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Numerical Modeling of Buried Pipeline Crossing a Fault

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NUMERICAL MODELING OF BURIED PIPELINE CROSSING A FAULT

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ABSTRACT

Pipelines are common transportation means for oil and natural gas, which act as an important lifeline facility for any nation. Often the design of these pipelines is a difficult task because they commonly are installed underground passing through different types of soil media. Many of these existing pipelines run through the faulted area, which continuously exposed to considerable risk of failure due to movement along the fault.

In this paper, a numerical study is carried out to understand stress development in buried pipeline subjected to fault motion with Mundra-Delhi pipeline as a case study. For this purpose, a 3D finite element program is developed and the same is used to study stress development in the pipe subjected to fault motion. Also here study has been done to find out the effect of different soil media and effect of fault-pipeline angle for both strike slip and dip slip fault motion.

INTRODUCTION

India has become a significant consumer of energy resources. In 2007, India was the fifth largest oil consumer in the world. Oil and gas account for 31 and 8 percentage of India's total energy consumption respectively proceeded by coal, which comprises 53 percentage (EIA (March 2009)). Due to Kandla, Mundra et al. ports and Indian Oil Corporation Limited (IOCL) refinery at Koyali near Baroda in western state of India, Gujarat have major pipeline network (Fig. 1), which is constantly spreading and will boost up after dreamed Iran-Pakistan-India pipeline. On the other hand because of active fault like Kachchh Mainland, Katrol Hill, Allah Band faults (Malik J.N. et al (2001)) area of Gujarat falls under zone III to V of seismic map of India (Fig. 1). Performance of the pipeline systems in India in past several earthquakes was relatively good. In 7.7 magnitude earthquake of 2001 in Gujarat most of the liquid fuel facilities was not affected only some damage occurred at the junctions of pipeline to the equipments at pump stations. But there are many examples of pipeline failure all over the world, 1994 North ridge earthquake at Balboa Boulevard in Granada Hills caused breakout of fire, rupture gas pipeline during 1964 Alaska Earthquake, massive damage during 1971 San-Fernando earthquake are few of them. In general pipelines are buried below ground primarily for aesthetic, safety, economic and environmental reasons which run through different soil media for long distances and expose to seismic hazards like ground shaking, permanent ground deformation and faulting. Here study has been done for finding out effect of fault motion on stresses in buried pipeline with considering the parameters of Mundra-Delhi Pipeline which is in vicinity of kachchh main land fault.

In last two decades growth of Indian pipeline network is significant. Presently IOCL operate network of 10329 km long crude oil and petroleum product pipeline (http://www.iocl.com/Aboutus/Pipelines.aspx), The Gas Authority of India Limited (GAIL) operates and maintains about 6700 km of natural gas high pressure trunk pipeline and 1922 km of LPG transmission pipeline network (http://www.gailonline.com/gailnewsite/aboutus/ataglance.html).

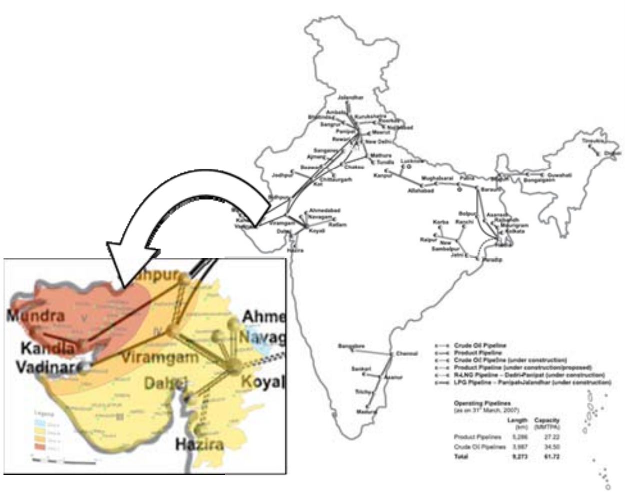

Fig 1. Major oil pipeline network and seismic zones of Gujarat region (www.iocl.com).

