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SEISMIC ANALYSIS OF SEGMENTED BURIED PIPELINES

V. H. VASSILEV and R. FLORES-BERRONES

Mexican Institute of Water Technology
Paseo Cuauhnahuac 8532, Jiutepec, Mor. México

ABSTRACT

This work presents the development of a mathematical model and a computer program based on the Finite Element Method in two-dimensional formulation to study the behaviour of straight jointed buried pipeline subjected to seismic wave propagation effects. Quasi-static analysis is adopted for assessment of the pipeline response. Buried pipeline is presented as a series of segmented elastic beams, connected longitudinally with joints. Soil is assumed to be homogeneous(or/and unhomogeneous) isotropic(or/and transversal isotropic) elastic media in plane strain conditions. Seismic forces at each finite element are determined as mass forces depending on the ground acceleration. The possibility of slippage at the surface between the pipe and the soil is evaluated as well when the seismic ground strain becomes very large. A computer program called SPLAN is developed under the above considerations.

Numerical experiments were done to study the influence of the geological, topographical and soil conditions on the stress strain state of the pipeline. Results from this study indicate that the variability of the conditions at the longitudinal profile of the pipeline affects the values of the axial stress at the pipes as well as the expansion-contraction at the joints. This influence is stronger at the connection points between the pipes and rigid structures, as well as at the sectors of the pipeline where sudden change of the geology, topography or soil occurs.

KEYWORDS

Buried Pipeline, Wave Propagation Effect, Soil-Pipe Interaction, FEM Analysis

INTRODUCTION

It has been recognized from previous earthquakes that buried pipelines are seismically very vulnerable. Most of the large earthquakes of this century has been accompanied with seriously damages on the pipelines systems. For example, during the quite recently earthquakes of Michoacan (1985), Northridge (1994), and Kobe (1995), many buried segmented pipelines suffered extensive damage (Ref. 6,7,15).

The earthquake response of a buried pipeline depends on the dynamic deformations of the surrounding ground. Effects of the ground motion during an earthquake on the buried pipelines are classified mainly into two groups: permanent ground movements and wave propagation effects. Permanent ground movements include fault movements, landsliding and liquefaction; these movements can occur during or after earthquakes. Wave propagation effects occur during the earthquake and can affect a large area, either near the epicenter (Northridge Earthquake), or far from it (Mexico City during Michoacan Earthquake).

The state of the art for seismic analysis of buried pipeline has been advanced during the last 15 years. The simplest methods assume that the maximum axial strain in the buried pipelines is approximately equal to the maximum strain of the surrounding ground. More realistic representations of the soil pipe system have been proposed in the Refs. 7,13,18. Soil behavior is idealized by linearly elastic springs and dampers. Pipeline segments are assumed to be infinitely rigid while joints are modeled by elastic springs. In Ref. 7 the joints are modeled by axial and rotational nonlinear springs. The pipe segment properties are constant along the pipeline, while the joint properties can vary from joint to joint. The seismic excitation for the pipeline models mentioned above is given in terms of the axial or and lateral displacements, which are assumed to be a function of the maximum ground strain, determined by Newmark's assumption (Ref. 17).

In this work Finite Element Method (FEM) is used to develop a numerical procedure for analysis of seismic wave propagation effects on the stress strain state of the straight jointed buried pipeline and the surrounding soil, taking into account the slippage effect as well. The objective of the study is the development of a mathematical model based on FEM , creating a computer program for PC and an analysis of the influence of geology, topography and soil conditions on the stresses and deformations of the pipeline.

SYSTEM DESCRIPTION

The pipeline system is composed of a number of straight pipe segments connected by special joints. The damage usually occurs at the joints, because they are the weakest points of the pipeline subjected to seismic ground movements (Refs. 6,11,14).

