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RESPONSE OF STEEL BURIED PIPELINES TO THREE-DIMENSIONAL FAULT MOVEMENTS BY CONSIDERING MATERIAL AND GEOMETRICAL NON-LINEARITIES

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SUMMARY

The purpose of this study is to evaluate the effects of three dimensional fault movements on the nonlinear response of steel buried pipelines. The steel pipeline is divided into a number of segments, and each segment is modeled as a beam element. The beam element has six degrees of freedom at each of the nodes. The beam elements are considered to have material and geometrical non-linearities. The surrounding soil is modeled by using nonlinear springs in the axial, lateral, and vertical directions. The fault is considered to be an oblique-slip, which has three-dimensional movements. By using some of the important system parameters the non-linear analysis of pipe-fault system is assessed. The parameters used in this study are: anchored length of pipeline, buried depth of pipe, frictional angle of soil-pipe system, geometrical characteristics of pipe, fault displacement, crossing angle of pipe with the fault, and the fault slope angle. The effects of these parameters are investigated on the response of buried pipeline crossing the oblique-fault movements. The detail parametric study reveals that the bearing capacity of the steel buried pipelines, subjected to the oblique-slip fault movements can be improved, if the effects of the above parameters are taken into consideration while designing the pipeline.

INTRODUCTION

The field observations indicate that the strong earthquakes of San Fernando 1971, Managua 1972, Haicheng 1975, Tang-shan 1976, Miyagiken-Oki 1978, Northridge 1994, Kobe 1995, Chi-Chi 1999, and Kocaeli 1999 severely damaged buried pipelines. Based on the damage mechanism of buried pipelines, seismic effects can be either caused by transient strain and curvature in the ground due to traveling wave effects or caused by permanent ground deformations; such as fault deformation, landslide, and liquefaction-induced soil movements. Among them, the ground movements of active faults can have the most severe earthquake effects on buried pipelines [1]. However, there are few cases in which the pipelines were damaged only by wave propagations [2].

The interruption in distributing energy, communication, water and wastewater provided by buried pipelines can cause much inconvenience to human life following an earthquake, and possibly result in unexpected disaster. In the past three decades, faults movements have been the focus attention for many

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researchers. The initiator of these studies is Newmark and Hall [3]. They studied the ability of a continuous pipe to resist large fault displacement. They assumed that when the pipeline is deformed into a single constant curvature curve, the uniform passive soil pressure would resist the large pipeline deflection. They discovered that the resistant capacity of a buried pipeline to fault movement is dependent upon the soil, pipe and fault characteristics. Minimizing the longitudinal and lateral resistance of the soil to the pipe motion maximizes the pipe resistance. They have also suggested that the pipe should be placed in a trench with shallow sloping sides so that it can accommodate itself to the transverse as well as the longitudinal components of the fault movement. Subsequently, kennedy et al [4,5] extended Newmark and Hall's procedure to determine the pipe capacity to resist fault movement by taking uniform passive soil pressure and the large deflection theory into consideration. It is assumed that the pipeline is a flexible cable deformed into a single constant curvature curve approaching asymptotically to the undistorted portion of the pipeline. In this model, only the axial tensile force at the point of inflection is used for equilibrium, no flexural resistance was considered. Therefore with the omission of the flexural rigidity of the pipe, this model cannot satisfy the equilibrium condition for a pipeline crossing a strike-slip fault or oblique-slip fault that will cause compression in the pipeline. Wang and Yeh [6,7] referred to this point and proposed a localized large deflection beam model to analyze pipeline behavior crossing the strike-slip fault. They modeled a large deflection pipe as a constant curvature curved segment and the remaining small deflection pipe as a semi-infinite beam on elastic foundation. This model includes the bending rigidity of the pipe, a shear force at the point of inflection of the curve pipe crossing the fault zone, and a boundary condition related to semi-infinite beam on elastic foundation at some distance away from the fault zone. This model yielded more realistic results provided that the appropriate parameters are chosen. However, the pipe response near the fault zone is a complicated nonlinear behavior. Chiou et al. [8] realized that the curvature of the deformed pipe is yet unknown and can hardly be predicted in advance. Moreover, the constant curvature model overestimates the stiffness of the buried pipe and consequently underestimates its strain. Takada et al. [9] studied elasto-plastic shell-mode buckling of a pipe subjected to normal and reverse fault movement using shell finite element method. They found that pipes are much more vulnerable to reverse fault movement, and seismic design shell model can be approximated by beam model for normal fault movement, but not for reverse fault movement.

