한국해양공학회지 제19권 제2호, pp 47~52, 2005 (ISSN 1225-0767)

Free Spanning of Offshore Pipelines by DNV

HAN SUK CHOI*

Dept. of Naval Architecture and Ocean Engineering, Pusan National University, Busan, Korea

KEY WORDS: Offshore Pipeline, Free Span, Fatigue, DNV

ABSTRACT: *This paper introduces a procedure for free span and fatigue analysis of offshore pipelines per DNV-RP-F105, 2002. The new method includes the axial force and deflection load in pipelines. The screening criteria were established to calculate the allowable span lengths in the new design codes. The screening criteria allows a certain amount of vortex-induced vibration due to wave and current loading. However, the induced pipe stresses are very small and usually below the limit stresess of typical S-N curves. In contrast, the conventional criteria did not allow any vortex-induced vibration in the free span of pipelines. Thus, the screening criteria yields reduced allowable span lengths. A simplified procedure was established to calculate the fatigue damage due to long-term current distribution. The long-term current statistics was assumed with a 3-parameter Weibull distribution. The fatigue damage was estimated for the span lengths obtained from the screening criteria for various conditions. Sample calculations show the effect of axial force for various boundary conditions. Comparisons with conventional criteria are included.*

1. INTRODUCTION

For a safety of offshore gas or oil pipeline during installation and operation phase, the free span (unsupported portion of pipelines) lengths should be maintained within the allowable span lengths, which are determined during the design stage. Free spans may be caused by seabed unevenness and change of seabed topology such as scouring or sand waves. When a flow due to wave and current passes an unsupported portion of the offshore pipelines, the vortices shed and periodic wakes are formed behind the pipeline. Each time a vortex is shed, it alters the local pressure distribution and the pipeline experiences vortex-induced vibrations (VIV). The VIV may cause fatigue damage on the pipeline and if the damage is excessive, it could lead to a catastrophic failure. This paper is to establish a simple procedure to calculate allowable free span lengths and fatigue damage based on the guidelines in the recent design codes (DNV, 1991, 1998, 2001, 2002). Fig. 1 shows a flow chart of design checks for a free span.

2. SPAN LENGTHS BY SCREENING CRITERIA

The screening criteria were proposed in DNV 2002 and this new criteria allows certain amount of VIV of pipelines.

If this small amplitude of motion does not contribute to the fatigue damage, then allowable span lengths can be determined.

In contrast, the conventional criteria did not allow any motion in the free span of pipelines. Thus, the screening criteria yields reduced allowable span lengths. The screening criteria are applied to fatigue damage caused by VIV and combined current and wave loading conditions. The screening criteria have been calibrated against full fatigue analyses to provide a fatigue life in excess of 50 years. The criteria are applied to spans with a response dominated by the 1st symmetric mode (one half wave) and should preferably be applied for screening analyses only and, if violated, more detailed fatigue analyses should be performed.

The screening criteria are based on the assumption that the current velocity may be represented by a 3-parameter Weibull distribution. If this is not the case, e.g. bi-modal current distribution, care must be taken and the applicability of these screening criteria checked by full fatigue calculation (DNV 2002).

The in-line natural frequency $f_{0,IL}$ must fulfil:

$$\frac{f_{0,IL}}{\gamma_f} > \frac{U_{c,100year}}{V_{R,onset}^{IL} \cdot D} \cdot \left(1 - \frac{L/D}{250}\right) \cdot \frac{\gamma_{IL}}{\alpha} \qquad (1)$$

