INTERACTION STUDY ON FREE SPANNING SUBMARINE PIPELINES UNDER COMBINED OPERATING LOADS AND EARTHQUAKE

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ABSTRACT :

Firstly, a discrete equation of motion of free spanning submarine pipeline was derived. The spatially varying earthquake ground motions, the internal pressure and the thermal load were imposed on the FE model. The nonlinear material constitutional relationships of the pipe and the soil as well as the large displacement effect were considered. Secondly, the numerical results were compared with the experimental results in order to validate the kind of pipe element employed in the analysis. Thirdly, the effects of internal pressure, thermal loading and the interaction between pressure and temperature on the multi-support input response of the submarine pipelines were studied respectively.

KEYWORDS: free spanning submarine pipeline, nonlinear seismic analysis, combined loads

1. INTRODUCTION

The Bohai Sea locates in a seismically active region in China. The combination of seismic load and operating loads is the critical case in the design of the submarine pipelines in the area. Submarine pipelines with high pressure and high temperature are widely used in the offshore exploration and production of marginal oil fields. Thus, it is of significance to study the interaction between operating loads including internal pressure and thermal load, and seismic load.

Many numerical simulations have been performed on the dynamic response of submarine pipelines under seismic excitation. Nath and Soh (1978)[1] studied the harmonic and seismic responses of simplified pipeline models in proximity to the seabed using finite element method. Datta and Mashaly (1988, 1990)[2-3] analyzed the transverse response of both buried and free spanning submarine pipelines under random earthquake excitation in the frequency domain using the spectral approach, which was based on the spatial discretization of the pipeline with nodal lumped masses. Kershenbaum et al. (2000)[4] investigated unburied 'snaked' pipeline behavior under various types of seismic faults. Duan et al. (2004)[5] analyzed the soil-pipeline interaction during earthquakes using the plastic slippage theory.

The study on subsea pipelines under combined internal pressure and temperature mainly focuses on local buckling for the pipeline with defects (Robertson, 2005 and Heitzer, 2002)[6-7] and globally upheaval and lateral buckling with initial imperfections (Pedersen, 1988 and Scoreide, 2005)[8-9]. Static analysis is used on the above researches. Discrete governing equation of partly buried and partly free spanning submarine pipeline under spatially varying earthquake ground motions is established in the paper. The interaction between operating loadings and earthquakes are studied.

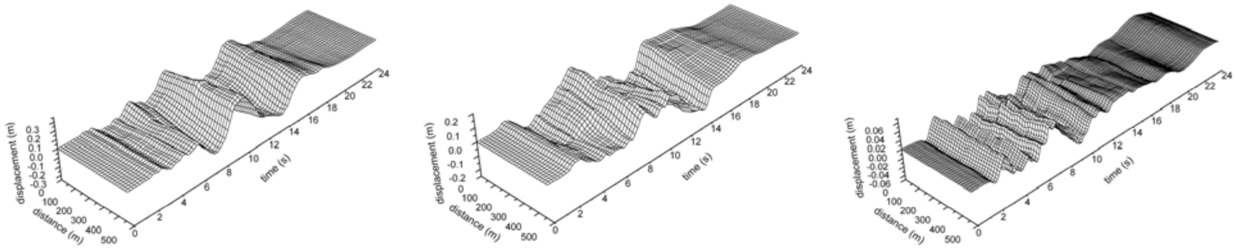
2. SIMULATION OF CORRELATIVE MULTI-POINT EARTHQUAKE GROUND MOTIONS

An improved method for simulating multiple-station ground motions is given as (Zhou and Li, 2008)[10]

$$u_j(t) = \sum_{m=1}^{n}\sum_{k=0}^{N-1} A_{jm}(\omega_k)\cos[\omega_k t + \theta_{jm}(\omega_k) + \varphi_k],\ j = 1,\ldots,n \tag{2.1}$$

where $u_j(t)$ is the ground displacement history at location j; ω_k is the frequency in the discrete frequency domain; amplitudes $A_{jm}(\omega_k)$ and phase angles $\theta_{jm}(\omega_k)$ are to be determined to insure the proper correlation relations between location j and m; φ_k is the original phase angle uniformly distributed in the range of zero and 2π.

