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Local Buckling Analysis of Free Span for Submarine Pipeline

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Abstract

Free span resulting from unevenness and scour of seabed often occurs and endanger the safety of submarine pipeline. Local buckling which is an important failure mode for free span should be considered for the safety assessment of pipeline. In this paper, considering the real service status of submarine pipeline, the structural response of free span under loads induced by vortex shedding, effective axial force, gravity and buoyancy was analyzed with numerical simulation and theoretical analysis method. Local buckling analysis for free span with different length was investigated based on the ULS criterion under load controlled condition given by DNV-OS-F101 standard.

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Keywords: local buckling; free span; submarine pipeline; structural response

1. Introduction

Recently, there is large requirement for oil and gas resource with the fast development of social production and economy in China. It is very urgent to exploit sea oil and gas in order to relieve the tense situation of energy supply. The offshore oil and gas are mainly gathered and transported by submarine pipeline due to its merits of continuity, convenience and less effect of climate. Free span often occurs[1~4] because of the unevenness and scour of seabed and endangers the safe running of pipeline.

Local buckling is an important failure mode for free span. Currently, some researches on the analysis of local buckling for free span have been carried out. For example, imperfect pipeline on lateral buckling was studied by Liu based on traditional thermal buckling theory[5], reliability for buried submarine pipelines in clay subjected to

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upheaval buckling was investigated[6], and Xing presented the analysis of buckling induced by thermal expansion[7]. However, few researches on the effect of current on local buckling for free span have been made. In this paper, considering the real service condition of some submarine pipeline, the structural response of free span under the load of vortex induced vibration(VIV) was analyzed first with numerical simulation method. Further, effective axial force, gravity and buoyancy were considered and local buckling analysis for free span with different length was investigated based on the ULS criterion under load controlled condition given by DNV-OS-F101 standard[8]. The results provide technical support for the treatment of free span.

2. Analysis parameter

This submarine pipeline was buried in the soil with pre-dredged trench method during installation. The pipeline and environmental parameters are listed in Table 1.

Table 1. The pipeline and environmental parameters.

Parameter name	Value
Pipeline dimension(mm)	Φ762×17.5
Steel grade	API 5L X60
Density of steel(kg/m3)	7850
Elastic module of steel(MPa)	2.07×105
Yield strength(MPa)	414
Tensile strength(MPa)	520
Design pressure(MPa)	5.1
Density of anticorrosive coating(kg/m3)	1500
Thickness of anticorrosive coating(mm)	0.5
Density of concrete(kg/m3)	3040
Thickness of concrete(mm)	80
Elastic module of concrete (MPa)	3.25×104
Density of sea water(kg/m3)	1025
Density of internal fluid(kg/m3)	867.7
flow velocity(m/s)	3.79
Depth of water(m)	6.0
Highest temperature of sea water(℃)	33.6
lowest temperature of sea water(℃)	4.7
Effective layer tension(kN)	230
Thermal expansion coefficient of pipeline (10-6)	11.00

3. Failure criterion of local buckling

The failure criterion of local buckling of submarine pipeline under the combined load of external pressure, internal pressure, bending moment and effective axial force is given by DNV-OS-F101 as following:

$$\left\{\gamma_{\mathrm{m}}\cdot\gamma_{\mathrm{SC}}\cdot\frac{|M_{\mathrm{Sd}}|}{\alpha_{\mathrm{c}}\cdot M_{\mathrm{p}}(t_2)}+\left\{\frac{\gamma_{\mathrm{m}}\cdot\gamma_{\mathrm{sc}}\cdot S_{\mathrm{Sd}}(p_{\mathrm{i}})}{\alpha_{\mathrm{c}}\cdot S_{\mathrm{p}}(t_2)}\right\}^2\right\}^2+\left(\alpha_{\mathrm{p}}\cdot\frac{p_{\mathrm{i}}-p_{\mathrm{e}}}{\alpha_{\mathrm{c}}\cdot p_{\mathrm{b}}(t_2)}\right)^2\leq 1 \tag{1}$$

where γ_m, $\gamma_{sc}$are material resistance factor and safety class resistance factor, and set as 1.15 and 1.138 according to DNV-OS-F101, M_{Sd} is bending moment, S_{Sd} is effective axial force, p_i and p_e are internal and external pressure, $p_b(t_2)$ is pressure containment resistance, and can be calculated with the following equation:

