



Numerical Evaluation of Polyethylene Pipes with Sandy Soil Interacting and Subjected to Strike-Slip Faulting

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ABSTRACT

Pipe-Soil interaction presents a challenging problem of analysis and design of buried pipelines. Even though the accuracy of ASCE relations for calculating pipe-soil interaction is good in certain cases as a number of researchers have demonstrated those relations are rather inaccurate for other cases such as under fault movement. This research evaluates the interaction between sandy soil and polyethylene pipes subjected to strike-slip faulting using a non-linear finite element numerical model. Upon verification of the results of the numerical model using previously conducted experiments, several numerical studies analyses were carried out for pipes with different diameters, thicknesses and burial depths. The results suggest that the pipe thickness and the fault-pipe angle affect the pipe-soil interaction. Such effects are not reflected in the ASCE relations considerably. Finally, based on the results obtained, the ASCE relation for the transverse-horizontal interaction between sandy soil and polyethylene pipes subjected to strike-slip faulting was modified.

Keywords:

Straight Polyethylene Buried pipeline;
Pipe-Soil interaction;
Strike-Slip Fault;
Nonlinear Finite Element Analysis

1. Introduction

Buried pipes are members of the great family of lifeline systems. Various studies have been conducted by O'Rourke and Liu on the effects of natural disasters, such as earthquakes, on the performance of lifeline systems [1]. Buried pipelines are endangered by Permanent Ground Deformation (PGD) and wave propagation. PGDs like landslides, faulting, lateral spreads, and subsidence, have more intensive localized effects and are therefore more dangerous for buried pipes and several cases of failure have been reported due to effects of PGDs. Investigating the effect of earthquakes on buried pipeline networks is typically done by calculating damage functions or fragility curves, which present the number of failures

on the unit area versus the peak ground acceleration or velocity. Studying the damages inflicted on water pipes as a result of Chi-Chi earthquake, Shih and Chang attributed 52 percent of failures to PGDs [2]. Therefore, failures due to PGDs accounts for a great percentage of failures and should be carefully taken into consideration in the design of such systems. Damage relations merely offer a general guess about the damages inflicted on a network. They cannot provide any information concerning the rate of the failures, their location or the performance loss of the network thereof. It should be particularly noted that failure relations do not take into account the damages inflicted on pipes under the effect of

fault movement. That is why analytical and numerical methods in analyzing buried pipelines under the effect of fault movement have become of more interest to researchers and numerous studies have been conducted in this area, some of which will be mentioned subsequently.

Perhaps the first successful attempt at modelling and analyzing buried pipelines in the presence of fault movements is the study by Newmark and Hall [3]. They considered the pipe deformation to be axial, defined fault movement on an individual plane and assumed soil mass as two moving solid bodies on the sides of the fault. Kennedy et al investigated the static response of buried pipes subjected to strike-slip faulting [4]. Arguing that the bending strain is small in the pipe, compared with axial strain at the fault-pipe intersection, they concluded that the pipe's bending stiffness may be ignored and the pipe can be modelled as a cable.

Wang and Yeh [5] studied the buried pipe response at the site of strike-slip faulting while allowing for the pipe's bending strength. They divided a long pipeline into four parts two of which were in the vicinity of the fault and under the effect of great curvature. The two other parts were considered to be on their farther sides of the fault. The farther parts were analyzed using a beam on elastic foundation model, while the middle parts and the ones closer to the fault were assumed as an arc of a circle. Chio et al [6] improved the model of Wang and Yeh [5]. In order to remedy the previous model's defect, they considered the pipeline's curvature to be variable in the middle parts. It should be noted that all of the above analytical studies, although efficient, cannot draw a complete picture of the pipe response, because of the complexity of the pipe-soil behavior under the effect of fault movement which is highly non-linear. Hence, researchers have focused on numerical analyses.

Takada et al [7] pointed out that the behavior of large diameter buried pipes is more like that of a shell. On this basis, and using the finite element method, they examined the effect of fault movements on buried pipelines. Considering the pipe section deformation as a result of fault movements, they put forward a new method for calculating the maximum strain in pipes. Liu et al [8] presented an equivalent spring for modelling boundary conditions of pipes at

a fault of the pipe was modelled as a shell. What they did was to reduce the pipe length and replace the eliminated part with equivalent springs.

