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Earthquake Effect Analysis of Buried Pipelines

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ABSTRACT: 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. The designation of pipeline system as “Lifelines” signifies that their operation is essential in maintaining the public safety and well being. A pipeline transmission system is a linear system which traverses a large geographical area, and soil conditions thus, is susceptible to a wide variety of seismic 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. Notable the most catastrophic damages are the once resulting from faulting and liquefaction. 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 of study.

This paper illustrates the performance of one of the high pressure gas pipeline in the state of Gujarat, under the fault movement and soil liquefaction. Based on the result from the study some recommendations are made to minimize the effect of earthquake on the existing pipeline,

1 Pipeline

Pipeline system consists of buried and above ground pipelines, above ground facilities such as pumping stations, storage tanks and miscellaneous terminal facilities. However the term pipeline in general implies a relatively large pipe spanning a long distance. They generally have a minimum diameter of 0.1 m and a minimum length of 1.6 km. Few of the largest and longest pipelines may have a diameter of over 3.0 m and a length of over 1600 km. Pipelines have been acknowledged as the most reliable, economic & efficient means for the transportation of water and other important commercial fluids such as oil and fuel gases.

1.1 Seismic Hazard and Indian Context

A pipeline transmission system being a linear system which traverses a large geographical area, and soil conditions thus, 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) others miscellaneous effects. While ground failure includes faulting, liquefaction and earthquake induced landslides, tsunamis, and other affect 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 the performance of buried and aboveground pipeline structures subjected to faulting and other seismic hazards have become important subject of study.

Currently, India has more than 7,000 km of pipelines. The oil and gas pipeline infrastructure is being accorded top priority by the nation's planners and a network of these pipelines criss-crossing the nation has been planned. 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, which is expected to take three-four years to reach completion, will 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. As noted in IS 1893 Himalayan-Nagaland region, Indo-Gangetic Plain, Western India, Kutch and Kathiawar regions are geologically unstable parts of the country, and some devastating earthquakes of the world have occurred there. 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.

2. Soil-pipeline interaction:

The soil around the pipeline plays a very important role in relation to its seismic behavior, if it is cohesive soil, the softer it is, the greater differential settlement there will be due to consolidation and higher amplification effects; if it is granular material, the probability of liquefaction becomes higher the looser it is. In case of soil pipeline interaction, the soil will not fail, but the soil displacement will produce friction-like forces at the soil-pipeline interface.

An elasto-plastic model is often adopted for the force-deformation behavior at soil-pipeline interface (O'Rourke et al, 1995). This model is fully defined by two parameters: the maximum axial force per unit length at the soil pipe interface, f_m , and the relative displacement at which slippage between pipe and soil occurs. The slippage displacement is small and conservatively neglected here.

The maximum axial force per unit of length f_m depends on the type of soil surrounding the pipe and the method of pipe installation (i.e., the compaction control of the backfill). For cohesionless soil f_m depends on the effective normal stress at the soil-pipe interface, the coefficient of friction and the effective friction angle ϕ between the soil and the pipe material, and the pipe diameter F_p . Considering that we have plane strain, and that the coefficient of lateral pressure k_o for compacted soil is approximately equal to unity, the effective normal stress s'_v is simply equal to the product of the effective unit weight of soil γ'_m and the depth H , to the pipe's centerline. Thus, for cohesionless backfill, the friction force per unit length becomes

$$f_m = s'_v \tan \phi \quad (1)$$

For cohesive soil, f_m depends on the undrained shear strength S_u of the soil. For normally consolidated clay, S_u gives a good estimation of the adhesion to the pipe. For overconsolidated soils Lambe and Whitman (1969) recommended the use, as adhesion, of the undrained shear strength of an equivalent normally consolidated soil. So for cohesive soil,

$$f_m = S_u \quad (2)$$

For the most general soil condition, when the soil surrounding the pipe has both friction and cohesive characteristics, f_m will be given by

$$f_m = (c + s'_v \tan \phi) \quad (3)$$

Where c = shear strength of the soil corresponding to zero-effective vertical stress on the shear-strength curve.