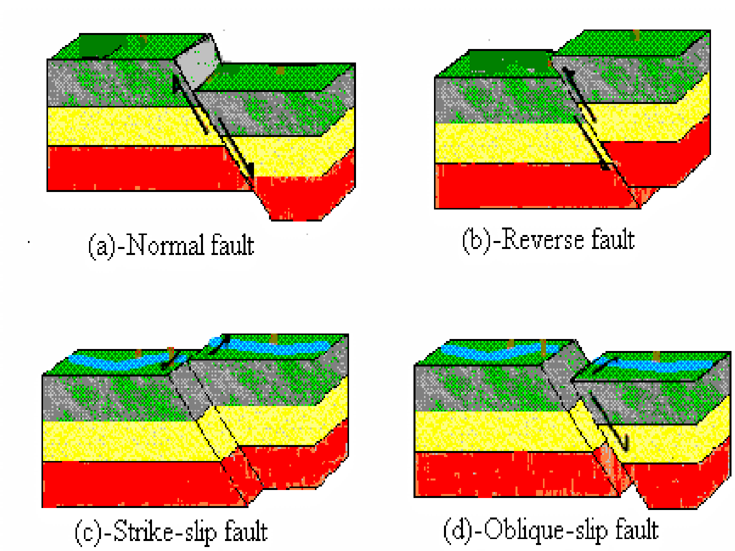


Fig.1- Types of the faults

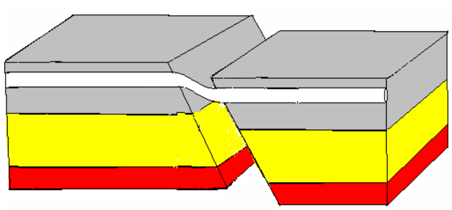
Ariman et al. [10,11] also studied shell-mode behaviour of pipelines subjected to fault movement. Liu and O'Rourke [12] reviewed and compared the response of buried pipelines to transverse permanent ground deformation. They presented a new numerical result and an analytical approach to buried pipelines subjected to transverse permanent ground deformation. In a recent study, Takada et al. [153] presented a simplified method for obtaining the maximum strain in steel pipes crossing faults. They assumed that the pipe will bend near the fault and the geometry of pipe in the longitudinal direction will change according to a bent deformation. They believe that their method can be used for calculating the maximum strains for fault-crossing steel pipes with different angles of crossing both in tension and compression.

Owing to the large number of studies carried out on fault deformations effects on buried pipelines, there can be two major categories as: the studies on the movement of blocks perpendicular to buried pipeline axis or the studies on the movements of blocks parallel to the buried pipeline axis. The first case refers to the dip-slip fault, which can be either normal (Figure-1 (a)) or reverse (Figure-1 (b)). These faults will be subjected to axial tension force and bending in the vertical plane and axial compression force and bending in the vertical plane respectively. However, the second case refers to the strike-slip fault (Figure-1 (c)) in which a continuous pipeline will stretch and bend in plane as it attempts to accommodate the transverse ground movement. In this case the failure mode for the pipe depends upon the relative amount of axial tension and flexural strain. Specifically, if the axial tension strain is low, the pipe wall may buckle in compression due to excessive bending [14]. In contrast, if axial tension is large, the pipe may rupture in tension due to combined effects of axial tension and flexure.

There is a type of fault in which the movements are neither parallel nor perpendicular to the axis of buried pipeline. This type of fault is known as the oblique-slip fault. This fault shows both dip-slip and strike-slip motions which are caused by a combination of shearing and tension of compressional forces (Figure-1 (d)). A continuous pipeline crossing oblique-slip fault stretches and bends in and out of plane as it attempts to accommodate the three-dimensional ground movements. Due to this kind of movements of the blocks, the behaviour of buried pipelines crossing this type of fault can be different from the effects of the other kinds of faults on the buried pipelines. Until now, no research has been carried out on the behaviour of buried pipelines crossing the oblique-slip fault. This paper is an attempt to investigate the response of steel buried pipelines due to three-dimensional movements of the fault. The effects of some of important parameters of the steel pipe, soil and the fault characteristics on the response of the pipelines are illustrated.

