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Determination of Seismic Load on Subsea Offshore Pipelines

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ABSTRACT

Buried pipeline to surrounding ground interaction is a vital factor that has an impact on the safe operation of the buried underground pipelines. Numerous earthquake research works describe above ground acceleration obtained in a single point which does not give full information about ground deformation. This article suggests using seismic loading calculation method for the buried offshore pipelines. The article contains formulas to evaluate the buried pipeline fatigue value.

Dynamic behaviors of underground pipe lines during earthquakes remain unknown, while the structures in weak ground have suffered damages from large earthquakes. From the seismic point of view, the problems lie in the fact that the dynamic behaviors' of the structures have little relations to ground acceleration, but to ground deformation and in the fact that such structures have two dimensional extension along the surface of ground. As many investigations of the earthquake engineering treated ground acceleration such as the one at a point, they give little information's for ground deformation or distribution of ground displacement along the surface. The article proposes a formula for determining the seismic load of a buried offshore pipeline.

The pipelines are generally recognized as a safe, economic and effective mean for gas and other commercial fluid transportation. Buried pipeline to surrounding ground interaction is a vital factor that has an impact on the safe operation of the buried underground pipelines. Buried pipeline behavior remains unknown during earthquakes. Pipeline needs to be buried in order to ensure its operational reliability and safety and minimize potential damages due to external and internal exposures. This article is dedicated to seismic load calculation methods for the subsea offshore pipelines during earthquakes. Dynamic pipeline behavior is related to ground acceleration and ground deformation. It should be taken in to consideration that the pipelines are exposed to two-dimensional deformations along the ground surface. The earthquake research reports review the above ground acceleration obtained in a single point. Accelerograms provide incomplete information about the ground deformations and ground displacements along the earth surface. Among the proposed earthquake protection methods is increase pipe wall thickness, increase steel grade, protect pipes with textile covers.

Keywords: Subsea offshore pipeline, Seismic loading, Fatigue

INTRODUCTION

Simulation model of the subsea buried pipeline is represented as a cylindrical beam rigidly fixed at the ends. Weight of water above the buried pipeline is considered as additionally added mass [1-4].

It is mentioned in the papers of the Japanese researchers, Sakurai and Takahashi [1] that bending stresses acting on the large diameter pipelines are comparable with the axial stresses. When ground surface moves according to the law $Y=a_0 \cdot \sin(p(t-x/V))$, bending strain of the pipeline can be determined by the following equation:

$$\varepsilon = \frac{r_0}{v^2} \cdot A \qquad (1)$$

where r_0 is pipe radius, is observable seismic wave velocity, A is seismic acceleration.

Axial strain of the pipeline is prevailing [1]. Axial strain to bending strain ratio of the pipeline can be written as follows [1].

$$\varepsilon = -a_0 \cdot \frac{p}{V} \cos p(t - x/V) \qquad (2)$$

where p is circular frequency of ground movement (equal to $\frac{2\pi}{T}$); a_0 is ground surface movement amplitude; V is

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seismic wave velocity.

Let us express the earth surface acceleration:

$$A = -a_0 \cdot p^2 \sin p(t - x/V) \quad (3)$$

where T is ground surface motion cycle.

AXIAL DISPLACEMENT OF THE PIPELINE

Maximum pipelines train is expressed in the equation below:

$$\varepsilon = \frac{a_0 \cdot p/V}{a_0 \cdot p^2} \cdot A = \frac{1}{2\pi} \cdot \frac{T \cdot A}{V} \quad (4)$$

The equation (4) is confirmed by the pipeline strain records represented in the research papers [1].

Earthquake causes relative axial displacement of the pipeline. Strain value can be calculated using the following equation:

$$\frac{AT^2}{4\pi^2} = u_0 \left\{ 1 + \frac{1}{\left(\frac{p}{\omega_0}\right)^2 + \left(\frac{V_a}{V}\right)^2} \right\} = u_0 \quad (5)$$

where u_0 is ultimate ground strength; V_a is longitudinal wave velocity spreading in the pipeline ($\sqrt{\frac{E}{\rho}}$).

The pipeline is exposed to friction forces over its entire length during earthquake. Straight pipeline strains are equal to its relative displacement:

$$\varepsilon_u = \frac{C_0 \cdot L}{4EA_0} = \frac{C_0 \cdot vT}{4EA_0} \quad (6)$$

where C_0 is friction force acting per unit of pipe length.

Axial pipeline vibrations can be expressed via the following equation during movement within $u<u_0$ range:

$$\rho A_0 \frac{\partial^2 y}{\partial t^2} - EA_0 \frac{\partial^2 y}{\partial x^2} + ky = k \cdot a_0 \sin p(t - x/v) \quad (7)$$

The equation (7) can be solved as follows:

$$y(x,t) = \frac{1}{1 + \left(\frac{\rho}{\omega_0}\right)^2 \left(\frac{V_0}{V}\right)^2 - \left(\frac{\rho}{\omega_0}\right)^2} \cdot Y(x,t) \quad (8)$$

Natural pipeline frequencies depend on the density of liquid to be transported via the pipeline. Medium contained side the pipeline creates an additional weight on the pipeline system. It has a downward effect on the dynamic properties of the pipeline [5].