Anderson et al conducted a full scale pull out laboratory testing on branched Polyethylene pipe-soil interaction [9]. The objectives of this research are to determine the contributing factors, and key parameters influencing the behavior of polyethylene pipe buried in soil. Vazouras et al [10] examined steel buried pipelines response under the effect of strike-slip faults perpendicular to the pipe axis. They assumed the pipe-soil behavior to be non-linear and calculated pipe stresses and deformations for different pipe diameters and thicknesses.

Hosseini et al [11] investigated the seismic functionality of water distribution networks. They have modelled pipe segments as beam elements and the connections by nonlinear springs to evaluate the performance of a sample distribution network subjected to seismic wave propagation. Hosseini and Tahamouli [12-13] performed a study on the effects of surface transverse waves on buried steel pipelines considering the nonlinear behavior of soil and pipe. They investigated the effect of three-dimensional earthquake wave propagation on straight continuous buried steel pipes. They determined the minimum effective length of continuous straight pipes and investigated the relation between strain of buried pipes and occurrence of local buckling. Deep Kumar et al evaluated the installation procedure of a steel-reinforced high-density polyethylene pipe in soil by laboratory test [14]. They showed that the pipe wall area was strong and stiff enough to resist the wall thrust during the installation and the highest measured strains recorded on pipe during the installation were below the maximum permissible limits.

The most logical way of modelling pipes in soil is to use SOLID elements for soil and SHELL elements for pipe. However, 3D modelling of soil and pipe with these elements is tedious, since these systems have very large dimensions and the time and cost of calculations would be high. Thus, modelling of soil is often overlooked and equivalent springs are used instead. Beam elements are also used for modelling pipes (Figure 1). In this case, one of the most important factors in analyzing buried pipelines subjected to seismic wave propagation or

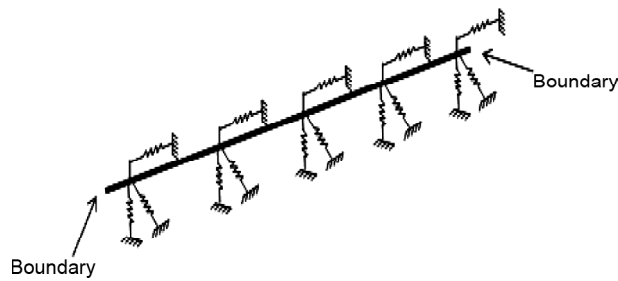


Figure 1. The conventional model of pipe buried in soil.

fault movements is realistic modelling of pipe-soil interaction. That is why a great deal of research has been conducted in this field.

2. Pipe-Soil Interaction

To model pipe-soil interaction, the ASCE Technical Council on Lifeline Earthquake Engineering (TCLEE) [15] has provided equivalent springs for the stiffness of soil, bilinear in Figure (2). This is an approximate model of the actual behavior of soil. The stiffness of these springs depends on parameters such as soil type, soil density, soil internal friction coefficient and adhesion, diameter and material of the pipe, the burial depth of pipe in soil, etc. At each point of the pipe, three springs are provided to model the soil in longitudinal,

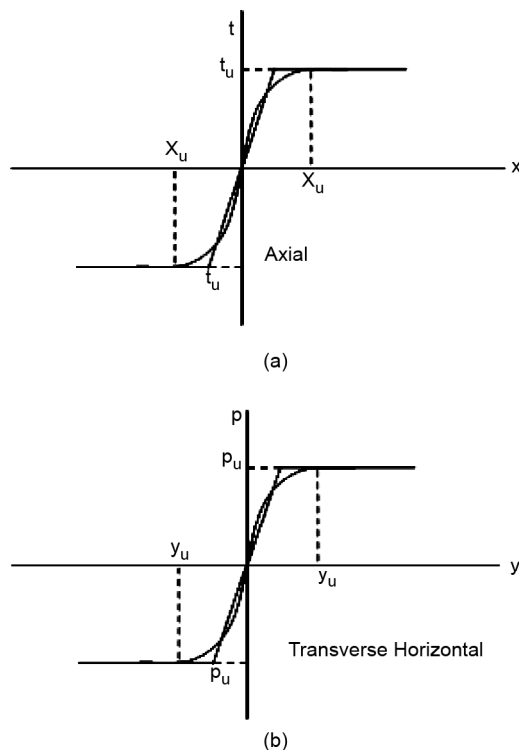


Figure 2. Stiffness of soil equivalent springs in (a) longitudinal and (b) transverse-horizontal directions.

