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Analytical Modeling of Well-Conductor Seabed Interaction in Complex Layered Soil in Newfoundland Offshore

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ABSTRACT

This paper presents an analytical study of the well-conductor in complexly layered soil by providing a theoretical basis for the stability of wellhead. Arbitrary seabed soil stratum from Newfoundland deep offshore was considered, where the seabed sediments have distinct layers with varying properties and thickness which has a certain effect on the lateral loading capacity of the casing string. Considering the lateral loads on the top of the casing string, variable stiffness of casing string and the geomechanical characteristics of the soil layers, the differential equation of casing deflection and its solutions were established below the mudline, and the results of the modal analysis were obtained. The study revealed the importance of soil layers with different stiffness on the peak bending moment and deflection of the conductor system. The influence is more significant in the shallower layers closer to the sea bottom. It was observed that an in-depth knowledge about the geological data of the layered soil is of paramount importance for the accurate design of the conductor and surface casing. The analytical approach was found an appropriate system for early assessment of conductor system performance in layered soil condition.

RÉSUMÉ

Cet article présente une étude analytique du conducteur de puits dans un sol à couches complexes en fournissant une base théorique pour la stabilité de la tête de puits. On a examiné la couche de sol arbitraire des fonds marins de Newfoundland au large des côtes, où les sédiments des fonds marins ont des couches distinctes ayant des propriétés et une épaisseur variables, ce qui a un effet certain sur la capacité de charge latérale de la colonne de cuvelage. Compte tenu des charges latérales au sommet du train de tassement, de la rigidité variable de celui-ci et des caractéristiques géomécaniques des couches de sol, l'équation différentielle de la flexion du tubage et ses solutions ont été établies sous la ligne de boue et les résultats de l'analyse modale ont été obtenus. L'étude a révélé l'importance de couches de sol de rigidité différente sur le moment de flexion maximal et la déflexion du système conducteur. L'influence est plus importante dans les couches moins profondes plus proches du fond de la mer. Il a été observé qu'une connaissance approfondie des données géologiques du sol stratifié était d'une importance primordiale pour la conception précise du conducteur et de la gaine. L'approche analytique s'est révélée être un système approprié pour l'évaluation précoce de la performance du système de conducteur dans des conditions de sol en couches.

1 INTRODUCTION

Typical offshore drilling operations are carried out using drilling risers and subsea Blowout Preventer (BOP) stacks deployed from drilling rigs. The BOP is placed on top of the subsea wellhead sometimes called the mudline wellhead which is located at sea bottom. While drilling the oil well, surface pressure control is provided by a blowout preventer (BOP).

If the pressure is not contained during drilling operations by the column of drilling fluid, casings, wellhead, and BOP, a well blowout could occur. Since the force transferred to wellhead through the bottom joint of the riser and the weights of BOP stack and all casing strings themselves have been undertaken by conductor and surface casing, vertical load-bearing capacity is important for determination of running depth of conductor and providing basis for prohibition of wellhead sinking (Guan et al., 2009).

However, conductor-seabed interaction plays a vital role in well integrity assessment in deep water drilling operation. Layered soil strata are often found in Newfoundland offshore. The ability to understand the interaction between the layered seabed and the casing string is essential for the accurate design and analysis of the conductor systems. Analytical solutions are very useful for the fast assessment of the riser performance at the early stages of design, prior to comprehensive numerical simulations. The seabed soil stratum is usually modeled with simplified homogeneous media represented by linear elastic springs. Variation of the soil stiffness through different soil layers may affect the structural response of the conductor system.

In this study, the differential equations proposed by Guan et al. (2009) were solved and the layered soil data from NL offshore was used to analytically investigate the lateral response of the well-conductor system.

2. LAYERED SEABED SOIL IN NEWFOUNDLAND OFFSHORE

Complex layered soil is quit common in NL offshore such as Flemish Pass Basin, 500 km away from St. John's coast line. The layered soil are also regularly observed in other Canadian offshore territories such as Beaufort Sea. Blasco et al. (1990) found that marine and continental regions are layered in Canadian Beaufort shelf. The overview of historical Beaufort Sea according to Timco and Frederking shows that the subsea sediments of Beaufort sea consist of 0.5m to 35m marine clays or silty clays.