A group of 3D multi-support earthquake ground motions was synthesized on the base of the above method. Using the Dynamic Programming method (Trujillo and Carter, 1982)[11], the synthesized acceleration histories were integrated to obtain the corresponding displacement histories. The spatially generated displacements time histories are shown in Figure 1.



(a) longitudinal component (b) transverse component (c) vertical component

Figure 1 Generated displacements fields

3. EQUATION OF MOTION

3.1 Hydrodynamic Force on Pipeline under Seismic Excitation

When the free spanning part of a submarine pipeline moves transversely, the hydrodynamic force perpendicular to the pipeline can be calculated by Morison's equation

$$f_s = C_D \frac{1}{2}\rho D(U - \dot{v})|U - \dot{v}| + C_M \frac{\pi}{4}\rho D^2 \dot{U} - (C_M - 1)\frac{\pi}{4}\rho D^2 \ddot{v} \tag{3.1}$$

where ρ is the density of water; D is the outer diameter of the pipe; U is the instantaneous flow velocity dependent on time; v is the horizontal displacement of the pipe; C_D and C_M are the drag coefficient and inertia coefficient respectively.

It is assumed that the effect of wave and current on pipeline can be neglected in seismic analysis, i.e., $U = 0$, and the quadratic of v can be neglected when pipe moving in low velocity, then Eq. (3.1) can be written as

$$f_s = -(C_M - 1)\frac{\pi}{4}\rho D^2 \ddot{v} \tag{3.2}$$

When the free spanning part of the submarine pipeline moves longitudinally, the hydrodynamic force is

$$f_s = 0 \tag{3.3}$$

Based on Eq. (3.2) and (3.3), the hydrodynamic force on the free spanning part of a submarine pipeline due to seismic excitation can approximately be expressed as

$$f_s = -m_A \ddot{v} \tag{3.4}$$

where m_A is the added mass, defined as

$$m_A = \begin{cases} (C_M - 1)\dfrac{\pi}{4}\rho D^2 & \text{transverse move} \\ 0 & \text{longitudinal move} \end{cases} \tag{3.5}$$

3.2 Numerical Procedures

Introducing hydrodynamic force, the equation of motion for *n*-degree-freedom pipeline model under ground motions input at *m* supports can be written in the matrix form

$$\begin{bmatrix} \mathbf{M} & \mathbf{M_c} \\ \mathbf{M_c^T} & \mathbf{M_g} \end{bmatrix} \begin{Bmatrix} \ddot{\mathbf{V}} \\ \ddot{\mathbf{U}}_\mathbf{g} \end{Bmatrix} + \begin{bmatrix} \mathbf{C} & \mathbf{C_c} \\ \mathbf{C_c^T} & \mathbf{C_g} \end{bmatrix} \begin{Bmatrix} \dot{\mathbf{V}} \\ \dot{\mathbf{U}}_\mathbf{g} \end{Bmatrix} + \begin{bmatrix} \mathbf{K} & \mathbf{K_c} \\ \mathbf{K_c^T} & \mathbf{K_g} \end{bmatrix} \begin{Bmatrix} \mathbf{V} \\ \mathbf{U_g} \end{Bmatrix} = \begin{Bmatrix} \mathbf{F_s} \\ \mathbf{F} \end{Bmatrix} \tag{3.6}$$

where $\mathbf{V}$ is the *n*-vector of displacements at unconstrained degrees of freedom; $\mathbf{U_g}$ is the *m*-vector of prescribed support displacements; $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the $n\times n$ mass, damping and stiffness matrices associated with the unconstrained degrees of freedom, respectively; $\mathbf{M_g}$, $\mathbf{C_g}$ and $\mathbf{K_g}$ are the $m\times m$ matrices associated with the support degrees of freedom; $\mathbf{M_c}$, $\mathbf{C_c}$ and $\mathbf{K_c}$ are the $n\times m$ coupling matrices associated with both sets of degree of freedom; $\mathbf{F}$ is the *m*-vector of the reacting forces at the support degrees of freedom; $\mathbf{F_s}$ is the *n*-vector of the hydrodynamic forces. $\mathbf{V}$ may contain translational as well as rotational components while $\mathbf{U_g}$ may only include translational components.

