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Expansion Spool Design of an Offshore Pipeline by the Slope Deflection Method

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ABSTRACT: *Offshore, sub-sea pipelines that transport oil and gas experience thermal expansion induced by the temperature of the transported medium during operation. The expansion of the pipeline can induce overload and cause damage to offshore platforms or sub-sea structures that are connected to the pipelines. To mitigate and prevent these incidents, expansion spools are installed between offshore, sub-sea pipelines and risers on the platform. This paper presents the results of the study and development of a simplified design method for expansion spools, using the slope deflection method for the purpose of preliminary design or front-end engineering and design (FEED).*

1. Introduction

Offshore subsea pipelines transporting oil and gas between offshore platforms or subsea structures are usually installed at the surrounding environment. During the operation, the inlet temperature dramatically increases and hence the temperature of the whole line is increased and the pipelines are also pressurized. Due to the increment of temperature and pressure, the pipelines are expanded longitudinally and simultaneously, the expansion is resisted by the frictional contact between the subsea pipelines and the seabed soil. if longitudinal force on pipelines due to expansion is larger than resistant force induced by soil friction, the expansion occurs in the pipelines, is transmitted to the platform through subsea pipelines and leads to the overload and damage to offshore platforms or subsea structures (Bai, 2001).

In order to mitigate and prevent the effect of expansion, expansion spool (also called pipeline tie-in spool) is installed between subsea pipeline and riser on the platform.

This paper studies and develops the simplified design method of the expansion spool using the slope-deflection equations for the purpose of preliminary design or FEED (Front end engineering and design).

2. Expansion Spool of Offshore Subsea Pipeline

2.1 Expansion spool

When expansion load which can be derived from thermal expansion analysis occurs in the subsea pipelines, expansion spool absorbs the expansion by self-deformation of spool and hence prevents the platform from the effect of expansion.

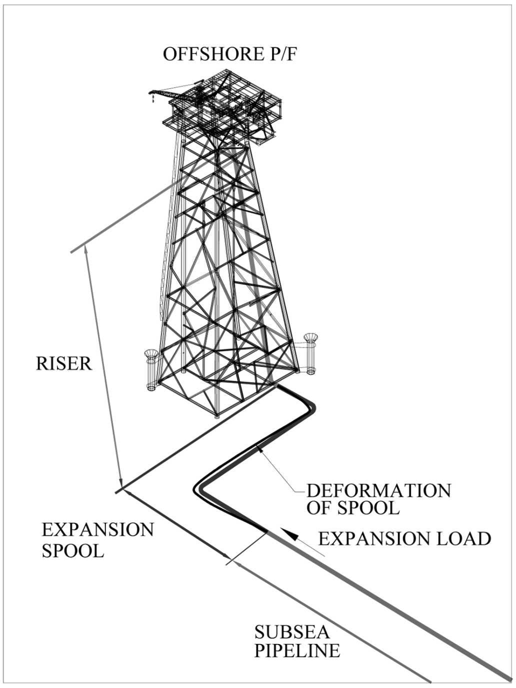

Fig. 1 Typical subsea pipeline, riser and expansion spool

Figure 1 shows typical subsea pipeline, riser and expansion spool system in offshore platform.

Basic expansion analysis methods for subsea pipelines to be performed to gain the expansion load have been well developed during the last two decades (Choi, 1995). The pipeline expansion was calculated with soil friction but without end restrictions. Thus very conservative results were obtained.

There are two representative theories of expansion analysis, one is free expansion with a uniform temperature and the

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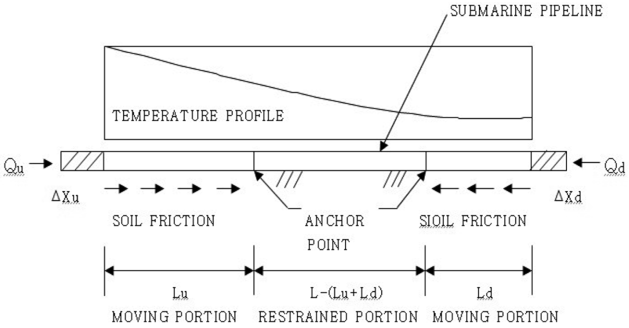


Fig. 2 Sketch of pipeline expansion

other is free expansion with a temperature gradient

2.2 Free expansion with a uniform temperature

The pipeline end expansion due to the temperature and pressure will create a soil friction force proportional to the length of the moving portion of the pipe. If the total friction force developed along the pipeline is sufficient to suppress expansion force, no expansion will occur.