transverse-vertical, and transverse-horizontal directions. The behaviors of longitudinal and transverse-horizontal springs are assumed to be symmetrical. ASCE proposes the following formula for the maximum force exerted on the pipe in transverse-horizontal direction inside sandy soil:

$$P_u = N_{qh} \cdot \gamma \cdot H \cdot D \quad (1)$$

Here γ is the soil's effective specific weight of the soil, H is the soil depth from the ground to the pipe center (pipe burial depth) and D is the external diameter of the pipe. N_{qh} is the horizontal bearing capacity factor for sand which is a dimensionless parameter obtained from Figure (3). N_{qh} is a function of the pipe diameter, the burial depth and sand's internal coefficient of friction of the sand.

The relations presented for pipe-soil interaction by ASCE are based on work by Oversen and Stromann [16], Audibert and Nyman [17] and especially Trautmann and O'Rourke [18-19]. It is noteworthy that the model developed by Trautmann and O'Rourke [19] was 2D and the interaction force was calculated by moving the pipe inside the soil. The relations found were generalized for all cases; That is, precisely the same springs were used to model pipe-soil interaction in fault movement, landslide and earthquake propagation.

Calveti et al [20] studied pipe-soil interaction

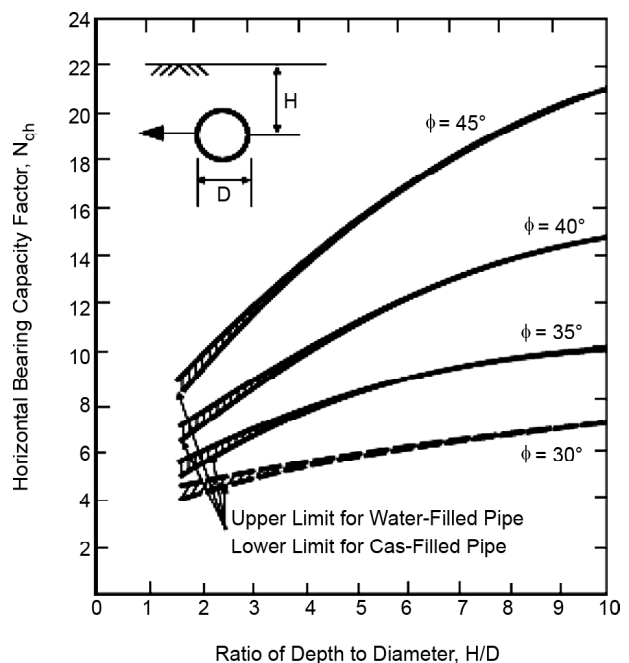


Figure 3. N_{qh} value in terms of pipe burial depth, pipe diameter, and sand internal coefficient of friction [1].

by means of small-scale experiments and numerical modelling. Laboratory and numerical results demonstrate that using independent springs for modelling pipe-soil interaction is inappropriate, especially when the pipe is close to the surface. This is because, the horizontal and vertical components of interaction forces are interrelated. Gou and Stolle [21] investigated the effect of laboratory model scale on pipe-soil interaction. They concluded that the effect of the pipe diameter and burial depth should be considered when evaluating the maximum force of pipe-soil interaction, caused by ground movement. They produced a relation for this case.

Tian and Cassidy [22] conducted research on numerical modelling of pipe-soil interaction. They proposed three different plasticity models for numerical modelling and finite element analyses and compared their efficiency. Abdoun et al [23] carried out experiments on buried polyethylene pipeline under the effect of strike-slip faulting movement. That will be examined in more detail in the following section of this paper.

