Vulnerability Assessment of Buried Pipelines: A Case Study

by

Chenna Rajaram, Srikanth Terala, Ajay Pratap Singh, Kapil Mohan, Bal Krishna Rastogi, Pradeep Kumar Ramancharla

in

Frontiers in Geotechnical Engineering (FGE)

Report No: IIIT/TR/2014/-1

Centre for Earthquake Engineering
International Institute of Information Technology
Hyderabad - 500 032, INDIA
July 2014
Vulnerability Assessment of Buried Pipelines: A Case Study

Rajaram Chenna¹, Srikanth Terala², Ajay Pratap Singh³, Kapil Mohan³, Bal Krishna Rastogi³, Pradeep Kumar Ramancharla⁴

¹Ph.D Scholar, Earthquake Engineering Research Centre, International Institute of Information Technology (IIIT-H), Gachibowli, Hyderabad, India.
²Research Scientist, Earthquake Engineering Research Centre, International Institute of Information Technology (IIIT-H), Gachibowli, Hyderabad, India.
³Scientist, Institute of Seismological Research (ISR), Raisan, Gandhinagar, India.
⁴Professor of Civil Engineering, Earthquake Engineering Research Centre, International Institute of Information Technology (IIIT-H), Gachibowli, Hyderabad, India.
*rajaram.chenna@research.iiit.ac.in; terala3012@gmail.com; dgisrgad@gmail.com; ramancharla@iiit.ac.in

Received 20 February 2014; Accepted 11 March 2014; Published July 2014
© 2014 Science and Engineering Publishing Company

Abstract

The pipeline systems are commonly used to transport water, sewage, oil, natural gas and other materials world over. These pipelines run over long distances and in some instances they cross high seismic areas including fault crossings. Many buried pipelines in India run through high seismic areas and are exposed to considerable seismic risk. These pipelines should be designed in such a way that they remain functional even when they are subjected to high intensity earthquake shaking. This paper illustrates the performance of one of the high pressure gas pipeline in the state of Gujarat, under the fault movement. Analysis shows that the burial depth of pipeline should be minimized in the fault zones in order to reduce soil restrain on the pipeline during fault movement.

Keywords

Pipelines; Fault Movement; Earthquake Hazard

Introduction

Pipelines have been acknowledged as the most reliable, economic and efficient means for the transportation of water and other commercial fluids such as oil and gas. These systems are commonly used to transport water, sewage, oil, natural gas and other materials. They are often referred to as “lifelines” since they carry materials essential to the support of life and maintenance of property. The earthquake safety of buried pipelines has attracted a great deal of attention in recent years. Many buried pipelines in India run through high seismic areas and therefore are exposed to considerable seismic risk. Pipelines running through high seismic zones should be designed in such a way that they remain functional even after being subjected to high intensity earthquake shaking. Pipelines are generally buried below ground primarily for aesthetic, safety, economic and environmental reasons.

India is currently making huge investments in pipelines. Considering high seismicity of India, it is important to ensure seismic safety of buried pipelines. Gujarat is one of the high earthquake prone states in India. And in last few years, many state owned and private organizations had build up their pipeline networks across the state. Owing to these facts the performance of buried and above ground pipeline structures subjected to faulting and soil liquefaction effect and other seismic hazards have become an important subject to study. This paper illustrates the performance of one of the high pressure gas pipeline in the state of Gujarat, under the fault movement. Based on the result from the study, some recommendations are made to minimize the effect of earthquake on the existing pipeline.

Past Pipeline Performances

A pipeline transmission system is susceptible to a wide variety of seismic hazards. The major seismic hazards which significantly affect a pipeline system are: i) ground failure, ii) ground motion and iii) other
miscellaneous effects. While ground failure including faulting, liquefaction and earthquake induced landslides, tsunamis, and other factors of supporting and surrounding structures are usually placed under miscellaneous hazards. Ruptures or severe distortions of the pipeline are most often associated with relative motion arising from fault movements, landslides, liquefaction, loss of support, or differential motion at abrupt interfaces between rock and soil. Notably the most catastrophic damages are the ones resulting from faulting or ground rupture. Owing to these facts that the performance of buried and above ground pipeline structures subjected to faulting and other seismic hazards have become an important subject of study.