These pipeline networks are expected to be double in coming years. Overall development of pipeline industry is significant, however the research work related to seismic risk of pipeline is not much focused for Indian seismic condition. In this regard Suresh R Dash (2008) has discussed regarding seismic hazards related to pipeline failure, methodology for seismic analysis and design of buried pipeline.

There are several simplified theoretical and numerical models have been proposed to study the response of buried pipeline under the fault movement. In the theoretical model, the pipes usually modeled as a cable (Newmark, Hall (1975), Kennedy, et al (1977)) or a beam (Wang (1995), Radan Ivanov (2000)). In numerical methods FEM beam-spring or FEM shell-spring (Dimitrios K Karamitros et al. (2006), LIU Ai-wen et al. (2004)) models are used. However both above said modeling types have certain limitations, cable model can work for fault angle less than 90^{o} (under tension), fails in compression and bending deformation. Beam type model cannot consider the effect of local buckling and large deformation in pipe section and in case of FEM shell-spring model stresses are concentrating at node to which springs are attached. Considering all above limitations here we have developed more realistic 3D finite element model to study stress development in pipeline (Fig. 4).

In this paper a numerical study is carried out by considering the complexities in soil-pipe interaction at fault site. Initially homogeneous soil media is considered for varying α and β angle from 30^{o} to 150^{o} for strike slip and dip slip respectively (fig-2). Further stresses along the length of the pipe are plotted and compared if the soil media is layered for 2 m fault displacement. Also the normal and shear stress variations along the thickness of pipe are discussed in details in rest of the paper.

MODEL DISCRIPTION

The system under consideration comprises two models of continuous pipe burial in an elastic soil media, crossing strike slip fault and dip slip fault. Pipeline-fault angle α in strike slip and dip angle β were varied from 30^{o} to 150^{o} to make out positive to negative stress variation in pipe length for δ_s and δ_d fault displacement (Fig. 3). Also to see the effect of change in soil property on pipe stresses Young's modulus ($E_{1,}$ E_2) and Poisson's ratio ($\mu_{1,}$ μ_2) have been varied for depth d_1 and d_2 (Fig.3). Here parameters of existing Mundra-Delhi pipeline (API-5L Grade X 65) are taken for analysis (Ministry for petroleum & natural gas government of India [2002]).

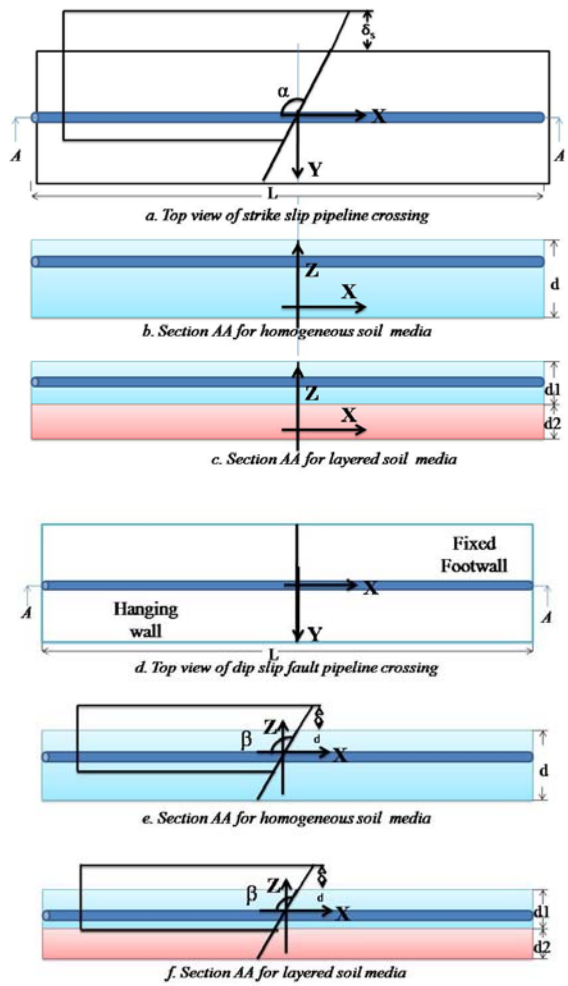

Fig.2.pipeline fault angle with homogeneous and layered soil during strike and dip fault