The effects of propagating seismic waves on the response behaviour of buried jointed pipelines have been studied analytically; the experimental works have been performed to assess the mechanism of pipe-ground interaction. (Ref. 7,9,12,14,16,18,21). Because of the high seismic activity in some areas of USA and Japan, the problem has been studied quite extensively by several US and Japanese researchers (see the publications from the ASCE in 1981, 1983, 1984, 1986, 1991 - Ref. 1,2,3,4,5, as well as the proceedings of the last three US.-Japan Workshops on Earthquake Resistance Design of Lifeline Facilities starting on 1990, - Ref. 19,20).

Based on the results of the above publications, model of this paper is constructed under the following main assumptions: a) Quasi-static analysis is appropriate for assessment of the pipeline response, i.e. the effect of the inertia forces and damping are negligible. b) Seismic forces at every finite element are determined as mass forces, which depend on the ground acceleration. c) Buried pipes are presented as a serie of segmented elastic beams, connected longitudinally with joints. d) The behaviour of buried pipelines depends mainly on the relative displacement of the ground, and the mass effect of the pipe is negligible. e) Since the axial strain is predominant in pipelines, the bending effect is assumed to be negligible. f) When ground strain becomes larger than a limit value, slippage occurs between pipes and surrounding soil. g) Soil is presented by homogeneous (or/and unhomogeneous), isotropic (or/and transversal isotropic), elastic media in plane strain conditions. h) There are not permanent displacements of the soil surrounding the pipe.

During an earthquake a buried pipeline may experience soil forces as a result of relative displacements of the ground along its longitudinal axis. It is assumed that the stresses in pipe segments under wave propagation effects are in the elastic range.

If the earthquake intensity is high, the slippage along the interface between the pipe and the soil is possible. If ground strain becomes large and slip occurs, it is assumed that the joints carry the total ground deformations.

FINITE ELEMENT METHOD MODEL

Based on the finite element method, a mathematical model is developed that takes into account the properties of the pipeline and the surrounding soil. Pre-processing and post-processing are developed for presentation and interpretation of the numerical results.

In the finite element discretization of the system **"pipeline-surrounding soil"**, the pipe segments are presented by elastic beams connected by joints. The geometrical dimensions of the pipes include the outside diameter **D** and the wall thickness **t**, which for preliminary design are only function of the hydraulics and static loads. The length of the segment **L** is necessary as well. The mechanical characteristic of the pipe segments is presented by the modulus of elasticity of the material (steel, concrete, etc.).

The soil surrounding the pipes is presented by 4-nodded quadrilateral finite elements. The soil-pipe interaction takes place by elastic connection in the finite element nodes between the beam finite elements (pipes) and the plane elements (soil). In isotropic case the soil is characterized by its modulus of elasticity **E** (Young's modulus) and Poisson's ratio **ν**. If the soil is stratified and its mechanical properties are different in two mutually perpendicular directions (transversal isotropy), the characteristic of the soil include modulus of elasticity and Poisson's ratio in the two planes of isotropy.

It is assumed elastic interaction between the discretized area and the earth mass. This is done by a special spring finite element, through the coefficient of subgrade reaction $\mathbf{K_0}$.

The possibility of slip depends on the friction force per unit area **f** between the ground and the pipe. It is assumed that **f** can be expressed by the shearing strength of soil:

$$f = C + K.\sigma_v.\mathrm{tg}\varphi \qquad (1)$$

$$\sigma_v = \gamma \mathrm{H}$$

where: **C** is cohesion of the backfilling, **K** is coefficient of earth pressure at rest, σ_V is vertical effective stress, φ is angle of internal friction of the backfilling, γ is the weight per unit volume of backfilling, **H** is the depth of the pipe center from the ground surface.

Depending on the site conditions and the geological particularities along the longitudinal profile, the deformability and strength parameters of the soil can vary from one finite element to the next one. Practically various combination of geological and topographical site conditions can be modeled and only the traditional physico-mechanical characteristics of the soil are necessary to know.

As a seismic wave propagates along a pipeline, axial strains are developed due to the relative displacements of the soil. The displacement of the soil depends on the seismic force given by:

$$F = m.a = v.\gamma\, a/g \qquad (2)$$

where: **m** is mass of the finite element, γ is weight per unit volume of soil, **v** is volume of the soil finite element, **a** is the ground acceleration and **g** is the gravity acceleration.