This paper primarily aims at modifying the relation suggested by ASCE (Eq. (1)) for the interaction between soil and polyethylene pipes in transverse-horizontal direction under the effect of strike-slip faulting in dense sandy soils. To this end, experiments conducted by Abdoun et al [23] were used. Once the numerical modelling results were verified, then numerous analyses were conducted for pipes with different diameters, thicknesses, and burial depths. The results indicate that the ASCE relation for pipe-soil interaction is adequate for small burial depths, while it is too conservative for greater depth. Therefore, efforts were made to modify some of the coefficients provided by ASCE. Meanwhile, analyses were conducted for pipes with different thicknesses and pipe-fault angles and it was thereby proven that these parameters have significant effects on pipe-soil interaction.

3. Verification of the Numerical Model

Abdoun et al [23] conducted experiments to better and more accurately understand the interaction between sandy soil and polyethylene pipes buried in the regions of strike-slip faulting. They measured axial and bending strains and the lateral force exerted on the pipe along its length.

These experiments were performed by using a centrifuge system that consisted of a fixed and a moving part. The pipe was placed in soil obliquely at a 63.5 degree angle. A fault movement of up to 1.06 m was applied and axial and bending strains were calculated along the pipe as well as the lateral force exerted on it. Figure (4) depicts the experiment system of Abdoun et al [23] schematically and shows the angle between pipe and the fault for 0.088 m fault movement.

The numerical modelling of the experiment carried out by Abdoun et al [23] was performed by Tahamouli et al [24] for different fault movements. Axial and bending strains along the pipe were obtained with great accuracy for $H/D=2.8$ and 6. They made use of finite element analysis and considered the pipe and soil behavior to be non-linear. They calculated the maximum axial and bending strains of the pipe with an accuracy of over 90% for maximum fault movement of 1.06 m.

ABAQUS finite element software was used for numerical modelling the work of Abdoun et al [23] in the same study. The soil was modeled using

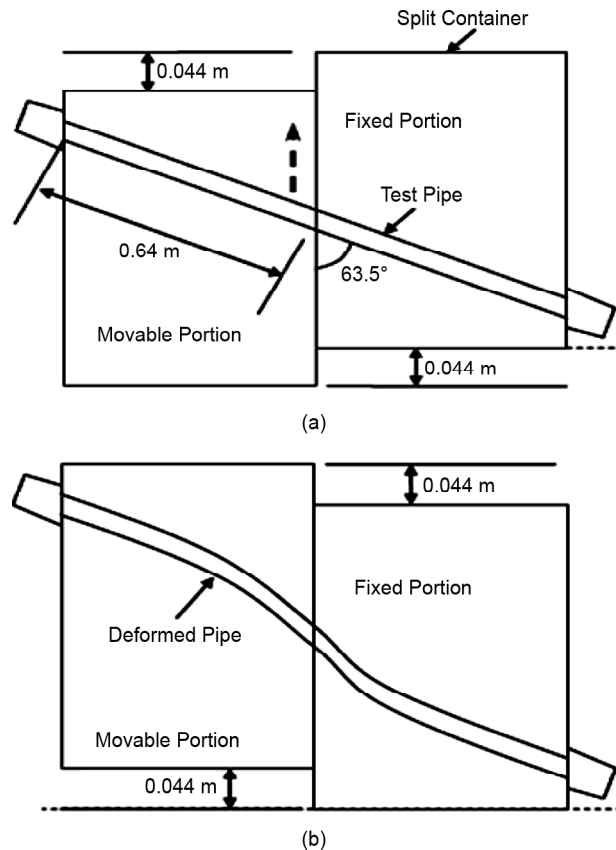


Figure 4. Schematic view of the centrifuge system (a) before and (b) after applying the movement [23].

Table 1. Parameters of Drucker-Prager model in ABACUS software.

