Buried pipelines subjected to normal fault: simulation vs experiment

Pipelines enterrées soumis à faille normale : analyse par rapport à l'expérience

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ABSTRACT Buried pipelines often cross tectonically active areas capable of producing large earthquakes and large ground deformations. Based on the observed damage mechanisms of buried pipelines during past earthquakes, faulting-induced ground deformations prove the most detrimental for their safety. Motivated by this, this paper presents a finite element methodology to simulate the response of a pipeline subjected to normal faulting, accounting for the nonlinear behavior of the pipe, the complex behavior of the soil and the rupture propagation through it, as well as the interaction between the pipe and the soil. The numerical methodology is validated against 1g small scale experiments conducted at the Laboratory of Soil Mechanics of NTUA. The good agreement between the predictions of the numerical model and the results of the experiment give confidence to our numerical tools.

RÉSUMÉ Pipelines enterrés traversent souvent des zones tectoniques actives capables de produire de grandes séismes et les grandes déformations du sol. Sur la base des mécanismes d'endommagement observés de pipelines enterrés lors séismes passés, déformations du sol induites par failles s'avèrent les plus préjudiciables pour la sécurité des pipelines enterrées. Motivé par ce, le présent article présente une méthode d'éléments finis pour simuler la réponse d'un pipeline soumis à des failles normales, en tenant compte du comportement non linéaire du pipeline, du comportement complexe du sol et de la propagation de la rupture, ainsi que de l'interaction entre le tube et le sol. La méthode numérique est validée par rapport à des expériences à échelle réduite réalisées au Laboratoire de mécanique des sols de NTUA. Le bon accord entre les prédictions du modèle numérique et les résultats de l'expérience donne confiance à nos outils numériques.

1 INTRODUCTION

Permanent ground-induced actions due to earthquakes, such as fault movements, landslides, liquefaction-induced lateral spreading are responsible for the majority of seismic damages in oil and gas buried steel pipelines. Therefore, substantial effort is dedicated by the research community in the last decades to unravel the behavior of buried pipelines subjected to excessive ground deformation.

Several methods to address this problem have been introduced. Early works on this issue are based on simplified analytical models that use beam-on-elastic foundation and elastic beam theories. Newmark and Hall (1975) were the first to use such a method to analyze the response of a pipeline subjected to large fault displacement. The most recent contribution to the simplified analytical method comes from Trifonov and Cherniy (2010). With the introduction of finite element methodology, an alternative approach has been introduced based on the numerical treatment of the problem. In numerical models, a pipeline is modeled with beam elements, while the pipe – soil interaction is modeled with springs (e.g. Takada et al. 1998; Calvetti et al. 2004). With the evolution of the computational capabilities, the numerical tools also evolved leading to the 3D simulation of the problem, with the soil being modeled with inelastic continuum elements (e.g. Vazouras et al. 2010). Modern numerical models are more rigorous, being able to capture the nonlinear behavior of the pipe, the pipe-soil interaction and second order effects due to large displacements.

This paper introduces a new 3D finite element methodology to realistically simulate the phenomenon of a continuous buried pipeline subjected to permanent ground displacement due to normal faulting. The numerical methodology aims to simulate the behavior of the soil stratum subjected to slip deformations at its base (bedrock), the pipe response subjected to deformations of the surrounding soil due to faulting and the interaction between the two. To gain confidence in our numerical tools, the methodology is extensively validated against a series of 1g small scale experiments conducted at the Laboratory of Soil Mechanics of NTUA. From the ensemble of the experiments conducted in the framework of this experimental series, one is selected and presented in this paper.

2 EXPERIMENTAL EQUIPMENT

2.1 *The Fault Rupture Box*

The present experimental series has been conducted utilizing the Fault-Rupture Box of the NTUA Laboratory of Soil Mechanics (Figure 1). This custom-built apparatus has been designed to simulate quasi-static fault rupture propagation and Fault Rupture–Soil–Structure Interaction. It comprises a stationary and a movable part, which can move downwards or upwards to simulate normal or reverse fault conditions. The movable part is connected to a servo-mechanical screw-jack actuator, which can generate a maximum stroke of 200 mm. The dip angle α can be adjusted from 45º to 90º (for this experimental series, a = 45º). The internal longitudinal dimension of the Fault Rupture Box is 2.65 m, its depth is 0.9 m, while the out-of-plane dimension is 0.9 m.