The ground-motion parameter of interest in this study is the peak or effective ground acceleration. The peak ground acceleration is defined as the largest value of acceleration contained in a particular time history (or accelerogram) of ground motion. Effective ground acceleration is defined as a percentage of the maximun real acceleration, usually smaller than 100% ; this value takes into account the local ground conditions of the pipeline site. The acceleration selected for the seismic design should be based also on an evaluation of the different factors such as the type of pipeline, importance of the pipeline and the consequences of its failure.

In this study the material model for soil is based on the equations of the lineal theory of elasticity, where the stress-strain relation is given by the Hook's law:

$$\{\sigma\} = [D] . \{\varepsilon\} \qquad (3)$$

here: {σ} is the stress vector, **[D]** is the matrix of elastic rigidity, {ε} is the strain vector.

Three types of finite elements are used: two dimensional isoparametric quadrilateral element for soil, two noded beam element for pipes and a spring element for boundary; see Fig. 1. The elements are connected to one another at a finite number of points (nodes). The basic assumption of the computational procedure is that displacements in the finite element may be interpolated from the element's node displacements. Knowing the components of the element's nodal points displacements, then the strains and the stresses of the system may be calculated as well.

It is assumed that the ground strain ε, might be given by the following (Ref. 9);

$$\varepsilon = \varepsilon_j + \varepsilon_p \qquad (4)$$

$$\varepsilon_j = e/L \qquad (5)$$

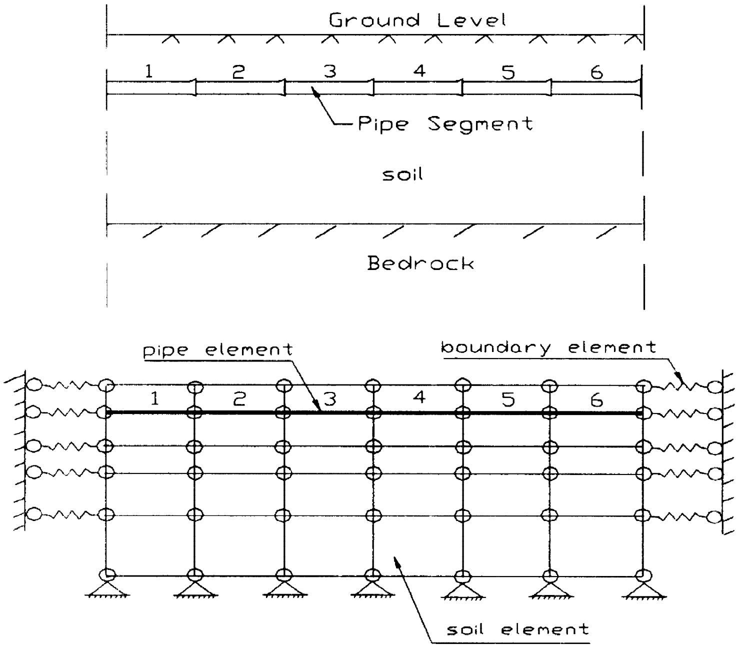


Fig. 1. Finite Element Discretization

where: ε_j is the joint strain, ε_p is the pipe strain, **e** is the expansion-contraction at joint, and **L** is the length of the pipe segment.

When ground strain becomes large, the expansion-contraction at joints arises proportionally. The field measurements (Ref. 9) show that during a earthquake the pipe strain arises very small as compared to that of ground and the pipe strain does not become larger than a certain value. This fact shows that slippage occurs at the interface between the pipe and the ground. The strain arising in the pipe when the slippage occurs may be expressed as follows (Ref. 9):

$$\varepsilon_p = \pi . D . f . L / 2AE \qquad (6)$$

where: **A** is the cross-sectional area of the pipe. The pipe strain ε_p obtained by equation (6) represents the limit value between the two types of work of the pipeline:

- if ground strain $\varepsilon < \varepsilon_p$, the stress at the pipe is proportional to ε.