Young's Modulus (N/m ²)	Poisson's Ratio	Angle of Friction (Deg.)	Flow Stress Ratio	Dilation Angle (Deg.)
50×10 ⁶	0.25	40	0.8	10

solid elements and the Drucker-Prager behavior model. Table (1) shows the parameters used in the Drucker-Prager model. For the interaction between the soil and the pipe, the "interaction" module in the ABAQUS software was used. The tangential soil-pipe interaction was defined as "penalty" with the friction coefficient of 0.4 and the normal interaction between the soil and the pipe was defined as "Hard Contact". Besides, the Polyethylene pipe was modeled by shell elements and the Ramberg-Osgood behavioral model based on Eq. (2) [25]. Figure (5) illustrates the finite element model used and Figure (6) shows the axial and bending strain diagrams of the pipe, obtained from experiments and the numerical model for $H/D=2.8$ in terms of distance from the pipe-fault intersection.

$$\epsilon = \frac{\sigma}{750 \times 10^6} \left[1 + \frac{7}{6} \left(\frac{\sigma}{14 \times 10^6} \right)^5 \right] \quad (2)$$

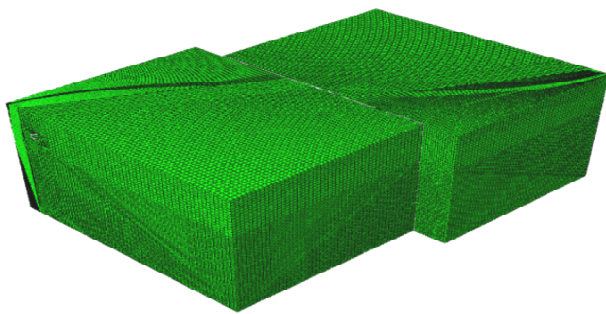


Figure 5. Finite element model of the experiment conducted by Abdoun et al [23].

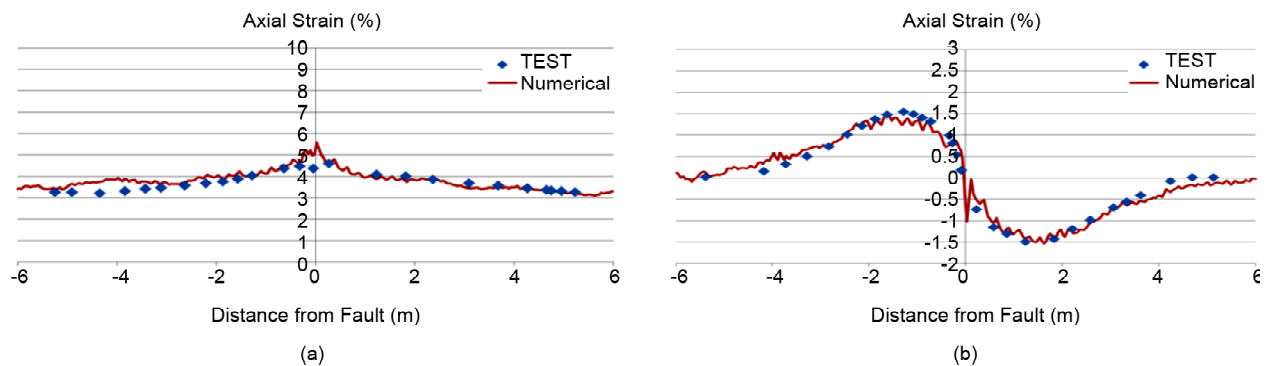


Figure 6. Comparing (a) axial and (b) bending strains of the numerical model with laboratory results for a movement of 106cm in terms of distance from the fault for $H/D = 2.8$.

As can be seen from Figure (6), numerical modelling results compare well with those of the laboratory values. The maximum bending strain of the pipe for a movement of 106 cm deviates less than 4% from the laboratory results. The maximum transverse-horizontal force exerted on the pipe for $H/D=2.8$ was 57.3 KN/m from laboratory test and 54.2 KN/m from numerical results. That is an error of 5.4%. The maximum interaction force in this mode is 59 KN/m according to the ASCE (Eq. (1)), which is very close to the results obtained from experiments and numerical results.

