THE EFFECT OF FAULT PLANE ANGLE ON THE STRUCTURAL RESPONSE OF BURIED STEEL PIPELINE SUBJECTED TO FAULT MOVEMENT

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ABSTRACT

Analysis and design of buried pipelines are complicated problems. The reason lies in the fact that it incorporates interaction between soil and pipeline as well as nonlinear behaviour of surrounding soil. In the present study, the effect of soil elastic and plastic characteristics on mechanical behaviour of pipeline is investigated numerically. Strike-slip fault displacement is imposed in various angles to longitudinal pipeline axis. Soil is considered as an elastic-perfectly plastic material conforming Mohr-Coulomb criterion. The results obtained numerically were compared to well-known analytical methods. Although, analytical methods and numerical softwares prepares loads of possibilities to take into consideration pipe and soil interaction more realistically, the present study shows that a comprehensive experimental study should be done in each of the cases to calibrate and determine realistic values for soil and pipe interaction needed for various methods.

INTRODUCTION

Buried pipelines are often referred to lifeline because play a vital role in the transporting of crude and refined petroleum, fuels such as oil, natural gas and biofuels. Earthquake is a major area of interest within the field of pipelines safety that consists of permanent movements of ground (i.e., PGD) or by transient seismic wave propagation.

Over the past decades, most research in the analysis of steel pipelines subjected to PGD has emphasized the use of analytical or numerical methods. Newmark and Hall (1975) analysed the fault-crossing pipe. However, they did not consider the bending stiffness of the pipe and lateral interactions between pipe and soil. Kennedy et al. (1977) developed the Newmark and Hall’s approach by considering effect of lateral interaction and pipe’s bending stiffness especially at large axial strains. Using a beam on elastic foundation Wang and Yeh (1985) introduced a new approach to study the behaviour of pipe. They neglect the effect of pipe axial stress on pipe bending stiffness. Karamitros et al. (2007) by adopting some ideas of Wang and Yeh (1985) developed the Kennedy’s model. On the other hand, a number of authors have used of finite element methods to study the fault-pipeline problem. Vazouras et al. (2012) studied a pipeline subjected to strike-slip fault movement taking into consideration the inelastic behaviour of soil and pipe.

Due to assumptions that were adopted in extending the above-mentioned analytical approaches, especially regarding the soil and pipe interaction, there will be some differences between analytical and numerical results. In the present paper, the effect of the angle between fault and pipe on steel pipeline behaviour in strike-slip movement was studied. Finally, a comparison between numerical and analytical approach was done.

PROBLEM STATEMENT AND METHODOLOGY

In the present paper, the study on the behaviour of steel pipeline subjected to earthquake was limited to strike-slip fault movement while the pipe-fault angle, Beta, is less than 90, as depicted in Figure 1. The steel pipeline was considered with outer diameter, D = 0.9144 m, and thickness, t = 0.0127m that burial depth in the soil is equal to 2D.

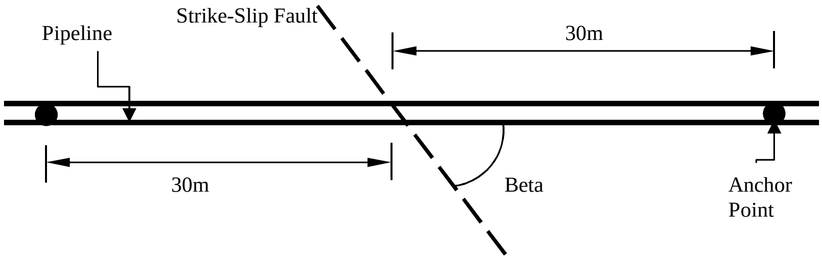


Figure 1. Plan view of pipeline crossing strike-slip fault

In order to simulate behaviour of buried pipeline in strike-slip fault movement three-dimensional finite element procedure was implemented using ABAQUS software. Three different angles that are considered for fault movement are 90, 60 and 30. Discretized geometry of typical model, which consists of pipeline and surrounding soil, is shown in Fig. 2.

Figure 2. (a) Soil discretization in the case of fault movement normal to longitudinal axis of pipeline (b) Pipeline

Four-node doubly-curved reduced-integration shell element is chosen for pipeline (S4R), whereas, eight-node linear brick reduced-integration element is considered for surrounding soil. The model is divided in two parts: (a) Fixed part (b) Movable part, connected to each other by fault zone. As shown in Fig. 2, finer mesh is employed for soil and pipeline near the fault. Owing to large displacements, Arbitrary Lagrangian-Eulerian (ALE) adaptive meshing scheme was used in the mesh near the fault (Vazouras et al., 2012 and Srinivasa et al., 2011).