2.1 Faulting

Faulting is the deformation associated with the relative displacement of adjacent parts of earth's crust. Ground ruptures can occur over an extended length of the fault, the length and amount of surface rupture depends mainly on the magnitude of the earthquake and focal depth.

Faults are classified on the basis of slip (direction of movement) or their angle of dip with respect to the ground surface and their attitude relative to adjacent beds. In general, depending upon the predominant component of movement, faults are classified as being strike-slip, normal-slip, or reverse-slip. In many cases faults exhibit a combination of two types of movements and are termed as oblique slip.

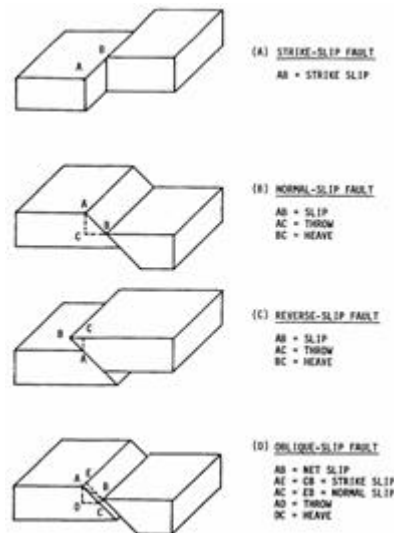


Fig. 1 Types of Faulting (after Krinitzsky, 1974)

Figure 1 illustrates the types of fault movement. For the purpose of illustration, the faults are represented as a single plane on which relative movement between each side of fault occurs. A strike slip fault is one in which the predominant component of movement is a horizontal displacement. If the movement of one side of the fault when viewed from the other side is to the right, the fault is called right lateral strike-slip fault. Conversely, when the movement is to the left, the fault is called a left lateral strike-slip fault. Normal-slip and reverse-slip faults are those in which the overlaying side moves downward and upward, respectively, with respect to the underlying side of the fault. A low angle reverse-slip fault (whose plane of movement is oriented less than 45° with the horizontal) is often referred to as an oblique-slip fault. The amount of horizontal shortening or lengthening in the plane perpendicular to the fault is referred to as heave. The vertical offset measured in the same plane is referred to as throw.

Along with the type of fault amount of fault displacement is an important consideration for design. Many empirical formulas have been developed from past observations which predict the amount of ground displacement. The amount of surface displacement due to surface fault rupture can be estimated using models such as those provided by Wells and Coppersmith.

$$\log(MD) = -5.26 + 0.79M \quad (4)$$

Where, M is the moment magnitude and MD is the maximum displacement, in inches.

Most fault offset models provide a median estimate of the maximum displacement along the length of the fault for a given magnitude earthquake. A dispersion estimate of the amount of fault offset is usually provided with the model. But in general fault offset will vary along the length of the surface rupture from zero inches to the maximum amplitude. Given this variation, it is recommended that the maximum displacement from such models be varied along the length of the fault, from zero to the maximum, with an expected value of some percentage of the maximum displacement.

Loads are induced in a buried pipeline when the soil restricts the free motion of the pipeline or when the pipeline attempts to resist the motion of the surrounding soil. Lateral fault movement causes the pipeline to displace laterally with respect to the soil. This results in the soil applying a lateral pressure on the pipeline and the pipeline in turn pushing away the soil. This loading imparts tensile strains and curvature to the pipeline on both sides of the fault.

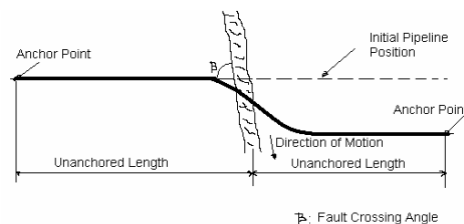


Fig.2.a. Plan of Pipeline Subjected to Both Normal and Strike Slip Movement at a Fault Crossing

Vertical fault movement is resisted by a pipeline in a different manner. For a shallow buried pipeline, the uplift resistance of the soil typically is much lower than the downward bearing resistance. Thus, the pipeline may be able to lift upward with relative freedom to accommodate the vertical fault movement, and the maximum pressure between the pipeline and the soil will occur predominantly on the up thrown side of the fault. The corresponding curvature and bending strains will generally be lower than those caused by strike-slip movements of equal magnitude.