In order to provide geotechnical engineering data for design of the conductor in the Jeanne d'Arc Basin, an investigation was done by Thompson et al. (1983). Sediments in this region consist of discontinues and thin layers of stiff clay.

Therefore; one of the most important parameters that may have influence on the mechanisms of the soil and soil deformation is the soil discontinuity such as soil layering.

Many of the theoretical solutions have been developed for homogeneous seabed soil condition without considering the effect of different layers stiffness. This may have significant impact on system performance.

The layered soil properties that were used in the current study are given Table and 2.

Table 1: Layered soil properties in central FPB

components	depth (m)	initial modulus (kN/m3) undrained shear strength (MPa)	dry density (Mg/m3)	underwater bulk density (kN/m3)	at depth
very dense sand	0 7	14.7	1.676	6.63156	7
layered sands and clays	7 11	0.083	1.618	6.06258	63.3
very dense to dense sand	11 60	14.7	1.818	8.02458	18.33
hard silty clay	60 63	0.216	1.666	6.53346	61.6
layered sand, silt and clay	63 74.2	0.083	1.618	6.06258	63.3
hard silty clay	74.2 79	0.216	1.666	6.53346	61.6
layered sand, silt and clay	79 92	0.083	1.618	6.06258	63.3
hard silty clay	92 96	0.465	1.297	2.91357	95.4
layered sand, silt and clay	96 104	0.626	1.329	3.22749	95.5

Table 2: Layered soil properties in Western FPB

components	depth (m)	initial modulus (kN/m3) undrained shear strength (MPa)	dry density (Mg/m3)	underwater bulk density (kN/m3)	at depth
very dense to dense sand	0 40.8	14.7	1.676	6.63156	26.35
hard silty clay	40.8 43	0.465	1.297	2.91357	95.4
dense sand	43 51.5	14.7	1.676	6.63156	7
hard clay	51.5 55.5	0.405	1.346	3.39426	54.4
layered sand, silt and clay	55.5 66.2	0.083	1.618	6.06258	63.3
hard silty clay	66.2 74	0.45	1.33	3.2373	71.4
layered sand, silt and clay	74 84	0.083	1.618	6.06258	63.3
hard silty clay	84 130	0.515 0.266	1.329 1.297	3.22749 2.91357	87.4 97.6

3. ANALYSIS MODEL OF LATERAL LOAD-BEARING CAPACITY FOR CONDUCTOR IN LAYERED SOIL

The mechanical behaviour of structures that are in contact with the layered soil is affected by the interaction between the soil and the conductor. An analysis model of lateral load-bearing capacity suitable for conductor and surface casing for deep water is presented.

3.1 Force Analysis

Environmental forces from the ocean are transferred to the subsea wellhead from the riser. Theoretical analysis has proved that dynamics loads on the subsea wellhead transferred by the riser are the bending moment and vertical force.

Then, the deflection differential equation of pipe string under the interaction of transverse moment and vertical force of casing string below the mudline is obtained according to the mechanical equilibrium relationship.

$$\frac{d}{dx^2}\left[EI(x)\frac{d^2y}{dx^2}\right]+\frac{d}{dx}\left[N(x)\frac{dy}{dx}\right]+D(x)\cdot p(x,y)=0 \qquad [1]$$

Where: $EI(x)$ $(\mathrm{kN}\cdot m^2)$ is the flexural rigidity changes along x axis, $N(x)$ (kN) is the axial force changes along x axis, $D(x)$ (m) is the variable outer diameter of the pipe string, $p(x,y)$ is the subgrade reaction per unit area: $p(x,y)=\bar{p}(x,y)/D(x)$ (kPa). Pipe strings above the mudline do not suffer from the subgrade reaction: $p(x,y)=0$.