Figure 2 shows a sketch of pipeline expansion with uniform temperature.

When the end restraining force is zero, the analysis is called a free expansion problem. In Fig. 2, the two points where the movement stops are called the anchor points and the lengths from the free ends to the anchor points are called the anchor lengths or moving length of the partially restrained zone. If the temperature is uniformly distributed along the pipeline, the anchor lengths at the upstream and downstream will be same. The portion of the length between the anchor points is called fully restrained zone (Nes et al., 1996; Palmer and Ling, 1981).

Once the anchor length, Lu and Ld, are obtained from the equilibrium of the forces in the pipeline, the total expansion and corresponding stresses can be easily obtained. The equilibrium of the forces in the pipeline is:

$$F_t + F_p + F_v = F_f \tag{1}$$

where, F_t, is the force due to the temperature, F_p is the force due to the pressure, F_v is the force due to Poisson contraction, and F_f is the force due to soil frictional resistance.

The above equations are conservatively used for the pipeline expansion. However, this approach is not valid for a very hot pipeline without good insulation system or a long pipeline whose temperature distribution has a considerable gradient along the pipeline.

2.3 Free expansion with a temperature gradient

A detailed analysis of the heat transfer can determine the temperature decay profile along the pipeline (MNET, 1991).

The temperature gradient will cause different anchor lengths at the upstream side and downstream side, i.e., the longer anchor length at the upstream side and short anchor length at the downstream side. Different anchor lengths will be resulted with temperature gradient. Both of the anchor lengths and fully restrained portion are dependent on each other and should be obtained from the same calculation. Most of the existing software do not consider the dependence of the upstream anchor length, downstream anchor length, and restrained length. A closed form solution to obtain the both of the anchor lengths simultaneously was derived (Choi, 1995; 2002).

The average temperature over the moving length, at the upstream of the pipeline, can be obtained as follow:

$$DT_u = \frac{1}{L_u}\int_0^{L_u} \Delta t \cdot \exp(-\frac{x}{\lambda}) \cdot dx = -\frac{\lambda \Delta t}{L_u}[\exp(-\frac{L_u}{\lambda}) - 1] \tag{2}$$

where L_u is the upstream anchor length, x is the distance from the upstream ends, and $\lambda = C_p\rho \cdot Q/U$ is the decay length of pipeline temperature, C_p is the specific heat of fluid contents, ρ is the fluid density, Q is the flow rate, and U is the overall heat transfer coefficients.

The average temperature over the moving length, at the downstream of the pipeline, can be obtained similarly:

$$\begin{aligned} DT_d &= \frac{1}{L_d}\int_{L-L_d}^{L} \Delta t \cdot \exp(-\frac{x}{\lambda}) \cdot dx \\ &= -\frac{\lambda \Delta t}{L_d}[\exp(-\frac{L}{\lambda}) - \exp(-\frac{L-L_d}{\lambda})] \end{aligned} \tag{3}$$

The anchor length of the downstream, L_d of the pipeline was given as;

$$\begin{aligned} L_d = \frac{1}{\mu W_s}[\alpha E A_s \cdot (\frac{\lambda \Delta T}{L_d})\exp(-\frac{L-L_d}{\lambda}) \\ - \exp(-\frac{L}{\lambda}) + PA_i - \nu A_s \sigma_h] \end{aligned} \tag{4}$$

The above Eqs. (2) through (4) are nonlinear and can be solved by using a numerical iteration method.

Choi (1995) indicates that the anchor points shift together depending on the temperature gradient and more realistic anchor lengths and expansions can be obtained. If the temperature is uniform, the upstream and downstream anchor lengths become same as described in the previous section.

3. Expansion Spool Design by Slope Deflection

3.1 Slope deflection (SD) method

All structures must satisfy equilibrium, load-displacement, and compatibility of displacements requirements in order to ensure their safety.

There are two different ways to satisfy these requirements when analyzing a statically indeterminate structure. one is force method of analysis and the other is displacement method.

The force method of analysis is based on identifying the unknown redundant forces and then satisfying the structure's compatibility equations.