Fig 2.b. Elevation of Pipeline Subjected to Both Normal and Strike Slip Movement at a Fault Crossing

The axial component of fault movement is resisted by friction forces at the soil-pipeline interface. For a given pipeline axial force, there is a length of pipeline required to develop opposing soil frictional forces. Beyond this length, the pipeline is not affected by the fault movement such that the pipeline is considered to be effectively anchored. Hence, the frictional resistance provided by soil-pipeline interaction governs the length of pipeline available to accommodate fault-generated strains.

It is noteworthy to understand that fault crossing is most crucial for the case of buried pipelines. This is so because in case of aboveground pipelines crossing a fault line the fault displacement can be accommodated via number of ways. One of the classical ways to do so is by using various kinds of flexible joints. Recent methods of placing the pipeline at low height bearings in set configurations have proved their efficacy. Further it is the surrounding soil and the interface friction and reaction which worsen the behaviour of pipelines to fault movements. Loads are induced in a pipeline by relative motion between the pipeline and the surrounding soil i.e. when the soil restricts the free motion of the pipeline or when the pipeline attempts to resist the motion of the surrounding soil. The entire fault displacement in that sense is dictated to the pipeline by soil over its entire length. Aboveground pipeline is completely free to move and unrestrained in this respect.

2.2 Liquefaction:

Liquefaction is the transformation of a saturated cohesion less soil from a soil to a liquid state as a result of increased pore pressure and loss of shear strength. When liquefaction is combined with conditions, such as ground slope, surface loads, and ejection of water and sediments, permanent movements develop such that structures supported or surrounded by soil can be severely damaged. Youd (1978) identified three basic types of ground failure associated with liquefaction: lateral spreading, flow failure, and loss of bearing. Another important effect of liquefaction is the uplift of buried structure such as pipelines due to buoyancy force.

Lateral Spreads:—this involves the horizontal movement of the surficial soils due to liquefaction of an underlying deposit. Lateral spreads can be especially destructive to buried pipelines, although the degree of damage depends on the magnitude and extent of lateral spreading and the composition of the pipeline. During the 1971 San Fernando earthquake, multiple failures occurred in two welded gas transmission lines in a lateral spread near Juvenile Hall (Youd, 1973; Southern California Gas Company, 1973; O'Rourke and Tawfik, 1983). In contrast, no breaks developed during the same earthquake in newly constructed three welded gas lines, where settlements and lateral movements of approximately 2 to 3 ft were caused by similar conditions of failure (Southern California Gas Company, 1973).

Flow Failures: A flow failure involves the displacement of completely liquefied soil often with blocks of intact earth transported within the liquefied mass. Many flow failures develop under water, as in evidence by the ground deformations adjacent to Lake Merced caused by the 1957 San Francisco earthquakes (Bonilla, 1959). The forces imposed by the lateral flow of liquefied soil are likely to be much less than those associated with the movement of competent soil during lateral spreading.

Loss of Bearing: Loss of bearing strength leads to bearing failures and large deformations in surface structures founded on liquefied soil. The movement of earth structures, though are not spectacular, are often more pervasive and potentially more damaging to pipelines. Bearing capacity loss beneath an embankment leads to settlement and spreading that may induce considerable tensile strain in a pipeline. Compressive strains develop in the zones parallel and immediately adjacent to the embankment

Subsidence: liquefaction often leads to the formation of sand boils, mud volcanoes, fissures and other channels through which water and sediments are ejected, often at high pressure, onto the ground surface.

Buoyancy Effects: When the soil around the buried pipeline liquefies, buoyancy forces are exerted on the pipeline which must be resisted by anchors and the drag forces imposed by the liquefied soil as the pipeline begins to elevate (Kennedy et al., 1977). Buoyancy effects are probably of greatest concern in areas such as flood plains and estuaries where massive liquefaction could take place in a large earthquake.