2.2 *The soil material*

Dry Longstone sand, an industrially produced fine and uniform quartz sand with d_{50} = 0.15 mm and uniformity coefficient $C_u = d_{60}/d_{10}$ = 1.42, was used in the experiments. The void ratios at the loosest and densest state have been measured as e_{max} = 0.995 and e_{min} = 0.614, and the specific weight of the solids as G_s = 2.64. Material and strength characteristics of the sand, as derived through a series of laboratory tests, have been documented by Anastasopoulos et al., (2010). During this experimental series the relative density of the sand was selected D_r = 90 %.

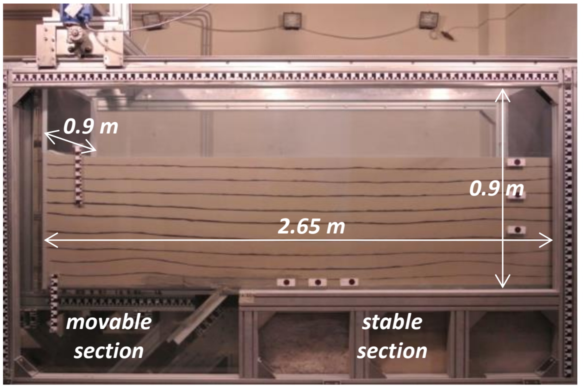

Figure 1. The Fault Rupture Box and its dimensions.

2.3 *The pipe models*

The pipe models were selected from a range of commercially available pipes. Pipes of various diameters were tested, yet for the purposes of this paper only the smaller available pipe of diameter D = 10 mm is presented. Commercially available small diameter pipes typically do not have large D/t ratios, hence the thickness of the pipe is t = 1 mm. The pipe models are made of *Aluminum 6036*. In order to accurately obtain the stress – strain relation for the pipe material, samples from the pipes were subjected to uniaxial tensile test. From the measured stress–strain curve, first yielding occurs at ε_{yield} = 0.0018.

2.4 *Instrumentation*

In order to record the pipe response within the soil, strains along the pipe were measured using 12 strain gauges. The strain gauges were 10 mm long, with resistance of 120 Ω and were temperature compensated. The gauges were placed at characteristic locations along the crown of the pipe. Each strain gauge was coated with scotch tape to protect the gauges from being dragged along by the moving soil around the pipe. Laser displacement transducers were used to measure the displacement distribution along the surface of the soil.

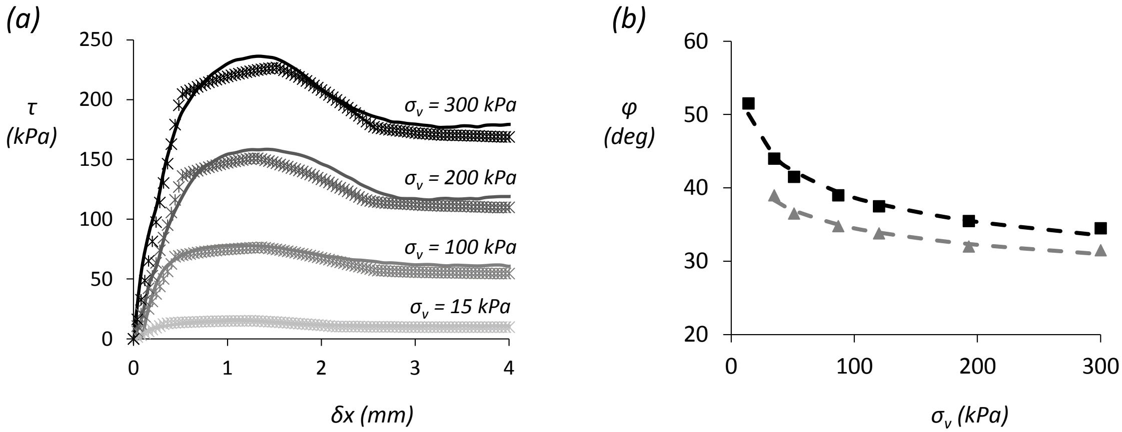

Figure 2. (a) Application of the soil constitutive model: comparison between laboratory direct shear tests and results of finite element modelling of these tests. (b) Dependence of the peak and post-peak friction angle on stress level.

