^T\underline{r} - \underline{H}\,\underline{z} - \underline{k}, \quad \underline{h} \leq \underline{0}, \quad \underline{z} \geq \underline{0}, \quad \underline{z}^T.\underline{h} = 0. \qquad (4)$$

Here, eq. (3) is the dynamic matrix equilibrium condition and eqs. (4) include the unilateral and the piece-wise linearized constitutive relations. Dots over symbols denote, as usually, time-derivatives. $\underline{M}$, $\underline{C}$ and $\underline{K}$ are the mass, damping and stiffness matrix, respectively; $\underline{u}$, $\underline{f}$ are the displacement and the force vectors, respectively; $\underline{A}$, $\underline{B}$ are kinematic transformation matrices; $\underline{z}$, $\underline{k}$ are the nonnegative multiplier and the unilateral capacity vectors; and $\underline{H}$ is the unilateral interaction square matrix, symmetric and positive semidefinite for the elastoplastic soil case. But in the case of soil softening, some diagonal entries of $\underline{H}$ are nonpositive [8]. Finally, the force vector $\underline{f}$ includes the effects due to high-speed moving sources in the surrounding soil along the pile-line.

Thus the so-formulated problem is to find ($\underline{u}$,$\underline{r}$,$\underline{g}$,$\underline{z}$) satisfying (1)-(4) when $\underline{f}$ and suitable initial conditions are given.

Assuming that the unilateral quantities $\underline{z}$ and $\underline{h}$ include all local nonlinearities and unilateral behaviour quantities, applying the central-difference time discretization, and after suitable elimination of some unknowns, we arrive eventually at

$$\underline{h}_n = \underline{D}\,\underline{z}_n + \underline{d}_n, \quad \underline{z}_n \geq \underline{0}, \quad \underline{h}_n \leq \underline{0}, \quad \underline{z}_n^T.\underline{h}_n = 0. \qquad (5)$$

Thus, at every time-moment $t_n = n.\Delta t$, where Δt is the time step, the problem of rels. (5) is to be treated. This problem is a *Non-Convex Linear Complementarity Problem* (NCLCP), can be treated as an hemivariational one and is solved by available methods and computer codes of nonconvex optimization [2, 5]. So, in each time-step Δt we compute which of the unilateral constraints are active and which are not. Due to soil softening, the matrix $\underline{D}$ is not a strictly positive definite one in general. But as numerical experiments have shown, in most civil engineering applications of soil-pile interaction this matrix is P-copositive, and thus the existence of a solution is assured [8].

Numerical Treatment of the Probabilistic Problem

In order to calculate the random characteristics of the response of the considered soil-pile system, the Monte Carlo simulation is used [13-16]. As mentioned, the·main element of a Monte Carlo simulation procedure is the generation of random numbers from a specified distribution. Systematic and efficient methods for generating such random numbers from several common probability distributions are available. The random variable simulation is implemented using the technique of Latin Hypercube Sampling (LHS) [16]. The LHS is a selective sample technique by which, for a desirable accuracy level, the number of the sample size is significantly smaller than the direct Monte Carlo simulation.

In more details, a set of values of the basic design input variables can be generated according to their corresponding probability distributions by using statistical sampling techniques. As concerns the uncertain-but-bounded input parameters [17,18] for the stochastic analysis, these are estimated here by using available estimates (e.g. by in-situ investigations) for upper and lower bounds, denoted as U_B and L_B respectively. So, the mean values are estimated as $(U_B + L_B)/2$.

The generated basic design variables are treated as a sample of experimental observations and used for the system deterministic analysis to obtain a simulated solution as in previous subsection is described. As the generation of the basic design variables is repeated, more simulated solutions can be determined. Finally, statistical analysis of the simulated solutions is then performed.