- if ground strain $\varepsilon \geq \varepsilon_p$, the stress at the pipe is constant, and equal to ε_p; it depends on the shear strength of the soil and the geometrical characteristic of the pipe.

Having the components σ_x , σ_y, τ_{xy} of the stresses at the "soil" finite elements, the values of the principal normal stresses can be calculated: (7)

$$\sigma_{1,2} = \frac{1}{2}(\sigma_x + \sigma_y) \pm \sqrt{\frac{(\sigma_x - \sigma_y)^2}{4} + \tau_{xy}^2}$$

To evaluate how far the stresses at a given point of the soil have reached the failure limits, the Mohr-Coloumb failure criterion is used:

$$K_{is}=\tau_{lim}/\tau_{\alpha} \tag{8}$$

$$\tau_{\alpha}= 1/2\,(\sigma_1-\sigma_2)\cos\varphi \tag{9}$$

$$\tau_{lim}=1/2\,(\sigma_1+\sigma_2)\,\mathrm{tg}\,\varphi\,\varphi - 1/2\,(\sigma_1-\sigma_2)\sin\varphi\,\mathrm{tg}\,\varphi + C \tag{10}$$

where: $\mathbf{K_{ls}}$ is the coefficient of local stability, τ_{α} is the value of shearing stress when, $\alpha=\pi/4+\varphi/2$ with the plane of the maximal principal compression stress, τ_{lim} is the limit soil shearing stress; φ, and **C** are the shear strength parameters of the soil.

Based on the numerical results obtained by the finite element computation, a graphical presentation of the stress strain state of the structure is done. In the present work the graphical system AUTOCAD is adopted for it.

COMPARISON WITH PREVIOUS RESULTS

An example of a pipeline subjected to propagation of seismic wave is presented in "Earthquake - Proof Design of Buried Pipelines" (Ref. 13). The example can not be repeated in 100% (for lack of data about the length, thickness and modulus of elasticity of the pipes as well as for the distribution of the ground acceleration with depth); nevertheless it gives a good basis for a comparison, at least in a qualitative way. The analysis is done by the Multi-Particle Response Method(MPRM) in which the ground is presented by a large number of small particle masses. The recorded data of the Tokachi-Oki Earthquake (1968) at Hachinohe Port is modified to have a maximum acceleration of 100 gal in the bedrock and it is used as input. The direction of vibration is horizontal, parallel to longitudinal axes of the pipeline. The damping constant for the ground is 0.1. The result of calculation are shown in Fig. 3a.

The Finite element method model was used to analyse the above example(Fig. 2), using the following additional information: L=6 m, t=20 mm, and E= 100,000 Mpa. The results from the Multi-Particle Response Analysis and FEM analysis are shown in Figs. 3a and 3b respectively, where it can be observed a good agreement.