3.2 Subgrade Reaction

According to different assumed conditions, the calculation methods of the subgrade reaction p can be divided into 3 kinds:

(i) Limit of subgrade reaction method: Without considering the deformation of the foundation itself, p is the function of depth: $p = p(x)$;

(ii) Elastic subgrade reaction method: Assuming that p is proportional to the nth power of the deflection of the pipe string: $p = kx^m y^n$, where k is a coefficient determined by the properties of the foundation which is also related to the choice of the exponential m $(m \geq 0)$, n $(0 < n \leq 1)$.

(iii) Elastoplastic subgrade reaction method: Here, the plastic region is analyzed with limit of subgrade reaction method while the plastic region is analyzed with elastic subgrade reaction method. Then the transverse reaction can be solved with the continuous condition of the boundary of the elastic region and the plastic region. Since it can describe the nonlinear characteristics between pipe strings and the foundation, it is able to make more exact analysis on the lateral loading-bearing capacity with large displacement of pipe string comparing to other methods. It has been adopted in the API RP 2A named as $p - y$ curve method. When no experimental material is available, theoretical equations provided by the practice can be referred to for the calculation of the $p - y$ curve of clay and sandy soil.

Secant modulus of the subgrade reaction at depth x can be determined according to the $p - y$ curve($E_s = p/y$), and therefore p corresponding to different y can be determined $(p = E_s y)$.

Substitute p with $p = E_s y$ in equation (1), we have:

$$\frac{d}{dx^2}\left[EI(x)\frac{d^2y}{dx^2}\right] + \frac{d}{dx}\left[N(x)\frac{dy}{dx}\right] + D(x) \cdot E_s y = 0 \qquad [2]$$

3.3 Forces

Risers in the deep-water conditions suffer from complex stress: the transverse component of the bottom tension, weight of the BOP and current force acting on it will render transverse moment M_t on the wellhead while the resultant force of the vertical component of the bottom tension and weight of the BOP is the vertical force N_t on the wellhead.

Axial force on the pipe string can be described as:

$$N(x) = \begin{cases} N_t + W(x) \cdot x & (x \leq x_{\mathrm{ml}}) \\ N_t + W(x) \cdot x - F_f(x)(x - x_{\mathrm{ml}}) & (x > x_{\mathrm{ml}}) \end{cases} \qquad [3]$$

Where, x_{ml} is the length of the pipe string above the mudline (m), $W(x)$ is the weight of the pipe string per unit length (kN), $F_f(x)$ is the soil friction on the external wall of the pipe string per unit length (kN).

3.4 Flexural Rigidity

If there is a double layer casing pipe structure with cement sheath at the upper cementing segment of the combination pipe string, the equivalent flexural rigidity K_1 is:

$$K_1 = E_{\mathrm{st1}}(I_{\mathrm{so}} + I_{\mathrm{si}}) + 0.6 \cdot E_{\mathrm{c}} I_{\mathrm{c}} \qquad [4]$$

where, E_{st1} is the modulus of elasticity of the steel of the pipe string (kPa), I_{so} is the moment of inertia of the surface casing (m^4), E_c is the modulus of elasticity of the cement sheath (kPa), I_c is the moment of inertia of the cement sheath (m^4).

If there is a double layer casing pipe structure at the upper segment of the combination pipe string without cement sheath, the equivalent flexural rigidity K_2 is:

$$K_2 = E_{\mathrm{st1}}(I_{\mathrm{so}} + I_{\mathrm{si}}) \qquad [5]$$

If it is a combination structure of cement sheath and surface casing rather than a conductor at the lower section of the combination pipe string, the equivalent flexural rigidity K_3 is:

$$K_3 = E_{\mathrm{st1}} I_{\mathrm{si}} + 0.8 \cdot E_{\mathrm{c}} I_{\mathrm{c}} \qquad [6]$$

4. NUMERICAL SOLUTION OF THE ANALYSIS MODEL OF LATERAL LOAD-BEARING CAPACITY

In this paper, the effect of layered soil mechanical properties on the well conductor integrity is investigated using the analytical method.

Since the reaction between pipe string and the foundation is quite complex, the length L of the pipe string can be equally divided into n segments with difference method. The length of each segment is h . Set the top node of the pipe string as node 0 while the bottom node of the pipe string is node n. Prolonging the two ends and set virtual node -1, virtual node -2, virtual node n+1, and virtual node n+2 as shown in Figure 1.