Indian Context

Currently, India has 7,000 km of pipelines. The oil and gas pipeline infrastructure is being accorded top priority by the nation’s planners. The pipeline market itself is estimated to be around US$ 9 billion over a period of five-six years. The National gas grid being implemented by GAIL (India) Ltd, lay a 17,000 km pipeline network. The proposed oil pipeline network, on the other hand, is expected to build a pipeline network spanning over more than 5,000 km. These projects will give an enormous boost to the pipeline demand in the country.

Notably, India has had more than five moderate earthquakes (Richter Magnitudes ~6.0-7.5) since 1988. A major part of the peninsular India has also been visited by strong earthquakes. From the past seismic performance of pipelines in various other countries, it can be noted that the consequences of pipeline failure due to earthquakes could be an exaggerated one, particularly so for India, both in terms of economic and social aspects. Thus implementing the seismic design considerations at the current phase of Indian pipeline scenario is absolutely essential.

Effects of Earthquake on Pipelines

The failure of pipelines during past earthquakes is described below.

a) 1971 San Fernando Earthquake: It resulted in direct losses to the pipeline systems by damaging a 1.24 m diameter water pipeline at nine bend and welded joints (Teoman Ariman, 1984). Ductile steel pipelines were able to withstand ground shaking but could not withstand ground deformation associated with faulting and lateral spread. Eleven transmission pipelines were damaged by liquefaction induced lateral spread and landslides. Eighty breaks occurred upon the underground welded steel transmission pipeline located in the upper San Fernando Valley, the most serious in an old oxyacetylene-welded pipeline. Although located in an uplift zone, the failure was caused by compressive forces wrinkling the pipes (Ref. Figure 1).

b) 1992 Landers and Big Bear Earthquakes: Two earthquakes occurred in San Bernadino County, California, a magnitude 7.5 another of magnitude 6.6. These two events were followed by numerous aftershocks. Horizontal fault rupture displacement associated with this event was from 5 to 9.5 feet. Most pipeline damage was associated with the rupture zone (Lund, 1994). Figure 2 shows damage of steel tank and pipe conning to it.

FIGURE 1. BUCKLING OF STEEL PIPELINE DUE TO COMRESSIVE FORCES DURING 1971 SANFERNANDO EARTHQUAKE

FIGURE 2. BOLTED STEEL 210,000-GAL TANK NEAR LANDERS WITH A DAMAGED SHELL AND RUPTURED OUTLET LINE (PHOTO COURTESY OF L. LUND, TCLEE).
c) 1994 Northridge Earthquake: This event caused about 1,400 pipeline breaks in the San Fernando Valley area. Outside the zone of high liquefaction potential, the dispersed pattern of breaks was attributed to old brittle pipes damaged by ground movement. In the On Balboa Boulevard, a 0.5588m pipe suffered two breaks, one in tensile failure and the other in compressive failure (Ref. Figure 3). These pipe failures were located in a ground rupture zone perpendicular to the pipeline. Leaking gas ignited at several locations. Some broken water and gas lines were found to have experienced 0.1524 to 0.3048 m of separation in extension. The area experienced widespread ground cracking and differential settlements. A 2.159 m sewage pipe ruptured in the Jensen Filtration (Lund, 1996).

FIGURE 3. TELESCOPED BELL AND SPIGOT JOINT 48-INCH WELD STEEL PIPE (L. LUND, TCLEE).

e) 1999 Kocaeli, Turkey Earthquake: Substantial water supply damage occurred in many cities (Ref: Figure 4). For example, the entire water distribution system in Adapazari was damaged. One of them, a water pipe made of steel with a diameter of 2.4 m, was damaged at Kullar due to right-lateral strike-slip. A butt-welded Thames raw water steel pipeline 2.2m in diameter crossed the Sapanca Segment of the North Anatolian fault and was damaged at the fault crossing. Damage was observed at three locations where a small surface leak was observed in the pipe at a point near the fault crossing; a significant leak occurred at yet another point and a minor leak happened at the bend of pipe (Farshad Vazinram et al., 2006).

