Permanent ground deformations induced by reverse fault: evaluation of mitigation measures for buried pipelines

Les déformations de terre permanentes ont incité par la faille contraire: l'évaluation d'atténuation mesure pour les pipelines enterrés

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ABSTRACT

Soil formations situated above a fault are often deformed by fault rupture propagation due to large earthquakes. This faulting often causes damage to underground lifelines, such as tunnels and pipelines, located in the shear zone formed by the fault movement. The paper studies the deformation behavior of the overburden soils and its influence on the buried structures by means of 2D FE simulations. The numerical model is validated using a case history from the literature, a tunnel cross section in Greece. A buried pipeline is modeled based on that validation. The effect of fault rupture on the movement of the free ground surface is studied first. The fault rupture – soil – pipeline interaction with and without mitigation measures is simulated afterwards. Based on the identified mechanisms, the application of all-around low density backfill or/and geogrid reinforcement beneath the buried pipeline is discussed. Results for various horizontal distances between the center of the pipeline and the fault tip are presented.

RESUME

Les formations de sol situées au-dessus d'une faille sont souvent déformés par la propagation de rupture de faille en raison de grands tremblements de terre. Ce produire des dommages souvent aux bouées de sauvetage souterraines, telles que les tunnels et les pipelines, localisés dans la zone de tondage formée par le mouvement de faute. Le contribution étudie le comportement de déformation des sols surcharger et de son influence sur les structures enterrées au moyen de 2ème simulations d'élément finies. Le modèle numérique est validé en utilisant une exemple de la littérature, une section transversale tunnel en Grèce. Un pipeline enterré est modelé basé sur cette validation. L'effet de rupture de faille sur le mouvement de la surface de terre libre est étudié d'abord. La rupture de faille – le sol – l'action réciproque de pipeline avec et sans mesures d'atténuation est simulé ensuite. Basé sur les mécanismes identifiés, l'application de tout autour de la densité basse remblai ou/et du renforcement geogrid sous le pipeline enterré est discutée. Les résultats pour les distances horizontales différentes entre le centre du pipeline et le bout de faille sont présentés.

Keywords: fault rupture, buried pipelines, ground deformation, low-density fill, mitigation, geogrid

1 INTRODUCTION

Permanent ground movements during earthquakes can be caused by surface faulting, seismic settlement, lateral spreading due to soil liquefaction, landslides, and the consolidation of relatively cohesion-less fills and loose natural deposits. All these sources of permanent deformation involve some distribution of the ground movement, for which the extreme case is an abrupt or knife-edge displacement in which all relative movement is concentrated along a single plane. Permanent ground deformations (PGD) generally are critical when working with high-pressure pipelines, for which there is concern related to system supply and safety. The differential ground movement of the two sides of the fault results in bending and tension or compression depending on the relative orientation of the fault and the pipe and the faulting direction. Various methods had been suggested to mitigate pipeline damage from PGD including the use of high strength and high ductility pipe materials, the use of expansion and contraction joints, the isolation of the pipeline from ground movement. Pipes which transverse a hazardous area can be isolated from the effects of the ground movements by repositioning in the vertical direction as done in the Trans-Alaska pipeline project (William et al, 2003) which was placed on above-ground supports at certain fault crossing points with the pipeline as shown in Figure 1. In case of the hazard source is lateral spreading only near ground surface, the increasing of the burial depth can present mitigation measure that can isolate the pipe from the potential damage by locating it below the hazardous area.

Figure 1. Pipe Location: Pre-Earthquake (Left) Post-Earthquake (Right), (William et al, 2003)

For continuous pipelines, the use of stronger materials and larger wall thickness improves the seismic performance, particularly for the cases in which the axial strain dominates in pipe. Alternatively, it has long been argued that the use of more flexible pipe materials tends to improve the seismic performance for the buried pipelines. Isenberg and Richardson (1989) suggested that flexible joints between pipeline segments could be used to mitigate major PGD, where the relative displacement is accommodated in the flexible joint leaving the rest of the line

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relatively without imposed major stresses. The locations of the plastic shear strain concentration zones reduced if the line is oriented perpendicular to the fault. Theoretically, the optimum situation for the pipeline is to be at right angles to the fault. For this situation the pipe is working under bending stresses. For other orientations, both axial strain and bending strain will be induced in the pipeline with the PGD.

