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Soil-Pipeline Interaction Along Active Fault Systems

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The problem of soil-pipe interaction along active faults is numerically taken into consideration by following a displacement-based approach. The interaction is analysed by means of lumped coupled elastoplastic springs, whose failure locus is linearized piece-wise, and the equations governing their behaviour are set in a form such that a linear complementarity problem can be formulated. The numerical formulation is conceived for taking large displacements into account. The ground motion is controlled; the solution is presented in terms of pipe displacements and internal pipe actions, and its dependency on geometrical parameters is discussed. The problem of the axial instability of the pipeline is also studied.

INTRODUCTION

The mechanical interaction between a buried pipeline and the surrounding soil is one of the most important factors that engineers have to account for in pipeline design. Relative soil-pipe displacements induce a change in actions on the external surface of the pipe (Fig. 1), thus resulting in a net additional load distributed along the buried structure.

When increasing relative soil-pipe displacements, these additional loads modify the pipeline layout, thus increasing actions within the structure and eventually inducing the loss of serviceability or even the failure of the pipe with consequent leakage of internal fluid. It follows that the soil-pipeline interaction is a crucial problem from an economic, technical and also environmental point of view.

Relative soil-pipe displacements can be due to several causes; the most common are related to landslides, where buried pipelines cross potentially unstable soil masses (either in mountain regions or in underwater environments) that can move several tens of centimetres per year. To these we must add relative soil-pipe displacements induced by seismic events. During an earthquake, a buried structure is subjected to 2 different effects: temporary ground deformation (TGD) due to seismic wave propagation; and permanent ground deformation (PGD) due to surface fault movements and liquefaction of sandy soils. As is well documented in the literature (e.g. O'Rourke and Deyoe, 2004), even though the effects of the wave propagation may affect very wide areas, normally they result in a lower rate of failure per kilometre compared to the rate of failure caused by PGD. Statistical methods have been developed to study the former, as well as analytical approaches based on very simplified hypotheses (Newmark, 1967; Sakurai and Takahashi, 1969; Shinozuka and Koike, 1979; O'Rourke and El Hmadi, 1988). On the other hand, the effects of PGD normally affect a relatively restricted area, but they result in quite a high rate of failure. PGD can be due either to the seismic- induced settlement of the soil, or to the liquefaction of the soil and consequent buoyancy uplift of the pipe. (There exists in the literature a considerable amount of analytical and empirical work on these

Fig. 1 Idealized normal stress distribution: (a) over pipe at rest, and (b) after a horizontal rightward pipe displacement (after Audibert and Nyman, 1977)

topics, such as by Tokimatsu and Seed, 1987; Bartlett and Youd, 1992.) In the following, particular attention will be paid to the study of the consequences of permanent slip across active faults on pipes.

In the last 30 years, several different approaches have been proposed in order to study this problem (Newmark and Hall, 1975; Kennedy et al., 1977; Wang and Yeh, 1985). These methods assign a deformed shape to the pipeline and try to compute the maximum expected strain within the pipe under external soil loads for a given strike-slip offset. An alternative approach consists of assuming that the pipeline will be subjected to a nonlinear behaviour, by introducing 2 plastic hinges: By minimizing with respect to their position the total virtual work, it is possible to locate them and to define the deformed shape of the pipeline. Obviously, these methods do not take into account the soil-pipe interaction correctly, and they are unlikely to be adapted to general 3-dimensional conditions, or to take into account a nonhomogeneity of soil mechanical properties.

In this paper we present a convenient numerical tool based on the discretisation of the pipeline by finite elements of the beam type, and a displacement-based numerical approach is described. Simple examples of straight pipelines and strike-slip faults will be discussed; however, the numerical code is conceived to analyse 3-D problems. A simple soil-pipe elastoplastic interaction law will be defined on the basis of the best-known experimental works, and an efficient numerical scheme will be implemented in a large displacement approach, capable of taking into account even possible Euler instabilities of the pipeline due to axial compressive loads.

The pipeline is considered a linear elastic structure, and its cross-section is assumed to be circular and rigid (i.e. no ovalisation is taken into account); the material (steel) and the geometrical properties of the cross-sections are assumed to be homogeneously distributed along the pipe axis. Since we are interested in evalu-

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