Soil was considered elastic-perfectly plastic material conforming Mohr-Coulomb criterion with non-associative flow rule. The steel pipe material was described Von Mises plasticity model. Properties of soil and pipe material are shown in Table 1-2.

Table 1. Soil material properties

Soil	E (MPa)	γ(kN/m^3)	φ(deg)	C (kN/m^2)
Clay I	25	19.6	0	30
Clay II	100	19.6	0	150

Table 2. Pipeline material properties

Steel	Modulus of Young (GPa)	Yield stress (MPa)	Failure stress (MPa)	Failure strain %
API5L-X65	210	490	531	4

NUMERICAL RESULTS AND DISCUSSION

Two types of prevalent pipe's failure mode are tensile rupture owing to bending and tension, and wrinkling of the wall of pipe in account of bending and compression. The prime indication of tensile rupture is the maximum axial strain in the pipes wall. Newmark and Hall (1975) assumed that failure occurs when the average strain is greater than 4%. Fig. 2(a) shows tensile rupture which is occurring in the pipe. Although, the tensile strain is less than 4%, the compression strain is about zero. This shows that by increasing the fault offset the amount of strain will rise and eventually tensile failure will occurs. Figs. 2(b-c) show the rupture due to compression. As depicted in Fig. 2(c) first wrinkling was turned up in the pipe, then strain near the wrinkling location rises to 4% , i.e. strain correspond to 70 cm fault offset, finally by increasing the fault movement the wall of the pipe experiences a remarkable drop in the strain which is indication of compression failure.

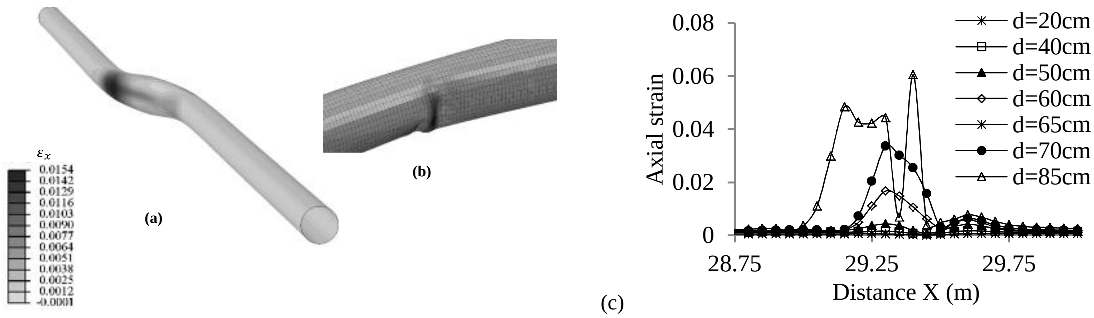


Figure 3. Types of failure mode (a) tensile rupture owing to bending and tension, Beta= 60
(b),(c) Wrinkling formation and rupture due to bending and compression, Beta= 90

A comparison between the results of numerical method and analytical approaches has been done. For small offset, peak strain obtained numerically were compared to Newmark methods. Fig. 3 represents that since Newmark method does not consider the bending strain in the pipe as well as the soil and pipe interaction in the case of specified unanchored length, the maximum axial strain in pipe surrounded by varied types of soil is identical.

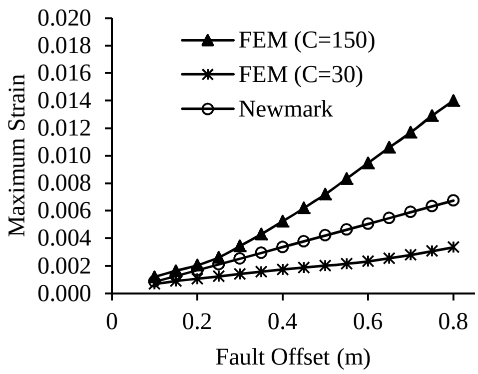
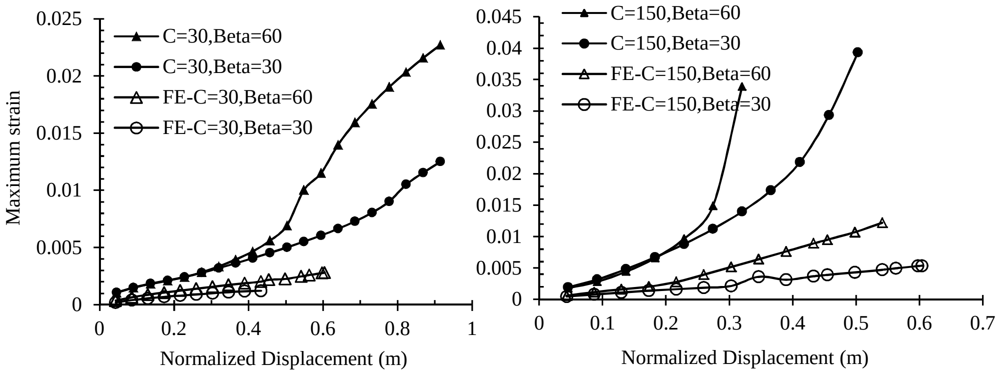