SYSTEM MODEL

In this study the pipeline is divided into a number of segments, each segment is modeled as a beam element (Figure-2). The beam element has six degrees of freedom at each of the nodes (i.e., translations in the nodal, x, y, and z directions, and rotations about the nodal x, y, and z-axes) with tension, compression, bending, and torsion capabilities. The beam element has material and geometrical non-linearities. The equations used in the development of this element are the standard equations of beam theory and all of the calculations made are based on the thin-wall theory.



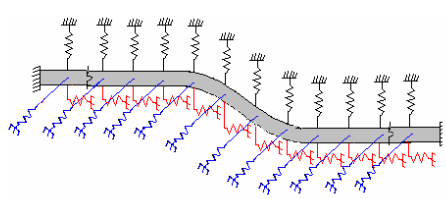


Fig.2-Model of the system

Two ends of pipelines are assumed to be fixed. Stress and strain relation of the pipe material is shown in Figure 3. The young modulus of pipe is assumed to be 3×10^7 Psi and its yield stress is taken as 74800 Psi;

where for 4% of strain it can be achieved. The soil surrounding the pipeline is modeled by nonlinear springs in the axial, lateral, and vertical directions.

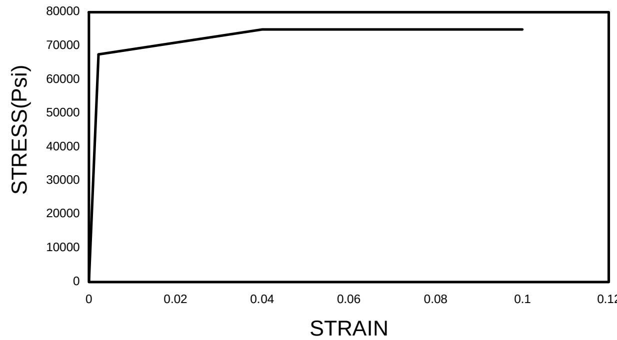


Fig.3- Stress-strain relation of the steel pipe material

The nonlinear behaviour of these springs is shown in Figures 4-a, 4-b, 4-c. It is assumed that the ultimate strength of soil in the upward movement of pipe is less than of its downward movement.

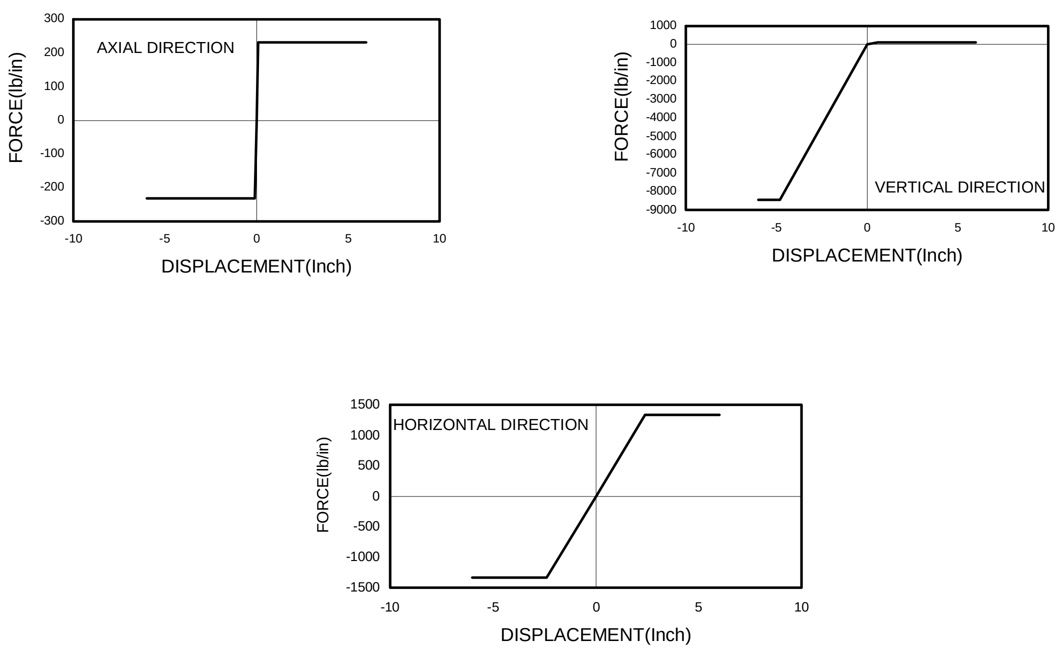


Fig.4- Nonlinear behaviour of the springs.