제1저자 최한석 연락처: 부산광역시 금정구 장전동 산 30
051-510-2343 hanchoi@pusan.ac.kr

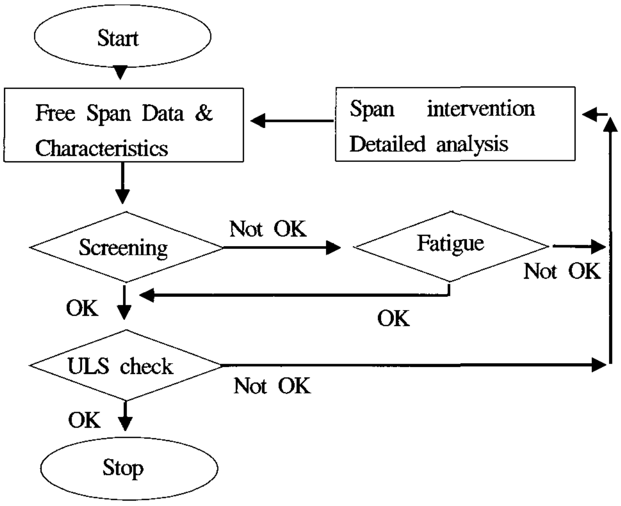

Fig. 1 Flow chart of free span design (DNV, 2002)

where,

γ_f = Safety factor on the natural frequency

γ_{IL} = Screening factor for in-line

$\bar{\alpha}$ = Current flow ratio

$= \max\left(\frac{U_{c,100year}}{U_{w,1year}+U_{c,100year}};0.6\right)$

D = Outer diameter of pipe including coatings

L = Free span length

$U_{c,100year}$ = 100 year return period value for the current velocity at the pipe level

$U_{w,1year}$ = Significant 1 year return period value for the wave induced flow velocity at the pipe level corresponding to the annual significant wave height $H_{s,1year}$

$V_{r,onset}^{IL}$ = In-line onset value for the reduced velocity

If the above criterion is violated, then a full in-line VIV fatigue analysis is required. Equation (1) merely compares the in-line natural frequency and vortex shedding frequency with a calibration of the normalized free span lengths and partial safety factors.

The cross-flow natural frequency $f_{0,CF}$ must fulfil:

$$\frac{f_{0,CF}}{\gamma_f} > \frac{U_{c,100year}+U_{w,1year}}{V_{R,onset}^{CF}\cdot D}\cdot\gamma_{CF} \tag{2}$$

where,

γ_{CF} = Screening factor for cross-flow

$V_{R,onset}^{CF}$ = Cross-flow onset value for the reduced velocity

If the above criterion is violated, then a full in-line and cross-flow VIV fatigue analysis is required.

The fundamental natural frequency of a pipe span may be approximated by DNV (2002):

$$f_0 \approx C_1\sqrt{1+CSF}\sqrt{\frac{EI}{m_e L_{eff}^4}\cdot\left(1+C_2\cdot\frac{S_{eff}}{P_E}+C_3\left(\frac{\delta}{D}\right)^2\right)} \tag{3}$$

where,

$C_1 - C_3$ = Boundary condition coefficients

CSF = Concrete stiffness enhancement factor

E = Youngs modulus for steel

I = Moment of inertia for steel

L_{eff} = Effective span length defined below

m_e = Effective mass

P_E = Euler buckling load = $(1+CSF)\pi^2 EI/L_{eff}^2$

δ = Static deflection, normally ignored for in-line direction

S_{eff} = Effective axial force (negative in compression)

Equation (3) was calibrated with boundary condition coefficients and can be compared with the exact solutions (Choi and Haun, 1994, Choi, 2001).

The L_{eff}/L term in Eq. (4) accounts for the effective span length in order to consider the span as fully fixed. This ratio decreased as the L/D ratio and soil stiffness in wave. For fix-fix boundary condition, L_{eff}/L = 1.

The L_{eff}/L term is given by (Hobbs, 1986):

$$\frac{L_{eff}}{L} = \begin{cases} \dfrac{4.73}{-0.066\beta^2+1.02\beta+0.63} & \text{for } \beta \geq 2.7 \\ \dfrac{4.73}{0.036\beta^2+0.61\beta+1.0} & \text{for } \beta < 2.7 \end{cases} \tag{4}$$

where,

$$\beta = \log_{10}\left(\frac{K*L^4}{(1+CSF)*E*I}\right)$$

where, K is the relevant soil stiffness (vertical or horizontal, static or dynamic).