2 STATE OF THE ART

2.1 *Sensitivity to pipe-soil frictional forces*

Buried pipeline response to faulting is very sensitive to frictional force mobilized between the pipeline and surrounding soil, O'Rourke and Trautmann (1980). For granular soils, the interface frictional resistance between pipe and soil often is estimated from a ratio of interface to soil friction angle, δ/Φ**.** Ranges of δ/Φ for various types of pipe surfaces and coatings are recommended in this paper. As a practical matter, δ/Φ should not be less than 0.5, and should be selected on the basis of the long-term pipe surface characteristics.

2.2 *Material stress-strain formulation*

Analytical models of pipeline response to fault movements are influenced strongly by the type of stress-strain representation used for the steel. It is recommended that continuous nonlinear representations, such as Ramberg-Osgood formulation can be used. Bi or tri-linear representations can be useful as an approximation, if care is taken to check that the strain predicted by a simplified bi- or tri-linear plot is very close to that of the measured stress-strain curve for the level of stress compatible with the design ground movement.

Two simplified models for buried steel pipeline response to abrupt surface faulting and similar types of ground rupture have been proposed by Newmark and Hall (1975) and Kennedy et a1.(1977)**.** Thin-walled pipelines are especially vulnerable to compression, which may induce local wrinkling. A pipeline orientation, however, is able to avoid buckling and wrinkling and take advantage of the inherent ductility of the steel. Newmark and Hall (1975) assumed that the pipeline is subjected to constant frictional resistance and that the pipeline deforms in an anti-symmetric pattern of two broad circular arcs, each extending from the fault intersection to an anchor point at a distance, from the fault. Anchors may be caused by bends, ties, or other constraints which resist axial movement. Alternatively, the anchor point may represent an effective anchor length, beyond which there is no axial stress imposed in the pipeline from fault movement.

Newmark and Hall (1975) used bi- and tri-linear represent-tations of the stress-strain response of steel, and did not consider bending strains. Kennedy et a1. (1977) assumed that the pipeline is subjected to increased axial friction in the zone of curvature near the fault. The radius of curvature is related to both the axial tension in the pipe and the lateral earth pressure mobilized against transverse movement of the pipe in the curved zone. Kennedy et al. (1977) assumed that the pipeline behaves as a cable under large deformation. Their model accounts for both axial and bending strains, and uses a Ramberg-Osgood formula-tion to represent the nonlinear stress-strain behavior of the steel

2.3 *A Case study: Cut and-cover tunnels in Kamena Vourla, Greece*

The case study cut-and-cover tunnels are situated in Kamena Vourla (Anastasopoulos and Gazetas,2005) being part of the new highway connecting Southern Greece with Northern Greece (PATHE). They are within the bypass section of the homonymous city. The scope of the study was the design of the cut-and-cover tunnels against a major fault rupture. Their proximity to the well known, and mapped, Kamena Vourla fault gave rise to the question of their seismo-tectonic performance. As depicted in Figure 2, the tunnel is of double section, with 1 to 5 m cover. Its cross-section is 24.4 m wide and 9.5 m in height, with a bottom slab of 1.3 m thickness and a top slab of 1.2 m. The side walls are 1.0 m in thickness, and the middle one 1.4 m. Based on the geology of the area, the depth of the soil layer was estimated to be H = 50 m. As always, the soil was modeled with quadrilateral plane-strain elements, and the tunnel with beam elements. The tunnel is connected to the soil through special interface elements, allowing for uplifting and sliding. Soil behavior is modeled through the modified Mohr-Coulomb constitutive law with isotropic strain softening. The analysis is performed in two steps. First, fault rupture propagation through soil is analyzed in the free field, ignoring the presence of the tunnel. The differential displacement h was applied to the left part of the model at an dip angle = 60^{o} (Figure 4) , with max h = 2 m. according to the aforementioned geotectonic studies.

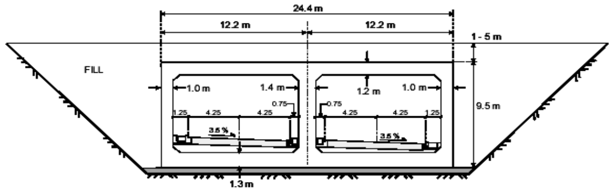

Figure 2. Design of Cut-and-Cover Tunnels in Kamena Vourla against a major fault rupture (Anastasopoulos and Gazetas, 2005)

Figure 3 depicts the bending moments along the structural members of the tunnel, with respect to the imposed displacement. As it would be expected, the maximum stressing of the base slab of the tunnel (4276 kNm) takes place for the maximum imposed displacement, h = 2 m. Interestingly, the response of the top slab is different. The maximum bending moment of 4703 kNm is attained for h = 0.5 m.