When the liquefaction of the soil around the pipeline occurs, buoyancy forces are exerted upon pipeline and must be resisted by anchors and the drag forces imposed by the liquefied soil as the pipeline begins to elevate. Buoyancy effects are probably of greatest concern in areas such as flood plains and estuaries where massive liquefaction could take place in a large earthquake. When the surface liquefies, the pipe keeps uplifting at most to a position where a portion of pipe is at ground surface near the centre of the liquefied zone. However, when a non-liquefied soil layer is present as a cover over liquefied layer, the pipe come to rest at the interface of the non-liquefied and liquefied layer.

2.2.2 Buoyant force on pipeline:

The net upward force on unit length of pipeline is:

$$F_b = \frac{pD^2}{4}(g_{sat} - g_{content}) - pDt g_{pipe} \quad (5)$$

Where

F_b = Upward force due to buoyancy per unit length of pipe

γ_{sat} = Saturated unit weight of soil

$\gamma_{content}$ = Unit weight of pipe content

γ_{pipe} = Unit weight of pipe material

D = Diameter of the pipe

t = Thickness of the pipe

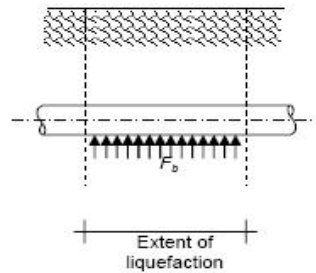


Fig:3 Longitudinal section of the pipeline showing the force upon it due to buoyancy (ALA, 2001)

Bending strain in the pipe due to buoyancy:

The bending strain in the pipeline due to uplift force may be approximated as:

$$e_b = \pm \frac{F_b L_l^2}{3pEtD^2} \quad (6)$$

Where,

E = Modulus of elasticity of pipe material

t = Thickness of the pipeline

L_l = Length of the pipe subjected to liquefaction

While calculating the bending strain, the pipe is considered as a stiff beam restrained due to non-liquefied soil beyond the margins of liquefied zone.

3. Seismic vulnerability assessment of a High pressure pipeline crossing a major fault in the Flood prone zone in the state of Gujarat, India

In this part a live example of a transmission pipeline of Grade API 5L X60 with a diameter 16" and operating with a pressure of 45 Kg/ cm² is considered from Gujarat, India. The pipeline is crossing a fault line in the Surat District and laid in the alluvial flood plain of river Tapi. The pipeline has a wall thickness of 0.0159 m and crossing the fault

at an angle, β , 40° . The dip angle, θ of the fault is 35° and the estimated fault movement is a strike-slip displacement, d_m of 1.5 m, which produces tension in the pipeline.

The pipeline is buried with a cover, H , of 1.5 m in dry sand having a unit weight $\bar{g} = 19000 \text{ N/m}^3$, Coefficient of cohesion, c of 0.2 kg/cm^2 and of Angle of friction, F of 32° . The various geotechnical data was obtained by geotechnical investigation report submitted by the consultancy firm.

The yield stress of the pipe material, $s_y = 413 \text{ MPa}$ and the Ramberg-Osgood parameters are $n = 10$ and $r = 12$ with a Coefficient of thermal expansion material, α is 12×10^{-6} (assume) and a Poisson's ratio, μ is 0.3
The pipe is FBE coated and the friction factor of the coating is 0.6.

3.1 Pipe strain due to internal pressure:

The longitudinal stress induced in the pipeline due to internal pressure is :

$$S_p = \frac{PDm}{2t} \quad (7)$$

$$= 18.25 \text{ MPa}$$

The longitudinal strain in the pipeline is:

$$e_p = \frac{S_p}{E} \left[1 + \frac{n}{n+1} \left(\frac{S_p}{s_y} \right)^r \right] \quad (8)$$

$$= 0.009\%$$

The longitudinal strain induced in the pipeline due to internal pressure is tensile.