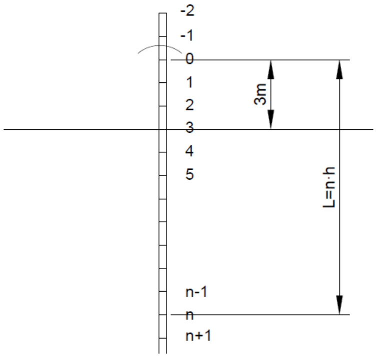


Figure 1: Numerical grid of casing string

The derivative scheme in Eq. [2] can be approximately substituted by the difference scheme. Then Eq. [2] becomes (n+1) difference equations.

$$\begin{cases} a_i y_{i+2} + b_i y_{i+1} + c_i y_i + d_i y_{i-1} + e_i y_{i-2} = 0 \\ a_i = (EI)_{i+1} \\ b_i = -2(EI)_{i+1} - 2(EI)_i + N_i h^2 \\ c_i = (EI)_{i+1} + 4(EI)_i + (EI)_{i-1} - 2N_i h^2 + D_i (E_s)_i h^4 \\ d_i = -2(EI)_i - 2(EI)_{i-1} + N_i h^2 \\ e_i = (EI)_{i-1} \end{cases} \quad [7]$$

Boundary condition: when there is a moment M_t at node 0 on the top of the pipe string, internal force of the pipe string will have the same value as it but in opposite direction, that is: $M_0 = -M_t, Q_0 = 0$. As for the pipe string which dives relatively deep in to the soil, the node at the bottom end can be regarded as a free end, that is: $M_n = 0$, $Q_n = 0$.

Difference of boundary conditions gives 4 equations. Together with equation [7], there are n+5 equations to solve the variables in n+5 nodes. Since the poor precision of matrix expunction computation, Gleser method is generally used to get the expression of y_i $(i = -2, -1, \ldots, n+2)$ through transformation. Since $(E_s)_i$ varies nonlinearly, the calculation needs to be performed by iteration. Firstly, a group of $(E_s)_i^0$ are assumed. There is no subgrade reaction on the pipe string above the mudline: $E_s = 0$. A group of y_i^o will be obtained after solving them for once, with which a group of p_i^0 will be obtained according to the $p - y$ curve. Then according to $E_s = p/y$, a new group of $(E_s)_i^1$ can be obtained. Using the new $(E_s)_i^1$ to repeat the iteration process until $\left|(E_s)_i^0 - (E_s)_i^1\right| < \varepsilon$, where ε is the allowable accuracy condition. The deflection (transverse displacement) of each node on the pipe string can be obtained, therefore rotation angle θ_i, moment M_i, shear Q_i, subgrade reaction p_i of each node can be calculated.

$$\begin{cases} \theta_i = -\dfrac{y_{i+1} - y_{i-1}}{2h} \\ M_i = -\dfrac{(EI)_i (y_{i+1} - 2y_i + y_{i-1})}{h^2} \\ Q_i = -\dfrac{(EI)_{i+1} y_{i+2} - [2(EI)_{i+1} - N_i h^2] y_{i+1}}{2h^3} + \\ \dfrac{(EI)_{i+1} y_{i+2} - [2(EI)_{i+1} - N_i h^2] y_{i+1}}{2h^3} \\ P_i = (E_s)_i y_i \end{cases}$$

[8]

5. Example and analysis of influencing factors:

Parameters of a deepwater well in Newfoundland offshore area are:

Conductor: length 85 m, outer diameter 914.4 mm, wall thickness 25.4 mm, weight per unit length 7.8 kN/m

Surface casing: length 650 m, outer diameter 508 mm, wall thickness 12.7 mm, weight per unit length 2.1 kN/ m, modulus of elasticity is 210 GPa

Cement sheath between two casing strings:

Modulus of elasticity is 18 GPa, weight per unit length is 45 kN/m

Length of pipe string above the mudline is 3m

Assuming in the adverse ocean environment maximum transverse moment conveyed to the wellhead is 3MN*m, vertical force is 1MN. To simplify the calculation, assuming it is clay layer from the mudline to 100 meters below it, of which the underwater bulk density is 7.0 kN/m^3 and the shear strength is 20 kPa.