From the first equation of Eqs. (3.6),

$$\mathbf{M}\ddot{\mathbf{V}} + \mathbf{C}\dot{\mathbf{V}} + \mathbf{K}\mathbf{V} = \mathbf{F_s} - \mathbf{M_c}\ddot{\mathbf{U}}_\mathbf{g} - \mathbf{C_c}\dot{\mathbf{U}}_\mathbf{g} - \mathbf{K_c}\mathbf{U_g} \tag{3.7}$$

supposing the lumped mass matrix, then $\mathbf{M_c}$=0. In general, the damping matrix $\mathbf{C_c}$ can hardly be evaluated and the damping force in the right side can be neglected. Eq. (3.7) can be approximately rewritten as

$$\mathbf{M}\ddot{\mathbf{V}} + \mathbf{C}\dot{\mathbf{V}} + \mathbf{K}\mathbf{V} = \mathbf{F_s} - \mathbf{K_c}\mathbf{U_g} \tag{3.8}$$

where $\mathbf{F_s}$ can be described by

$$\mathbf{F_s} = -\mathbf{M_A}\ddot{\mathbf{V}} \tag{3.9}$$

where $\mathbf{M_A}$ is the added mass matrix. Substituting Eq. (3.9) to Eq. (3.8)

$$(\mathbf{M} + \mathbf{M_A})\ddot{\mathbf{V}} + \mathbf{C}\dot{\mathbf{V}} + \mathbf{K}\mathbf{V} = -\mathbf{K_c}\mathbf{U_g} \tag{3.10}$$

Equation (3.10) is the equation of motion for the submarine pipeline under multiple-station seismic excitation including hydrodynamic force.

3.3 Consideration of Temperature and Internal Pressure

A kind of pipe element shown in Fig. 2 is employed to mesh the free spanning submarine pipeline. Each element is comprised of four nodes, and each node includes six degrees of freedom. The stiffness matrix of element can be given

$$\mathbf{K^e} = \mathbf{K_b^e} + \mathbf{K_s^e} \tag{3.11}$$

in which $\mathbf{K_b^e}$ is the stiffness matrix related to flexural deformation; $\mathbf{K_s^e}$ is the stiffness matrix associated with shear deformation.

Assumed that hoop stress is only caused from internal pressure and radial stress is equal to zero, the stresses due to internal pressure are calculated according to thin shell theory. Then axial stress can be given

$$\sigma_{aa} = E(\varepsilon_{aa} - \varepsilon_{aa}^{IN} - \varepsilon^{TH}) + \nu\sigma_{cc}^{p} \tag{3.12}$$

$$\sigma_{cc}^{p} = \frac{pr}{t} \tag{3.13}$$

in which σ_{aa} is the axial stress; σ_{cc}^{p} is the hoop stress due to internal pressure; ε_{aa}, ε_{aa}^{IN} and ε^{TH} are total axial strain, inelastic strain and strain due to temperature, respectively; E is the elastic modulus; v is the Possion ratio; r is the average radius; t is the wall thickness. The strain due to temperature is taken as:

$$ {}^t\varepsilon^{TH} = {}^t\bar{\alpha}({}^t\theta - {}^0\theta) \tag{3.14} $$

where

$$ {}^t\bar{\alpha} = \frac{1}{({}^t\theta - {}^0\theta)}[\alpha({}^t\theta)({}^t\theta - \theta_{REF}) - \alpha({}^0\theta)({}^0\theta - \theta_{REF})] \tag{3.15} $$

in which ${}^t\theta$ is the temperature at time t; ${}^0\theta$ is the initial temperature; α is the linear expansion coefficient; θ_{REF} is the reference temperature of material.

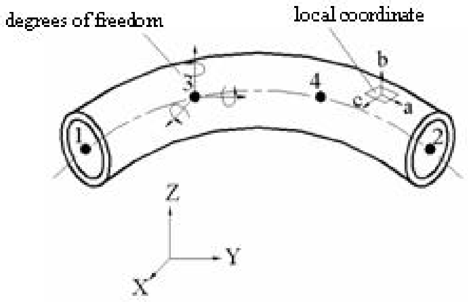


Figure 2 Configuration of pipe element

3.4 Validation of Pipe Element under Combined Operating Loads

To validate the pipe element to analyze the pipeline subject to combined internal pressure, bending moment and axial force, a numerical model is established to simulate the model test made by Bouwkamp (1973)[12]. The model pipe was comprised of three welded segments, which both of end segments are X65 steel pipe, and the middle segment is X60 steel pipe. The sizes of pipe and loading positions are shown in Fig. 3. To keep internal pressure p=6.3 MPa and axial force P_A=11210 kN constant during loading, the later force P_L is applied incrementally. The comparison of numerical and experimental results is displayed in Fig. 4. The numerical results are in agreement with experimental results. Thereby, using pipe element is feasible to study on the submarine pipeline under combined internal pressure, bending moment and axial force.

