SEISMIC DESIGN OF CONTINUOUS BURIED PIPELINE

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Abstract
Buried pipelines perform vital function in maintaining integrity of the nation's economy and population. Seismic hazards can cause devastating effects on these pipelines. Rupture of oil and gas pipeline may lead to drastic effect on environment and public. Integrating the seismic design in the design phase of pipeline system is of at most importance. This paper deals in providing a guideline for calculating the seismic resistance of oil and gas pipeline under various seismic events like permanent ground deformation, fault, landslide, wave propagation etc. Finally various measures that are to be adopted to prevent failure of pipeline system under these seismic events are also described. This guideline is applicable only for continuous buried steel pipeline.

Keywords: *Seismic design, Earthquake, fault, Liquefaction, Buoyancy, Permanent ground deformation.*

1. Introduction
Pipelines are often designated as "Lifelines" owing to its significance in distributing life dependent supplies such as water, oil and gas etc. Although its importance is under estimated or even unknown to the common society or public, its failure can result in drastic effects to the public. So it's important to maintain the integrity of these "Lifelines" at any cost, in any circumstances. The main advantages of pipelines include low cost, environment friendly, high reliability, less maintenance cost, most safe to the public etc. So, maintaining the integrity of pipeline system is essential for sustaining the level of life presently enjoyed by the urban population of the country. The resistance of pipeline against the seismic hazards is of high importance as it may result in devastating events like rupture/ failure and thus leading to leakage. Rupture of continuous pipeline can directly affect the public life, environment, the flora and fauna of the area etc. Rupture of gas pipeline is considered more dangerous than liquid as there is greater chance of spreading and inflammation. So, seismic aspects are important consideration for the design of any pipeline facility, to improve public safety and reduce environmental risks to acceptable levels and to ensure economic viability. This paper illustrates an outline or steps involved in computing the resistance of pipeline under probable seismic hazard conditions and the methods to be adopted to minimize the effect of seismic hazards on the pipeline.

2. Seismic hazards affecting pipeline
Seismic hazard have been classified as either ground deformations or wave propagation. Ground deformations deal with permanent ground deformations due to soil failure, liquefaction induced buoyancy effects, landslides, faulting etc. While the second type hazard is mainly related to propagation of seismic waves originating under the ground from an epicenter and releases energy as waves.

3. Failure modes of pipeline under seismic event
The principal failure modes of a corrosion free continuous pipeline are rupture due to axial tension, local buckling due to axial compression, beam buckling and flexural (bending) failure. The strain associated with axial tensile rupture is taken above 4%. Buckling refers to a state of structural instability in which an element loaded in compression experiences a sudden change from a stable to an unstable condition. It involves local instability of pipe wall leading to distortion of shape. The limiting strain is considered as the strain at onset of wrinkling, given by

$$\varepsilon_c = 0.175\frac{t}{R}$$

Beam buckling can be related to Euler buckling of slender column undergoing upward displacement. The relative displacement or strain in pipeline is distributed over a large area and hence the compressive strains are relatively small. This happens mainly in shallow buried pipelines. Usually it does not create any discontinuity problem in distribution of contents in the pipeline.

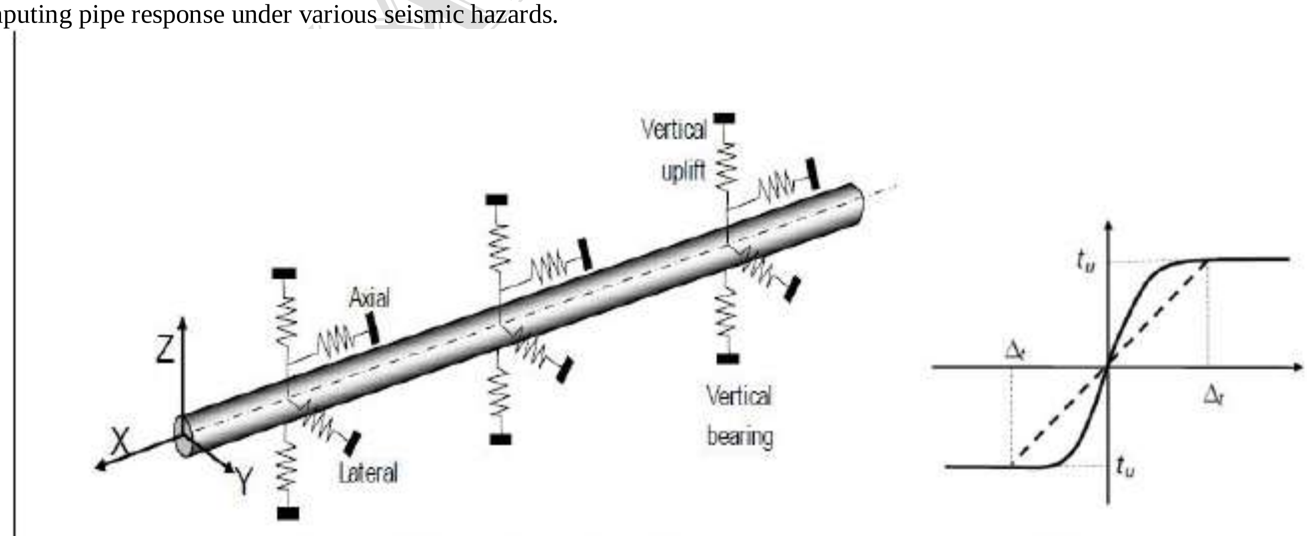
4. Steps involved in seismic design
The methodology used for seismic design and the countermeasures adopted will depend upon the nature of project cost implications and the risk factor involved in public safety, effect on environment, loss of product etc. Depending on these factors seismic factors are incorporated in the design of the pipeline system. Generally the steps involved in seismic design of a continuous buried steel pipeline are given below.