An accurate analysis of pipe-fault system is impossible without considering the nonlinear pipe-soil interaction [14]. The nonlinear stress-strain relationship of the pipe steel is considered in this study. The model accounts for the pipe axial and bending resistance. The soil resistance is typically idealized as an elastic-perfectly-plastic spring. The distributed soil resistance is modeled as a Winkler foundation; i.e., the soil support is modeled as a series of discrete springs (Fig.2), which provide a specified resistance per unit length of pipe.

The maximum axial soil force per unit length of pipe that can be transmitted to the pipe is:

$$T_u = \pi D H \bar{\gamma} \frac{1+k_o}{2} \tan\delta \qquad (1)$$

Where: H = depth to pipe centerline; D = pipe outside diameter; $\bar{\gamma}$ = effective unit weight of soil; k_o= coefficient of pressure at rest; and $\delta =$ interface angle of friction for pipe and soil. Angle of soil/pipe friction is considered to be 0.7φ and 0.8φ for ductile steel pipe material and hard steel pipe material respectively. φ is the internal friction angle of the soil.

The soil reaction to the vertical pipe movements in upward direction is different from that in downward direction. The experimental studies show that the soil strength in the upward movement of the pipe is much less than its strength in the downward movement. The magnitude of load imposed from soil to the pipe, when the pipe movement is downward, is considered to be equal to the soil bearing capacity and it can be computed by the following relation:

$$Q_d = N_q \bar{\gamma} H D + N_\gamma \frac{D^2}{2}\gamma \qquad (2)$$

where

$$N_q = e^{\pi tg\varphi} \tan^2(45 + \frac{\varphi}{2}) \qquad (2\text{-a})$$

and

$$N_\gamma = e^{0.18\varphi - 2.5} \qquad (2\text{-b})$$

In the above relations φ is in term of degree and the soil is considered to be of the medium sand type. The relative displacement to the ultimate load is equal to 0.1D. On the other hand, the following relation determines the magnitude of the imposed load due to the upward movement of the pipe:

$$Q_u = N_{qv} \bar{\gamma} H D \qquad (3)$$

where

$$N_{qv} = \frac{\varphi H}{44D} \le N_q \qquad (3\text{-a})$$

The relative displacement in this case can be computed by using the following approximate relation:

$$\Delta_{qu} = 0.01H \text{ to } 0.02H \le 0.1D \qquad (4)$$

The ultimate load P_u for relative displacement Δ_p is of the following form:

$$P_u = (6.816 + 2.019\frac{H}{D} - 0.146(\frac{H}{D})^2 + 7.651\text{x}10^{-3}(\frac{H}{D})^3 - 1.683\text{x}10^{-4}(\frac{H}{D})^4)\bar{\gamma} H D \qquad (5)$$

where

$$\Delta_p = 0.04(H + \frac{D}{2}) \le 0.15D \qquad (5\text{-a})$$

In this study the fault is considered to be an oblique-slip fault. The activation of this fault causes the ground displacement in x, y, and z-direction, say by Δx, Δy, and Δz; where x, y, and z will be in axial, lateral, and vertical directions of the pipe. The pipe/fault crossing angle (β) and fault slope angle (θ) are defined as:

$$\beta = \tan^{-1}\left(\frac{\Delta y}{\Delta x}\right) \quad ; \quad \theta = \tan^{-1}\left(\frac{\Delta z}{\Delta x}\right) \qquad (6)$$

Δ in the following paragraphs and figures refers to the square root of the fault movements (i.e. $\Delta = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}$).