The screen criteria in Eqs. (1) and (2) allow small amplitudes of VIV and corresponding stress may occurs in the free spans.

Fig. 2 shows the empirical in-line response curves obtained from DNV 2002. $Amplitude/D$ is defined as the maximum in-line VIV response amplitude (nomalised with D) as a function of the reduced velocity and stability parameters.

Maximum amplitude is only 18% of the pipe parameter. For a given flow condition, the actual maximum response should be calculated by the response model general principle in DNV 2002.

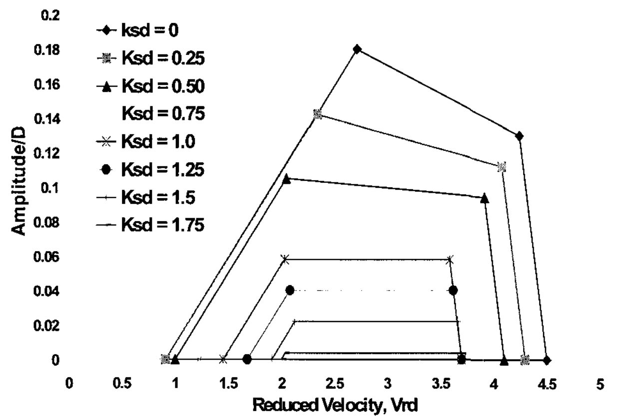

Fig. 2 Response of in-line VIV (DNV, 2002)

Fig. 3 also shows the empirical cross-flow response curves obtained from DNV 2002. The maximum cross-flow amplitude is much higher than those of in-line cases. Response model generation principle in DNV 2002 should be used to find maximum cross-flow response.

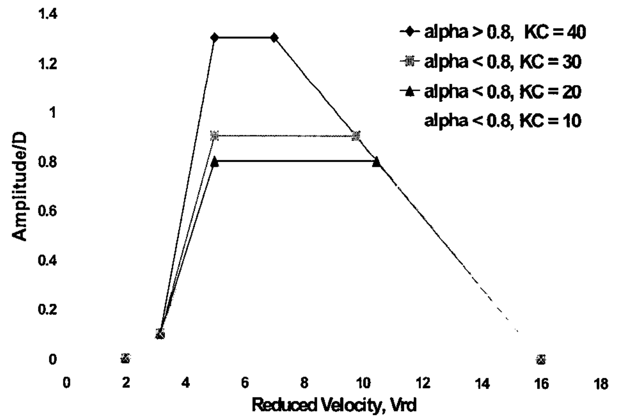

Fig. 3 Response of cross-flow VIV (DNV, 2002)

If the induced stress ranges are less than the limit stress of a typical S-N curve, no fatigue analysis is required for the given environmental data. However, a fatigue analysis for a long-term distribution of wave and current is still required. The allowable span lengths are calculated from Eqs. (1), (2), and (3).

The following steps are established to calculate the allowable span lengths:

1) Collect pipeline data including the safety class and structural damp-ing.
2) Collect environmental data (100-year current, 1-year wave, hydrodynamic damping).
3) Collect soil data including soil damping and stiffness.
4) Establish the partial safety factors for the pipelines.
5) Calculate the ratio of the effective span length and a free span length from soil stiffness.
6) Establish the pipeline boundary conditions.
7) Calculate the reduced velocity using the combination of the wave particle velocity and current velocity.
8) Increase the span lengths iteratively until the screening criteria are satisfied.
9) Calculate the amplitude of the VIV motion from DNV's empirical curves.
10) Calculate the stress ranges from the VIV induced motion, and compare them with the limit stress in S-N curve.