NUMERICAL EXAMPLE

An empty horizontal 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 is considered. As depicted in Figure 1, the pipeline is clamped by the two anchor blocks A and B imbedded into a rock soil. The soil, into which the horizontal pipeline is buried, has an elastoplastic behaviour as in Figure 2 and consists of two regions with the following statistical data:

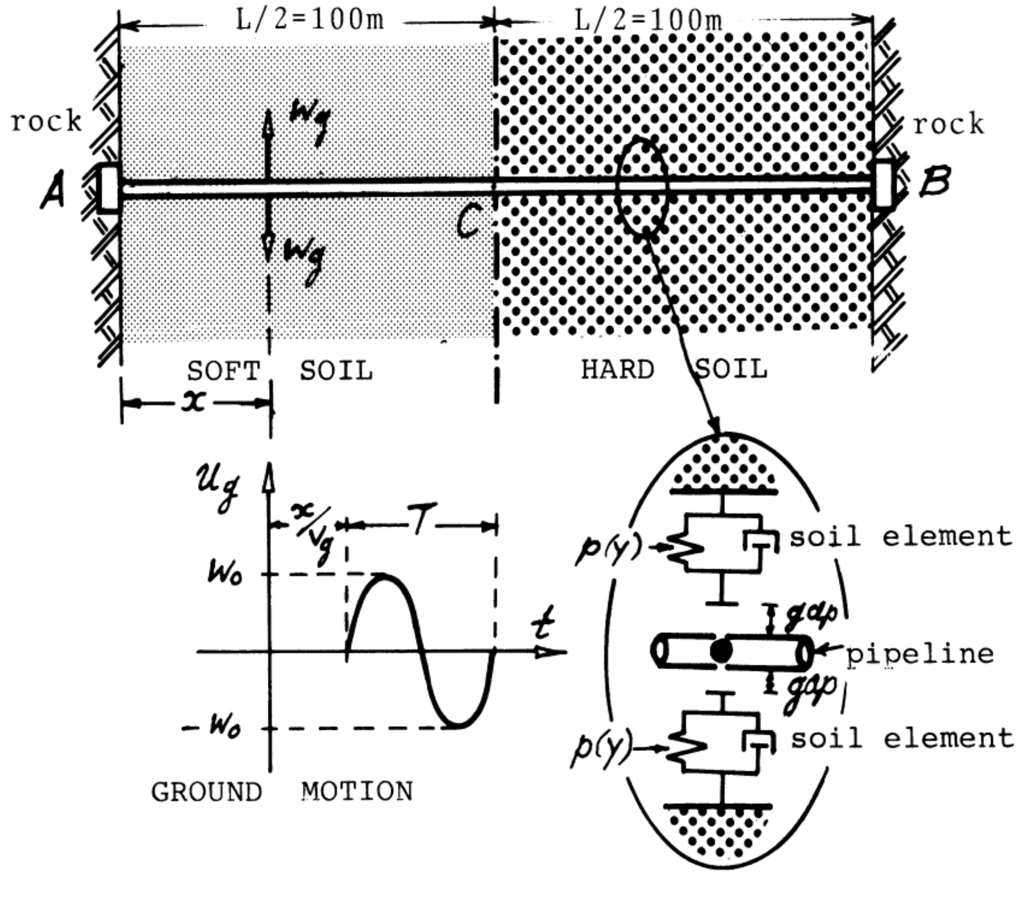

Figure 1. Soil-pipeline system, horizontal wave travelling ground motion and soil-pipeline interaction modelization.