The default input parameters are shown in Table 3.

Input Data				
Section	Characteristics		Value	Unit
wellhead	length of pipe string above mudline	xm1	3	m
	mum transverse moment on the well	Mt	3	MN·m
	vertical force on the wellhead	N	1	MN
conductor	length	Lcd	85	m
	outer diameter	dcd	914.4	mm
	wall thickness	tcd	25.4	mm
	weight per unit length	Wcd	7.8	kN/m
surface casing	outer diameter	dsc	508	mm
	wall thickness	tsc	12.7	mm
	weight per unit length	Wsc	2.1	kN/m
	modulus of elasticity	Estl	210	Gpa
cement sheath between casings	modulus of elasticity	Ec	18	Gpa
	weight per unit length	Wc	45	kN/m
	return height		0	m
soil layer (Western Locatoin sheet)	depth range (under mudline)		130	m
	underwater bulk density		-	kN/m3
	initial modulus		-	kN/m3
Calculated Constants				
Section	Characteristics		Value	Unit
conductor	inertia moment of the conductor	Iso	0.00701	m-4
surface casing	inertia moment of the surface casing	Isi	0.00061	m-4
cement sheath	inertia moment of the cement sheath	Ic	0.02403	m-4
double layer casing pipe structure with cement sheath	equivalent flexural rigidity	K1	1.85981	GPa
cement sheath and surface casing	equivalent flexural rigidity	K3	0.47344	GPa

5.1 Effects of the Forces on the Wellhead

As shown in Figure 2 to 6, an analysis was performed on the lateral load-bearing capacity of the combination pipe string under the interaction of different transverse moments and vertical forces.

The result shows that the transverse displacement, rotation angle, moment, shear, and subgrade reaction are almost zero when the depth goes over a certain value. That is, the forces on the wellhead only concentrate on a relatively short region at the upper pipe string and hardly bring any effects on the lower region.

Comparing the effects of different values of forces, the conclusion is that the transverse displacement on the top of pipe string has relatively obvious increase when the transvers moment is greater. Meanwhile, the moment and shear of the pipe string increase gradually with the increase of the transvers moment. Transverse displacement and moment become larger when there is a greater vertical force acting on the top of the pipe string. However, the effects of vertical force is not as obvious as the effects of the transverse moment. Forces undertaken by the subsea wellhead in deepwater drilling come from BOP stack above the wellhead, risers, drilling platform in the ocean environment. It’s very important to reasonably control the drifting of the platform and the drilling ship and tension force on the top of the risers to guarantee the stability of wellhead and pipe strings.