3. FATIGUE DAMAGE ESTIMATION

A 3-parameter Weibull distribution is often appropriate for modeling of the long-term statistics for current velocity. The Weibull distribution is given by:

$$F_x(x) = 1 - \exp\left(-\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right) \tag{5}$$

where, Fx(x) is the cumulative distribution function and α is the scale, β is the shape and γ is the local parameter. α=0.9, β=3.0 and 2.0 (Rayleigh distribution), γ=0 was used for the sample calculations described in next section. Fig. 4 shows a 3-parameter Weibull distribution and a Rayleigh distribution of the long-term current velocities. The high probabilities occur at low current velocities in Rayleigh distribution.

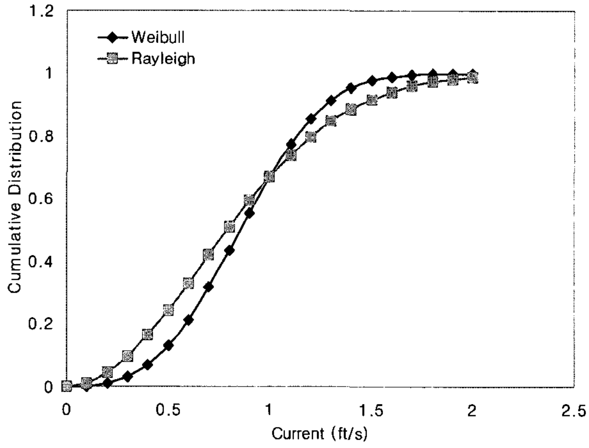

Fig. 4 Distribution of the long-term current velocities

The fatigue damage assessment is based on the accumulation law by Palmgren-Miner:

$$D_{fat}=\sum\frac{n_i}{N_i} \tag{6}$$

where,

D_{fat} = Accumulated fatigue damage.

n_i = Total number of stress cycles corresponding to stress range S_i

N = Number of cycles to failure at stress range S_i

$\sum$ = Implies summation over all stress fluctuations in the design life

The number of cycles to failure at stress range S_i is defined by the S-N curve of the form:

$$N=\begin{cases}\overline{a_1}\cdot S^{-m_1} & S > S_{sw}\\ \overline{a_2}\cdot S^{-m_2} & S\leq S_{sw}\end{cases} \tag{7}$$

where,

m_1, m_2 Fatigue exponents (the inverse slope of the bi-linear S-N curve)

$\overline{a_1}, \overline{a_2}$ Characteristic fatigue strength constant defined as the mean-minus-two-standard-deviation curve

S_{sw} Stress at intersection of the two S-N curves given by:

$$S_{sw}=10^{\left(\frac{\log\overline{a_1}-\log N_{sw}}{m_1}\right)}$$

where,

N_{sw} = Number of cycles for which change in slope appear

The following steps are established to calculate the fatigue damage due to a long-term distribution of the wave and current:

Step 1), 3)-6) are same as the steps in allowable lengths.

2) Collect the long-term distribution of wave and current data.

7) Assume a span length for the fatigue damage estimation.

8) Discrete the distribution of flow velocity and probability with a finite segment (10-20 are recommended).

9) For each segment of flow velocity, calculate the reduced velocities, obtain the amplitude of the motion and corresponding stress ranges.

10) For each segment of flow velocity, calculate n_i, N_i.

11) Combine the n_i, N_i to calculate the fatigue damage.

12) If the calculated damage exceeds the allowable damage level, go to step 7) with a reduced span length and vice versa.

4. SAMPLE CALCULATIONS

Sample calculations were performed for a 12.75-inch x 0.5-inch wall thickness oil pipeline with product density of 45 pcf. Following are the conditions used in the calculation.

- Wave height (1-year) = 6.1 m
- Wave period (1-year) = 8 sec
- Bottom current (100-year) = 0.5 m/s
- Water depth = 91.5 m
- Soil coefficient (fix-fix) = 50,000 kN/m2
- Soil coefficient (fix-pin) = 10,000 kN/m2
- Soil coefficient (pin-pin) = 3,000 kN/m2

Fig. 5 shows the calculated values of the allowable span lengths for various boundary conditions. The allowable lengths are clearly depend on the axial forces and boundary conditions. The effect of the deflection load is not significant for in-line if the steady current is not accounted for. In case of cross-flow allowable lengths, care should be taken to avoid Euler buckling of the pipe span.