3 NUMERICAL METHODOLOGY

The simultaneous modeling of the rupture propagation through the whole depth of the soil deposit within the Fault Rupture Box and of the interaction between the pipe and the surrounding soil poses a substantial obstacle. The dimensions of the pipe cross-section (diameter D = 10 mm) calls for small elements, of the order of d_{FE} = 1 mm, in order to accurately capture its response. On the other hand, the dimensions of the Fault Rupture Box are several orders of magnitude larger (*length* x *width* x *height* = 2650 x 900 x 650 mm), rendering the simultaneous simulation of the pipe and the soil within the rupture box impossible. To overcome this obstacle, the problem is decoupled. First, the rupture propagation is analyzed through the whole soil deposit considering free field conditions (i.e. without the presence of the pipe). Taking advantage of the plane strain conditions of the fault rupture propagation phenomenon, this analysis is conducted in 2D. Subsequently, the pipe – soil interaction problem is analyzed; due to the demand for small elements only a soil prism around the pipe is regarded. Yet, the dimensions of this prism are adequately large to avoid any effect of the boundaries on the pipe response and on the accurate simulation of the pipe – soil interaction. The displacement history during the fault rupture propagation computed from the free field analysis is imposed at the boundaries of this prism. The proposed decouple analysis methodology tactically assumes that the presence of the pipe does not affect the evolution of the fault rupture propagation at the global level – a reasonable assumption. This can be justified through the small relative stiffness of the pipe compared to that of the displacing soil mass of the hanging wall. Moreover, ensuring that the boundaries of the 3D model are adequately far from the pipe (distance at least 10 times the pipe diameter), allows any potential interaction between the pipe and the surrounding soil at the immediate vicinity of the pipe to take place.

4 FREE FIELD RUPTURE PROPAGATION

Tectonic faulting takes place at bedrock, which is typically at a large depth, and propagates towards the ground surface through the soil. During such fault rupture propagation, the rupture path and the consequent displacement pattern may be substantially altered by the overlying soil strata (e.g., Bray et al., 1994). To realistically account for the soil behavior an appropriate constitutive model for the soil behavior is needed, that incorporates the localization of shearing within a narrow shear band. Thus, an elastoplastic Mohr–Coulomb constitutive model with isotropic strain softening is utilized to simulate soil behavior (Anastasopoulos et al., 2007). Shearing of a soil element from a fault is quite similar to the shearing of a specimen subjected to direct shear testing. Therefore, the constitutive model parameters are calibrated through direct shear test results. Figure 2a presents the comparison between the laboratory direct shear tests and the results of the constitutive model utilized in the analysis for various magnitudes of vertical effective stress.