The displacement method works the opposite way. It first requires satisfying equilibrium equations for the structure. To do this the unknown displacements are written in terms of the loads by using the load-displacement relations then these equations are solved for the displacements. Once the displacements are obtained, the unknown loads are determined from the compatibility equations using the load-displacement relations. The procedure will be generalized to produce the slope deflection equations (Hibbeler, 2006).

3.2 Slope deflection equations

The slope-deflection method was originally developed for the purpose of studying secondary stresses in trusses. Later, the refined version of this technique is developed and applied to the analysis of indeterminate beams and framed structure.

For internal span or end span with far end fixed, the below equation will be applied.

$$M_N = 2Ek(2\theta_N + \theta_F - 3\psi) + (FEM)_N \quad (5)$$

For end span with far end pinned or roller supported, the below equation will be applied.

$$M_N = 3Ek(\theta_N - \psi) + (FEM)_N \quad (6)$$

where,

M_N = internal moment in the near end of the span; this moment is positive clockwise when acting on the span.

E, k = modulus of elasticity of material and span stiffness $k = I/L$.

θ_N, θ_F = near- and far-end slopes or angular displacements of the span at the supports; the angles are measured in radians and are positive clockwise.

ψ = span rotation of its cord due to a linear displacement, that is, $\psi = \Delta/L$; this angle is measured in radians and is positive clockwise.

$(FEM)_N$ = fixed-end moment at the near-end support; the moment is positive clockwise when acting on the span.

3.3 Application of slope deflection method

When thermal expansion occurs in the subsea pipelines, the pipeline expansion is propagated to expansion spool along the pipeline, the expansion spool is going to deform its configuration in order to release the axial load induced by expansion load shown in Fig. 1.

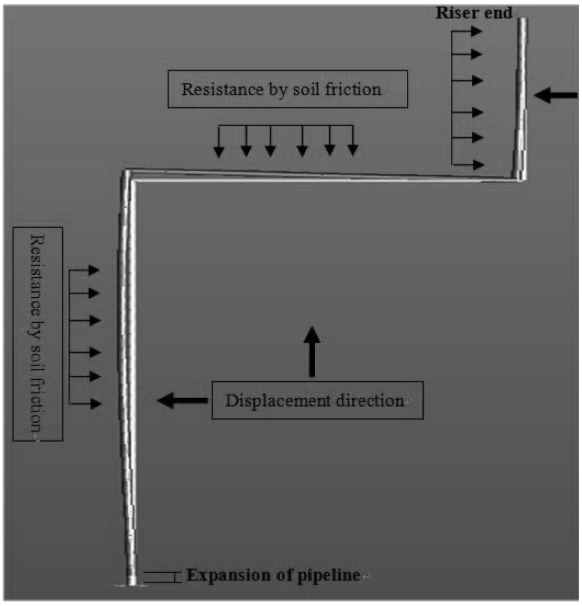


Fig. 3 Interaction between displacement and soil friction

Figure 1 demonstrates the subsea pipelines connected to a platform riser through expansion spool and the whole axial load induced by pipeline expansion is propagated to the expansion spool and then the load is released by displacement of expansion spool itself.

In this time, the lateral displacement of expansion spool is resisted by soil friction force. By interaction between load of lateral displacement and resistant load of soil friction, final displacement of expansion spool is determined.

Actually, resistance by longitudinal soil friction is also induced during displacement of expansion spool simultaneously but longitudinal soil friction on the expansion spool is conservatively neglected as it has generally little influence on the results.

Accordingly, soil friction resistance is assumed as the lateral uniform distribution load on the expansion spool according to the opposite direction of lateral displacement of expansion spool shown in Fig. 3.

Uniform distribution load can be estimated as "soil friction x Submerged subsea pipeline weight" and this load is applied to the opposite of the direction of lateral displacement of expansion spool.

3.4 Calculation of expansion spool by slope deflection

This paragraph defines the calculation process using slope deflection for the configuration of expansion spool used