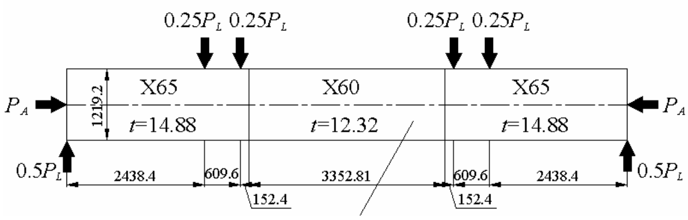


Figure 3 Configuration of test model

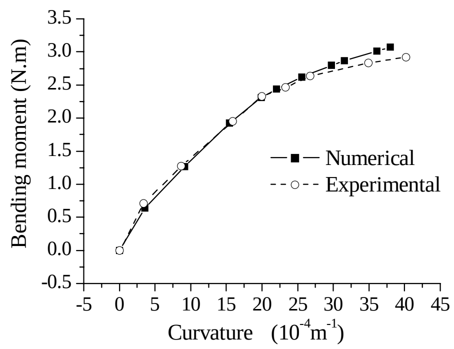


Figure 4 Comparison between experimental and numerical results

4. MATERIAL MODELS

4.1 Constitutional Relationship of Pipe Steel

The ultimate limit state analysis on submarine pipeline has to take account into plastic characteristics. Ramberg-Osgood model are selected to simulate the elastic-plasticity properties of the steel. For Ramberg-Osgood model,

$$\varepsilon = \frac{\sigma}{E_0}\left[1 + \frac{n}{1+\gamma}\left(\frac{\sigma}{\sigma_y}\right)^{\gamma}\right] \tag{4.1}$$

where E_0 is the initial Young's modulus; σ the stress; ε the strain; σ_y the yield stress; n and γ are Ramberg-Osgood parameters. The von Mises yield condition with the associated flow rule and kinematic hardening rule are adopted.

4.2 Constitutional Relationship of Surrounding Soil

The soil surrounded pipe is modeled as nonlinear springs. The force-displacement relationship of soil spring is a perfectly elasto-plastic model suggested by ALA's guidelines (ALA, 2001)[13]. For ALA model,

$$f = \begin{cases} K_0 u & u \le u_p \\ K_0 u_p & u > u_p \end{cases} \tag{4.2}$$

in which f is the resistant force; u the displacement; K_0 the initial stiffness; u_p the limit displacement. The stiffness of the concrete coating was neglected (Datta and Mashaly, 1990).

5. NUMERICAL ANALYSIS

5.1 Basic Information of Submarine Pipeline FE Model

The submarine pipeline may become suspended in many cases. Thus, it is necessary to analyze the response of the submarine pipeline with free spans under the multi-support seismic excitations. The pipeline simulated is a concrete-coated steel pipe buried in medium stiffness soil with a span in the center. The pipe model is shown in Figure 5. The parameters of the model are: outside diameter of the steel pipe D =0.355 m; wall thickness of the steel pipe t=5.562 mm; thickness of the concrete coating C_t=50 mm; density of the steel ρ_s =7800 kg/m^3; initial Young's modulus E_0 =2.03e5 MPa; Poisson's ratio of the steel υ=0.3; yield stress of the steel σ_y=358 MPa; linear expansion coefficient of the steel α=1.15e-5 1/℃; density of the concrete ρ_c=3040 kg/m^3; density of the oil ρ_o =880 kg/m^3; density of the sea water ρ_w =1040 kg/m^3; initial temperature T_0 =4 ℃.

