Master Thesis in Marine Technology - 2013
Upheaval Buckling of Buried Pipelines

Shengsheng Fan
shengshf@stud.ntnu.no
Supervisor(s): Professor svein.savik

NTNU – Trondheim
Norwegian University of Science and Technology

Problem

The main purpose of this thesis was to develop a MATLAB program based on Terndrup-Pedersen' analytical method for upheaval buckling analysis and verify the analytical model by comparing with FE analysis using software SIMLA. Analytical method is very useful during the screening design work, which may save a lot of time during the start stage. However, it is necessary to develop a program that may efficiently implement the analytical method, it is very important to verify that the analytical model will give good results for design. The thesis will describe and formulate the Terndrup-Pedersen model in terms of inputs and related procedures. Comparison of analytical model and FE model is to be made to verify the analytical model. In addition, an elastic-plastic pipe model was built in SIMLA to investigate the plastic behavior of pipe and its effect on the pipeline design. Some suggestions for using the analytical model are made according to the results of cases study.

Introduction

Pipelines have been the main way of transporting oil and gas from offshore districts all over the world in the last decades. Pipelines are buried to avoid interference with other marine activities, like fishing activity. Pipeline operating at high temperature and pressure are subjected to global buckling due to the plane strain condition introduced by axial soil friction and or subsea facilities. While lateral or horizontal buckling occurs for exposed pipelines, upheaval or vertical buckling occurs for buried or trenched pipelines.

Palmer and Baldry [1] published the first paper on pipeline buckling in 1974. It is demonstrated that the constraint of expansion of a pipeline on account of raised internal pressure could induce buckling through a small-scale test. Then in 1981 and 1984, Hobbs [2-3] summarized basic models of buckling of pipeline. A major interest at that time was to study thermal induced buckling as some upheaval buckling (UHB) incidents occurred in the North Sea. Guijt, Nielsen N J R, Lyngberg B, and Pedersen T [4-5] pointed out several incidents caused by upheaval buckling of pipelines occurred around 1990. The failure of pipeline caused a significant of loss due to repairs and loss of production. Thermal induced buckling became a vital problem for oil and gas industry afterwards and a substantial study has been conducted in the past 30 years on upheaval buckling.

Analytical modeling of the upheaval buckling response of buried pipelines has progressed rapidly in the last decades [6-12]. It is initially progressed from the classical analysis method for vertical stability of railroad. Then it is further studied to pipeline with initial imperfections, pipeline with additional cover material with non-linearity and pipeline with large displacements. A significant number of studies have been conducted by Taylor and Gan, Boer, Friedman, Richards and Andronicou, Ju and Kyriakides, Pedersen and Jensen, Ballet and Hobbs [6-12], which mainly focus on the imperfection studies. The basic models presented by Hobbs [2-3] have been modified and refined with considering the pipeline imperfection and the elastic-plastic behavior of buckling pipelines in the past decades. Recently, numerical methods [15-17] have been applied to analyze the upheaval buckling of pipeline. All those progress contribute to improve the accuracy and consistency of upheaval buckling assessments.

References

[1] Palmer A C, Baldry J A S. Lateral buckling of axially-compressed pipelines[J]. Journal of Petroleum Technology, 1974, 26 (11): 1283-1284.
[2] Hobbs R E. Pipeline buckling caused by axial loads[J]. Journal of Constructional Steel Research, 1981, 1(2): 2-10.
[3] Hobbs R E. In-service buckling of heated pipelines[J]. Journal of Transportation Engineering, ASCE, 1984, 110(2): 175- 189.
[4] Guijt J. Upheaval buckling of offshore pipeline: overview and introduction [C]// In proceedings of the 22nd Annual OTC. Houston, Texas, 1990: 573-578.
[5] Nielsen N J R, Lyngberg B, Pedersen P T. Upheaval buckling failures of insulated burial pipelines-a case story[C]// In proceedings of the 22nd Annual OTC. Houston, Texas, 1990: 581-592.
[6] Ballet J P, Hobbs R E. Asymmetric effects of prop imperfections on the upheaval buckling of pipelines[J]. Thin- Walled Structures, 1992, 13: 355-373.
[7] Taylor N, Tran V. Prop-imperfection subsea pipeline buckling[J]. Marine Structures, 1993, 6: 325-358.
[8] Taylor N, Tran V. Experimental and theoretical studies in subsea pipeline buckling [J]. Marine Structures, 1996, 9(2): 211-257.
[9] Maltby T C, Calladine C R. An investigation into upheaval buckling of buried pipelines--i. Experimental apparatus and some observations[J]. International Journal of Mechanical Sciences, 1995, 37(9): 943-963.
[10] Maltby T C, Calladine C R. An investigation into upheaval buckling of buried pipelines--ii. Theory and analysis of experimental observations[J]. International Journal of Mechanical Sciences, 1995, 37(9): 965-983.
[18] Pedersen P T, Jensen J J. Upheaval creep of buried heated pipelines with initial imperfections[J]. Marine Structures, 1988, 1: 11-22.
[19] DNV. Recommended Practice DNV-RP-F110[S], Global buckling of submarine pipelines, 2007.
[20] Yong Bai, Qiang Bai. Subsea pipelines and risers[M]. 2005.
[21] Torgeir Moan. Lecture notes in TMR4190 - Finite Element Modelling and Analysis of Marine Structures. Department of Marine Technology NTNU, 2003.
[22] Torgeir Moan. Lecture notes in TMR4305 – Nonlinear Analysis. Department of Marine Technology NTNU, 2012.
[23] Svein Sævik. Lecture notes in TMR4305 – Advanced Dynamic Analysis. Department of Marine Technology NTNU, 2012.
[24] Svein Sævik. SIMLA - Theory Manual, 2008 edition.
[25] Bernt J. Leira. Kompendium for Marine Structure, Basic Course [M]. NTNU: August, 2011.