Abdoun et al. [23] repeated their experiment for $H/D=6$. In that case, laboratory results differed widely from those of the ASCE relation. The maximum force exerted on the pipe was almost three times smaller than the values obtained from the ASCE relation. They could not justify this considerable difference and attributed it to the fact that the experimentation device was probably not calibrated, while the numerical model in this research gave the interaction force of 64.9 KN/m for $H/D=6$ differing as much as 8% from the laboratory results, i.e. 60 KN/m. It is interesting that the ASCE relation gives 184 KN/m for the interaction force in this case, a very conservative value. Tahamouli et al. [24] also confirmed this result and showed that the ASCE relation is very conservative in this case and therefore needs to be modified.

4. Sensitivity Analysis

A total of twenty numerical analyses were conducted in order to study the effect of different parameters on the maximum transverse-horizontal force exerted on polyethylene pipes. Table (2) shows

Table 2. Selected specifications for polyethylene pipes in sensitivity analysis.

No.	Diameter (cm)	Thickness (cm)	Burial Depth (m)	Fault Angle (Degree)
1	81.28	6.0198	2.4	63.5
2	81.28	6.0198	1.8	63.5
3	81.28	6.0198	1.2	63.5
4	38.86	4.318	2.4	63.5
5	38.86	4.318	1.8	63.5
6	38.86	4.318	1.2	63.5
7	34	2	1.2	63.5
8	66	2	1.2	63.5
9	82	2	1.2	63.5
10	34	4	1.2	63.5
11	66	4	1.2	63.5
12	82	4	1.2	63.5
13	34	6	1.2	63.5
14	66	6	1.2	63.5
15	82	6	1.2	63.5
16	40.7	2.4	1.2	40
17	40.7	2.4	1.2	60
18	40.7	2.4	1.2	70
19	40.7	2.4	1.2	80
20	40.7	2.4	1.2	90

the specifications of pipes, burial depths, and the fault movement angles in these twenty cases.

All the assumptions and specifications of the numerical model were selected according to the verified model. Even the angle between the pipeline and the fault movement was taken at 63.5 degrees in the first fifteen analyses, in accordance with the work of Abdoun et al [23]. In all these analyses a lateral displacement of 106 cm was applied to the fault and the maximum transverse-horizontal force per unit length of the pipe was calculated (P_u). Owing to soil ruptures under large deformations, the maximum value of P_u does not necessarily take place at the maximum displacement, i.e. 106 cm, and it may occur at smaller displacement which was addressed in the finite element analysis. In what follows, the sensitivity of P_u to pipe burial depth, diameter, and thickness as well as fault movement angle will be discussed.

4.1. The Effect of Pipe Burial Depth

Figure (7) shows the P_u variations in terms of the pipe burial depth according to analyses 1 to 6. In this figure, results obtained from the numerical model are compared with those of the ASCE relation. For

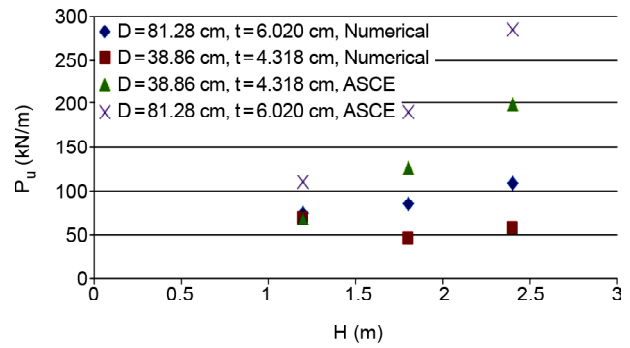


Figure 7. P_u variations in terms of pipe burial depth.

small pipe burial depths, at around 1.2 m, the forces obtained from the numerical model and those of the ASCE relation are close. However, for greater values of H , forces obtained from Eq. (1) are remarkably bigger than those obtained from the numerical model.

Calculation results indicate that the force exerted on the pipe is not directly related to the pipe burial depth. The reason is that soil rupture modes vary as pipe burial depths change. This is also pointed out in the experiments carried out by Abdoun et al [23].

4.2. Effect of Pipe Diameter

Figure (8) shows variation of P_u in terms of the pipe diameter according to analyses 7 to 15. Although it was found that as the pipe diameter increases, the maximum interaction force exerted on the pipe also increases, the force increase rate is much smaller compared with that of the ASCE relation. It may be concluded upon careful examination of the diagram that the effect of pipe thickness is much stronger on the interaction force than that of the pipe diameter.