f) 1999, Chi-Chi Earthquake: In Taiwan many buried water and gas pipelines were damaged at many sites (Ref: Figure 5). It was reported that buried gas pipelines underwent bending deformation due to ground displacement at a reverse fault near the Wushi Bridge about 10 km south of Taichung. The bending deformation in a 100A-size pipeline was V - shaped, with the pipeline being bent at three points. The deformation of a 200A-size pipeline was Z-shaped, with the pipeline being bent at two points. There have been virtually no cases of substantial deformation comparable to this case in gas pipelines comprised of welded steel pipes (Farshad Vazinram et al., 2006).

FIGURE 4. FAILURE OF PIPE DURING 1999 KOCAELI EARTHQUAKE

FIGURE 5. FAILURE OF PIPE DURING 1999 CHI-CHI EARTHQUAKE

Vulnerability Assessment of Buried Pipelines

Seismic design of buried pipeline has great importance in the field of lifeline engineering. In certain circumstances, it may be required to take the pipes above ground but this case is relatively uncommon. Generally the oil and gas pipelines are designed and constructed as continuous pipelines, while water supply pipelines are constructed as segmented pipelines. Failures have mostly been caused by large permanent soil displacements.
This section discusses seismic analysis method for buried pipes subjected to a strong earthquake. This can be used as a basis for evaluating the level of strengthening or increased redundancy needed by existing facilities to improve their responses during seismic events. So this covers design criteria for wave propagation, fault crossing and permanent ground deformation (PGD) due to liquefaction, lateral spreading, etc.

Analysis and design criteria require the following engineering information.

**Pipeline Information**
- a) Pipe geometry (diameter, thickness);
- b) Type of joint;
- c) Stress-strain relationship of pipe material;
- d) Pipeline function and its post seismic performance requirement;
- e) External pipe coating specification;
- f) Operating pressure in the pipe;
- g) Operational and installation temperature;
- h) Pipeline alignment detail (plan, profile location of fittings, etc); and
- i) Reduced strain limit for existing pipelines.

**Site Information**
- a) Burial depth of the pipeline;
- b) Basic soil properties (unit weight, cohesion, internal friction angle and in situ density).
- c) Properties of backfill soil in the trench;
- d) Depth of water table; and

**Seismic Hazard Information**
- a) Expected amount of seismic ground motion at the site;
- b) Expected amount and pattern of permanent ground deformation and its spatial extent;
- c) Length of pipeline exposed to permanent ground deformation;
- d) Active fault locations; expected magnitude of fault displacement, and orientation of pipeline with respect to direction of fault movement.

The seismic safety evaluation of a continuous oil pipeline as follows:

**Design Case Study:**

The continuous buried pipeline is designed to carry natural gas at a pressure of 9.3 MPa. The pipe is of API X-60 grade with 30-in (0.762m) diameter (D) and 0.0064 m wall thickness (t). The installation temperature and operating temperature of the pipeline are 30 °C and 65 °C respectively. The pipeline is buried at 1.5m of soil cover. Poisson’s ratio and coefficient of thermal expansion of the pipe material can be considered as 0.3 and 12 x 10⁻⁶ respectively. This pipeline is checked for four cases they are

Case I: Permanent ground displacement (PGD)
Case II: Buoyancy due to liquefaction
Case III: Fault crossing
Case IV: Seismic wave propagation

For API X-60 Grade pipe:

Yield stress of pipe material = σy = 413 MPa

Ramberg-Osgood parameters n = 10 and r =12.

Figure 6 shows pipeline crossing ground movement both in parallel and perpendicular directions.