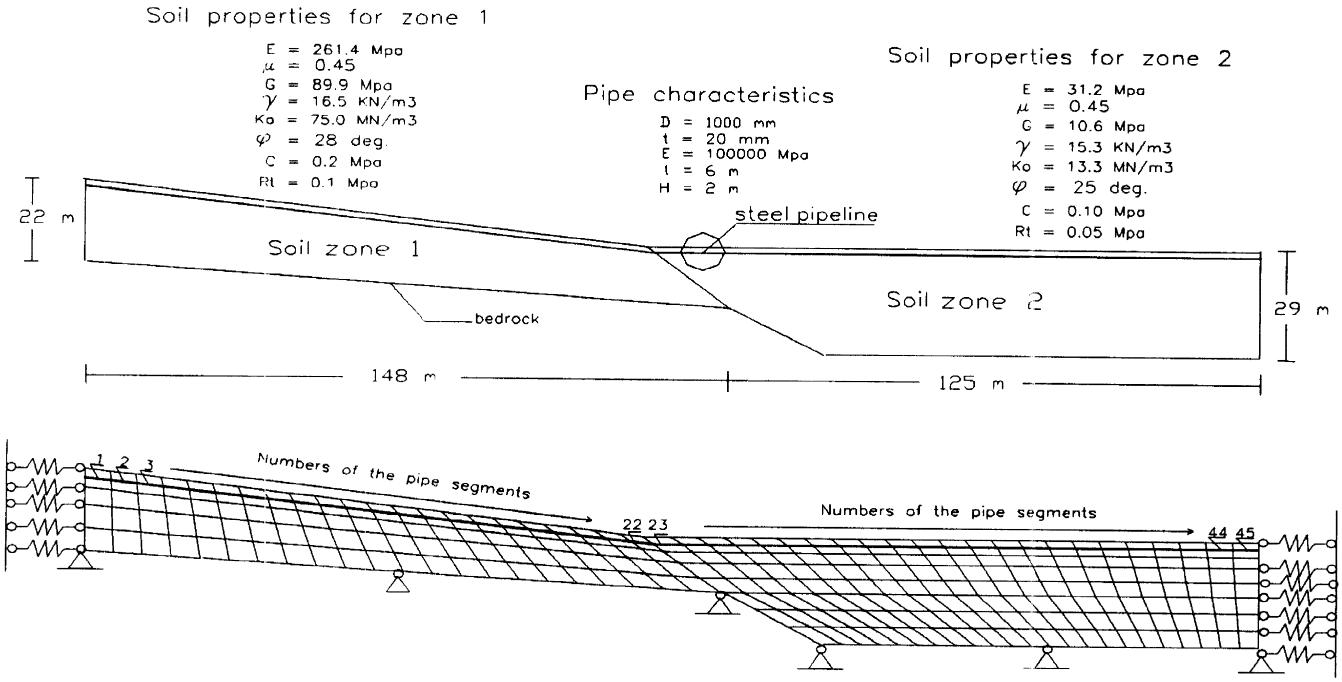
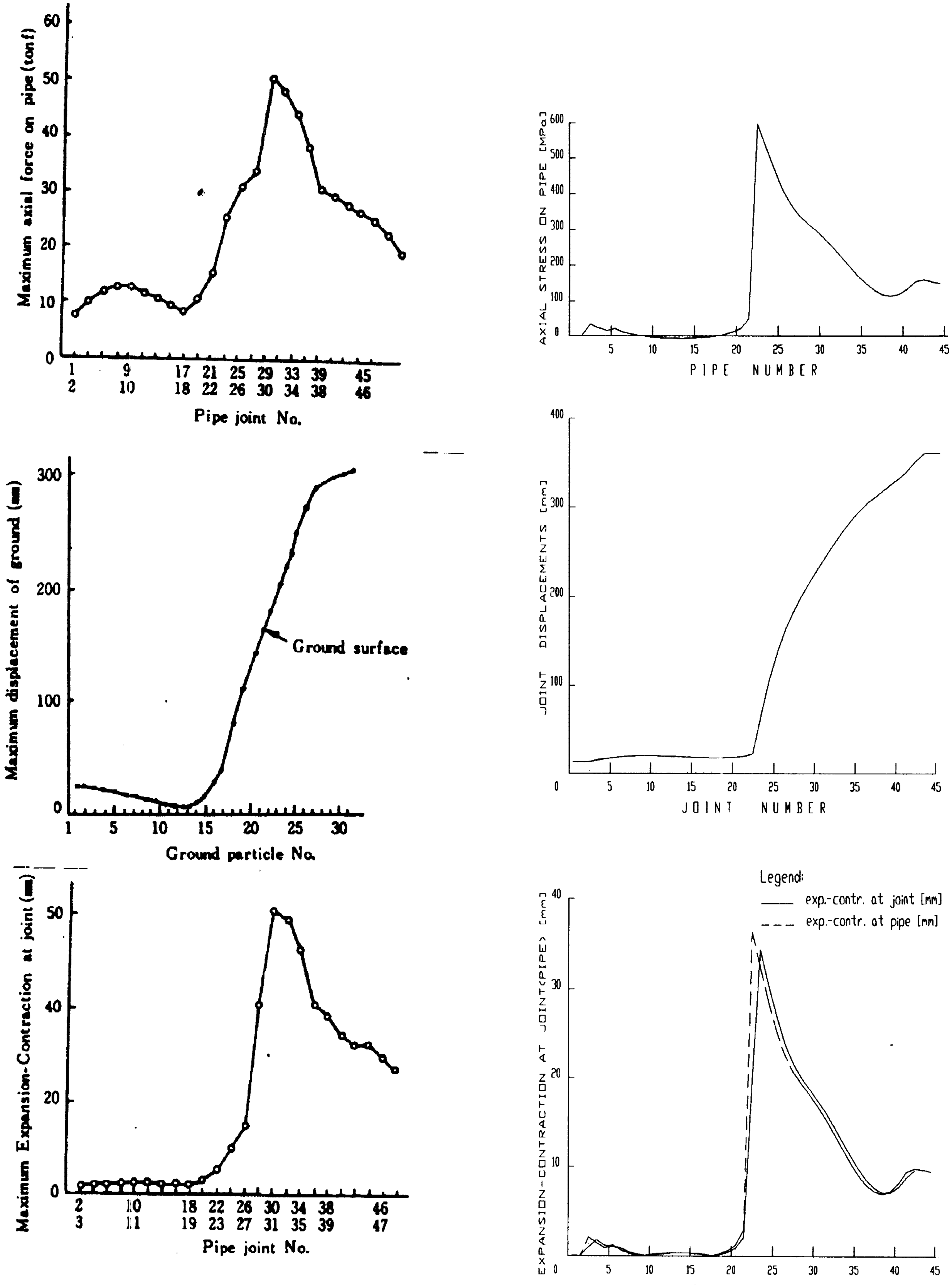