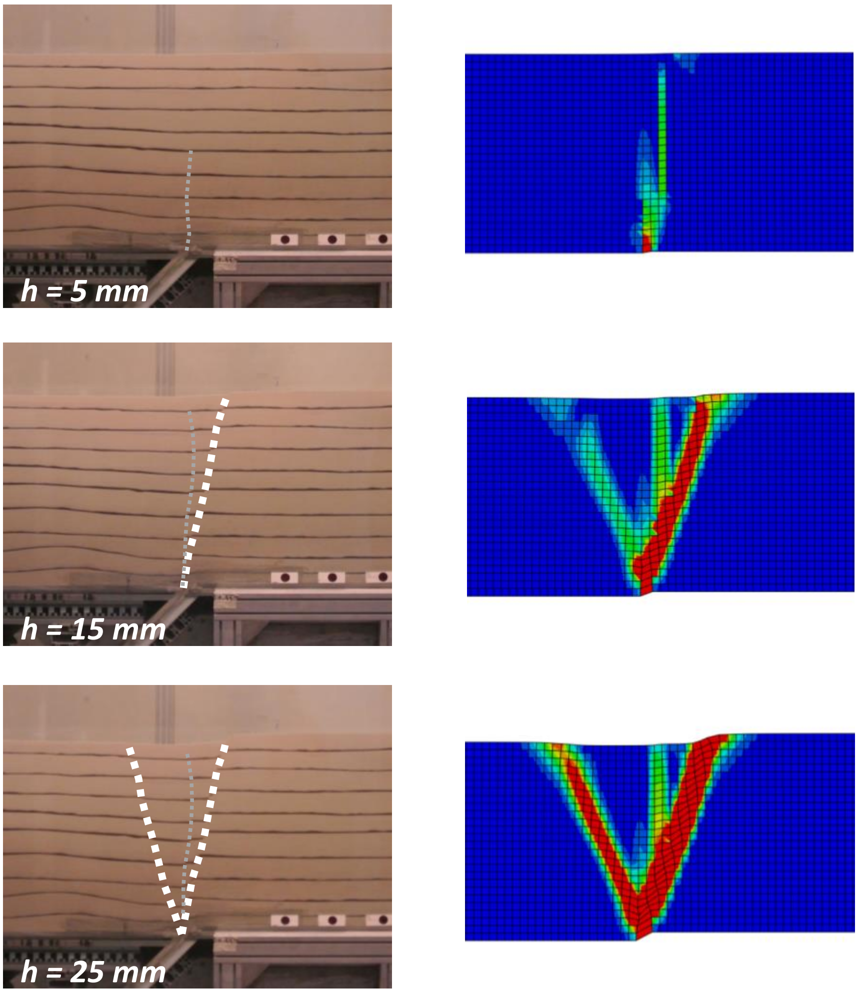

Figure 3. Simulation of normal fault rupture propagation: Comparison between the numerical prediction and the results of the experiment for various magnitudes of fault offset (h = vertical component of the bedrock displacement).

In addition, since the experiments were conducted at small scale without using a centrifuge, small scale effects are expected to make an effect. In particular, the computed peak and residual internal friction angle of the sand was found to increase as the vertical effective stress decreases, as revealed from the direct shear test results (Figure 2b), a dependence that was accounted for in the analysis.

Figure 3 presents the results of the numerical analysis in terms of mesh deformations and the associated shear strain localization compared to the observed deformation during the experiment for various magnitudes of vertical fault offset h. To facilitate comparison, the shear band formed during the experiment is highlighted with dashed lines. The analysis is in good accordance with the Fault Rupture Box test as far as the evolution of the phenomenon is concerned. Initially, a practically vertical shearing path is detected within the soil mass. As the bedrock offset increases the primary rupture is gradually formed and it propagates towards the surface. For h = 15 mm it reaches the surface. Further increase in the fault offset leads to the formation of a secondary antithetic rupture. For bedrock offset h = 25 mm, the analysis successfully predicts the emergence of the secondary antithetic rupture all at the surface. Figure 4 presents the prediction of the surface displacement profiles according to the numerical analysis compared to the measured surface displacements during the experiment. The comparison between the analysis and the experiment proves that the numerical analysis realistically captures the soil behavior.

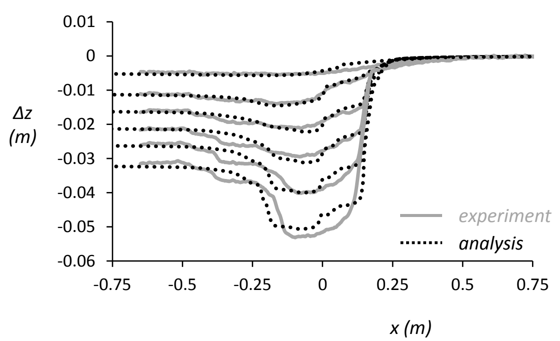

Figure 4. Comparison between the numerical prediction and the results of the experiment in terms of vertical displacements along the surface.

5 PIPE–SOIL INTERACTION

In the ensuing, the numerical methodology focuses on the pipe – soil interaction. The pipe and a soil prism around it are modeled in 3D, and the computed displacements from the free field analysis are imposed as input at the boundaries of this prism. The pipe is placed at depth z = 0.55 m from the surface. This was made to realistically model the interaction forces between the pipe and soil. This means that the pipe to soil stiffness, and strength ratios are consistent with a case of common practice. Suppose we have a steel pipe buried at depth 1 – 1.5 m – a rather common case in practice. Since these experiments are conducted in 1 g (and not in a centrifuge), the pipe must be placed at the same depth to achieve analogous interaction forces. However, with the simultaneous reduction of the pipe stiffness (aluminum instead of steel pipe), the pipe can be placed at smaller depth (z = 0.55 m).