Pipe strain due to internal pressure is calculated as follows:

The longitudinal stress induced in the pipe due to internal pressure will be

\[ S_p = \frac{PDh}{2t} = \frac{9300000 \times 0.762 \times 0.3}{2 \times 0.0064} = 166.09 \times 10^6 \text{ N/m}^2 = 166.09 \text{MPa} \]

Using Ramberg-Osgood’s stress-strain relationship the longitudinal strain in the pipe will be

\[ \varepsilon_p = \frac{S_p}{E} \left[ 1 + \frac{n}{1 + r} \left( \frac{S_p}{\sigma_y} \right)^{1/r} \right] \]  \hspace{1cm} (1)

\[ = \frac{166.1 \times 10^6}{2 \times 10^{11}} \left[ 1 + \frac{10}{1 + 12} \left( \frac{166.1 \times 10^6}{413 \times 10^6} \right)^{12} \right] \]

\[ = 0.0008305 = 0.08305\% \text{ (tensile)} \]

**Pipe Strain Due to Temperature Change:**

The longitudinal stress induced in the pipe due to change in temperature will be

\[ \varepsilon_t = \frac{S_t}{E} \left[ 1 + \frac{n}{1 + r} \left( \frac{S_t}{\sigma_y} \right)^{1/r} \right] \]  \hspace{1cm} (2)

\[ = \frac{2 \times 10^{11} \times 12 \times 10^6 (65-30)} = 84 \text{ MPa} \]

Using Ramberg-Osgood’s stress-strain relationship the longitudinal strain in the pipe will be

\[ \varepsilon_t = \frac{S_t}{E} \left[ 1 + \frac{n}{1 + r} \left( \frac{S_t}{\sigma_y} \right)^{1/r} \right] \]

\[ = \frac{84 \times 10^6}{2 \times 10^{11}} \left[ 1 + \frac{109}{1 + 12} \left( \frac{84 \times 10^6}{413 \times 10^6} \right)^{12} \right] \]
\[ \varepsilon = 0.00042 = 0.042\% \text{ (tensile)} \]

The total strain in the continuous pipeline due to internal pressure and temperature is

\[ \varepsilon = 0.08305 + 0.042 = 0.125\%. \]

Ignoring the strain in pipe due to installation imperfection or initial bending, the above calculated strain can be considered as the operational strain in pipe (i.e., \( \varepsilon_{oper} = 0.125\% \)).

**Case I: Permanent Ground Displacement (PGD)**

The permanent ground deformation refers to the unrecoverable soil displacement due to faulting, landslide, settlement or liquefaction induced lateral spreading.

Here the length and width of PGD zone are 120m and 50m respectively. Soil is sandy soil with an angle of friction (\( \phi \)) = 32° and effective unit weight of 18 kN/m³. The ground displacement (\( \delta^v \) and \( \delta^s \)) due to liquefaction can be taken as 2m.

The operational strain in pipeline = 0.125% (tensile)

Yield stress of pipe material \( \sigma_y = 413 \]
Ramberg-Osgood parameter (n) = 10
Ramberg-Osgood parameter (r) = 12

**Parallel Crossing (Longitudinal PGD)**

The expected amount of permanent ground movement parallel to pipe axis = \( \delta^v = 2m \)

The design ground movement = \( \delta^v_{design} = \delta^v \times \frac{I_p}{L} = 2 \times 1.5 = 3m \)

**Case-1:**

The amount of ground movement (\( \delta^v_{design} \)) is considered to be large and the pipe strain is controlled by length (L) of permanent ground deformation zone. The peak pipe strain is calculated as

\[ \varepsilon_a = \frac{t_u L}{2\pi DL E} \left[ 1 + n \left( \frac{t_u L}{2\pi D L E} \right)^r \right] \]

Where

\( t_u = \) maximum axial soil force per unit length of pipe for soil condition.

The maximum axial soil resistance (\( t_u \)) per unit length of pipe can be calculated as

\[ t_u = \pi D c a + \pi D H \gamma \left( \frac{1 + K_o}{2} \right) \tan \delta^v \]

Where \( D = \) diameter of pipe = 0.762m

\( C = \) Coefficient of cohesion = 30kpa

\( \alpha = \) Adhesion Factor

\[ \alpha = 0.608 - 0.123 x 0.3 - 0.27/(0.3^{1.5}) + 0.695/(0.3^3 + 1) = 0.99645 \]

\( H = \) soil cover above the centre of the pipeline = 1.5m

Interface angle of friction between soil and pipe \( \delta^v = f \phi \)