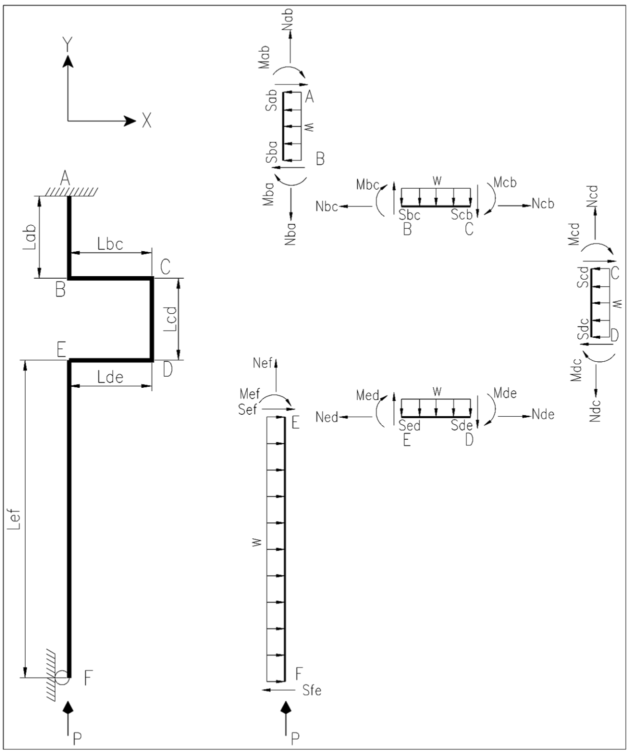


Fig. 4 Expansion spool used commonly in the offshore

commonly in the offshore industry shown in Fig. 4.

3.4.1 Calculation of fixed-end moment (FEM)

As shown in Fig. 3, when displacement of expansion spool occurred due to the longitudinal force, this displacement is resisted by soil friction which can be modelled as uniform distributed load.

Accordingly, the fixed end moment and pin end moment can be derived from the soil resistance for the expansion spool in Fig. 4 as below;

$$(FEM)_{AB} = -\frac{wL_{AB}^2}{12} \tag{7}$$

$$(FEM)_{BA} = \frac{wL_{AB}^2}{12} \tag{8}$$

$$(FEM)_{BC} = -\frac{wL_{BC}^2}{12} \tag{9}$$

$$(FEM)_{CB} = \frac{wL_{BC}^2}{12} \tag{10}$$

$$(FEM)_{CD} = -\frac{wL_{CD}^2}{12} \tag{11}$$

$$(FEM)_{DC} = \frac{wL_{CD}^2}{12} \tag{12}$$

$$(FEM)_{DE} = -\frac{wL_{DE}^2}{12} \tag{13}$$

$$(FEM)_{ED} = \frac{wL_{DE}^2}{12} \tag{14}$$

$$(FEM)_{EF} = \frac{wL_{EF}^2}{8} \tag{15}$$

where, $\omega = W_s \times \mu$

W_s : submerged subsea pipe weight per unit length

μ : lateral soil friction coefficient

3.4.2 Calculation of span stiffness

$$K_{AB} = \frac{I_{AB}}{L_{AB}} \; K_{BC} = \frac{I_{BC}}{L_{BC}} \; K_{CD} = \frac{I_{CD}}{L_{CD}} \; K_{DE} = \frac{I_{DE}}{L_{DE}} \; K_{EF} = \frac{I_{EF}}{L_{EF}} \tag{16}$$

3.4.3 Calculation of slope deflection equation

$$M_{AB} = 2EK_{AB}(2\theta_A + \theta_B - 3\psi_{AB}) + (FEM)_{AB} \tag{17}$$

$$M_{BA} = 2EK_{AB}(\theta_A + 2\theta_B - 3\psi_{AB}) + (FEM)_{AB}$$

$$M_{BC} = 2EK_{BC}(2\theta_B + \theta_C - 3\psi_{BC}) + (FEM)_{BC} \tag{19}$$

$$M_{CB} = 2EKC_B(\theta_B + 2\theta_C - 3\psi_{BC}) + (FEM)_{BC} \tag{20}$$

$$M_{CD} = 2EK_{CD}(2\theta_C + \theta_D - 3\psi_{CD}) + (FEM)_{CD} \tag{21}$$

$$M_{DC} = 2EK_{DC}(\theta_C + 2\theta_D - 3\psi_{CD}) + (FEM)_{CD} \tag{22}$$

$$M_{DE} = 2EK_{DE}(2\theta_D + \theta_E - 3\psi_{DE}) + (FEM)_{DE} \tag{23}$$

$$M_{ED} = 2EK_{DE}(\theta_D + 2\theta_E - 3\psi_{DE}) + (FEM)_{DE} \tag{24}$$

$$M_{EF} = 2EK_{EF}(\theta_E - \psi_{EF}) + (FEM)_{EF} \tag{25}$$

where, $\theta_A = 0$, $\theta_F = 0$,

Accordingly, final 9 number of unknowns are as below;