i. Adopting a performance criterion for pipeline under seismic event according to design philosophy established.
ii. Identification of potential seismic areas or loads along the pipeline.
iii. Estimating the seismic loads/magnitude by probabilistic or deterministic methods – HAZARD ASSESMENT
iv. Computing the present seismic resistance of pipeline (before applying seismic resistance strategies) using various analytical and FEM approaches
v. Identifying the potential failure zones of pipeline
vi. Selection of a proper construction measures and mitigation strategies.
vii. Implementing these strategies in the pipeline design and during construction phase.

The first step involves identification and finalizing various parameters concerned with seismic design incorporating cost and risk analysis. The design engineer has to finalize various parameters related to pipeline performance after seismic event. Most of the design guidelines adopt the design philosophy that "*there should not be leakage of oil or gas after the seismic event and the operation should be resumed shortly after minor repairs"*.

Hazard assessment is another important step in seismic analysis. This helps to provide the seismic event magnitude and other related data's required for the design engineer. Two approaches are normally utilized for this purpose-Probabilistic and Deterministic. The probabilistic approach is used to determine ground motions corresponding to the "Probable Design Earthquake" (PDE) and the "Contingency Design Earthquake" (CDE) provided the return period associated with these events is not too large. Normally the return periods are 50 and 500 years. In deterministic approach the return period doesn't apply/ignored. Ground motions with higher return period (about 10,000years) are taken for critical cases or for those pipeline systems of importance or high risk. For such type of cases, deterministic approach is used, which uses high magnitude design earthquake. It means that for probabilistic approach, only those seismic hazard that have high probability of affecting pipeline are used. But in deterministic approach, it is assumed that a seismic event of highest magnitude selected from the historical data will definitely occur during the pipeline operation life. To design the pipeline against the seismic hazards, the resistance of pipeline under these events have to be calculated. This is mentioned in step IV. Various analytical and FEM approaches are used for this purpose. This depends upon the type of seismic hazard, soil properties, pipeline properties etc. Analytical approaches used to compute pipeline resistance for various seismic hazards are explained below.

Soil plays an important role in the seismic behavior of pipeline. Loads are induced in between pipeline and soil. This is due to friction between soil and pipeline surface. The amount of restraint or load exerted on the pipeline is a non linear function of the relative soil-pipeline displacement. The actual three dimensional soil-pipe interactions can be ideally modeled as pipe resting on continuous multilinear soil springs. The three dimensional soil restraints can be represented by a series of discrete springs. It is an elasto-plastic model often adopted to represent the soil restraint against the deformation of pipeline. Soil-pipeline interaction is generally represented by components in the axial (longitudinal), transverse horizontal and transverse vertical directions. The pipeline is modeled as a beam and nodal forces t, P, Q are used to represent soil loads. These maximum soil forces on the pipeline decreases at large displacements and becomes constant once it reaches maximum value. For large relative displacements that occur between soil and pipeline, soil loads may reach a constant ultimate value tu, Pu,Qu. These soil resistant forces are used for computing pipe response under various seismic hazards.



soil representation with soil springs load-displacement diagram

*The maximum axial soil resistance (*tu*) per unit length of the pipe can be calculated as:

$$t_u := \pi \cdot D \cdot C \cdot \alpha + \pi \cdot D \cdot H \cdot y \cdot \frac{1 + K_0}{2} \cdot \tan(S) \quad \textbf{(1)}$$