Here \( f = \) friction factor = 0.7 for smooth steel pipe

\( \delta^v = f \phi = 0.7 \times 32^v = 22.4^o \)

\( K_0 = \) coefficient of soil pressure at rest

\[ K_0 = 1 - \sin 32^o = 0.47 \]

\( t_a = \pi x 0.762 x 30000 x 0.99645 + (\pi x 0.762 x 1.5 x 18000 x ((1 + 0.47)/2) tan 22.4^o) \]

\[ = 91144N/m = 91.144kN/m \]

\[ \varepsilon_a = \frac{t_a L}{2\pi DL E} \left[ 1 + n \left( \frac{t_a L}{2\pi D L E} \right)^r \right] \]

\[ = \frac{91144 x 120}{2 x \pi x 0.762 x 0.0064 x 2 x 10^{11}} x \left[ 1 + \frac{10}{1 + 12} \left( 91144 x 120 \right) \right] \]

\[ = 0.002023 = 0.2023\% \]

**Case-2:**

The length (L) of permanent ground deformation zone is large, and the pipe strain is controlled by the amount of ground movement (\( \delta^v_{design} \)). The peak pipe strain for this case is calculated as

\[ \varepsilon_a = \frac{t_u L}{2\pi DL E} \left[ 1 + n \left( \frac{t_u L}{2\pi D L E} \right)^r \right] \]

Where

\( L_e = \) Effective length of pipeline over which the friction force (\( t_u \)) acts, which can be calculated by the following equation.

\[ \delta^v_{design} = \frac{t_u L_e^2}{\pi D L E} \left[ 1 + \left( \frac{2}{2 + r} \right) \left( \frac{n}{1 + r} \right) \left( \frac{t_u L_e}{2\pi D L E} \right)^r \right] \]

From this effective length of pipeline is calculated as

\[ L_e = 100m \]

\[ \varepsilon_a = 0.0015095 \]

The design strain in pipe is taken as the least value between the two cases = \( \varepsilon_{elastic} = 0.0015095 \)

The operational strain in the pipeline = \( \varepsilon_{oper} = 0.00125 \)

The total tensile strain in the pipeline = \( 0.0015095 + 0.00125 = 0.0027595 \)
The expected amount of transverse permanent ground deformation \( \delta t = 2 \text{m} \)

The design transverse ground displacement \( \delta d_{\text{design}} = \delta t \times l_P = 2 \times 1.5 = 3 \text{m} \).

The maximum bending strain in the pipe is calculated as the least value of the following two equations:

\[
A. \quad \epsilon_b = \frac{\pi D \delta d_{\text{design}}}{W^2} \quad (8) \\
\quad = \pm \pi \times 0.762 \times 3 / 50^2 \\
\quad = \pm 0.00287267
\]

\[
B. \quad \epsilon_b = \frac{Pw^2}{3\pi EtD^2} \quad (9)
\]

Where

\( P_u \) = maximum resistance of soil in transverse direction.

The maximum transverse soil resistance per unit length of pipe is

\[
P_u = N_{ch}cD + N_{gh}D \quad (10)
\]

Where

\( N_{ch} \) = Horizontal bearing capacity factor for clay

\[
N_{ch} = a + bx + \frac{c}{(x+1)^2} + \frac{d}{(x+1)^3} \leq 9 \quad (11)
\]

Where

\[
x = H/D = 1.5/0.762 = 1.968503937 \\
a = 6.752
\]

\[
b = 0.065 \\
c = -11.063 \\
d = 7.119
\]

N_{ch} = 6.752 + (0.065 \times 1.96) + (-11.063/1.96+1)^2 + (7.119/1.96+1)^3

\[
= 5.896
\]

N_{gh} = Horizontal bearing capacity factor for sandy soil

\[
N_{gh} = a + bx + cx^2 + dx^3 + ex^4
\]

Where

\[
x = H/D = 1.5/0.762 = 1.968503937 \\
a = 5.465 \\
b = 1.548 \\
c = -0.1118 \\
d = 5.625 \times 10^{-3} \\
e = -1.2227 \times 10^{-4}
\]