θ_B, θ_C, θ_D, θ_E, ψ_{AB}, ψ_{BC}, ψ_{CD}, ψ_{DE} and ψ_{EF}

3.4.4 Nine equilibrium equations

[1] Equation of relative linear displacement

$$R_{AB} = \frac{\Delta 1}{L_{AB}} \; , \; R_{CD} = \frac{\Delta 2}{L_{CD}} \; , \; R_{EF} = \frac{\Delta 3}{L_{EF}}$$

$$\Delta 1 + \Delta 2 + \Delta 3 = 0$$

$$R_{EF} = -\frac{R_{AB} \cdot L_{AB} + R_{CD} \cdot L_{CD}}{L_{EF}} \tag{26}$$

[2] Equation of (Eq. (18) M_{BA} + Eq. (19) $M_{BC} = 0$)

$$2EK_{AB}(2\theta_B - 3\psi_{AB}) + FEM_{BA} + 2EK_{BC}(2\theta_B + \theta_C - 3\psi_{BC}) + FEM_{BC} = 0 \tag{27}$$

[3] Equation of (Eq. (20) M_{CB} + Eq. (21) $M_{CD} = 0$)

$$2EK_{BC}(\theta_B + 2\theta_C - 3\psi_{BC}) + FEM_{CB} + 2EK_{CD}(2\theta_C + \theta_D - 3\psi_{CD})$$

$+ FEM_{CD} = 0$ (28)

[4] Equation of (Eq. (22) M_{DC} + Eq. (23) $M_{DE} = 0$)

$$2EK_{CD}(\theta_C + 2\theta_D - 3\psi_{CD}) + FEM_{DC} + 2EK_{DE}(2\theta_D + \theta_E - 3\psi_{DE}) + FEM_{DE} = 0 \quad (29)$$

[5] Equation of (Eq. (24) M_{ED} + Eq. (25) $M_{EF} = 0$)

$$2EK_{DE}(\theta_D + 2\theta_E - 3\psi_{DE}) + FEM_{DE} + 3EK_{EF}(\theta_E - \psi_{EF}) + FEM_{EF} = 0 \quad (30)$$

[6] Equation of (ΣX direction force = 0)

$$S_{AB} + w(L_{AB} + L_{CD} + L_{EF}) - S_{EF} = 0$$

where, $S_{AB} = -\frac{1}{L_{AB}}(M_{AB} + M_{BA} + \frac{wL_{AB}^2}{2})$

$S_{EF} = -\frac{1}{L_{EF}}(M_{EF} + \frac{wL_{EF}^2}{2})$

accordingly,

$$-\frac{1}{L_{AB}}(M_{AB} + M_{BA} + \frac{wL_{AB}^2}{2}) + w(L_{AB} + L_{CD} + L_{EF}) + \frac{1}{L_{EF}}(M_{EF} + \frac{wL_{EF}^2}{2}) = 0 \quad (31)$$

[7] Equation of (ΣY direction force = 0)

$$S_{BC} + P - w(L_{BC} + L_{DE}) = 0$$

where, $S_{BC} = -\frac{1}{L_{BC}}(M_{BC} + M_{CB} - \frac{wL_{BC}^2}{2})$

accordingly,

$$-\frac{1}{L_{BC}}(M_{BC} + M_{CB} - \frac{wL_{BC}^2}{2}) + P - w(L_{BC} + L_{DE}) = 0 \quad (32)$$

[8] Equation of ($S_{CD} - S_{DE} = 0$)

$$-\frac{1}{L_{CD}}(M_{CD} + M_{DC} + \frac{wL_{CD}^2}{2}) + \frac{1}{L_{DE}}(M_{ED} + M_{DE} + \frac{wL_{DE}^2}{2}) = 0 \quad (33)$$

where,

$$S_{CD} = -\frac{1}{L_{CD}}(M_{CD} + M_{DC} + \frac{wL_{CD}^2}{2}),$$

$$S_{DE} = -\frac{1}{L_{DE}}(M_{ED} + M_{DE} + \frac{wL_{DE}^2}{2})$$

[9] Equation of ($\Sigma M_A = 0$)

$$M_{AB} + \frac{wL_{AB}^2}{2} + \frac{wL_{BC}^2}{2} + wL_{CD}(L_{AB} + \frac{L_{CD}}{2}) + \frac{wL_{DE}^2}{2} - wL_{EF}(L_{AB} + L_{CD} + \frac{L_{EF}}{2}) + S_{EF}(L_{AB} + L_{CD} + L_{EF}) - P(L_{BC} - L_{DE}) = 0 \quad (34)$$

Resolve the 9 (nine) simultaneous equations from Eq. (26) to Eq. (34).