NUMERICAL MODELING OF BURIED PIPELINE

A three dimensional finite element model of 18 inches diameter and 7.9 mm wall thickness buried pipe (Mundra-Delhi pipeline executive summary) is developed with 8 nodded isoperimetric brick element (Fig. 4). Usually pipe near fault suffers large deformation, which is about 10 m ~ 30 m

(LIU Ai-wen [2004]) and after performing the test on various pipe lengths. Here 80 m length of pipe is considered with 1.25m pipe segment and the depth of the pipeline center below the ground surface is 1.5 m. Lithostratigraphy of kachchh main land shows sedimentary structure with top two layers of about 2m ~ 3 m gravel sand overlain by sandy soil with the 1m ~ 2m thickness (D. M. Maurya, et al [2003]). By considering this here total depth in a model is taken as 4m with 1.5m thick sandy soil layer over 2.5m thick gravel sand (Fig 3), for homogeneous condition only sandy soil is considered. To understand complete stress behavior acting on pipe, 2 m vertical and horizontal displacement are applied in this study for dip slip and strike slip respectively.

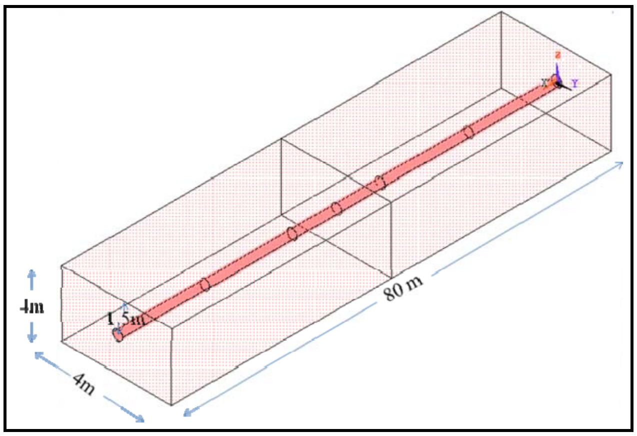

Fig.3. buried pipe model

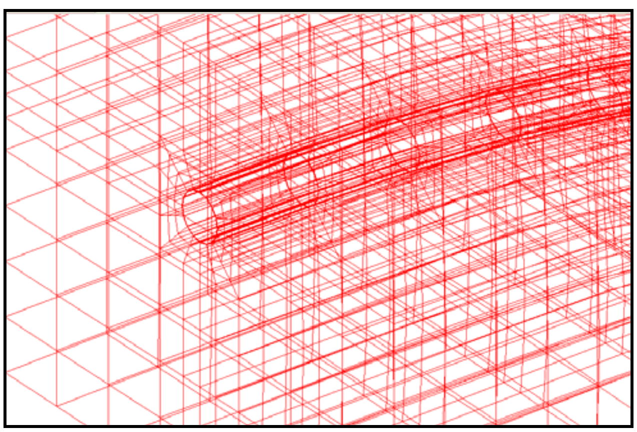

Fig.4. Proposed 3D Finite Element Model of buried pipeline

The finite element model is developed from total potential energy and strain energy equation, given by

$$\Pi = \frac{1}{2}\int_L \sigma^T \varepsilon \;\; A \;\; dx - \int_L u^T f \;\; A \;\; dx - \int_L u^T T \;\; dx \;\; - \sum_i u_i p_i \qquad (1)$$

$$U = \int_v \frac{1}{2} \;\; \sigma^T \varepsilon \;\; dv \qquad (2)$$

$$\mathbf{K}\,\mathbf{u} = \mathbf{f} + \mathbf{Q} \qquad (3)$$

Where

K is stiffness matrix,
f force vector,
u and **Q** are primary and secondary nodal degree of freedom.