Hence,

N_{gh} = 5.465 + (1.548 \times 1.96) + (-0.1118 \times 1.96)^2 + (5.625 \times 10^{-3} \times 1.96)^3 + (-1.2227 \times 10^{-4} \times 1.96)^3

\[
= 8.120
\]

Hence

P_u = 5.896 \times 30000 \times 0.762 + (8.120 \times 18000 \times 1.5 \times 0.762) = 301869N/m = 301.869kN/m

\[
\epsilon_b = \frac{301869 \times 50^2}{3 \times \pi \times 2 \times 10^3 \times 0.0064 \times 0.762^2} = 0.1077
\]

Hence, the maximum strain induced in the pipeline due to transverse PGD is taken as

\( \epsilon_{\text{oper}} = 0.0013 \)

The operational strain in the pipeline = \( \epsilon_{\text{oper}} = 0.0013 \)

Total longitudinal strain in the pipe in tension 0.00287267+0.0013 = 0.004172

Total longitudinal strain in the pipe in compression = 0.00287267-0.0013 = 0.0016

The allowable strain in tension for permanent ground deformation is = 3% = 0.03

The allowable strain in compression for steel pipe is

\( \epsilon_{\text{cr-c}} = 0.175t/R = 0.175 \times 0.0064/0.381 = 0.00293 \)

The total strain in pipe due to transverse PGD is less than the allowable strain for both tension and compression.

**Case II: Buoyancy Due to Liquefaction**

The net upward force per unit length of pipeline can
be calculated as

The extent of liquefaction \( L_b = 50m \)

\[
F_b = \frac{\pi D_l^2}{4} \left( \gamma_{sat} - \gamma_{content} \right) - \pi D_t^2 \rho \]  

(12)

\( F_b = \pi \times 0.762/4 \) \((18000-0)\times 0.762 \times 0.0064 \times 78560 \)

= 7005.05N/m

It is assumed that the weight of gas flowing through pipe has negligible weight. The unit weight of steel pipe \( (\gamma_{pipe}) \) is taken as 78560N/m³.

The bending stress in the pipeline due to uplift force \( (F_b) \) can be calculated as

\[
\sigma_{bf} = \frac{F_b L_b^2}{10Z} \]  

(13)

Where

\( L_b \) = length of pipe in buoyancy zone

\( Z \) = section modulus of pipe cross section

\[
= \pi \left( 0.762^2 - 0.7492^2 \right) \]

\[
= \frac{32}{0.762} \]

\[
= 0.0028459m^4 \]

\( \sigma_{bf} = \pm 7005.05 \times 50)^2/ (10 \times 0.0028459) \)

= 615360117N/m²

Maximum strain in pipe corresponding to the above bending stress calculated as

\[
\varepsilon = \frac{\sigma_{bf}}{E} \left[ 1 + \frac{n}{1 + \rho} \left( \frac{\sigma_{bf}}{\sigma_y} \right)^n \right] \]  

(14)

\[
= 615360117 \left[ 1 + \frac{10}{1 + 12 \left( \frac{615360117}{413 \times 10^6} \right)^{10}} \right] \]

= 0.130705674

The operational strain in the pipeline = \( \varepsilon_{oper} = 0.0012505 \)

The total longitudinal strain in the pipe in tension = \( 0.130705674 + 0.0012505 = 0.1319562 \)

The total longitudinal strain in the pipe in compression = \( 0.130705674 - 0.0012505 = 0.1294551 \)

The allowable strain in pipe in tension is = 3% =0.03

The allowable strain in pipe in compression is

\( E_{acc} = 0.175t/R = 0.175 \times 0.0064/0.381 \)

= 0.0029396

The maximum strain in the pipeline due to buoyancy effect is greater than the allowable strain for steel pipes in tension and compression.

**Case III: Fault Crossing**

Here the pipeline crosses a normal slip fault with fault displacement of 1.5m and a dip angle of 35°. The pipeline crosses the fault line at an angle of 40°. The source to site distance can be considered as 20km.