NUMERICAL STUDIES

The fracture mechanism of buried pipelines crossing the active fault occurs in the static state [8]. In this study, the non-linear analysis of fault-pipe system is carried out. The effects of anchored length of pipeline, buried depth of pipe, frictional angle of pipe with soil, and the geometrical characteristics of pipe, fault displacement, crossing angle of pipe with the fault, and the fault slope angle on the response of buried pipeline crossing the oblique-slip fault movements are investigated in detail. A series of analysis has been performed for the above parameters to study the influence of the oblique-slip fault movements on the response of buried pipelines. In each analysis only the effect of one parameter is investigated, while the remaining parameters are kept constant. The axial force, bending moment, and maximum strain of the steel buried pipeline are obtained. However, the axial force and the bending moment obtained in this study are normalized by their plastic values.

One of the most prominent parameters, which can highly influence the response of buried pipelines crossing an active fault, is the anchored length of the pipe. The steel pipeline is assumed to be anchored at points A_1 and A_2 on the either side of the fault with a distance L_e. Beyond these points, it is assumed that the pipe moves with the surrounding soil. Sharp over-bends, under-bends or side-bends have a tendency to anchor the line and can be consider the anchored points. The effect of anchored length is not considered in the models proposed by Kenedy [4], Wang [6], and Takada [11].

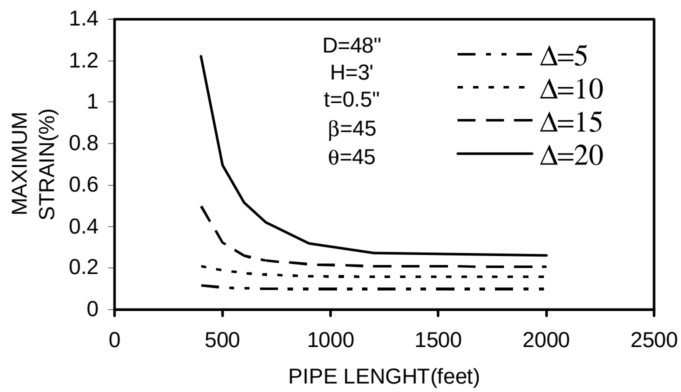


Fig.5- Variation of the buried pipeline responses versus anchored length of the pipeline due to the oblique-slip fault movements

Figure 5 illustrates the variation of maximum strain versus anchored length of the pipe crossing the oblique-slip fault. The maximum strain is considerably decreased by increasing the anchored length of the steel buried pipeline crossing the fault, followed by constancy in the anchored length. As the fault displacement increases the slope of the response reduction is considerably increased. Nevertheless, the maximum strain decrease sharply by increasing the anchored length; this is also followed by constancy in the anchored length. The smaller the value of Δ, the faster the maximum strain gets to a constant value over the anchored length of the pipeline. When the responses remain constant for the anchored pipe length, the initial state can be referred as the 'effective anchored length', and it is strongly dependent to the fault displacement. In other words, as the fault displacement become larger, more of buried pipeline length will be affected. Therefore, in order to increase the bearing capacity of the pipe crossing the fault, the effective anchored pipe length should be conservatively estimated.

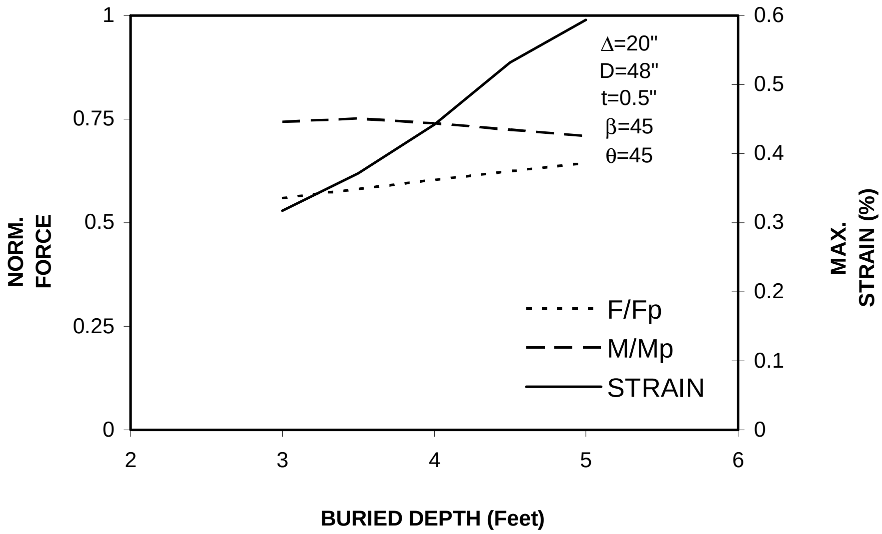


Fig.6- Variation of the buried pipeline responses versus buried depth due to the oblique-slip fault movements.