Acknowledgements

All the work in this thesis is done under the supervision of Professor Svein Sævik (Department of Marine Technology). I would like to express my deepest appreciation to him for his support and his discussion of my work during the last one year. His excellent work in pipeline analysis has greatly inspired me to devote myself to the research of pipeline.

I would also like to thank my co-supervisors and future colleagues, Tornes Knut and Helland Lars-Rune in JP Kenny, for their help and advice for my work. Their involvement in the thesis was essential for the development of the procedure of the thesis. I really appreciate the help from people in JP Kenny during the last semester.

I would also like to warmly thank my friends and some seniors at NTNU. Among these, I would like to mention Rui Zhang for his encouragement and help during the last six years, and Xiaopeng Wu for his help and guidance as I started my work on pipeline in SIMLA.

The content of this thesis is generated as my final thesis for the master degree in Marine Technology at NTNU. I would like to thank NTNU and Marintek for providing so many help, such as software, literature and services provided by them..

Modeling

The design method adopted in this thesis taken from Terndrup-Pedersen's [18] analytical model. Following the Hobb's [3] method, some other studies suggested that minimum - temperature criteria was insensitive to imperfections. A minimum-temperature criterion was suggested for analyzing subsea pipeline with initial imperfections. Pedersen's approach demonstrates if the pipeline with given initial imperfection is subjected to cyclic pressure and temperature load conditions, then Hobb's method can yield non-conservative result.

Analysis of Buckle Region:

Assume a linear beam theory of the imperfection pipe uplifted in the x-w coordinate system, as shown in Figure 1, the vertical equilibrium differential equation can be given as equation 1.

$$EI\frac{d^4}{dx^4}(\omega-\omega_P)+N\frac{d^2\omega}{dx^2}+q=0 \qquad (1)$$

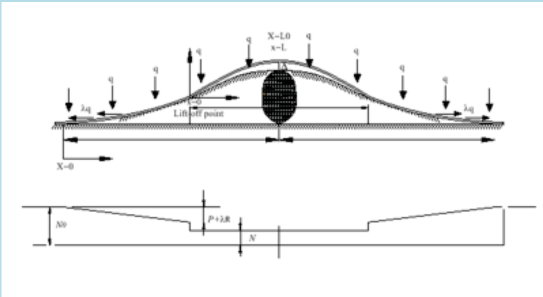

Figure 1 Force distribution along pipeline

Where, q is the total download due to the pipe submerged weight and burial resistance in the buckle region, *EI* is the bending stiffness of the pipe, N is the buckle force, ω_P is the pipe imperfection, ω is the uplift of the pipe.