The expected normal-slip fault displacement = \( \delta_n = 1.5m \)

Dip angle of the fault movement \( \Psi = 35° \)

The angle between pipeline and fault line \( \beta = 40° \)

Component of fault displacement in the axial direction of the pipeline

\[
\delta_{fax} = \delta_n \cos \psi \sin \beta \]  

(15)

\[
= 1.5 \cos 35° \times \sin 40° = 0.789811m \]

Component of fault displacement in transverse direction of pipeline:

\[
\delta_{fax} = \delta_n \cos \psi \cos \beta \]  

(16)

\[
= 1.5 \cos 35° \times \cos 40° = 0.94126m \]

Importance factor for fault movement for pipe = \( I_p = 2.3 \)

Applying importance factor,

The design fault displacement in axial direction becomes

\[
= \delta_{fax \ x \ I_p} = 0.789811 \times 2.3 = 1.816565707m \]

The design fault displacement in transverse direction becomes

\[
= \delta_{fax \ x \ I_p} = 0.94126 \times 2.3 = 2.164898707m \]

The average pipe strain due to fault movement in axial direction can be calculated as

\[
\varepsilon = 2 \left[ \frac{\delta_{fax \ x \ I_p}}{2L_u} + 1 \left( \frac{\delta_{fax \ x \ I_p}}{2L_u} \right)^2 \right] \]  

(17)

Where

\( L_u \) = effective unanchored length of the pipeline in the fault zone

\[
L_u = \frac{E_{acc} \pi D_t}{t_u} \]  

(18)

\[
= 2 \times 10^{-1} \times 0.002 \pi \times 0.762 \times 0.0064 \]

\[
= 67.238m \]

Or

\( L_s \) = the actual length of anchorage = 120m
Hence, the anchored length to be considered is the lower the above two values. So \( L_a = 67.238 \text{m} \)

Axial strain in the pipe

\[
\varepsilon = 2 \left[ \frac{1.8165}{2 \times 67.238} + \frac{1}{2} \left( \frac{2.164}{2 \times 67.238} \right)^2 \right] \]

\[= 0.02728 \]

The operational strain in the pipeline = \( \varepsilon_{\text{oper}} = 0.0013 \)

Total strain in pipe in tension = 0.0306 + 0.0013 = 0.0285

The allowable strain in pipe in tension is 3% = 0.03

The total tensile strain in pipe due to fault crossing is less than the allowable strain.

**Case IV: Seismic Wave Propagation**

The expected peak ground acceleration of the site at base rock layer = PGA\(_b\) = 0.45g

For this soil Peak ground acceleration (PGA) at ground = 0.45g \times 1.8

= 0.81g

Converting the soil as soft and the magnitude of design basis earthquake (M) is equal to 6.5, and distance of site from earthquake source is about 20km

\[ \text{PGV} = 0.405 \times 140 = 56.7 \text{cm/s} \]

Converting the soil as soft and the magnitude of design basis earthquake (M) is equal to 6.5, and distance of site from earthquake source is about 20km

\[ \text{PGV} = 0.405 \times 140 = 56.7 \text{cm/s} \]

Design peak ground velocity = \( V_g \) = PGV \times \( I_p \)

= 56.7 \times 1.5

= 85.05cm/sec

= 0.85m/s

Maximum axial strain in the pipe due to wave velocity can be calculated as

\[ \varepsilon_u = \frac{V_g}{\alpha_u C} = \frac{0.85}{2 \times 2000} = 0.00021 \]

Maximum axial strain that can be transmitted by soil friction can be calculated as

Maximum axial strain in the pipe due to wave velocity can be calculated as

\[ \varepsilon_u = \frac{V_g}{\alpha_u C} = \frac{0.85}{2 \times 2000} = 0.00021 \]

Maximum axial strain that can be transmitted by soil friction can be calculated as

\[ \varepsilon_u = \frac{V_g}{\alpha_u C} = \frac{0.85}{2 \times 2000} = 0.00021 \]

\[ \varepsilon_u = \frac{I_p \varepsilon}{4AE} = \frac{91144 \times 1000}{4 \times 0.0151922 \times 2 \times 10^{11}} = 0.00750 \]

The calculated axial strain due to wave passage need not be larger than the strain transmitted by soil friction.