Another important parameter in the design of buried pipeline crossing an active fault is the buried depth of pipe. The increase of the buried depth increases the ultimate strength of the soil surrounding the pipe. Figure 6 illustrates the variation of normalized axial force, normalized bending moment, and maximum strain versus the buried depth. As the figure indicates, increasing the buried depth of the pipe decreases the bending moment and while it increases the maximum axial force and maximum strain. With due attention to the nonlinear springs relations, the increase of the buried depth causes the increase of the elastic coefficient of axial springs and the increase of axial force accordingly. Based on this effect, with the intention of increase the bearing capacity of the pipeline to the fault movement it is necessary to reduce the buried depth to its minimum amount.

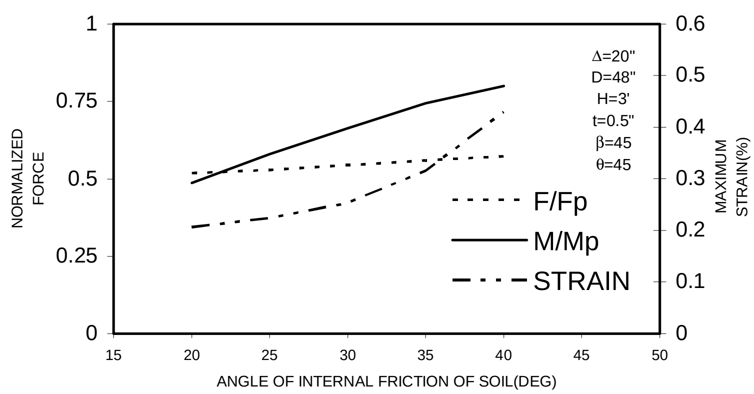


Fig.7- Variation of the buried pipeline responses versus angle of internal friction of soil ϕ due to the oblique-slip fault movements

The variation of normalized axial force, normalized bending moment, and maximum strain of the buried pipeline crossing the fault versus angle of internal friction of soil (ϕ) is shown in Figure 7. It demonstrated that the normalized axial force and the maximum strain increase by increasing ϕ. The slope of increase is more pronounced for maximum strain. Therefore, angle of friction is a parameter, which can highly influence the response quantity of the buried pipelines crossing the active oblique-slip fault.

Figures 8 and 9 display the variation of pipe responses crossing the fault movement versus pipe diameter and pipe thickness respectively. As the figure point out, increasing diameter and pipe thickness of the buried pipeline reduces the maximum strain of the buried pipeline. Therefore, the increase of wall thickness of pipe and the increase of pipe diameter considerably increase the bearing capacity of the pipe to the fault movement. However, due attention to the ratio of pipe diameter to pipe thickness is necessary and unavoidable in order to control the local stability of the wall thickness.

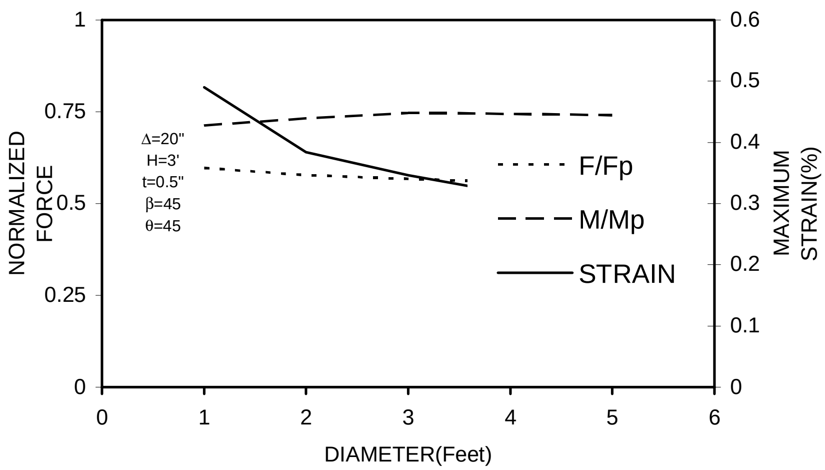


Fig.8- Variation of the buried pipeline responses versus pipe diameter due to the oblique-slip fault movements