3.1.2 Pipe strain due to temperature change:

The longitudinal stress induced in the pipeline due to the change in temperature is:

$$S_T = E \alpha (T_2 - T_1) \quad (9)$$

$$= 72 \text{ MPa}$$

The longitudinal strain induced in the pipeline

$$e_t = \frac{S_t}{E} \left[1 + \frac{n}{n+1} \left(\frac{S_t}{s_y} \right)^r \right] \quad (10)$$

$$= 0.36\%$$

The longitudinal strain induced in the pipeline due to increase in temperature is tensile.

The initial strain due to imperfection in installation or initial bending has been neglected.

Therefore, the total strain in the pipeline during operation is

$$= 0.009 + 0.036$$

$$= 0.045\%$$

For continuous pipeline the initial strain can be considered as:

$$e_{\text{operation}} = 0.045\%$$

3.1.3 Axial soil force:

The maximum axial soil force transmitted to the pipe per unit length is:

$$t_u = pDca + pDH\bar{g} \left(\frac{1+K_0}{2} \right) \tan d' \quad (11)$$

Where,

$$a = \text{adhesion factor} = 0.608 - 0.123c - \frac{0.274}{c^2 + 1} + \frac{0.695}{c^3 + 1} \quad (12)$$

$$= 1.00$$

$$\text{Interface angle of friction between soil and pipe} = \mathbf{d'} = \mathbf{ff} = 0.6 \times 32^\circ = 19.2 \quad (13)$$

Coefficient of soil pressure at rest

$$K_0 = 1 - \sin 32^\circ = 0.47 \quad (14)$$

Hence,

$$t_u = 36.87 \text{ KN/m}$$

3.1.3 Fault crossing:

The expected normal-slip fault displacement at site = $d_{fn} = 1.5 \text{ m}$

Dip angle of fault movement = $\gamma = 35^\circ$

Pipe and fault crossing angle = $\beta = 40^\circ$

Importance factor for fault movement for high pressure pipeline = $I_p = 2.3$

As per Seismic Guidelines for water Pipelines (ALA 2005)

Component of fault displacement in the axial direction of the pipeline (Newmark and Hall, 1975)

$$= \mathbf{d}_{f-ax} = \mathbf{d}_{fn} \times \cos \mathbf{y} \times \sin \mathbf{b}$$

$$= 1.5 \times \cos 35^\circ \times \sin 40^\circ$$

$$= 0.7898 \text{ m}$$

Component of fault displacement in the transverse direction of the pipeline

$$= \mathbf{d}_{f-lat} = \mathbf{d}_{fn} \times \cos \mathbf{y} \times \cos \mathbf{b}$$

$$= 1.5 \times \cos 35^\circ \times \cos 40^\circ$$

$$= 0.0941 \text{ m}$$

Component of fault displacement in the vertical direction of the pipeline

$$= \mathbf{d}_{f-ver} = \mathbf{d}_{fn} \times \sin \mathbf{y}$$

$$= 1.5 \times \sin 35^\circ$$

$$= 0.86 \text{ m}$$

The average pipe strain due to axial pipe movement =

$$\mathbf{e} = 2I_p \left[\frac{\mathbf{d}_{f-ax}}{2L_a} + \frac{1}{2} \left(\frac{\mathbf{d}_{f-lat}}{2L_a} \right)^2 \right] \quad (18)$$

Where

L_a = effective unanchored length of the pipeline in the fault zone;

$$L_a = \frac{EepDt}{t_u} = \frac{2 \times 10^{11} \times .002 \times p \times 0.430 \times 0.0156}{36871} = 228.62 \text{ m} \quad (19)$$

Hence, unanchored length is taken as 100 m as effective unanchored length is more than actual.

The axial strain in the pipe =

$$e = 0.01822 = 1.82\%$$

The operational strain in the pipe = 0.045%

Hence total strain in the pipe is (1.865%) is within the limiting strain value (3%) for steel pipe subjected to Permanent ground deformation

(ASCE 1984, ALA 2005.)