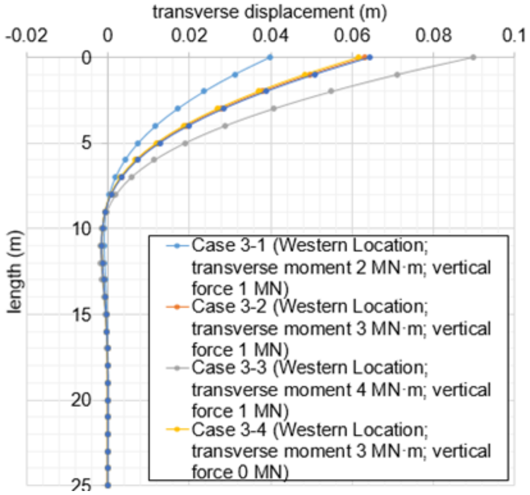


Figure 2: Transverse displacement

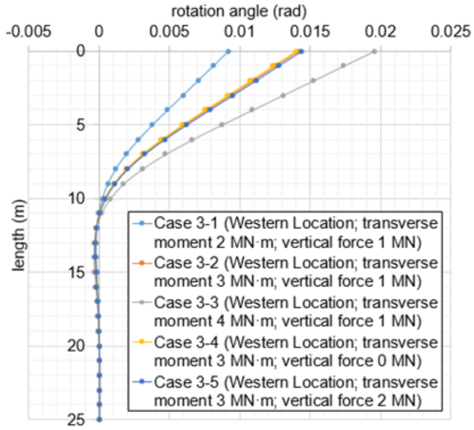


Figure 3: Rotation angle

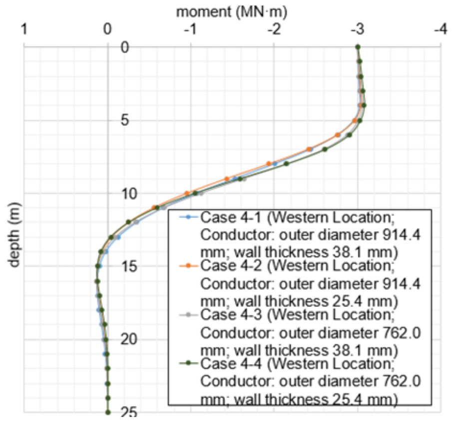


Figure 4: Moment

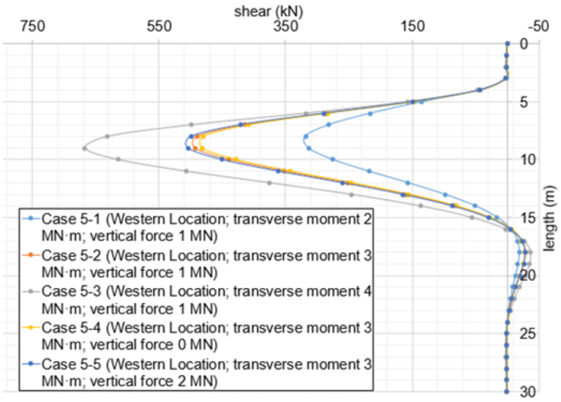


Figure 5: Shear force

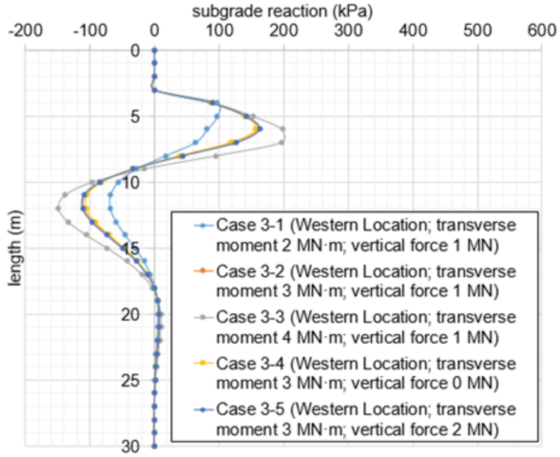
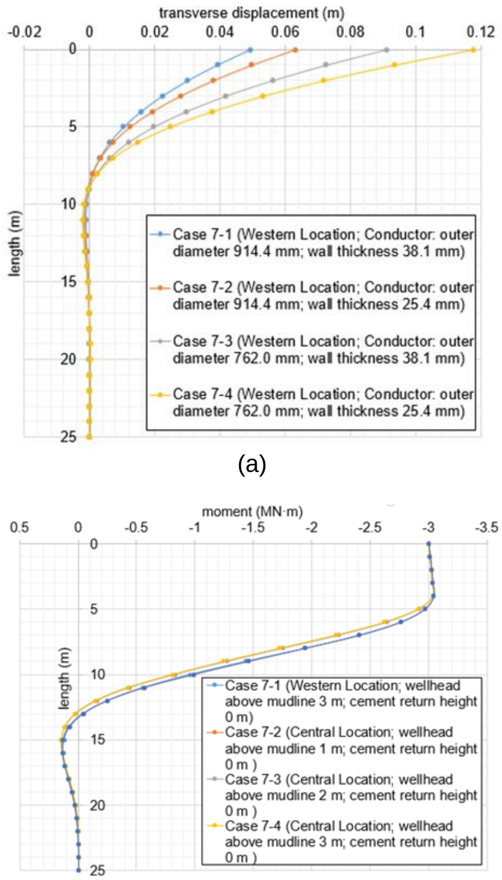


Figure 6: Subgrade reaction

5.2 Effects of The Diameter and Wall Thickness of The Conductor

As shown in figure 7, analysis has been done on lateral load-bearing capacity of pipe string with different outer diameters and wall thicknesses.