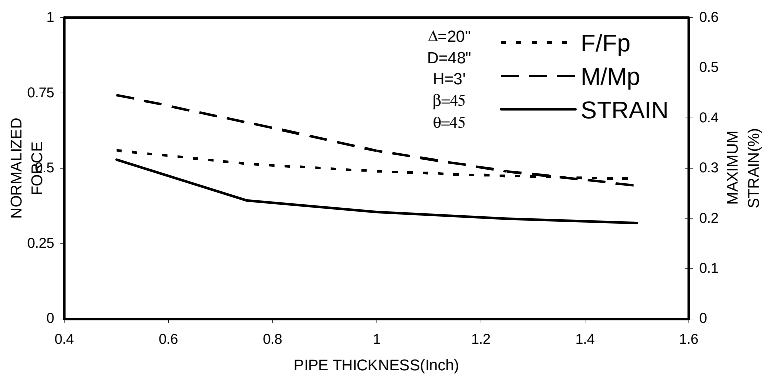


Fig.9- Variation of the buried pipeline responses versus pipe thickness due to the oblique-slip fault movements

Figures 10 shows the variation of the buried pipeline responses crossing the fault versus fault displacement of the oblique-fault for $\beta=45^o$ and $\theta=45$. The normalized axial force of the buried pipeline increases by increasing the fault displacement. The increase is linear with a constant slope over the entire range of fault displacement considered for the different values of θ. The normalized bending moment variation versus fault movement reveals the same pattern of variation as the normalized axial force up to nearly 20 inches fault displacement. It afterward decreases considerably by increasing the fault displacement. This illustrates that the steel pipeline yields at this specific point and the bending moment of the pipe achieve to its maximum value. The reduction of the cross sectional bending moment after this point may be due to the reduction of bending stiffness after reaching the plastic state. From the pattern of the variation of the responses it can be concluded that for large displacement of fault, one can neglect the effect of bending moment of cross section. Hence, the failure of the pipe in such cases can be attributed the effect of axial forces. Based on the above statement, the use of Kennedy model [4] for large displacement is acceptable.

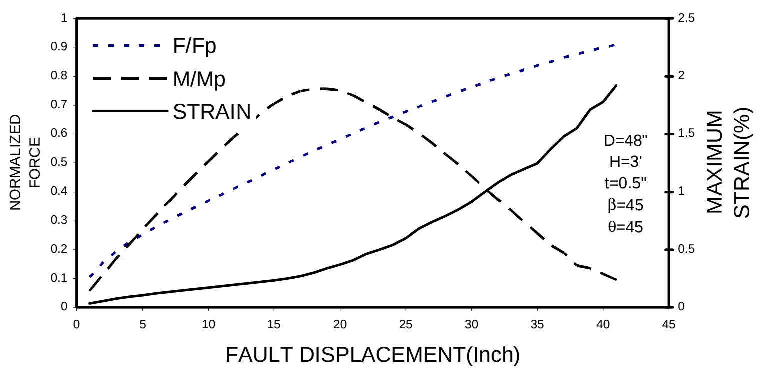
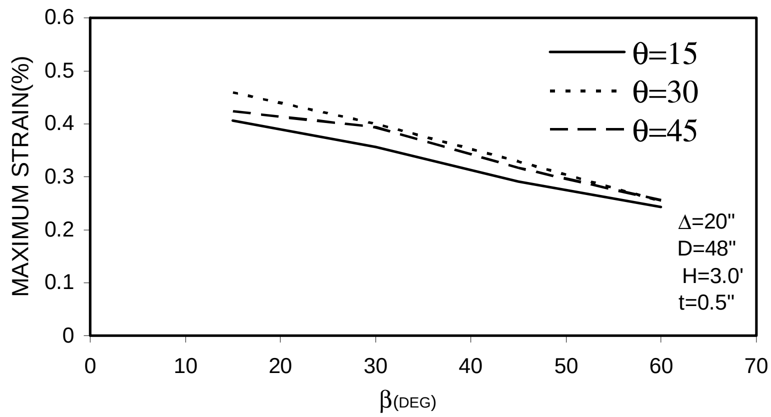