Figure 4. Pipe tensile strain for small fault offset in different soil for Beta=60

The second set of analyses examined the impact of fault angle on the maximum tensile strain in the pipe for pipeline buried in various soils, i.e. Clay I and Clay II. As shown in Fig. 5, surprisingly, there are a considerable difference between the results obtained by numerical, i.e. FE analysis, and analytical approach, which is proposed by Karamitros et al. (2007). There are several possible explanations for this result. A possible explanation for this might be that the soil and pipe interaction is applied in the different ways for the numerical and analytical approaches. While the interaction is applied by contact element in FE, the proposed approach by Karamitros et al. (2007) adopted beam on elastic foundation theory to consider that interaction. Another possible explanation for this is that soil considered to be elastic-perfectly plastic material in FE analysis, thus, the plastic deformations of soil are taking into account in it while analytical approach neglect the soil material's plastic deformations effect.



(a) Clay I (b) Clay II

Figure 5. Maximum tensile strain V.S. normalized displacement obtained by FE method and Karamitros's approach for various soils and fault angles (Beta)

As mentioned in the literature review, Vazouras et al. (2012) studied the effect of fault angle on the steel pipe subjected to strike-slip fault movement employing a rigorous software based on finite element. The results obtained by Vazouras et al. (2012) compared to pipeline in fault crossing analysed by employing Karamitros's approach. The investigation was done based on the soil and pipe material properties considered by Vazouras (2012), however, the plastic behaviour of pipe converted to a straight line to use in analytical approach, i.e. a bilinear stress and strain relationship. Fig. 6 compares the normalized ultimate displacement versus different fault angles obtained as mentioned earlier. It is worth mentioning that when the analysis was performed for the same value of adhesive and tangential behaviour factor of soil and pipe axial contact in the Karamitros and Vazouras's approach, the normalized ultimate fault displacements correspond to 3% or 5% strain get about twice in Karamitros's method.

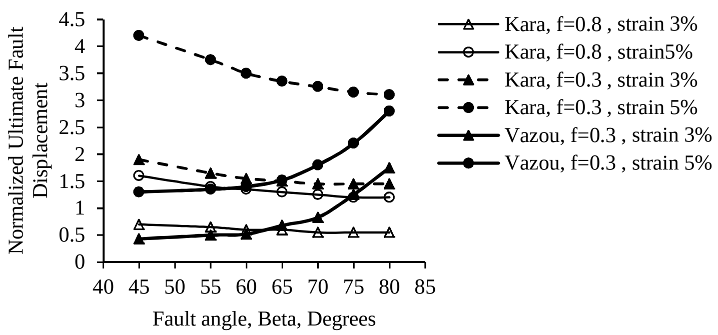


Figure 6. Normalized ultimate fault displacement V.S. different angles of Beta in varied tensile strains in pipeline obtained by Karamitros's approach and by Vazouras et al (2012)

One unanticipated finding was that, unlike Vazouras's results when using Karamiros's method for a pipe in the smaller pipe-fault angle, e.g. 45 degrees, the normalized fault movement corresponding to 3% tensile strain is more than the ones with greater fault angle, e.g. 70 degrees. As shown by Vazouras et al. (2012), based on finite element analysis, and the concept of pipe and soil interaction, the smaller beta angle should lead in the greater tensile strain in a pipe. Consequently, the normalized fault movement corresponding to 3% tensile strain should be less than the ones with greater fault angle, e.g. 70 degrees.

CONCLUSIONS

The present study was designed to determine the effect of fault angle on the mechanical behaviour of pipeline subjected to strike-slip fault movement. The most obvious finding to emerge from this study is that despite rigorous analytical and numerical attempts that have been performed in the past, the effect of soil-pipe interaction in conjunction with soil material property, which was not considered realistically in the previous studies, has considerable effect on the results. For example, the effect of small fault movement angle, e.g. 45 degrees, on the maximum tensile strain is more than greater angles, e.g. 70 degrees that seems unrealistic. Furthermore, when normalized displacement of fault reaches 0.6, the numerical results still show elastic behaviour in the soil Clay I , Clay II for Beta = 60 or 30 degrees, the analytical method proposed by Karamitros indicates 0.7 % and 1.2 % tensile strain in the Clay I, for Beta = 30 and 60, respectively. On the other hand, the tensile strain in Clay II reaches 4% for Beta = 30 and 60. Findings of this study suggest that a comprehensive experimental study should be done in each of the cases to calibrate and determine realistic values for soil and pipe interaction.

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