The equation may be rewritten as equation 2.

$$\frac{d^4\omega}{dx^4}+k^2\frac{d^2\omega}{dx^2}+\left(\frac{q}{EI}-\frac{d^4\omega_P}{dx^4}\right)=0 \qquad (2)$$

Where, $k^2=\frac{N}{EI}$ and $\alpha=\frac{q+q_P}{EI}=\frac{q}{EI}+\frac{72\delta_P}{L_0^4}$

The solution may be written as equation 3,

$$\omega(x)=A\cos(kx)+B\sin(kx)+\frac{1}{k^2}\left(-\frac{1}{2}\alpha x^2+\beta x+\frac{\alpha}{k^2}+\gamma\right) \qquad (3)$$

The parameter *k* and *N* in the equation is determined by the boundary condition and may be calculated from equation corresponding to a uplift of 2cm, according to the following equation 4.

$$\left(\frac{\alpha}{k^3}+\frac{\gamma}{k}\right)\sin(kL)-\left(\frac{\beta}{k^2}-\kappa\right)\cos(kL)+\frac{1}{k^2}(-\alpha L+\beta)=0 \qquad (4)$$

Where, β γ α κ A & B are parameters dependent on L.

Other results like effective axial force and allowable buckle temperature may be calculated by equation 5 and 6 based on the compatibility of displacement.

$$N_0=N+\left[\lambda q A_s E\int_0^L\left(\left(\frac{d\omega}{dx}\right)^2-\left(\frac{d\omega_f}{dx}\right)^2\right)dx-(\lambda qL)^2\right]^{0.5} \qquad (5)$$

$$N_0=\frac{\pi}{4}E\alpha_S(D_e^2-D_i^2)\Delta T+\frac{\pi}{4}(1-2\nu)(P_iD_i^2-P_0D_e^2) \qquad (6)$$

Simulations

Based on the analytical model, a group of cases with imperfection level δ_P varying from 0.1m to 0.6m has been defined and analyzed in both analytical model and FE model. In addition, a group of burial depth H varying from 0.4m to 1.6m has been studied for each imperfection level. For each case with given imperfection level and burial depth, the magnitude of allowable operating temperature, buckle force in the buckle region, effective axial force away from buckle region and maximum bending moment given by the analytical can FE method are compared to inspect and verify the analytical model. The relative deviation between the analytical results and FE results is therefore identified. Due to symmetry, as shown in figure 2, half of the actual pipeline is modeled in two models as shown in figure 3.

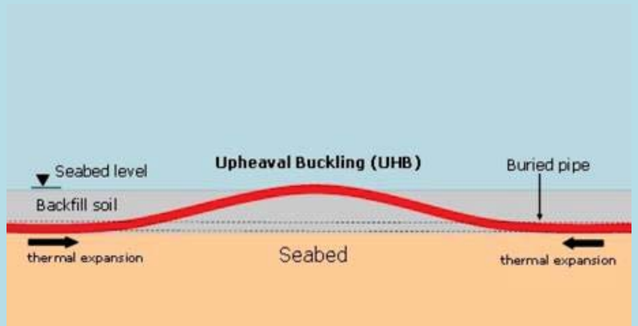

Figure 2 Actual configuration

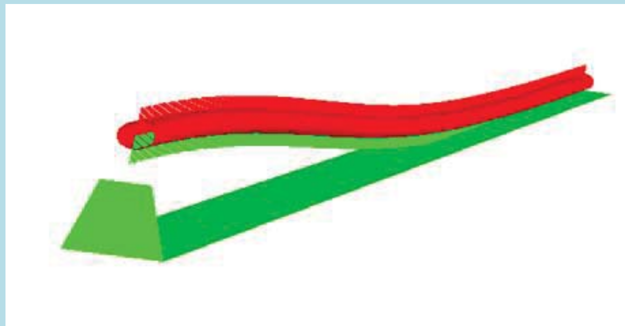

Figure 3 Model in SIMLA

A summary of the axial force and maximum bending moment and corresponding allowable temperature rise will be given in Figure 4-6, which also gives out how they vary as the burial depth increases. To be noted, the value of interest is taken from a state where the maximum uplift reaches 2cm at the left hand side of the FE model.