Fig.10- Variation of the buried pipeline responses versus fault displacements of an oblique-fault with $\beta=45^o$ and θ

Figure 11-a and 11-b explain the variation of maximum strain of the steel buried pipeline crossing the oblique-slip fault versus fault/pipe crossing angle (β) and slope angle of the fault (θ). As the figure 11-a shows, increasing the fault/pipe crossing angle causes the reduction of the response. The rate of response reduction in this case is almost independent of the angle θ. Figure 11-b shows the variation of maximum strain versus the slop angle of the fault (θ) for different values of fault/pipe crossing angle (β). As it can be observed for $\beta>60$ the value of maximum strain is independent of angle θ.



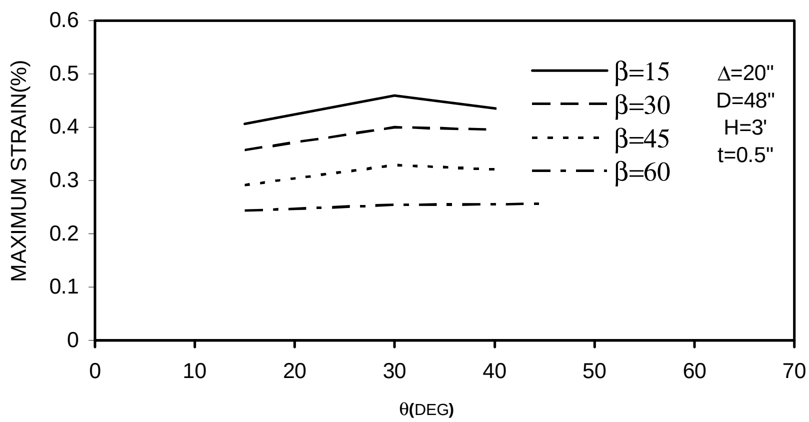


Fig.11- Variation of the buried pipeline responses versus slope angle of the fault and fault/pipe-crossing angle β (i.e., $\beta=0^0$, 30^0, 45^0, 60^0, 75^0)

CONCLUSION

In this study, a steel buried pipeline is modeled as a beam and the soil surrounding the pipeline is modeled by the nonlinear springs. The nonlinear response of steel buried pipeline to oblique-slip fault movements is evaluated by a series of parametric studies and the following conclusions have been achieved:

The anchored length of the pipe crossing the oblique-slip fault is strongly dependent on the fault displacement. As the fault displacement becomes larger, more of the buried pipeline length will be affected. Therefore, in order to increase the bearing capacity of the pipe crossing the fault, the effective anchored pipe length should be conservatively estimated.

The bearing capacity of the pipeline increases as the buried depth of the pipeline crossing the oblique-fault reduces. The increase of the buried depth increases the ultimate strength of the soil surrounding the pipe. Therefore, it is necessary to reduce the buried depth, in order to increase the bearing capacity of the pipeline due to the fault movement.

By increasing the pipe diameter and pipe wall thickness, the bearing capacity of the steel pipeline to the oblique-slip fault is increased. However, due attention is to be paid to the ratio of pipe diameter to pipe thickness, in order to control the local stability of the wall thickness.

The reduction of angle of friction of soil increases the bearing capacity of the pipeline. Therefore, in order to increase the bearing capacity of the pipeline in fault zone, the pipe can be sheltered with a suitable covering.

The response of buried pipeline to the oblique-slip fault movements is highly influenced by the fault displacement. For the large value of fault displacement the bending moment of pipe can be neglected and the pipeline can be modeled as a flexible cable.

The maximum strain for large pipe/fault crossing angle (β>60) is almost independent to fault slope angle (θ). Therefore, by assuming θ=0, the pipe crossing the oblique-fault can be modeled for two dimensional fault movements.

Increasing in pipe/fault crossing angle (β) causes the reduction of the response of the steel pipeline. Therefore, the pipeline should be installed in a way that the value of β reaches it's maximum.

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