Cross-flow cases result longer allowable span lengths than those of the in-line cases. For the flexible boundary conditions in cross-flow cases, Euler bucklings occur at high compressible axial forces. In-line conditions result in very conservative span lengths.

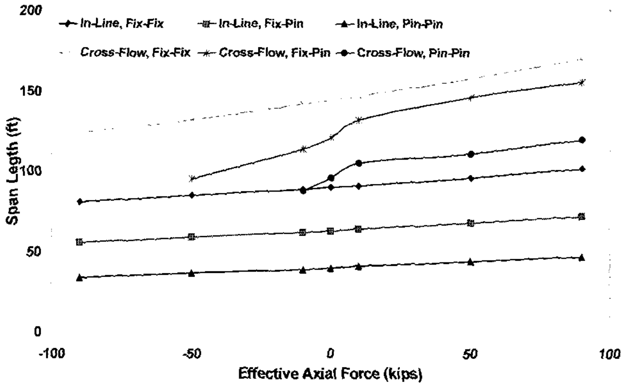

Fig. 5 Allowable span lengths for various boundary conditions

Fig. 6 shows the fatigue damage calculated for the same span lengths and boundary conditions in Fig. 5. A Weibull distribution of current in Fig. 4 was used for the fatigue damages. Allowable fatigue levels are depending on the pipeline safety classes in design codes. Calculated fatigue damages on the pipeline spans are very low except for the in-line vibration with fix-fix boundary condition, which is very unrealistic condition for the free spans of offshore pipelines.

Fatigue damage level is very sensitive to the span lengths and boundary conditions, axial force and long-term current distribution. Allowable span lengths can be limited by the allowable fatigue level and the pipeline safety classes in design codes.

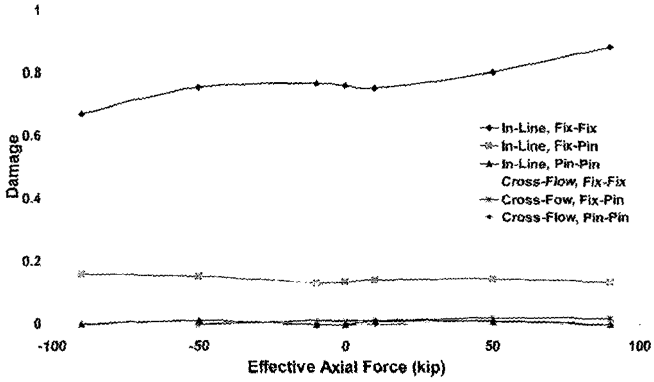

Fig. 6 Fatigue damage calculated for the same span lengths in Fig. 5 (Weibull Distributions of Current)

Fig. 7 shows the fatigue damage calculated for the same conditions in Fig. 5. However, a Rayleigh distribution of current in Fig. 4 was used. No fatigue damages occur on the pipeline spans except for the in-line vibration with fix-fix boundary condition.

It shows that fatigue damage is very sensitive to the long-term distribution of currents. If the long-term current distribution is deviated from Weibull distribution, the screening criteria should be checked by full fatigue calculation.