*The maximum lateral resistance of soil per unit length of pipe can be calculated as

$$P_u := N_{ch} \cdot C \cdot D + N_{qh} \cdot y \cdot H \cdot D \quad \textbf{(2)}$$

*The maximum soil resistance per unit length of the pipeline in vertical uplift can be calculated as:

$$Q_u = N_{cv} cD + N_{qv} yHD \quad \textbf{(3)}$$

*The maximum soil resistance per unit length of pipeline in vertical bearing can be calculated as

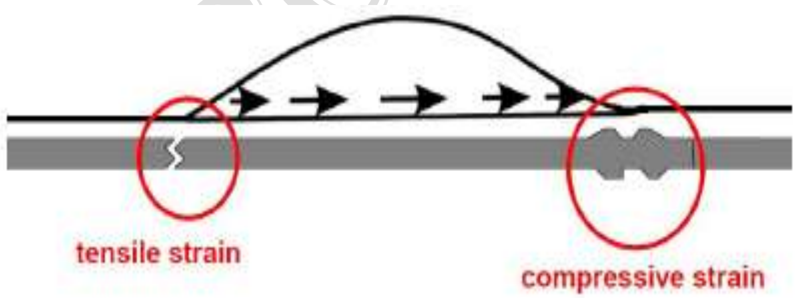
$$Q_d = N_d\, cD + N_q\, yHD + N_y \gamma\, D^2/2 \quad (4)$$

*Refer ALA (2001), Guidelines for the design of buried steel pipes

Permanent ground deformation refers to the unrecoverable soil movement due to faulting, landslide, settlement or liquefaction induced lateral spreading. There are many patterns of permanent ground deformation depending on local soils and geological settings. Permanent ground deformation can be resolved into longitudinal permanent ground deformation and transverse permanent ground deformation depending upon the angle by which the pipeline crosses the PGD. These are explained below:

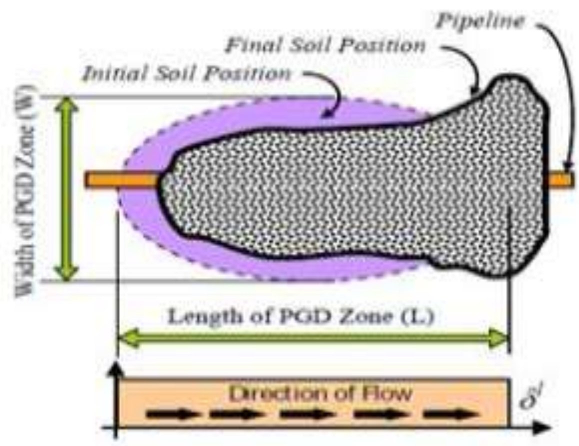
4.2.1. Pipeline response under longitudinal PGD

Longitudinal permanent ground deformation occurs when the soil movement is parallel to the pipe axis. Under longitudinal PGD, the main failure modes of a corrosion free continuous pipeline are local buckling (wrinkling) in compressive zone and tensile failure. Tensile strains act on initial start position of pipeline and compression strains act at the end/final position of PGD.

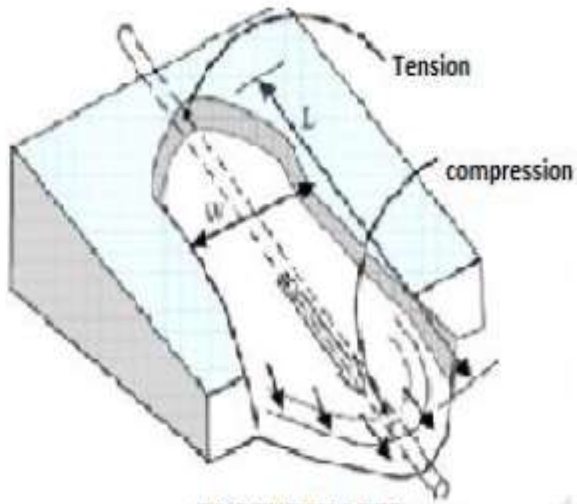


Pipeline response against longitudinal PGD

The ground movement is characterized by amount of movement (δ), length of PGD zone (L), width of PGD zone (W).



Block pattern of longitudinal PGD



LONGITUDINAL PGD

Two models/cases are considered in order to apply analytical equations.

In case-1, the amount of ground movement (δ design) is large and the pipe strain is controlled by length (L) of the PGD zone.