Fig. 2. Soil Profile and Finite Element Model



a). MPRM(Ref. 13)

b). FEM

Figure 3. Comparison of Results Obtained by Multi-Particle Response Method(MPRM) and FEM

ASEISMICITY EXAMINATION OF TYPICAL CASES OF STRAIGHT BURIED JOINTED PIPELINES

A wide range of geological and soil conditions along the pipeline profile were studied to investigate the effect of abrupt changen in both, the pipe stresses and the joint displacements. Details of this part of the investigation appear in another publication (Vassilev V. and Flores-Berrones, R., 1995); nevertheless the results derived from the numerical experiments may be summarized as follows:

- The displacements of the joints at the longitudinal profile of the pipeline depend on the dynamic deformations of the soil, i.e. the stress strain state of the pipeline depends on the soil deformability.
- The sector of a pipeline with abrupt change of the soil (transition from afirm soil - to a weak soil) is more vulnerable to damage than homogeneous soil sector with lower strength and deformability parameters.
- For the sector of a pipeline where the change of the geological conditions occurs, there is a concentration of the axial stresses in the pipes and a large expansion-contraction at the joints.
- The fixed points (connection points) at the longitudinal profile of a pipeline are very vulnerable to damage and special construction measures have to be taken to provide the continuity of the pipeline at those places.
- The stress strain state of a given part of the pipeline depends on the particular combination of the geological, soil and topographical conditions at the site, as well as of the construction particularities of the pipelines.

CONCLUSIONS

In this paper a mathematical model and the computer program SPLAN, based on FEM for analysis of the stress strain-state of straight segmented buried pipelines, are presented. This computer program was used to study the influence of typical cases of topographical, geological and soil conditions on the stresses and deformations of the pipes and on the expansion-contraction at the joints: this program is able to take into account the slippage between the soil and the pipes when the ground strain is very large.

A major result of interest for the design practice found from this numerical study is that the sectors of the pipeline with abrupt change of geology or soil conditions, appear as concentration points of the axial pipe stresses and the expansion-contraction at joints. It was also found that when slippage occurs at the soil-pipe interface, the axial stress at the pipe decreases significantly.

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