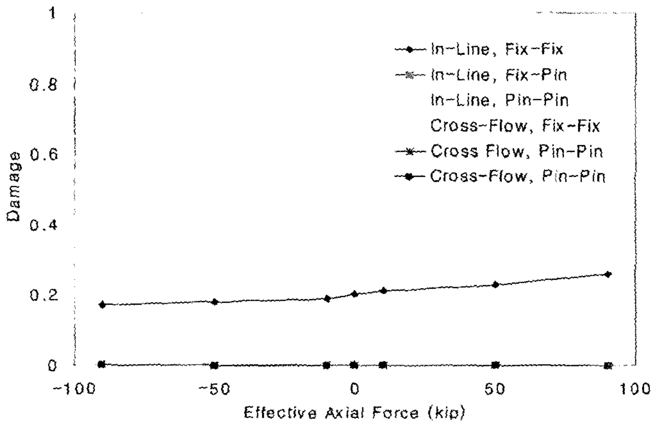

Fig. 7 Fatigue damage calculated for the same span lengths in Fig. 5 (Rayleigh Distributions of Current)

5. COMPARISON WITH RIGOROUS METHOD

A rigorous procedure was established on the free span analysis of offshore pipelines. The closed form solutions of the beam-column equation, considering the axial force, were derived for the various possible boundary conditions (Choi, 2001). This rigorous solutions were applied to the conventional free span criteria, which does not allow any VIV motion of free spans. Calculations were done to compare the two different criteria. The calculated results for the cross-flow, fix-fix boundary condition are shown in Fig. 8. The conventional criteria yields much longer span enths.

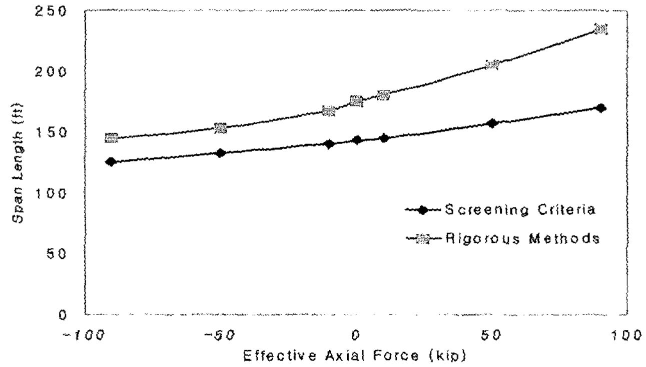

Fig. 8 Comparison of Screening Criteria vs. Rigorous Method (Cross-Flow, Fix-Fix)

6. CONCLUDING REMARKS

1. A simple procedure was established to calculate the allowable span lengths and fatigue damage per DNV 2002.
2. The effect of axial force on the free span lengths and fatigue damage is significant.
3. The effect of deflection load on the face span lengths and fatigue damage is not significant except the high compressive load cases.
4. The free span lengths are very sensitive to the soil boundary condition and axial forces.
5. The fatigue damage is very sensitive to the span lengths, boundary condition, axial forces, and long-term current distribution.
6. The screening criteria in DNV 2002 yields less span lengths. Care should be taken to follow all the requirements in the code.
7. If the long-term current distribution is deviated from Weibull distribution, the screening criteria should be checked by full fatigue calculation.

REFERENCES

Choi, H.S. and Haun, R.D. (1994). "The Effect of Residual Tension and Free Span-Induced Moments on Vortex Shedding of Deep Water Pipelines," 4th International Offshore and Polar Engineering Conference, Osaka, Japan, Vol 2, pp 102-109.

Choi, H.S. (2001). "Free Spanning Analysis of Offshore Pipelines," Ocean Engineering, Vol 28, No 10, pp 1325-1338.

DNV (1991). Environmental Conditions and Environmental Loads, Det Norske Veritas, Classification Notes No 30.5.

DNV (1998). Free Spanning Pipelines, Det Norske Veritas, Guideline No 14.

DNV (2001). Fatigue Strength Analysis of Offshore Steel Structures, Det Norske Veritas, Recommended Practice DNV-RP-C203.

DNV (2002). Free Spanning Pipelines, Det Norske Veritas, Recommended Practice *DNV-RP-F105*.

Hobbs, R.E. (1986). "Influence of Structural Boundary Conditions on Pipeline Free Span Dynamics", Proc. of Offshore Mechanics and Arctic Engineering, Vol 5, pp 121-129.

2004년 10월 20일 원고 접수
2004년 12월 16일 최종 수정본 채택