4. Verification by Commercial Software

4.1 Ceasar software

CAESAR II which is commonly used to design expansion spool in the industrial practice is a PC-based pipe stress analysis software program. This software package is an engineering tool used in the mechanical design and analysis of piping systems and allows the direct input of user-defined soil stiffness on a per length of pipe basis. Input parameters include axial, transverse, upward, and downward stiffness, as well as ultimate loads. Users can specify user-defined stiffness separately, or in conjunction with CAESAR II's automatically generated soil stiffness.

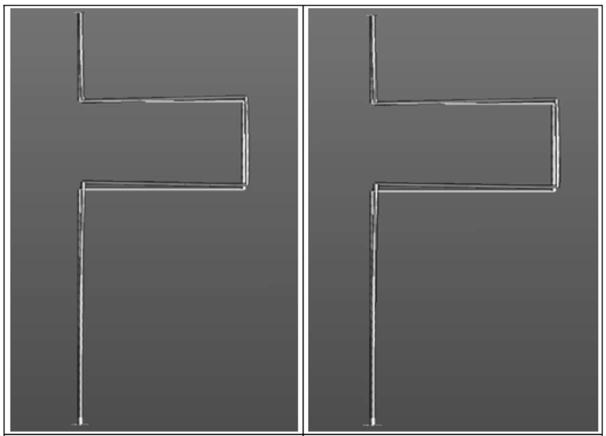
4.2 Verification by caesar software

The calculation approach by slope deflection method to design expansion spool is developed using Mathcad spread sheet and the analysis results between them will be compared to verify in order that the slope deflection method results is acceptable or not.

The verification will be performed through the case number 18 in Table 1 and each case is calculated with different variable such as spool length, soil friction, expansion load and submerged pipe weight. These results were compared with slope deflection method.

4.3 Expansion spool displacement configuration

The displacement configuration is almost same between the results from slope deflection and the results from Caesar software in Fig. 5.



Configuration from Slope-deflection	Configuration from Caesar incorporating the seabed

Fig. 5 Displacement configuration of SD and Caesar

Table 1 Case for expansion spool type verification

No.	Case	Variables						Remark
		Friction/Expansion load or pipe submerged weight	L_{AB}	L_{BC}	L_{CD}	L_{DE}	L_{EF}	
			ft	ft		ft		
1	Case 1	0.5/41 kips	20	20	20	20	80	Spool length change
2	Case 2	0.5/41 kips	20	20	20	20	70	
3	Case 3	0.5/41 kips	10	20	20	20	80	
4	Case 4	0.5/41 kips	30	20	20	20	80	
5	Case 5	0.5/41 kips	20	30	20	30	80	
6	Case 6	0.5/41 kips	20	40	20	40	80	
7	Case 7	0.5/41 kips	20	20	30	20	80	
8	Case 8	0.5/41 kips	20	20	40	20	80	
9	Case 9	0.5/41 kips	30	40	30	40	80	
10	Case_5F1	0.3/41 kips	30	40	30	40	80	Friction change
11	Case_5F2	0.4/41 kips	30	40	30	40	80	
12	Case_5F3	0.6/41 kips	30	40	30	40	80	
13	Case_5P1	0.5/30 kips	30	40	30	40	80	Expansion load change
14	Case_5P2	0.5/60 kips	30	40	30	40	80	
15	Case_5P2	0.5/80 kips	30	40	30	40	80	
16	Case_5W1	0.5/30 kips	30	40	30	40	80	Pipe weight change
17	Case_5W2	0.5/50 kips	30	40	30	40	80	
18	Case_5W3	0.5/90 kips	30	40	30	40	80	