The results illustrate that transverse displacement of the pipe string gradually decreases with increase diameter. Bending resistance of the pipe string increases with increase in the wall thickness. When the value of loading is certain, diameter and wall thickness do not have great effects on the moment of the pipe string because the transverse displacement is relatively small.



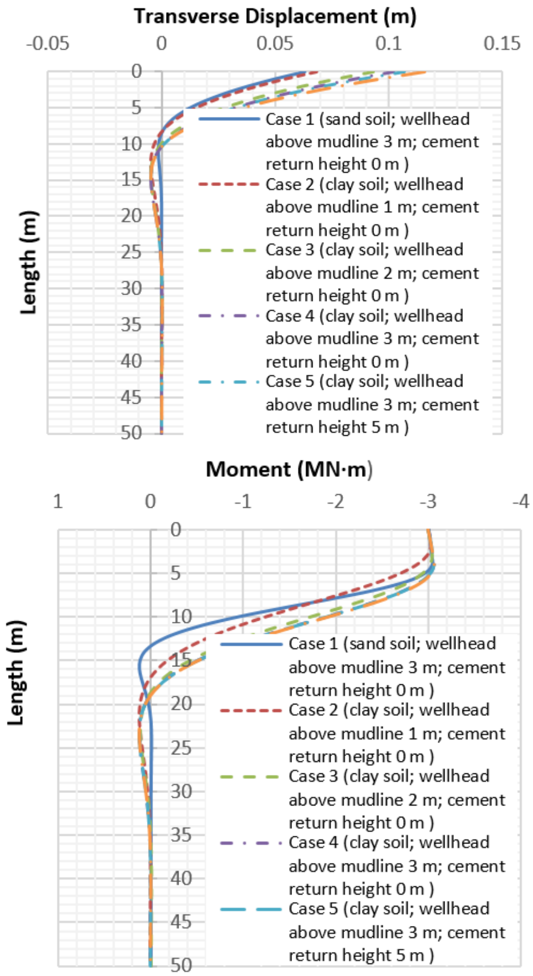
(a)

(b)

Figure 7: a., Transverse displacement , b., Moment.

5.3 Effects of the Distance between Mudline and Wellhead, Cement Return Height, and Type of Foundation

Analysis was performed on lateral load-bearing capacity of pipe string while changing the distance between mudline and wellhead, the return height of the cement sheath on the surface casing, and the layered soil as shown in figure 8. The results illustrate that the larger distance is between the wellhead and mudline. However, scouring at the mudline has great effects on the lateral load-bearing capacity of the casing strings. Since relatively less contribution to the flexural rigidity of the combination pipe string has been made by the cement sheath, the return height of the surface casing does not have great effects on the transverse displacement and moment of the pipe string. When it is the sandy soil foundation, the transverse displacement and moment of the pipe string is smaller than those in the clayey soil foundation, meanwhile the length of the pipe being affected is also shorter (Guan et al., 2009).



6. CONCLUSIONS

In this study the influence of well-conductor seabed interaction in a complexly layered soil in Newfoundland Offshore was investigated analytically. The dynamic differential equations of the casing deflection below the mud line and its numerical solutions were established. It can be concluded that the seabed sediments have a certain effect on the lateral loading capacity of the casing string with a more significant effect in the shallower layers closer to the sea bottom. Distance between wellhead and mudline has relatively great effect on the lateral load-bearing capacity of the pipe string. Cementing sheath return height degree of the surface casing does not have great effect on the transverse displacement and moment of the pipe string. However, the diameter and the wall thickness of conductor also have effects on the bending moment of the pipe string. Hence, increase in wall thickness causes increasing the bending resistance of the pipe string.

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