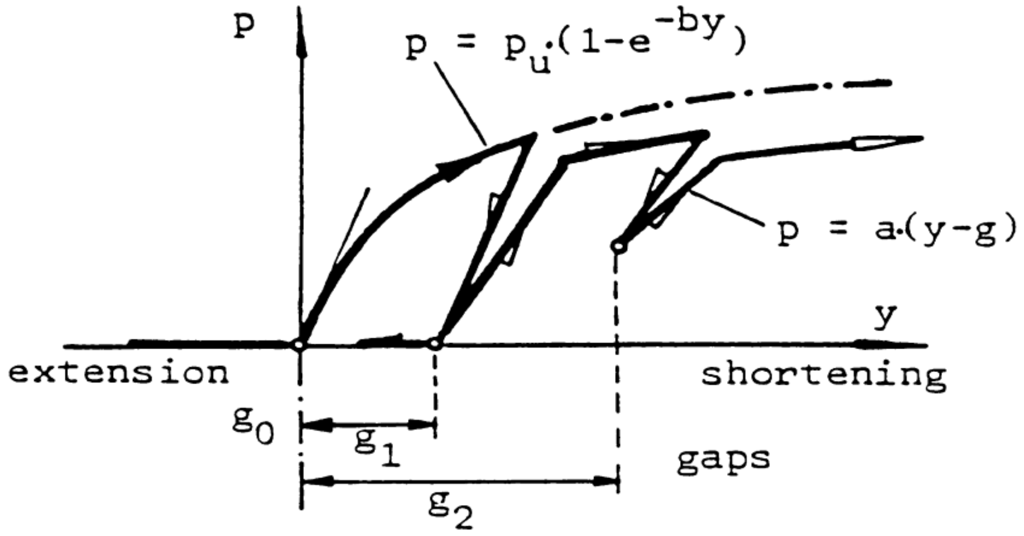

Figure 2. Unilateral, degradating soil behaviour in loading-unloading with remaining gaps.

- The first soil region (I) is soft soil, degraded due to environmental actions, with a shear modulus having mean value $G_i = 5$ MPa and upper and lower bound estimates

$$4 \text{ MPa} < G_i = 5 \text{ MPa} < 6 \text{ MPa} \qquad (6a),$$

- The second (II) soil region is hard (non-degraded) with a shear modulus having mean value $G_{ii} = 100$ MPa and upper and lower bound estimates

$$96 \text{ MPa} < G_{ii} = 100 \text{ MPa} < 104 \text{ MPa} \qquad (6b),$$

The parameters for the elastoplastic behaviour in Figure 2 are taken to be $a = p_u.b$, $b = 100$ m^{-1}, where the mean values are $p_{uI} = 100$ KN/m^2 for the soft region (I) and $p_{uII} = 2000$ KN/m^2 for the hard region (II), and the coefficient of variation COV = 20%.

All the above reported input parameters G_i, G_{ii}, p_{uI} and p_{uII} are considered as random variables having uniform probability distributions [14].

Further, the seismic ground excitation is assumed to be a sinusoidal horizontal wave propagation parallel to the pipeline axis (Figure 1), with mean speed $v_g = 0.4$ km/sec in the soft region (I) and $v_g = 0.8$ km/sec in the hard one (II), frequency $f_g = 10$ rad/sec, duration $T = 2\pi / f_g$ and maximum ground displacement $w_o = 5$ cm. Thus the horizontal ground motion, perpendicular to the pipeline axis x, is expressed mathematically by the following relation, where H(t) is the Heaviside function:

$$u_g(x,t) = w_o \sin(t - x/v_g) \, . \{H(t - x/v_g) - H(t - x/v_g - T)\}. \qquad (7)$$

By using 250 Monte Carlo samples, some indicative results from the numerical ones, obtained by applying the presented procedure, are here reported. So in Figure 3 the mean values of the gaps along the pipeline due to permanent soil deformations are shown for the time moments $t_1 = 0.6$ sec and $t_2 = 2.1$ sec. The difference of the gap widths in the soft and in the hard soil region is remarkable. Because of these created gaps, for a subsequent soil excitation the part of the pipeline in the soft region may not have a behaviour of a beam fully supported by foundation.