$$p_b(t_2) = \frac{2t_2}{D_s - t_2} \cdot f_{cb} \cdot \frac{2}{\sqrt{3}} \tag{2}$$

$$f_{cb} = \min[f_y; \frac{f_u}{1.15}] \tag{3}$$

$$\alpha_c = (1-\beta) + \beta \cdot \frac{f_u}{f_y} \tag{4}$$

$$\alpha_p = \begin{cases} 1-\beta & \frac{p_i - p_e}{p_b} < \frac{2}{3} \\ 1-3\beta(1-\frac{p_i - p_e}{p_b}) & \frac{p_i - p_e}{p_b} \geq \frac{2}{3} \end{cases} \tag{5}$$

$$\beta = \begin{cases} 0.5 & D_s / t_2 < 15 \\ (\frac{60 - D_s / t_2}{90}) & 15 \leq D_s / t_2 \leq 60 \\ 0 & D_s / t_2 > 60 \end{cases} \tag{6}$$

$$f_y = (SMYS - f_{y,temp}) \cdot \alpha_U \tag{7}$$

$$f_u = (SMTS - f_{u,temp}) \cdot \alpha_U \tag{8}$$

where *SMYS*, *SMTS* are yield strength and tension strength, $f_{y,temp}$, $f_{u,temp}$ are derating on yield and tension strength which are ignored here because the temperature is lower than 50℃ according to the standard, α_u is set as 0.96, D_s is outer diameter of pipeline, t_2 is thickness of pipeline, $M_p$and S_p denote plastic capacities for a pipe defined by

$$M_p(t_2) = f_y \cdot (D_s - t_2)^2 \cdot t_2 \tag{9}$$

$$S_p(t_2) = f_y \cdot \pi \cdot (D_s - t_2) \cdot t_2 \tag{10}$$

4. Numerical simulation of structural response under VIV load

Water flow through free span resulting in vortex shedding and vortex induced vibration, and horizontal and vertical alternative load are applied to the pipe. Because the vibration amplitude under vertical load is much larger than the one under horizontal load, the vertical vibration is consider only during the numerical analysis.

The harmonic response analysis was carried out by the finite element method to investigate the structural response.

(a) The structural model

The models for free span with different length which is 25m,30m,35m,40m and 45m respectively were established to make the research, and the models were similar. The 30m-long model is presented in Fig.1.

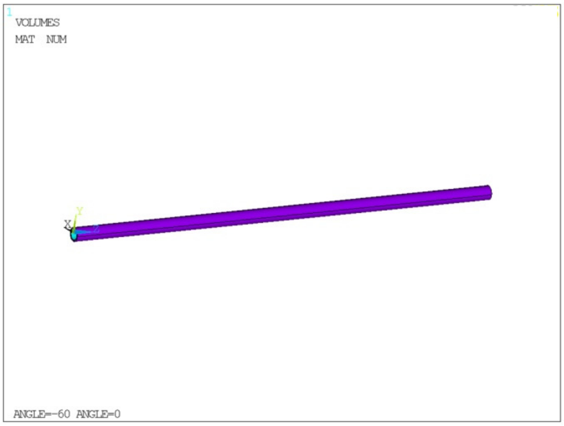

Fig. 1. The structural model of free span.

(b) The finite element model

The 3D solid element is applied to the model, and there are 1920 elements and 10816 nodes for the model with 30m long.

(c) The loads

The load induced by the cross flow vortex shedding obeys the simple harmonic rule, and its amplitude F_{LVIV} is calculated with the equation below:

$$F_{\text{VIV}} = \frac{1}{2}\rho U^2 D C_{\text{VIV}} \tag{11}$$

where ρ is the density of the sea water, U is the flow velocity, $D$is the outer diameterof the submarine pipeline including the concrete, C_{LVIV} is the lift coefficient which is set as 0.9 according to DNV-RP-C205[9].

The frequency of the load f_{LVIV} is calculated as:

$$f_{\text{VIV}} = \frac{US_{\text{t}}}{D} \tag{12}$$

where S_{t} is Strouhal number affected by parameters such as Reynolds number, etc. and is set as 0.5 conservatively according to DNV-RP-C205[9].