BOUNDARY CONDITIONS

Here it is assumed that pipe and soil are perfectly bonded, so separation between pipe and soil is not considered. All three u_x u_y and u_z degrees of freedom of exterior nodes on one side of fault are constrained and displacement along fault plane is applied on external nodes of other side by constraining all other degrees of freedom. Generally stresses in pipe due to over burden pressure of soil are diminutive compare to stresses due to fault motion and are not considered in this analysis.

MODEL PARAMETERS

The material properties of soil and pipe are given in Table 1.

Table 1. Material Properties

Material	Young's Modulus (kN/m^2)	Poisson's Ratio
Sandy soil	4×10^4	0.4
Gravel sand	10×10^4	0.3
Steel pipe	2×10^8	0.3

RESULTS AND DISCUSSION

After performing test on various possible combination of pipeline fault angle and fault displacement. It is found that the normal stresses along the longitudinal axis of pipe are the governing stresses in the pipe. It is also being seen that the normal stresses in pipe are decreasing with increase in acute angle between pipe and fault (Fig 10 & 16). Additional displacement component of fault motion along the longitudinal axis could be the one reason for this effect.

Note the symbols and notation used in plotting are mentioned in Fig 5.

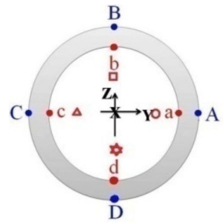

Fig. 5. Notation and symbols used in plotting

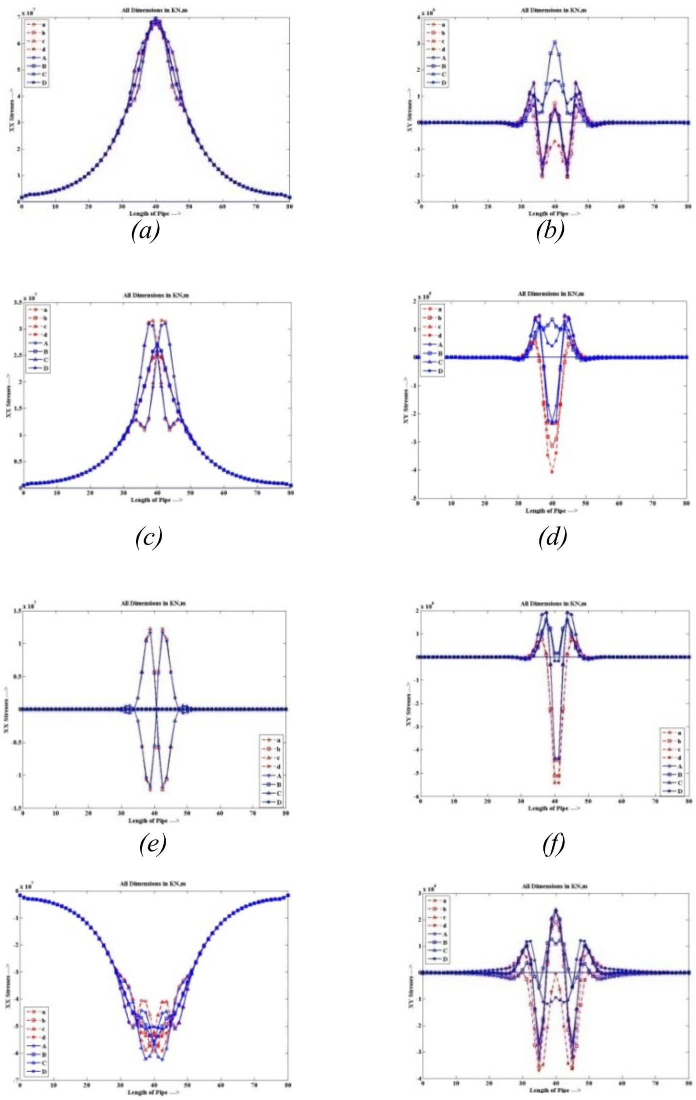

Fig 6 graph of normal (left column) and shear (right column) stresses long the longitudinal axis of pipe for α=30^o, 60^o, 90^o & 150^o

For optimization of pipe route crossing fault or in design analysis peak stresses in pipe are to be calculated. These maximum stresses are depended on various factors. These factors and their effects are discussed in detail below.

The normal stresses are distributed over the large length of the pipe. These stresses are intense about 10m ~15m around the fault plane (Fig 6) depending upon angle α. The location and peak value of normal stresses are not permanent and it does depend on three major factors the angle α, amount of fault motion and sign of normal stresses (compressive or tensile). The effect of acute angle α can be seen on both bending stresses and shear stresses. The bulging near apex of normal stress graph shows the bending stresses at point