3.2.1 Buoyancy due to liquefaction:

Due to the liquefaction of upper soil layer, the net upward force on unit length of pipeline is:

$$F_b = \frac{pD^2}{4} (\mathbf{g}_{sat} - \mathbf{g}_{content}) - pDt \mathbf{g}_{pipe} \quad (5)$$

Where

F_b = Upward force due to buoyancy per unit length of pipe

γ_{Sat} = Saturated unit weight of soil = 19000 N/ m³

$\gamma_{Content}$ = Unit weight of pipe content

γ_{Pipe} = Unit weight of pipe material = 78560 N/ m³

D = Diameter of the pipe = 0.43 m
t = Thickness of the pipe = 0.0156 m

F_b = 1071.786 N/m

The bending strain in the pipe due to uplift force is:

$$e_b = \pm \frac{F_b L_l^2}{3pEtD^2}$$

Where,

E= Modulus of elasticity of pipe material

t = Thickness of pipeline

L_l = Length of pipe subjected to liquefaction = 100 m

Hence,

e_b = ± 0.001934

The allowable strain in tension is 3%

The allowable strain in compression

= e_{cr-c} = 0.175 (t/R) = 0.01294

The strain due to buoyancy is less than the allowable strain in compression.

Hence, to prevent compression wrinkling due to buoyancy effect, the wall thickness of the pipe may be increased.

4. Conclusions and Recommendations:

Newmark and Hall's theoretical model is considered here to analyze the laid pipeline. It was found out that the stiffness of the pipeline is the major aspect in this seismic zone for the safe operation of the pipeline system. The stiffness of the pipeline depends on various physical parameters of the pipe such as diameter, thickness and material property.

The study results shown that the following high level countermeasures could be recommended for pipeline crossing fault and soil liquefaction zone.

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.

1. 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 of the fault plane and the expected type of movement. And it should be within 90 degree
2. Pipeline ductility should be increased in fault-crossing region to accommodate large fault movement without rapture.
3. Abrupt changes in wall thickness should be avoided within fault zone.
4. In all areas of potential ground rapture, pipelines should be laid in relatively straight section avoiding sharp changes in direction and elevation.
5. To the extent possible, pipelines should be constructed without field bends, elbows, and flanges that tend to anchor the pipeline to the ground.
6. If longer length of pipeline is available to conform to fault movement, level of strain gets reduced. Hence, the points of anchorage should be provided away from the fault zone to the extent possible in order to lower the level of strain in the pipeline.
7. A hard and smooth coating on the pipeline such as an epoxy coating may be used in the vicinity of the fault crossing to reduce the angle of friction between pipeline and soil.
Example: Three layer of epoxy coating
8. The burial depth of pipeline should be minimized within fault zones in order to reduce soil restrain on the pipeline during fault movement.
9. Pipelines may be placed on the above ground sliding supports. Fig 4, 5