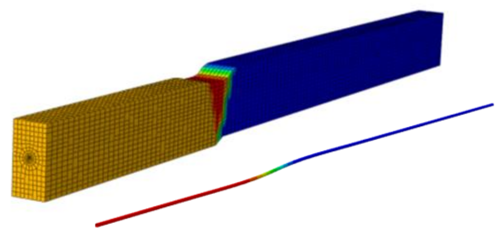

Figure 5. Deformed mesh of the pipe-soil interaction model with superimposed displacement contours for h = 20 mm.

Figure 5 presents the deformed mesh for vertical fault offset h = 20 mm. Figure 6 presents the comparison of the predicted strain distribution at the top centerline of the pipe according to the numerical analysis compared to the measure strain distribution for various magnitudes of fault offset. The numerical methodology succeeds in predicting the maximum strains as well as the distribution of strains along the pipe, hence, both the stressing of the pipe as well as the deflection due to faulting is accurately predicted.

6 CONCLUSIONS

This paper presents a new 3D finite element methodology to simulate pipeline response subjected to normal faulting. The numerical methodology can successfully capture the soil response and the fault rupture propagation, the pipe response and the interaction between the pipe and the surrounding soil. It decouples the phenomenon, analyzing first the fault rupture propagation assuming that the pipe does not affect the evolution of the rupture at global level. Subsequently, the pipe – soil interaction problem is analyzed; the computed displacement time histories are applied to the boundaries of the local, more detailed model (i.e., having a much finer mesh), comprising the pipeline and the surrounding soil. The proposed methodology was validated against 1g small scale experiments conducted at the Laboratory of Soil Mechanics of NTUA. The results of the numerical models compare very well to the response of the pipe during the experiments. The agreement between the numerical and the experimental results give confidence to the numerical tools.

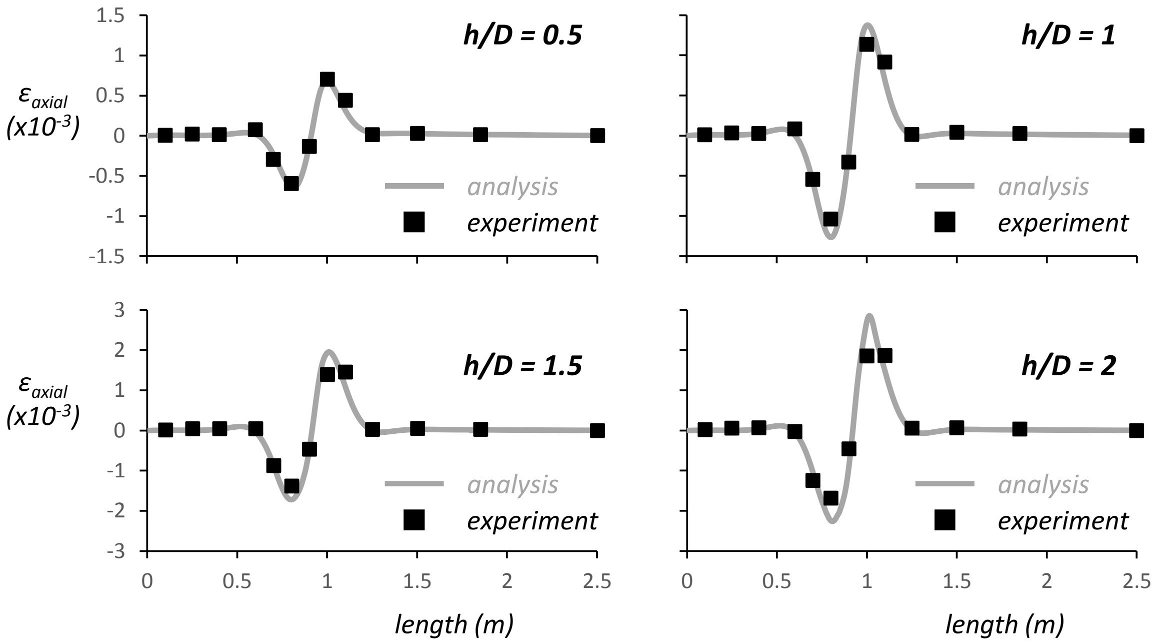

Figure 6. Comparison between the numerical model prediction and the results of the experiment in terms of strain distribution along the top centerline of the pipe for various magnitudes of fault offset.

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