(d) Boundary conditions

The effect of stress concentration is ignored here. According to the beam theory, for the load vertical to the axis of the pipe, larger bending moment is generated under pinned-pinned condition than that under fixed-fixed condition. Pinned-pinned boundary condition is applied on the ends of the pipe.

(e) Calculation results of structural response for VIV

The flow velocity is set as 3.79m/s, and the load frequency can be calculated with equation (12). The vertical stress amplitude for free span with different length under VIV load is obtained shown in Table2.

Table 2. The vertical stress amplitude under VIV load.

Length of free span(m)	Stress amplitude σ_{CF} (MPa)
25	7.5
30	70.1
35	116.3
40	162.2
45	195.6

5. Effective axial force, gravity and buoyancy

(a) Effective axial force

The effective axial force is related to the factors such as internal and external pressure, thermal expansion, and constraint, etc. The pipe is conservatively considered as totally restrained, and the effective axial force is calculated with the following equation by DNV standard:

$$S_{sd} = H - \Delta p_i A_i (1-2v) - A_s E \Delta T \alpha_e \quad (13)$$

where H is effective layer tension,Δp_i is internal pressure difference relative to laying, $A_i$is internal cross section area of pipe, $v$is passion ration, As is pipe steel cross section area, ΔT is temperature difference relative to laying which is conservatively set as the difference of the highest temperature and lowest temperature, α_e is thermal expansion coefficient.

The effective axial force is obtained as shown in the following table.

Table3. The effective axial force S_{Sd}.

Variable	Value
H(kN)	230
Δp_i(MPa)	5.1
A_i(m^2)	0.422
A_s(m^2)	0.0334
ΔT (℃)	28.9
α_e (10^{-6})	11.00
S_{Sd}(N)	-2.82×10^6

(b) Gravity and buoyancy

The mass of steel pipe m_{steel}, anticorrosive coating m_{cor}, concrete m_{con} and internal fluid m_{in} is considered for the gravity F_G which is calculated as:

$$F_G = (m_{steel} + m_{cor} + m_{con} + m_{in})g \quad (14)$$

The buoyancy F_F is calculated as:

$$F_F = m_{add} g \quad (15)$$

where m_{add} is the mass of displaced water.

6. Moment bending and assessment of local buckling

According to DNV-OS-F101, the stressσ_{CF}induced by VIV is environmental load, and the gravity F_G and buoyancy F_F is functional load. When calculating bending moment, environmental load should multiply coefficient γ_E, and functional load should multiply coefficients γ_F and γ_C. γ_E, γ_F, γ_C are set as 1.3, 1.1, 1.0 respectively based on the standard.

The bending moment can be obtained with the following equation

$$M_{sd} = \frac{(F_G - F_F)\times\gamma_F\gamma_C\times L^2}{8} + \sigma_{CF}\frac{2I_{steel}}{D_s - t}\times\gamma_E \quad (16)$$

whereI_{steel} is moment of inertia of cross section of steel pipe.

The local buckling assessment result of free span with different length was shown in Table.4 based on the criterion equation (1), which shows the critical length for free span is 40m.

Table4. local buckling assessment result.

L(m)	Msd($\times10^6$N·m)	$M_p(t_2)$($\times10^6$ N·m)	S_{Sd}($\times10^6$N)	$S_p(t_2)$($\times10^6$N)	p_i(MPa)	p_e(MPa)	$P_b(t_2)$(MPa)	Result
25	0.6	3.85	-2.82	16.3	5.1	0.06	22.5	0.07
30	1.31	3.85	-2.82	16.3	5.1	0.06	22.5	0.21
35	1.94	3.85	-2.82	16.3	5.1	0.06	22.5	0.43
40	2.61	3.85	-2.82	16.3	5.1	0.06	22.5	0.75
45	3.23	3.85	-2.82	16.3	5.1	0.06	22.5	1.13

7. Conclusions

In this paper, based on the harmonic response analysis, the structural response for free span was obtained first. Further, considering the loads such as effective axial force, gravity and buoyancy etc., local buckling analysis for free span with different length was investigated and the critical length was acquired. The assessment results provide technical support for the treatment of free span.

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