In case-2, length (L) is large and the pipe strain is controlled by δ. The strain developed in pipeline (Reference 6) for both the cases can be found from following equations

Case-1

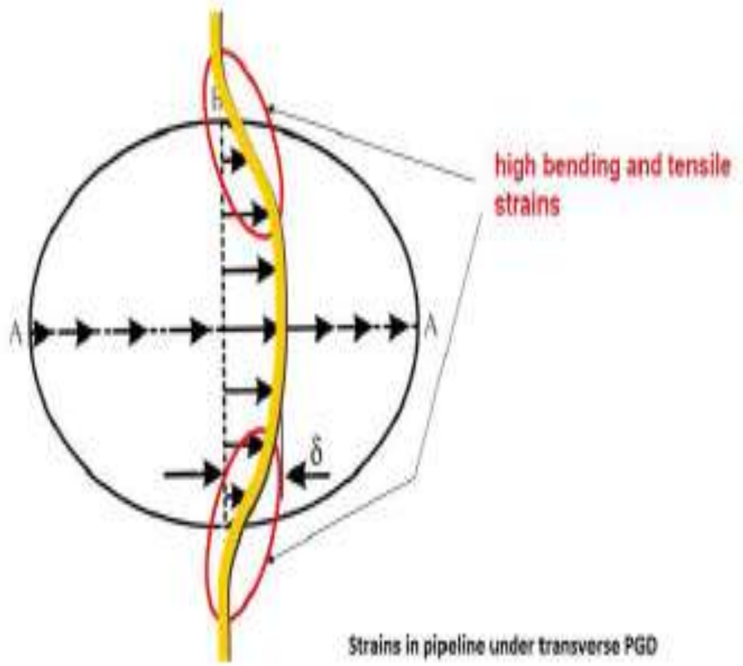
$$\varepsilon_{a1} := \frac{t_u \cdot L}{2 \cdot \pi \cdot D \cdot t \cdot E}\left[1 + \frac{n}{1+r}\left(\frac{t_u \cdot L}{2 \cdot \pi \cdot D \cdot t \cdot \sigma_y}\right)^r\right] \tag{5}$$

Case- 2:

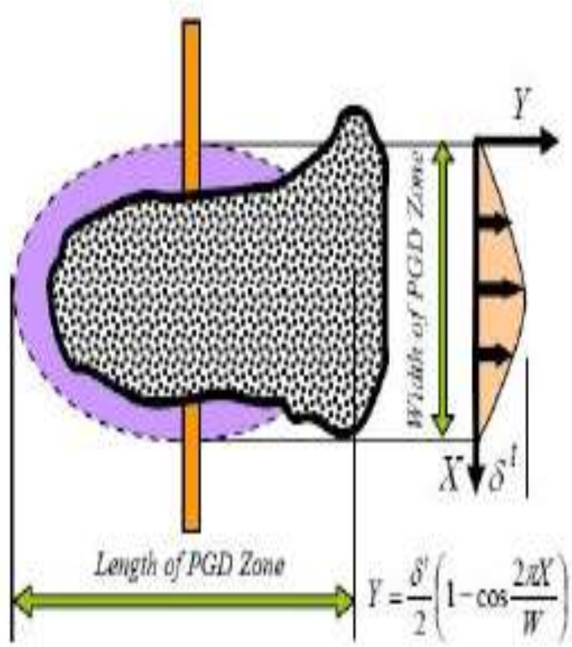
$$\varepsilon_{a2} := \frac{t_u \cdot L_e}{\pi \cdot D \cdot t \cdot E}\left[1 + \frac{n}{1+r}\left(\frac{t_u \cdot L_e}{\pi \cdot D \cdot t \cdot \sigma_y}\right)^r\right] \tag{6}$$

4.2.2. Pipeline response under transverse PGD

Transverse PGD refers to the movement of soil or PGD perpendicular to the pipe axis. When subject to transverse PGD, the pipeline will stretch and bend. So, the failure of a pipeline under transverse PGD are due to axial tension (stretching) and flexural (bending) strain.



Strains in pipeline under transverse PGD



Pattern of transverse PGD

For calculation of strains induced in pipe by transverse PGD can be calculated by considering two cases.
This is on the basis of behavior of pipeline as 'flexible' and 'stiff' as mentioned earlier. Thus two conditions can be considered:

1) Large width of PGD zone (flexible)
2) Narrow width of PGD zone (stiff).