4.4 The calculation results between SD and Ceasar

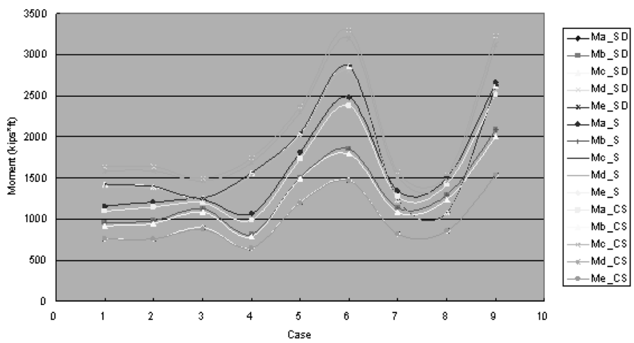


Fig. 6 Analysis results for the spool length change

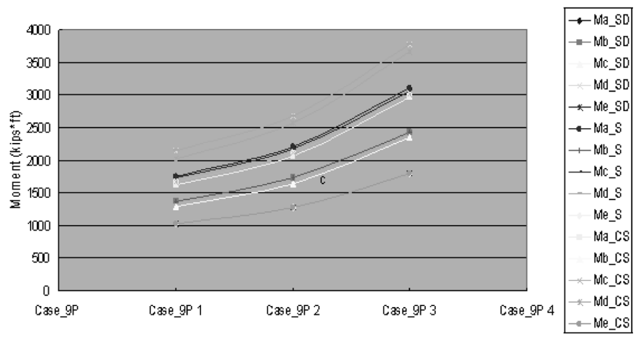


Fig. 8 Analysis results for the expansion load change

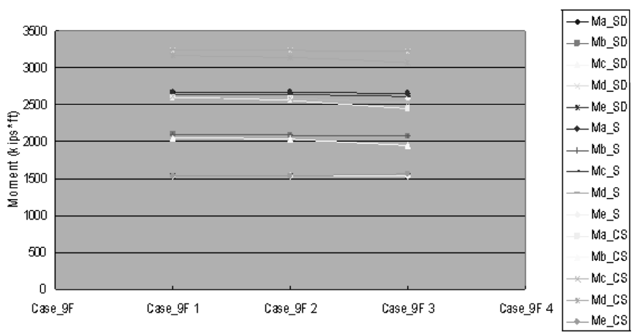


Fig. 7 Analysis results for the soil friction change

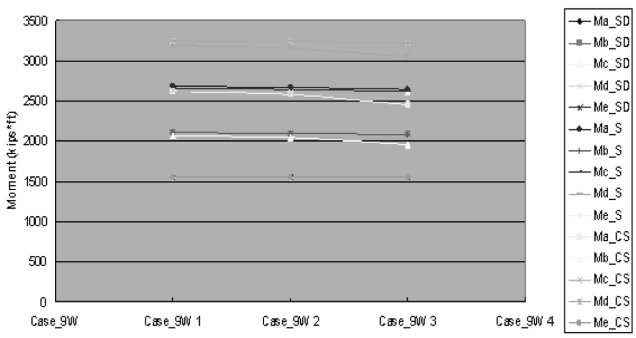


Fig. 9 Analysis results for the submerged pipe weight change

Table 2 Average values of each moment from analysis

Case	Slope deflection				Structural analysis					
	MA	MB	MC	MD	MA	MB	MC	MD	ME	
AVG	2086	1660	2127	2586	1240	2086	1660	2127	2586	1240
Case	Caesar model including Soil friction and stiffness									
	MA	%*	MB	%*	MC	%*	MD	%*	ME	%*
AVG	1985	95	1597	96	2084	98	2500	97	1238	100

where,

Mx_SD : Results from slope deflection
Mx_S : Results from structural base analysis
Mx_CS : Results from Caesar with soil

The Structural base analysis is performed to verify whether there are any mistakes in the calculation itself.

5. Conclusions

Considering the values between Mx_SD and Mx_S defined in Table 2 are same, it can be understood that the calculation process of slope deflection is correct.

While the results of Caesar including soil friction and stiffness is not the same with the results of slope-deflection method, but the results from Caesar model are maintained in the range of 94~100% of the results of slop deflection method, that is, the results from slope-deflection method is bigger than the results from Caesar model.

Therefore, it is considered that the result from slope deflection method is reasonable and expansion spool design by slope deflection method is feasible for practical design work.

Consequently, the design method using slope-deflection method which is developed from this study is feasible for the purpose of preliminary design and FEED of expansion spool. It's expected that final expansion spool design by commercial software becomes more and effective and accurate through the pre-process of preliminary design by slope-deflection method.

Acknowledgements

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