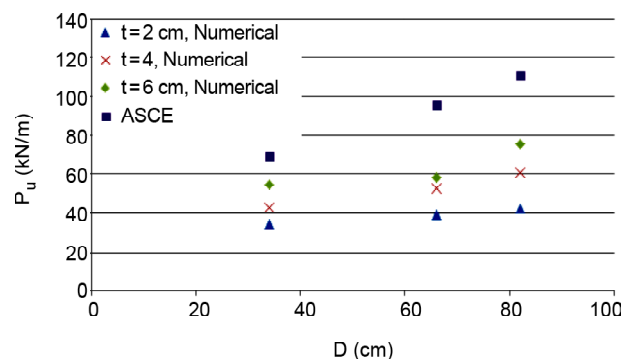


Figure 8. P_u variations in terms of pipe diameter.

4.3. Effect of Pipe Thickness

Figure (9) illustrates variations of P_u in terms of pipe thickness according to analyses 7 to 15. It can be said that with increase in the pipe thickness, the maximum force exerted on the pipe also increases. Here, the increase rate of the interaction force, Figure (9), is more than that of Figures (7) and (8). This is indicative of the sensitivity of the interaction force to the variation of the pipe thickness. The ASCE relation does not consider the pipe thickness as a parameter.

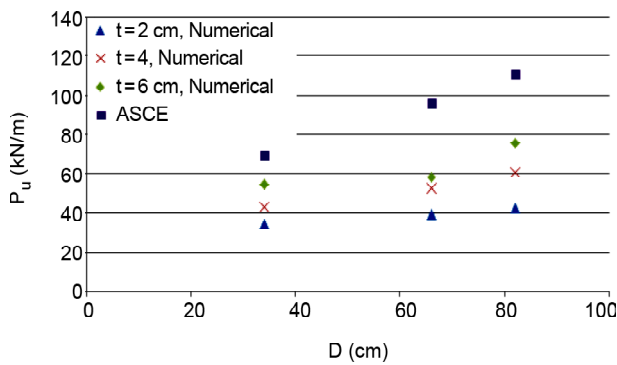


Figure 9. P_u variations in terms of pipe thickness.

4.4. Effect of Fault Movement Angle

Figure (10) shows variation of P_u with the fault movement angle according to analyses 16 to 20. It can be concluded that the interaction force is sensitive to the angle between the pipe and the fault plane and the greatest force exerted on the pipe takes place at an angle between 70 to 90 degrees. However, the interaction force given by the ASCE relation does not taken into account the effect of movement angle between the pipe and the fault.

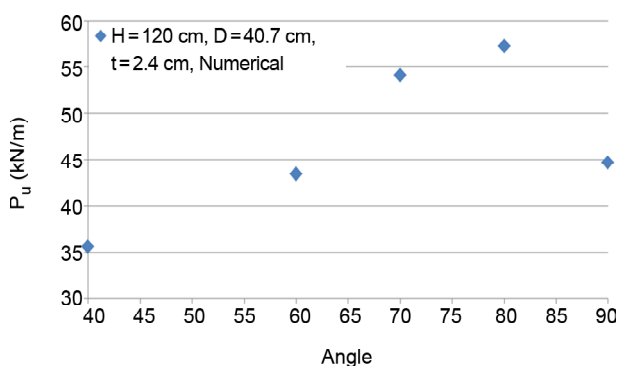


Figure 10. P_u variations in terms of fault angle.