For case 1:

Since the PGD zone is wide, both bending and axial strains are produced.
The maximum bending strain, ε_b, in the pipe, is given by

$$\varepsilon_b = \pm \frac{(\pi^2 \delta D)}{W^2} \tag{7}$$

The average axial tensile strain, ε_a, is approximated by

$$\varepsilon_a = \frac{(\pi/2)^2 \delta^2}{W^2} \tag{8}$$

For case 2:

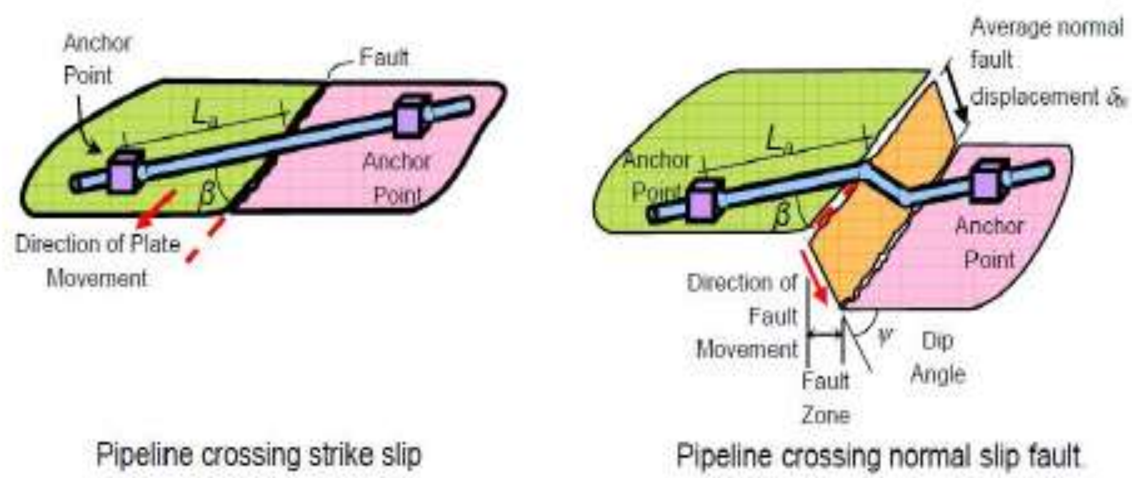
Since the PGD zone is small, pipe is considered as stiff.
The maximum strain in the pipe is given by

$$\varepsilon_b = \pm \frac{(p_u W^2)}{3\pi E t D^2} \tag{9}$$

4.3. Faulting

An active fault is a discontinuity between two portions of the earth crust along which relative movement occurs. This differential movement may occur suddenly due to an earthquake or gradually over a long period of time. The surface displacement of the ground depends upon the geology, type of fault, magnitude of the earthquake and also its distance from epicenter. Faults are classified by their direction of movement or slip or angle of dip with respect to the ground surface. The main failure modes of pipeline under fault movement are tensile rupture, local buckling and beam buckling. Faults are classified as strike slip fault,normal slip fault or reverse slip fault. In many cases, the faults can be a combination two type of movements. This can be understood from the figure

The pipeline performance under fault movement depends on pipeline characteristics (diameter, material etc), pipeline-fault crossing angle, effective unanchored length, soil properties etc.



For strike slip fault

Component of fault displacement in the axial direction of pipeline is:

$$\delta_{f\_ax} = \delta_{fs} \cos\beta \qquad (10)$$

Component of fault displacement in the transverse direction of pipeline is:

$$\delta_{f\_lat} = \delta_{fs} \cos\beta \qquad (11)$$

Where δ_{fs} is the strike slip fault movement in meters.

For normal slip fault

Component of fault displacement in the axial direction of pipeline is:

$$\delta_{f\_ax} = \delta_{fn} \sin\beta \cos\psi \tag{12}$$

Component of fault displacement in the transverse direction of pipeline is:

$$\delta_{f\_lat} = \delta_{fn} \cos\psi \ \cos\beta \tag{13}$$

Component of fault displacement in the vertical direction of pipeline is:

$$\delta_{f\_ver} = \delta_{fn} \sin\psi \tag{14}$$

where δ_{fn} is the normal fault movement in meters.