The operational strain in the pipeline = \( \varepsilon_{\text{oper}} = 0.0013 \)

The total strain in pipe in tension = 0.00750 + 0.0013 = 0.0088

The allowable strain in pipe in tension is 3% = 0.03

The maximum strain in pipe due to wave propagation pipe is less than the allowable strain.

**Parametric Studies**

Four pipelines of different diameters as 12", 18", 24" and 30" which are operating under the same pressure of 7.5 Mpa. The installation temperature and operating temperature of the pipeline are 30\(^\circ\) and 60\(^\circ\)C respectively. The pipe is of API X-52 grade with different thicknesses. Poisson’s ratio and coefficient of thermal expansion of the pipe material can be considered as 0.3 and 12 \times 10^{-6} respectively. The unit weight of saturated soil at the site is 18 kN/m\(^3\). The pipeline crosses a normal slip fault with fault displacement of 1.5m, 2.5m and a dip angle of 35\(^\circ\). The pipeline crosses the fault line at an angle of 40\(^\circ\).

The source to site distance can be considered as 20km. The expected peak ground acceleration (PGA) in the site is 0.45g at the base rock layer. The strain variation with pipe thickness is shown in figures 7-10.

**FIGURE 7. TOTAL STRAIN VS PIPE THICKNESS FOR PIPE DIAMETER IS 12"**

**FIGURE 8. TOTAL STRAIN VS PIPE THICKNESS FOR PIPE DIAMETER IS 18"**
Modern pipelines, whether onshore or offshore, are typically buried to provide protection and support. Buried pipelines are normally designed on the basis of hoop stress limitations for internal pressure. For pipelines subjected to large temperature differentials, special stress analysis may be required for bend configurations. In addition, buried pipelines may require design for external loads, e.g., loads imparted by heavy equipment at ground surface.

During earthquake, a buried pipeline may experience significant loading as a result of large relative displacement of the ground along its length. Large ground movements caused by faulting, liquefaction, lateral spreading, landslides and slope failure. The exposure to these hazards can be minimized through careful selection of a pipeline route, especially in the case of such localized conditions as slope failure. However, faulting and liquefaction – induced movements, such as lateral spreading, often cannot avoid on long pipeline routes through areas of high seismicity.

Conclusions

In the design of a pipeline for crossing a fault line, the following considerations generally will improve the capability of the pipeline to withstand differential movement.

- The pipelines crossing fault line should be oriented in such a way to avoid compression in the pipeline. The optimum angle of fault crossing will depend upon the dip plane and the expected type of movement. And it should be within 90°.
  - Abrupt changes in wall thickness should be avoided within fault zone.
  - In all areas of potential ground rupture, pipelines should be laid in relatively straight section avoiding sharp changes in direction and elevation.
  - The burial depth of pipeline should be minimized within fault zones in order to reduce soil restrain on the pipeline during fault movement.
  - Pipelines may be placed on the above ground sliding supports. An increase in pipe wall thickness will increase the pipeline’s capacity for buoyancy force due to soil liquefaction.

REFERENCES

Ariman Teoman., “Buckling and Rupture failures of Pipelines Due to Large Ground Deformations” Proc. of 8th World Conference on Earthquake Engineering, California, 1984.


Rajaram. Chenna received his MS by Research degree in Computer Aided Structural Engineering (CASE) from IIIT-H and is currently pursuing his Ph.D under the guidance of Dr. Ramancharla Pradeep Kumar at Earthquake Engineering Research Centre (EERC), International Institute of Information Technology, Hyderabad (IIIT-H). He has published 11 papers in various journals and conferences. His areas of interests are Earthquake engineering and Structural Dynamics, Applied Element Method and Analysis and design of RC structures.

Pradeep K Ramancharla holds his PhD degree from University of Tokyo, Japan. Presently, he is professor of Civil Engineering and head of Earthquake Engineering Research Centre (EERC) at IIIT Hyderabad. His research interests are numerical modelling of faults and tectonic plates, collapse simulation of buildings, seismic evaluation and strengthening of buildings and concrete codes in India. Presently he is a panel member of CED 2: IS 456 and IS 1343.