Stress level and allowable deformations of the pipeline walls are evaluated during subsea pipeline seismic strength analysis.

It is important to know natural frequencies of the structure to calculate is MIC loads and avoid a resonance effect.

NATURAL FREQUENCIES OF THE SUBSEA BURIED GAS PIPELINE

Natural frequencies of the subsea gas pipeline fixed at both ends are calculated using the following equation:

$$\omega_n = \sqrt{a_1{}^2 \lambda_n^2 + b^2} \quad (12)$$

where $a_T = EF/m; b^2 = \frac{\pi D_H k_x}{m}$, k_x is linear proportionality factor between shear stresses τ_x, in the surrounding ground $\tau_x = k_x u(x,t)$.

MODEL OF INERTIA SEISMIC LOAD FOR BURIED PIPELINE

Inertia seismic load acting on the buried pipeline is calculated as follows:

$$S^*_{ik} = k_A A \cdot g m_k \eta^*_{ik} \beta_\varepsilon (\omega_k^*) \cdot \tau_x \quad (20)$$

where k_A is a factor that considers possibility of a seismic event with in the design service life of the structure; g is gravitational acceleration (9.81 m/s^2); $\eta^*_{ik} = X_{ik}$ is mode factor; X_i are natural frequency modes of the pipeline (beam functions); τ_x are shear stresses; A is design acceleration amplitude of the foundation g expressed as fractions is calculated using table of the SP [6].

When we calculate inertia of seismic load, we should take into account a factor that is dependent on the damage which can be caused during earthquake; seismic wave directional angle towards the structure cos $\left(U_i, \ddot{\vec{U}}_0\right)$; a factor that takes into account damping properties of the structure [6].

Due to in sufficient information about their life and non-available country-wise classification of these is MIC data, seismic load on the buried pipelines shall be calculated more precisely using a spectral method as per the following procedure:

1. Select the most loaded sections for subsequent strain-stress state analysis of the pipeline.
2. Plot frequency response characteristics to calculate deformations in the selected locations $\varepsilon_{i(\omega)}$ (taking into consideration damping properties of the ground), where ω is excitation seismic frequency, ω_0 is natural frequency of the pipeline [7].

Frequency response characteristic is represented below:

$$|\Phi(i\omega)|^2 = \frac{1}{\left(\omega_0(l)^2 - \omega^2\right)^2 + \left(2(\xi_{st} + \xi_{gr}) \cdot \omega_0(l) \cdot \omega\right)^2}$$

3. Spectral strain density in i-th point is calculated as follows:

$$S_{\varepsilon_i}(\omega) = \varepsilon_i^2(\omega) \cdot S_I(\omega) \qquad (21)$$

where $S_I(\omega)$ is design spectral density of the spectral earthquake force *I* [4] (Annex 8).

4. Strain dispersion in i-th point,

$$D_{\varepsilon_i} = \int_0^{\infty} S_{\varepsilon_i}(\omega) d\omega \qquad (22)$$

5. The required design strain is calculated as follows:

$$\varepsilon_{i.p} = \sqrt{D_{\varepsilon_i}} \qquad (23)$$

6. Subsea pipeline dynamic response factor equals to:

$$\beta_\varepsilon(\omega_k) = \omega_{0k}^2 \sqrt{D_\varepsilon / D}$$

Subsea pipeline service life is 50 years; however seismic events do not occur as scheduled. Operating modes and corrosion damages affect the service life of the pipeline.

Subsea pipeline cannot be seen by the observers. Variation of the transported fluid pressures and low cycle loading of the pipeline may initiate structural defects [8].

Seismic damage is non-local, it affects the whole structure. Taking in to account low-cycle loading, significant plastic strain observed in the circular welds of the pipelines, it is necessary to evaluate the fatigue cracking start in the pipeline during the seismic analysis of the subsea pipeline. Fatigue characteristics of the offshore subsea pipelines have not been studied. Structural life calculation method described in the article is based on the structural stress spectrum analysis.

FATIGUE OF BURIED SUBSEA PIPELINE

Fatigue failures are associated with the stress cycle band:

$$\delta_D = \frac{\delta_n}{N} = \frac{\delta_n}{A\sigma_r^{-m}} = \frac{n(\sigma_r/4m_0)exp[-(\sigma_r^2/8m_0)]\delta\sigma_r}{A\sigma_r^{-m}} \qquad (24)$$

where n is a number of stress cycles; misnegative slope of the stress-number curve S-N; σ_r is stress range (difference between maximum and minimum stress per cycle); A is stress-number fatigue factor of steel.

Fatigue failures for all stress cycle bands are expressed in the following way:

$$D = \int_0^{\infty} \frac{n(\sigma_r/4m_0)exp[-(\sigma_r^2/8m_0)]\delta\sigma_r}{A\sigma_r^{-m}} \qquad (25)$$

where A is stress-number fatigue factor of steel.

CONCLUSION

The article describes seismic load calculation method for the subsea offshore pipelines, fatigue calculation ratios of the buried underground pipelines; a conclusion has been made to perform fatigue tests of the buried pipelines.

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