For reverse slip fault

The displacement components are considered in the same manner as normal slip fault with negative slip. For oblique faults, the strike slip displacement and normal slip (or reverse slip) displacement may be added algebraically in axial, transverse and vertical direction of the pipeline axis.
The average pipe strain for a fault crossing can be calculated as:

$$\varepsilon = 2.I_p.\left[\frac{\delta_{fax}}{2.L_{a_{eff}}} + \frac{1}{2}\left(\frac{\delta_{ftr}}{2.L_{a_{eff}}}\right)^2\right] \tag{15}$$

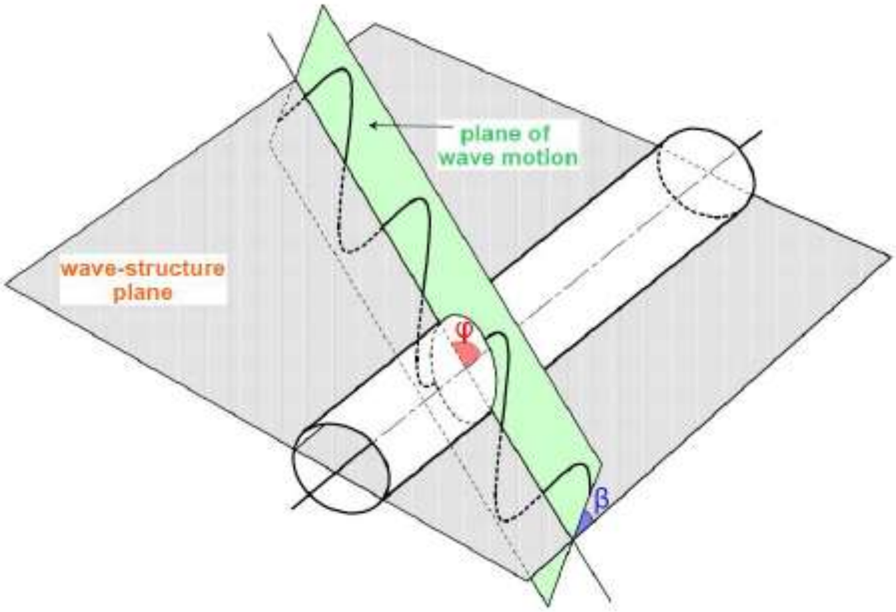
Effective unanchored pipe length can be calculated as:

$$L_a = \frac{E \cdot \varepsilon_y \cdot \pi \cdot D \cdot t}{t_u} \tag{16}$$

The strain calculated helps design engineer to select appropriate countermeasures to reduce failure of pipeline under fault movement.

4.4. Seismic wave propagation

When earthquake occurs, seismic waves are propagated from the epicenter and they manifest themselves as strong ground shaking. Ground motions are composed of two types of waves- body waves and surface waves. Body wave travel through earth's crust and surface wave travel along the surface. Body waves attenuate more rapidly than the surface waves since higher frequency waves attenuate more rapidly than low frequency waves. The above ground structures are more susceptible to the wave hazards than the underground structures. Shallow buried pipelines are more susceptible to these hazards although there will be no permanent ground deformation. The depth of the pipeline is an important factor in the designing of pipeline against these hazards.



Peak ground acceleration and peak ground velocity are major parameters affecting the pipeline under wave propagation. Axial/longitudinal strains are the only value that is of concern as the flexural/bending strains are considerably small. The axial strain depends on the ground strain, the wave length of the travelling waves and the interaction forces at the soil-pipe interface. For small to moderate ground motion one can assume pipe strain equal to ground strain. For large ground motion, slippage typically occurs at soil-pipe at greater depth can reduce the design levels of ground shaking.

Maximum longitudinal/axial strain in pipeline due to wave propagation can be computed from the following equation.

$$\varepsilon_a = \frac{V_g}{a_\varepsilon C} \quad (17)$$

The maximum strain induced in the pipeline by friction at the soil-pipe interface is calculated as:

$$\varepsilon_{soilpipe} = \frac{t_u \lambda}{4AE} \quad (18)$$

The strain induced at soil-pipe interface (ε soil pipe) has to be greater than maximum axial induced strain (εa).Finally this maximum axial strain has to be verified with failure criterion and check whether it is within allowable limit.

4.5. Buoyancy due to liquefaction

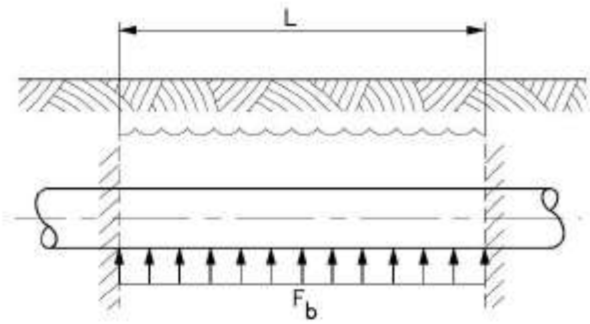
Liquefaction is the transformation of a saturated cohesion less soil from a solid state to liquid state as a result of increased pore pressure and loss of shear strength. This results in reduction of the capacity of the ground to bear the structure. Usually moderate to large earthquakes are required for liquefaction to take place. In some cases, liquefaction can be observed as sand boils, ground settlement and fissures. Liquefaction is mainly depended upon the saturation of soil, pore water pressure, particle size of sand, compaction of sand etc. Buoyancy occurs due to liquefaction of soil in which the pipeline is buried. This can happen in flood plains, estuaries etc where potential of liquefaction is high during earthquake. Shallow burial of pipeline above water table, concrete encasement and intermittent anchors are the general mitigation measures.