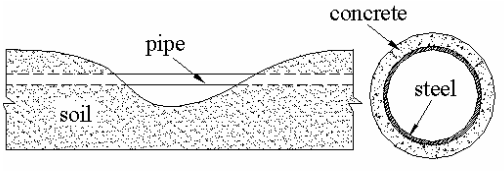
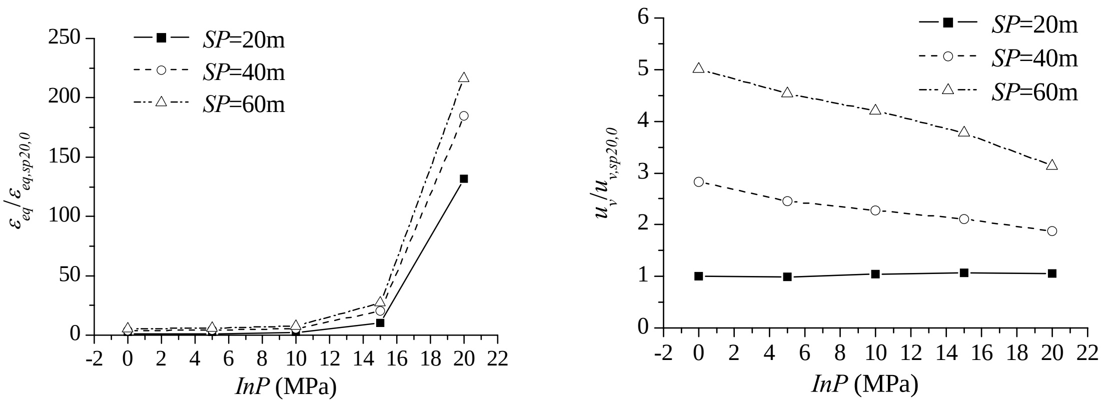


Figure 5. Models of pipe

The operating loadings including internal pressure and temperature are applied to the subsea pipeline above all during dynamic response analysis. To keep the operating loadings constant along the whole pipeline, then spatially varying seismic inputs are imposed on the pipeline.

5.2 Effect of Internal Pressure on Dynamic response

The relation of peak response versus internal pressure (*InP*) is shown in Fig. 6, in which ε_{eq} is the peak equivalent strain; $\varepsilon_{eq,sp20,0}$ is the peak equivalent strain for the pipeline with spanning length (*SP*) 20 m and *InP* = 0 MPa; u_v is the peak vertical displacement in the middle of the pipeline; $u_{v,sp20,0}$ is the peak vertical displacement in the middle of the pipeline with *SP* = 20 m and *InP* = 0 MPa.



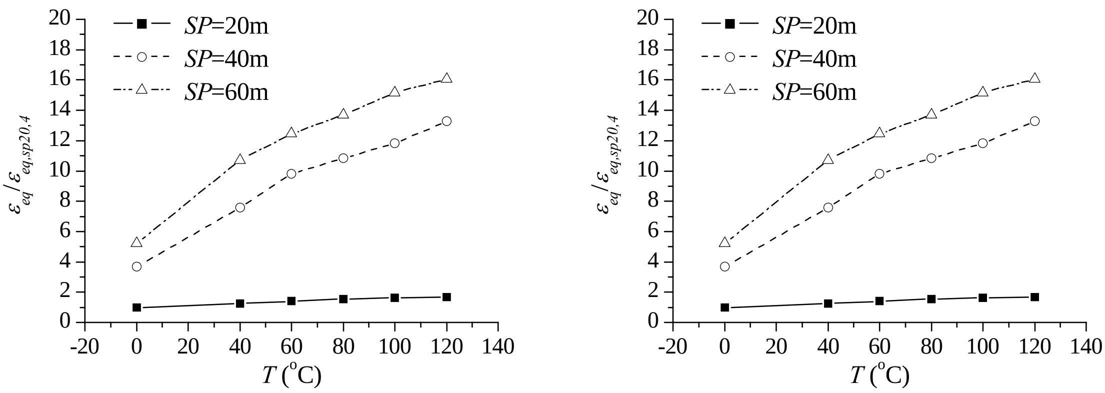
(a) Strain results (b) Displacement results

Figure 6 Effect of internal pressure on pipe response

The peak equivalent strain increases with the increasing internal pressure. The longer the spanning length is, the more obvious the trend is. The peak vertical displacement reduces with the increase of internal pressure. The pressure stiffening effects causing the increase of pipeline stiffness results in the decreasing of vertical displacement in higher pressure.