5. Modification of the ASCE Interaction Relation

As previously stated, the relation presented by ASCE, (Eq. (1)), is very conservative for pipe-soil interaction at the site of strike-slip faulting for large H/D values. In order to modify this relation, polyethylene pipes with diameters 30, 35, 40, 45, and 50 cm and thicknesses 2, 2.5, 3, and 3.5 cm were subjected to the effect of a strike-slip faulting with 1 m movement. The soil type was assumed to be dense sand, the fault-pipe angle was 90 degrees, and the pipe burial depths were 1.2, 1.5, 1.8, and 2.1 m. Hence, a total of eighty non-linear finite element analyses were conducted. In each case, the maximum force exerted on the pipe unit length was calculated. Afterward, according to Eq. (1), the modified N_{qh} value was calculated for each of the analyses. The result was a new modified N_{qh} diagram for the interaction between dense sandy soil and polyethylene pipes at the site of strike-slip faulting. Figure (11) shows the modified N_{qh} results for all eighty analyses in terms of H/D for pipes with different thicknesses.

It may be stated in view of Figure (11), that the ASCE relation yields results that are unsafe for low H/D values (around 2.4). This relation gives good estimates for H/D equal to 3 to 5. However, it is very conservative for high H/D values. The N_{qh} slope given by the ASCE relation and N_{qh} obtained from numerical analysis do not generally conform. For close estimation of the maximum interaction force, modification of this parameter seems to be necessary. For each pipe thickness the bound of high N_{qh} values can be considered aiming at safety. Figure (12) shows the final modified N_{qh} values for the interaction between dense sandy soil and polyethylene pipes at the site of strike-slip faulting.

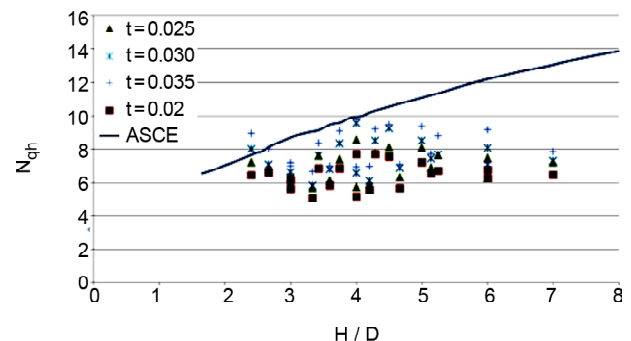


Figure 11. Results obtained for N_{qh} according to eighty non-linear finite element analyses.

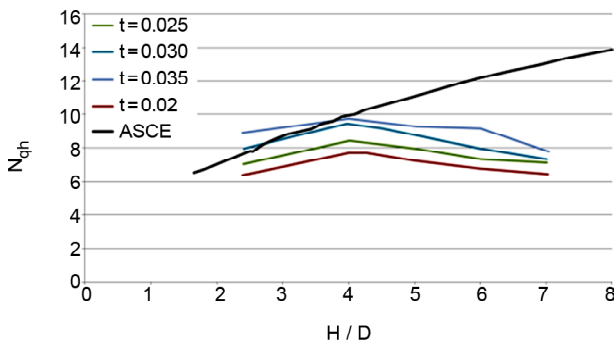


Figure 12. Modified N_{qh} for interaction between dense sandy soil and polyethylene pipe at the site of strike-slip faulting.

6. Conclusion

The results of an experiment carried out by Abdoun et al [23] on pipe-soil interaction at the site of strike-slip faulting were verified using a non-linear finite element model and a parametric study was conducted on pipe-soil interaction. The results of numerical analyses of dense sandy soil and polyethylene pipe indicated that as the pipe diameter and its burial depth increase, the interaction force exerted on the pipe does not necessarily increase, whereas in the relation put forward by ASCE, the maximum pipe-soil interaction force is directly and significantly related to the pipe diameter and burial depth. Meanwhile, with increase in pipe thickness, the lateral force exerted on the pipe also increases, an effect not taken into consideration in the ASCE relations. The pipe-fault angle also affects the lateral force exerted on the pipe and the greatest force is exerted on the pipe at an angle between 70 to 90 degrees. A total of eighty non-linear finite element analyses were conducted to modify N_{qh} coefficient of the ASCE relation. The results showed that the ASCE relation delivers results that can be unsafe for some low H/D values (around 2.4). This relation gives proper estimates for H/D values 3 to 5. However, it is very conservative for high H/D . Finally, by allowing for pipe thickness, a diagram for modified N_{qh} was presented in order to calculate the maximum interaction force between sandy soil and polyethylene pipe at the site of strike-slip faulting.

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