The net upward force acts on the pipe when the buoyancy force created by pipe below the water table (or the liquefied level) exceeds the combined downward weight of the pipe, its contents (if present) and the soil column above the pipeline. The upward force imposed on a straight continuous buried pipeline from the liquefied soil is taken as:

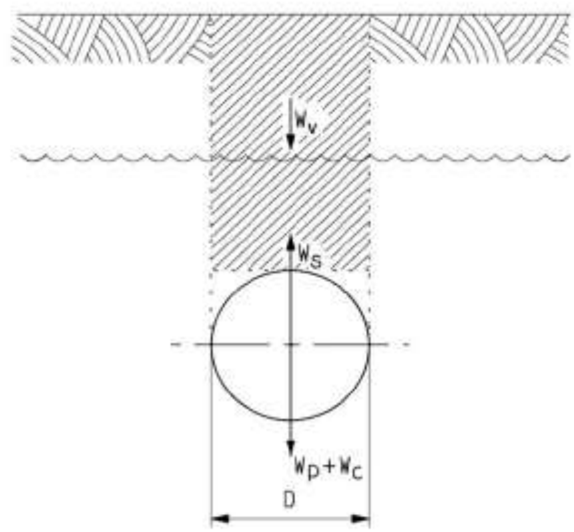
$$F_b = W_s - [W_p + W_c + (P_v - \gamma_w h_w)D] \quad \textbf{(19)}$$

Bending strain induced for a relatively short section of continuous pipeline (stiff pipe) subjected to buoyancy can be calculated as

$$\varepsilon_{bf} = \frac{F_b {L_b}^2}{3\pi E t D^2} \quad \textbf{(20)}$$



Distributed buoyant forces acting on pipeline under liquefaction



Forces acting on a pipeline under buoyancy effects

On the basis of the upward force and bending strain found, necessary steps are taken to reduce the buoyancy by concrete coating, anchoring etc.

5. Mitigation strategies/recommendations

There are many strategies that can be adopted to prevent failure of pipeline under seismic hazard. These include using high grade material of higher ductility in pipeline, increasing thickness for fault mitigation, use of joints with enhanced expansion/contraction or rotation capability, methods to isolate the pipeline segment from ground movement during seismic event, methods to reduce ground movement, improving the quality of backfill soil and/or finally, avoiding or rerouting the pipeline from the areas susceptible to damaging ground movements. Mitigation measures for each type of seismic hazard are specific. Appropriate measures should be selected carefully after considering the economics involved. Earthquake monitoring system (EMS) also aids in emergency rupture situations. Beside all this, every operating company should have a seismic contingency plan for immediate action during emergency situations. Hazard specific mitigation measures are given below.

Mitigation strategies for PGD

- Soil improvement in the potential areas by compaction, strengthening, soil densification etc thereby reducing the ground movement. Stabilized soil mattresses for liquefiable soil deposit areas
- Using appropriate coating for reducing the soil pipeline frictional force. This helps in reducing strains.
- Pipeline should be routed below the lowest depth of liquefiable soil as far as possible.
- Trenches, deformable walls can be constructed in upslope so as not to affect the pipeline while ground movement along slope.
- Expansion joints can be used for compensating for expansion, contraction, rotation and bending during a seismic event.

Mitigation strategies for faults

- Pipeline crossing strike slip fault should be aligned in such a way that only tension strains act on pipeline.

- For reverse slip faults where compression is anticipated, pipeline should cross at oblique angles to make allow only tensile stresses to act on pipeline.

- As far as possible the pipelines on either side of fault line should be devoid of bends, stub-ins, flanges or sharp edges which may restrict the pipeline from absorbing the stresses there by resulting in concentration of strains in local areas and leading to rupture.
- Pipeline should be shallowly buried in fault zones to reduce the soil restraints on pipeline.

- Special trench design proposed by NIST, 1996 can be used.

- Increasing the thickness of pipeline along the fault zone helps to absorb/ withstand more strains.Weld integrity should also be taken care of in this case.