A and C in opposite direction. These bending stresses are increasing with acute angle α (Fig 6(a, c, e)). The shear stresses in the pipe are also increases with acute angle α which are accumulating in middle. These large shear stresses in middle cause change in sign of the bending stresses at middle of the pipe length. This changing in sign of bending stresses result in increase in normal stresses on either side of fault with opposite sign. This shifts peak on either side of fault plane (Fig 6). Hence the bending stresses are developing only at point A and C, maximum stress point also shifts along circumference.

The second factor is the component of fault motion along the longitudinal axis of pipe. This component of fault motion straight forward increase the normal stresses and further causes buckling in pipe near fault plane. The shear stress variation along the circumference is little bit a complicated phenomena as it is depend on many factor. The above said buckling could be the one among them. As it may causes preservative or subtractive the shear stress at various point along the circumference which results in variation of shear stresses along the circumference of the pipe.

The third factor on which the peak value of normal stress depends is the nature of normal stresses. The peak normal stresses in pipe under compression and tension are not matching for equivalent fault displacement in opposite direction. The local buckling during the compression in pipe reduces the peak value (Fig 7) but the peak is distributed over wider length (Fig 6(a), 6(g)).

The stresses in pipe also depend on few more parameters like diameter, wall thickness, depth, and soil conditions. Here effect of layered soil media over homogeneous soil is studied and plotted in Fig 7, 8.

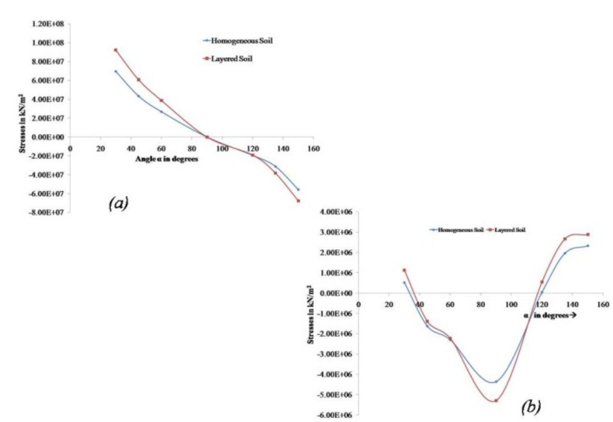

Fig 7 Effect of layered soil on normal (a) and shear (b) stresses at Middle of pipe length for strike slip fault motion

Fig 7 shows an increment in both normal and shear stresses due to layered soil media over homogeneous soil media. The extra stiffness of gravel sand layer results in decrease of internal deformation of soil media compare to homogeneous sandy soil media. This reduction in the internal deformation exerts more soil pressure on the pipe which directly results in an increment in stresses in pipe.