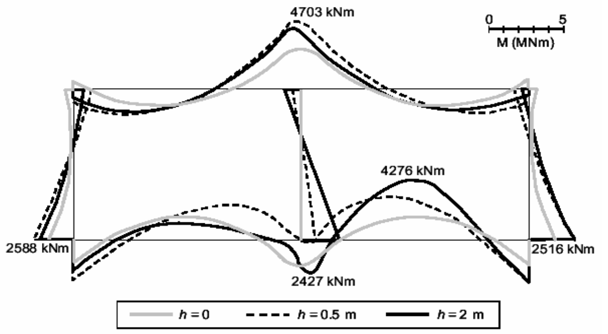

Figure 3. Design of cut-and-cover tunnels in Kamena Vourla against a major fault rupture: Bending moments with respect to the imposed bedrock displacement h, for rupture scenario 1, with 5 m cover. (Anastasopoulos and Gazetas, 2005)

Then, the increase of h only leads to a slight decrease of the bending moment. The same observation also holds for the left wall and the left half of the bottom slab. This performance is indicative of the strong non-linearity that characterizes the interplay between the rupturing fault, the bearing soil, and the tunnel.

3 FEM SIMULATION

The FE simulation using Plaxis 8.0 go through three-step methodology to draw out the pipe line behavior against major fault rupture. The first step is the construction of finite element model in complete simulation with that of the real case history study to validate the proposed model for all of its constituents. The second step is applying the validated nonlinear FEM to analyses fault rupture propagation in the free field without the presence of the buried pipeline, knowing the location of the rupture zone in the free field. Then in the third step, the buried structure is placed to perform the analyses of fault rupture-soil-pipe interaction (FR-SPI) mechanism.

The main factors influencing the FR-SPI are evaluated; the density of the backfill surrounding the pipeline and its extension zone, the burial depth of the pipeline, the distance of the pipeline from the fault tip as a function of its diameter, the state of stresses within the soil and the exerted loads on the pipe cross section, the ground surface vertical and horizontal movement pattern against the fault rupture in both free field and FR-SPI mechanism, the effect of using low density backfill around the pipe with its configuration, and the use of the geogrid layers for the fill material as a mitigation measure for the pipe line safety against fault movements.

3.1 *Numerical model validation*

To validate the proposed FE model used in this study, a complete simulation of the case study of cut and cover tunnel in Kamena vourla, Greece (Anastasopoulos and Gazetas, 2005), and comparing the output bending moments in all the tunnel elements is performed. In the validation procedure, maximum vertical of fault movement of 2m is applied on the left part of model at tip angle of 60 degree with the fault rupture outcropping at distance of 6m from the left edge of the tunnel as shown in the obtained total displacement shading in Figure 4.

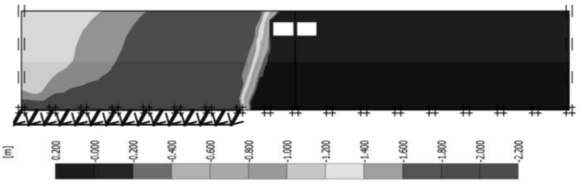

Figure 4. Total Displacements of validation tunnel, m

Hardening soil model (HSM) is used as a constitutive model for the soil with γ_{dry} = 17 kN/m^3, γ_{sat}= 20 kN/m^3, C=1 kN/m^2,Φ= 35^o, E_{ref}=4.5*10 ^{04} kN/m^2, E_{50}=3.75*10 ^{04} kN/m^2 . Beam elements with linear elastic constitutive law is used for the tunnel with reinforced concrete properties, with E=30*10^{06} kN/m^2. The model is tested for the cases of static, 0.5 m, 2.0 m for the vertical fault movement. For simplicity , all of the tunnel elements are of 1.2m thickness, so we get some reasonable variation in bending moment values, but with the same general behavior and bending trends and most of the values for tunnel elements as shown in Figure 5.

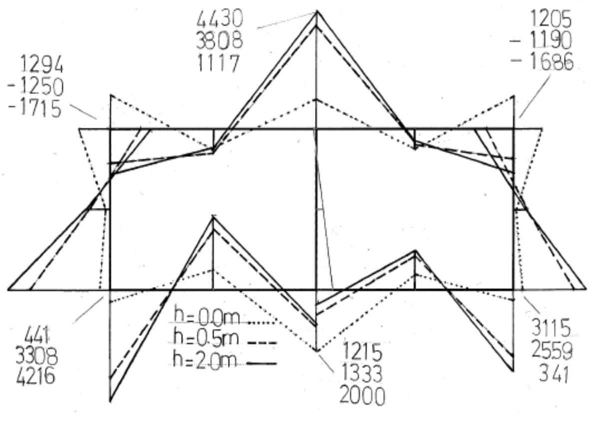

Figure 5. Bending moment for the FEM, kN.m

3.2 *Fault rupture- Free field*

Fault rupture propagation through soil is analyzed in the free field, ignoring the presence of the pipeline as in Figure 6-a to know the exact location of the rupture outcropping in the free field as shown in Figure 6-b.