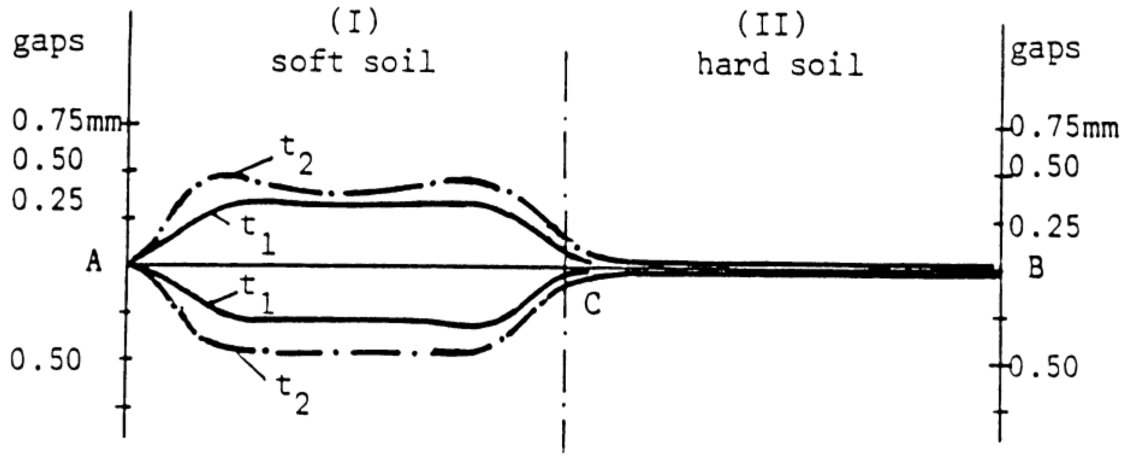

Figure 3. Gaps mean values along the pipeline at times $t_1 = 0.6$ sec and $t_2 = 2.1$ sec.

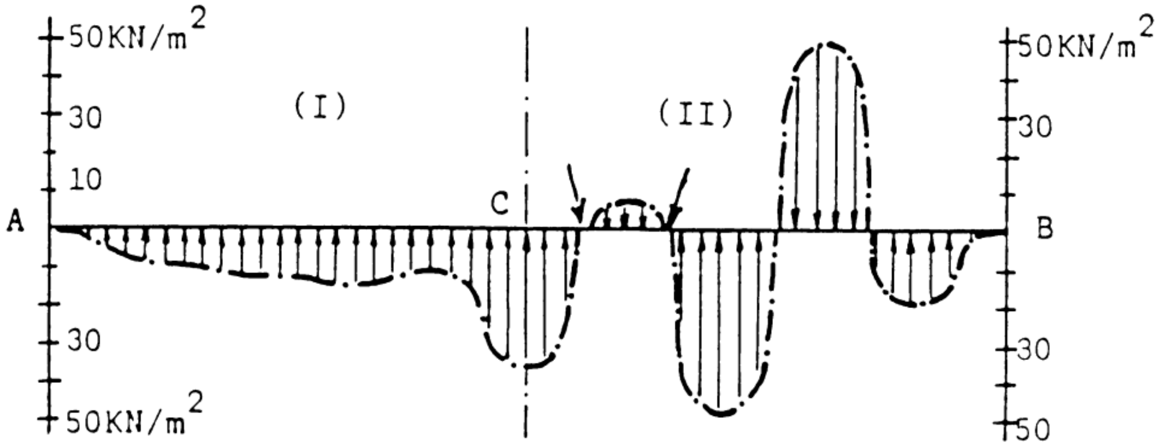

Figure 4. Soil-pressure distribution mean values along the pipeline at the time $t_1 = 0.6$ sec

On the other hand, in Figure 4 it is shown the distribution of the soil-pressures mean values at the time $t_1 = 0.60$ sec. The stresses are smaller in the soft region than in the hard one. Furthermore, a concentration of stresses is observed around the pipeline middle C, where the soil quality changes.

The statistical performance of the above 250 Monte Carlo samples has given a coefficient of variation COV = 27.8% for the gaps and COV = 28.4% for the soil-pressure distribution along the pipeline.

CONCLUDING REMARKS

The herein presented stochastic procedure provides a numerical tool for the probabilistic analysis of soil-pipeline analysis interaction under uncertain input parameters. The representative results of the numerical example show that unilateral contact effects due to tensionless soil capacity, reduced by environmental effects, and due to gapping, may be significant and have to be taken into account for the dynamic soil- pipeline interaction. So the herein presented stochastic procedure can be useful in the geotechnical praxis for the earthquake resistant construction, design and control of pipelines.

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