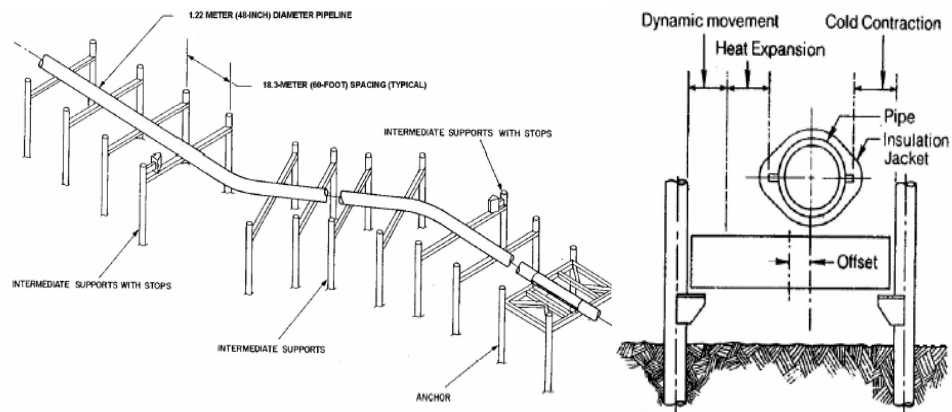


Fig 4: Pipeline placed in aboveground sliding support

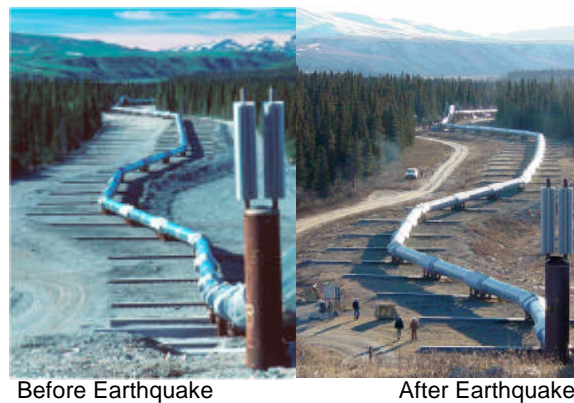


Fig 5 Pipeline crossing Denali Fault, Alaska

In the design of a pipeline for in the Liquefied zone, the following considerations generally will improve the capability of the pipeline to withstand buoyancy force due to soil liquefaction.

10. Pipeline may be encased in concrete pipes Fig 6 to reduce the buoyancy effects, but the increase diameter will also increase lateral drag forces on the pipe.
Example : Gunniting



11. Concrete weights or gravel filled blankets can be utilized to provide additional resistance to buoyancy.
12. The buoyancy effect can also be minimized by shallow burial of the pipeline above the ground water level.
13. Where uplift is the main concern, one may provide anchors at a spacing of up to 150 m to prevent uplift
14. An increase in pipe wall thickness will increase the pipeline's capacity for buoyancy force due to soil liquefaction.
15. Use of shutoff valves may be increased to protect the pipeline of gas leakage in case of any severe damages.
16. Distance between SV (Sectionizational valve stationals, basically ball valves) stations is 8 km, 16 km, 24 km and 32 km as per ASME code for gas pipeline for class I, II, III and IV zones. But to minimize the effect

of any damage due to leakage or full bore rupture of the pipeline , these distances between the SV stations can be minimized to 8 Km for the entire zone for transmission pipelines.

17. As there is no such code for the distance between the SV stations for the oil pipelines ,it is recommended that to minimize the effect of oil spill due to leakage or rupture in the pipeline the distance between the SV stations can be taken as 8 Km for that zone.
18. Proper backfilling and compaction of the soil is essential in seismic zone. A well compacted soil along with the trapezoidal shaped trench in clay area and rectangular shaped trench in the rock area is recommended. Fig 7 below is the recommended trench dimension for the city gas distribution projects.

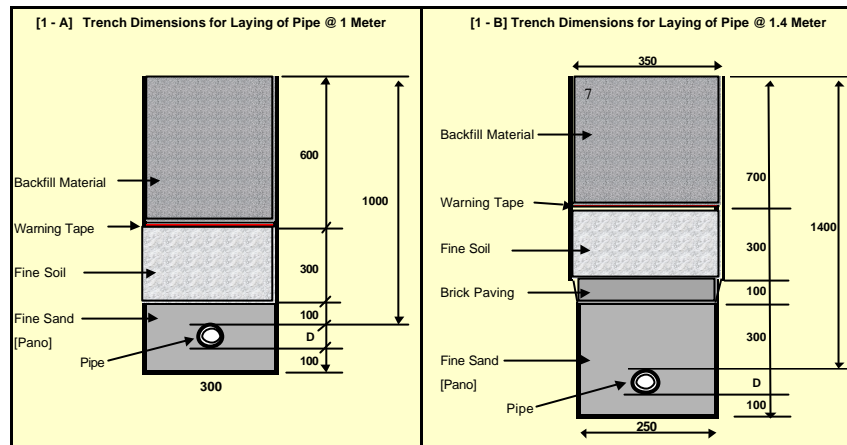


Fig: 7 Trench Dimension for City gas distribution projects in seismic zone

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