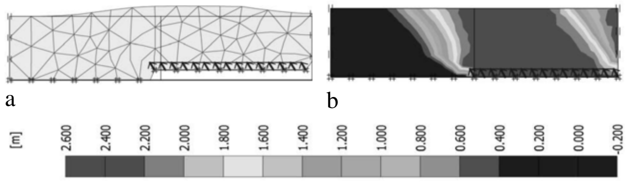

Figure 6. a) The deformed mesh, b) total displacement, m for free field

The case in concern for this paper is for reverse fault with a maximum of 2 m for vertical movement applied on the right part of the model with tip angle of 60 ^{o,} using the same verified constitutive model and movement mechanism.

3.3 *Fault rupture-soil-pipe interaction (FR-SPI)*

The pipe of 2.54 m and 1cm thick. is placed at a distance of 2 times the pipe diameter(2D) from the fault tip, at burial depth of 2.25 m. The analysis of the (FR-SPI) is performed, Figure 7. Comparing the results of the two analysis (Free field&(FR-SPI)), the effect of the interaction mechanism is visualized and quantified.

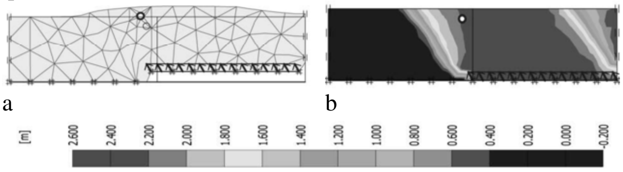

Figure 7. a, The deformed mesh, b, total displacement, m for fault rupture-soil-pipe interaction

Beam elements with linear elastic constitutive law is used for the pipe with steel properties, with EA =2 *10 ^{06} kN.· This case is considered as a references for evaluating the effect of the different used remediation methods through comparing the resulting straining actions in the pipe wall. For the case of no remediation the distributions of bending moment, axial force, and shear force on pipe cross section in Figure 8. and their values

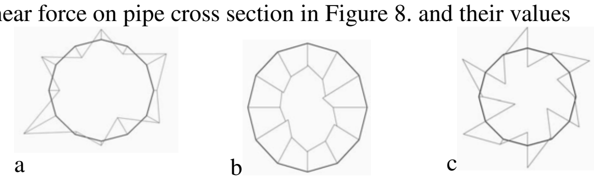

Figure 8. a) Bending moment, b) axial , and c) shear forces diagram for case of no remediation

obtained are plotted versus the pipe distance from fault tip in Figure 9.

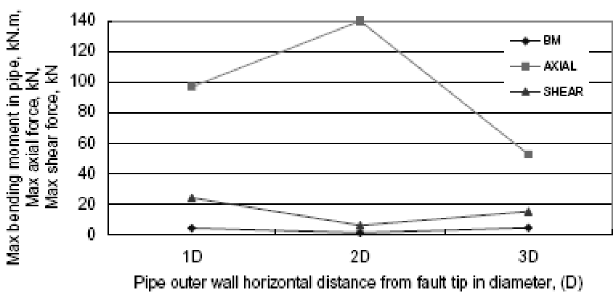

Figure 9. Bending moment, axial , and shear forces for case of no remediation

3.4 *Mitigation measures evaluation*

The mitigation techniques for the buried pipeline system subjected to permanent ground deformations are proposed through using the foam as a low-density backfill around the pipe or/and geogrid reinforcement beneath the pipeline. Also the effect of controlling the ordinary soil unit weight (γ) and stiffness(E) as a fill around pipeline is evaluated. The behavior and the resulting straining actions in pipe wall for each of the proposed mitigation measures are compared with that of the reference case to construct a conclusion which on of these measures improve the pipe behavior and reduce the stresses in pipe wall.