5.3 Effect of Temperature on Dynamic response

The relation of peak response versus operating temperature (*T*) is shown in Fig. 7, where $\varepsilon_{eq,sp20,4}$ is the peak equivalent strain for the pipeline with *SP* = 20 m and *T* = 4°C; $u_{v,sp20,4}$ is the peak vertical displacement in the middle of the pipeline with *SP* = 20 m and *T* = 4°C.



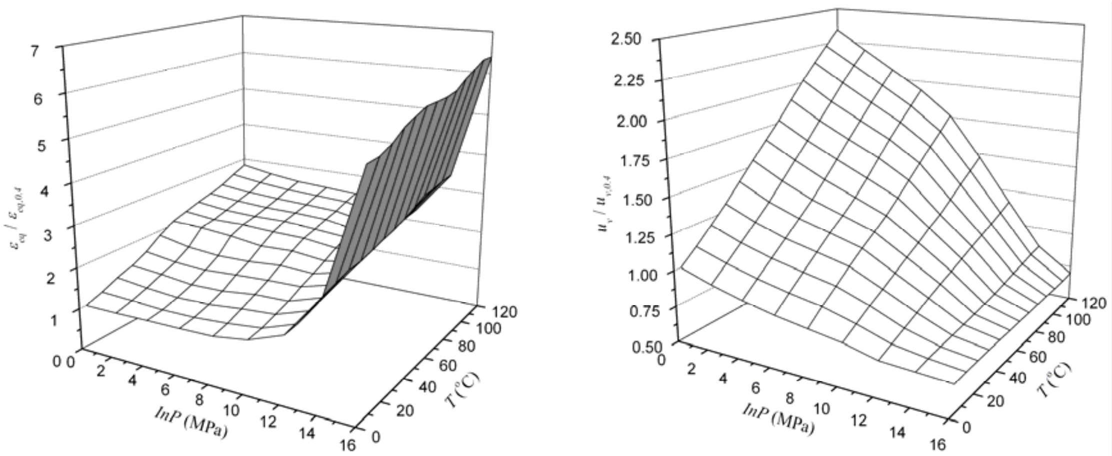
(a) Strain results (b) Displacement results

Figure 7 Effect of temperature on pipe response

From Fig. 7, the peak equivalent strain and peak vertical displacement increases with the increasing temperature. The increasing of internal temperature would cause axial compressive force due to the constraint of the soil surrounded the pipeline. Initial imperfection or displacement exists in the free spanning part of pipeline due to gravity. Global buckling will take place in the free spanning pipeline under the increase of axial compressive force. Thus, the longer the spanning length is, the more remarkable the increasing of equivalent strain and vertical displacement is.

5.4 Effect of Internal Pressure and Temperature on Dynamic response

The relation of peak response versus operating temperature and internal pressure is shown in Fig. 8, where $\varepsilon_{eq,0,4}$ is the peak equivalent strain for the pipeline with *InP* = 0 MPa and *T* = 4°C; $u_{v,0,4}$ is the peak vertical displacement in the middle of the pipeline with *InP* = 0 MPa and *T* = 4°C.



(a) Strain results (b) Displacement results

Figure 8 Effect of combination of internal pressure and temperature on pipe response

During the studying range of *InP* = 0MPa~16MPa and *T* = 4°C~120 °C, equivalent strain and vertical displacement increase with the increase of internal temperature subject to different internal pressure. The trend that equivalent strain firstly decreases and then increases with the increasing internal pressure under different internal temperature indicates critical pressures exist for different temperature conditions. When internal pressure is lower than the critical pressure, equivalent strain decreases with the increase of internal pressure subject to different temperatures; when internal pressure is higher than the critical pressure, equivalent strain increases with the increase of internal pressure under different temperatures. However, vertical displacement always decreases with the increasing internal pressure under different internal temperature.

6. CONCLUSIONS

More and more high temperature/high pressure subsea pipelines are installed in seismically active zone with the exploration of offshore oil. The effects of combined internal pressure and temperature on the dynamic response of submarine pipeline are obvious and complicated. The further study on the issue shall be carried out.

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