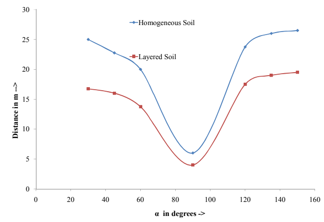

Fig 8 comparison of affected length for 10% of normal maximum stresses in pipe for homogeneous and layered soil media

The effect of soil layer is also observed on the affected length of the pipe. The distance of 10 percent of maximum normal stress point from fault plane were calculated and plotted for both homogeneous and layered soil in Fig 8. The reduce deformation in surrounding soil offer more resistance to the pipe deformation along the length. This result in less distribution of stresses in pipe this reduces the affected length of the pipe. Finally the effect of gravel sand layer can be recapitulate as stresses are converges towards the fault plane.

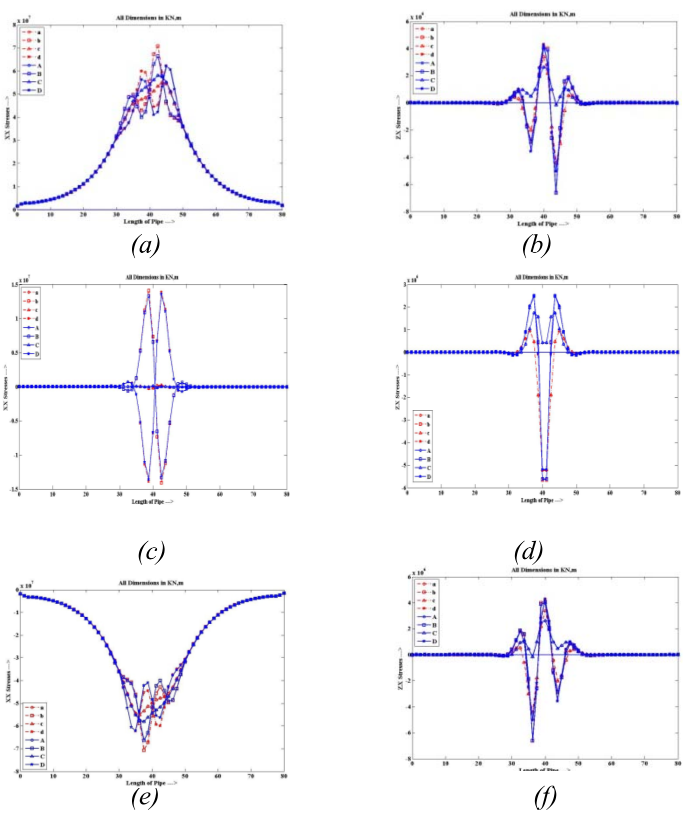

Fig 9 graph of normal (left column) and shear (right column) stresses long the longitudinal axis of pipe for β= 30° 90° & 150°

Here the study of pipeline crossing a dip slip fault is also carried out. In this study effect of pipeline fault angle and soil layer were considered. The same effects of angle β and soil layer were found out like in strike slip. But the stress distribution near fault is not similar to that of strike slip fault motions.

The main in this case can be seen that the bending stresses near the fault are developing under both tension ($\beta < 90^o$) and compression ($\beta > 90^o$) (Fig 9). Comparatively less depth of above soil layer offer less resistance to the pipe which results in bending of pipe near fault. Again because of lesser depth of soil, pipe bends more on hanging wall side when compare to foot wall side and this causes shift of peak stresses toward hanging wall (Fig. 9)

CONCLUSION

Stress behavior in buried pipes has been studied for both strike slip and dip slip fault motions by changing the fault parameters. For more realistic results dynamic and nonlinear analysis is been introduced in our further study.

Future work and results of this study can mainly used in the design of buried pipelines in vicinity of faults, crossing of faults and for permanent ground deformation. It also helps in the route optimization of buried pipelines.

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