- Pipeline coating with smooth and hard material helps to reduce soil restraints on pipeline. This is done by reducing angle of interface friction between soil and pipe.

- Use of loose to medium granular soil without cobbles or boulders helps to minimize the soil restraint on pipe. If the native soil varies with this soil, geo wrappings should be provided to resist mixing of backfill and native soil by period.

- Placement of pipeline on aboveground sliding supports helps to isolate pipeline from ground movement during seismic event.

- Making the pipeline aboveground is another option although it is expensive. So an economic analysis should be done based on probabilistic studies to come to a decision on this.

- Encasement of pipeline in large underground culverts or conduits.

- Shut off valves can be provided on either side of the fault line to reduce the risk of fire or other impacts to environment and public.

Mitigation strategies for buoyancy effects

- Pipeline should be encased in concrete pipes to reduce the buoyancy effects (increased diameter also increases the upward buoyant force).
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- Liquefaction of soil should be avoided by placing pipe above ground water table.

- Concrete weights or gravel filled blankets can be utilized to reduce buoyancy effect on pipeline.

- Making drainage system to reduce the water level is also effective.

- Anchor spacing can be reduced at potential buoyancy affected areas

Mitigation strategies for seismic wave propagation effects

- Seismic wave propagation generally does not have serious effect on welded buried pipelines in good condition. Some situations where the wave propagation imply serious damage to the pipeline

- system include: a) transition between very stiff and very soft soils, b) penetration of pipe into valve boxes, c) pipes located at or near pump stations, d) T-connections, e) pipe fittings and valves, etc. Therefore, special care should be taken while designing the pipeline system in above situations.

- The pipelines weakened by corrosion, and the old cast iron pipes with bell and spigot joints are vulnerable to seismic wave propagation. Therefore special attention should be given to them.

- As far as possible, the selection of the seismic waves and the corresponding wave propagation speeds should be based on geophysical considerations.

- The effect of wave propagation on pipelines can be minimized by minimizing the interaction force at soil-pipe interface with suitable pipe coating or wrapping or using suitable backfill soil.

Earthquake monitoring system

An earthquake monitoring system (EMS) serves as a cornerstone for planning and guiding field reconnaissance. The EMS will automatically process ground motion data immediately after the event, which helps system operators to evaluate the severity of the earthquake ground shaking and, in turn, to make a general assessment of the potential for damage to the pipeline and supporting facilities.

Conclusion

The importance of seismic design in pipeline system is inevitable. The attention given to seismic design in Trans Alaska paid off where the pipeline survived an earthquake of magnitude of 7.9 Richter scale. The guideline proposed in this paper can be used to calculate the behavior of pipeline under various seismic hazards and according to these computed strains; necessary mitigation measures should be adopted to prevent failure of pipeline. While selecting the mitigation measures -cost involved in application, after effects of pipeline rupture, importance of pipeline etc should be considered.

Nomenclature

D = Outside diameter of pipe
C = Coefficient of cohesion of backfill soil
H = Depth of soil above the center of the pipeline
y= Effective unit weight of soil
α =adhesion factor
S = Interface angle of friction between pipe and soil
Φ = Internal friction angle of the soil
f = Friction factor for various types of pipes (obtain from figure)
Ko = Coefficient of soil pressure at rest.
Nch= Horizontal bearing capacity factor for clay
N qh= Horizontal bearing capacity factor for sandy soil
N cv = Vertical uplift factor for clay
Nqv = Vertical uplift factor for clay
Nc, Nq and Ny = bearing capacity factors
εa = Peak axial strain in pipe
L = length of permanent ground deformation
σy = yield stress of pipe material
n,r = Ramberg-Osgood parameter
E = Modulus of elasticity of pipe material
t = Thickness of pipe
R = radius of pipe
δ = amount of ground displacement due to the seismic hazard
W = width of PGD zone
β = angle of pipeline crossing a fault
ψ = dip angle of fault
La_eff = effective unanchored pipe length
Ip = importance factor
Vg = design peak ground velocity
aε = ground strain coefficient
C = Velocity of seismic wave propagation
λ = apparent wave length of seismic waves at ground surface (can be assumed as 1.0km in the absence of further information)
A = cross sectional area of pipe
tu = maximium soil resistance in axial direction
Pu = maximium soil resistance in lateral direction
Qu = maximium soil resistance in vertical direction
Ws = Total weight of soil displaced by pipe per unit length
Wp = Weight of pipe per unit length
Pv = Vertical earth pressure
γw = Unit weight of water
hw = height of water over pipeline
Lb = Length of pipe in buoyancy zone
Fb = Buoyant force acting on pipeline

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