For low-density backfill, the expanded polystyrene(EPS) foam is used, with these engineering properties, the unit weight range is 25-200 kg/m^3 and stiffness range is 3000-3600MPa. This light weight and high stiffness material is required to reduce stresses on underlying soils and surrounded buried structures. The foam effect in the FR-S-P interaction mechanism is shown in Figure 10 as the relatively high stiffness fill zone is moved like a one rigid body as a result of the fault movement

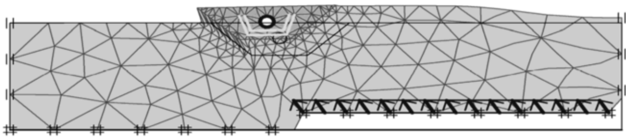

Figure 10. The deformed mesh for (FR-SPI) with foam and geogrids

The foam highly reduce the straining action values in the pipe wall. The reduction percentages for bending moment, axial, and shear forces are, 98%, 93.3%, and 97.7% respectively as shown in Figures 11 when compared with that of Figure 9.

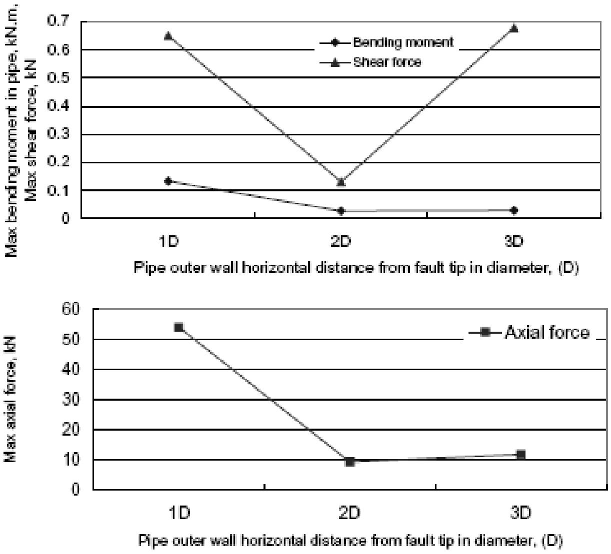

Figure 11. The effect of using polystyrene foam (EPS) around the pipe bending moment and shear force(top), axial force (bottom)

The geogrid reinforcement used is plastic material as Tensar geogrids produced in England, is represented by linear elastic constitutive law with EA= 2 *10 ^{05} kN/m^2 , and placed in two layers at 0.5 and 1.0 m beneath the pipe tip with the configuration shown in Figure 10. The evaluation of this measure includes each of them separately and both together, and the effect on the pipe behavior and stresses. the geogrid reinforcement reduced the stresses on pipe with 10%, 11%, and 6% for bending moment, axial forces, and shear forces respectively, and there was no great enhancement when using two layers instead of only one layer of the geogrid.

The effect of use of the controlled unit weight soil as a fill around the pipe is evaluated through Mohr-Colum constitutive law with studying parametrically for the value of fill unit weight, and the results are shown in Figures 12.

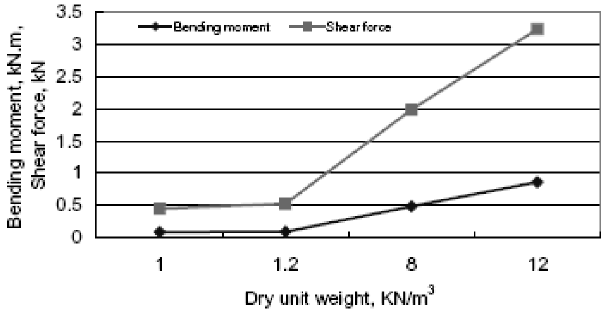

Figure 12. The effect of the fill unit weight around the pipe on bending moment and shear force.

4 CONCLUSION

Mitigation measures techniques utilizing geogrid reinforcement beneath the pipe line and Polystyrene (EPS) foam as a low-density backfill around the pipeline subjected to permanent ground deformations (PGD) are investigated. The 2D FEM proofs to be a successful tool to model the fault movement and the interaction mechanism of (FR-SPI) system, but with great concern with the constitutive laws that represent all model elements. The low-density backfill was very successful in reducing the stresses exerted in pipe cross section, as it reduced the percentages of bending moment, axial force, and shear force by 98%, 93%, 97% respectively in comparison with the reference (no remediation) case. These high reduction percentages are owing to the relatively high stiffness (3000-3600MPa), and very low density (25-200 kg/m3) of the all-around backfill material that reduced the soil –pipe interaction forces acting on the pipeline.. Whereas the geogrid reinforcement was also effective in stresses reduction in pipe cross section but in much lower percentages in comparison with that of EPS foam, the reduction percentages were 10%, 11%, and 6% for bending moment, axial forces, and shear forces respectively, and there was no great enhancement when using two layers instead of only one layer of the geogrid.

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