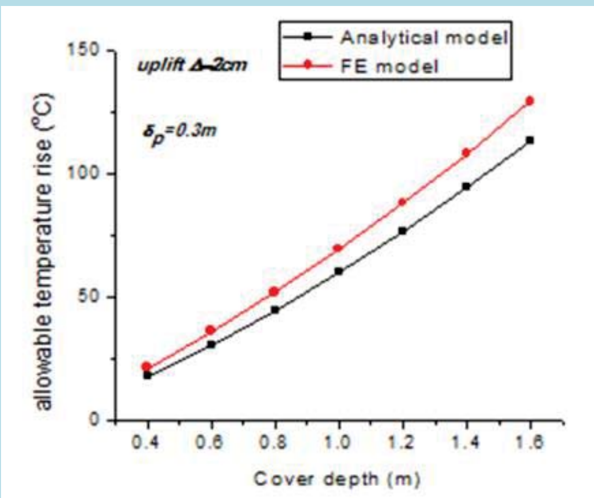

Figure 4 Temperature rise versus cover depth, $\delta_p=0.3m$

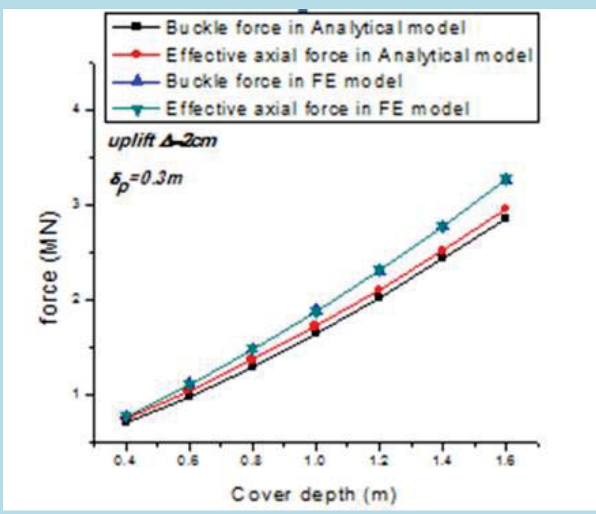

Figure 5 Force versus cover depth, $\delta_p=0.3m$

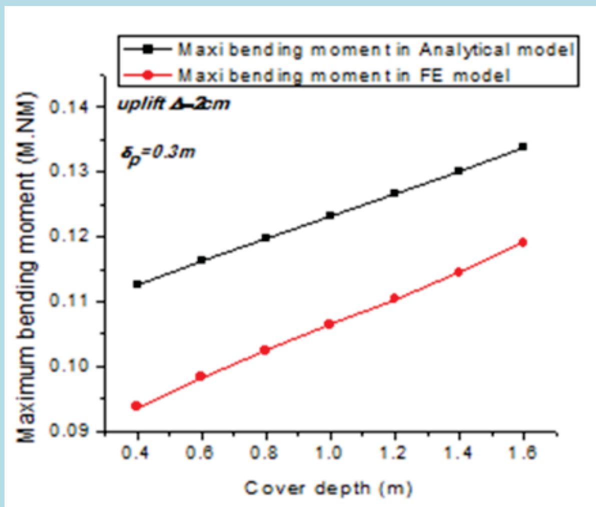

Figure 6 Max bending moment versus cover depth, $\delta_p=0.3m$

Conclusions

By comparing the results of analytical and FE model, according to the discussions presented in chapter 8, it is clearly verified the analytical model proposed by Terndrup-Pedersen will always give results that will be consistent with results of FE modeling in SIMLA. The MATLAB program developed is able to implement the analytical method and give very good results for design. However, it should be noted that the analytical model will always give conservative results compared with the results given by FE model.

The simulations of both analytical model and elastic FE model clearly indicate the allowable operating temperature and buckle force will decrease significantly as the imperfection level increases, on the contrary the maximum bending moment will increase as the imperfection level increases. It is also evident to see the allowable operating temperature and buckle force will increase as the burial depth increase, while the maximum bending moment increase a little bit and is nearly a constant for given imperfection level.

The comparison study of the analytical and FE model in section 8.6.1 clearly shows the deviation of the analytical and FE results. The analytical model tends to give results close to FE model for large imperfection levels, say 0.3m or larger in the thesis, while the deviation may be larger for small imperfection level, say 0.2m or smaller. As it has been discussed, it is affected by the difference in the modeling of soil/pipe model in two models. The penetration of pipe into the seabed in the FE model may result a difference. The assumption that the foundation is infinite stiff will always lead to conservative results. Bear in mind that the soil/pipe interaction should be considered in detail design stage for give pipeline design projects. In this thesis, all the comparison is based on fact that the pipe will have a penetration of about 0.013m, which is greatly dependent on the soil conditions or soil stiffness where the pipeline is to be installed. It would be wise to make some refinements or modifications for the analytical model after considering the soil conditions. It may be achieved by introducing some safety factors, say about 1.5 for small imperfection level and 1.1 for large imperfection level, to refine the results given by the analytical model, according to discussion in section 8.6.2.

Furthermore, it is found that the burial depth will have little effect on the deviation between the analytical and FE model, namely the burial depth will not influence the accuracy of the analytical model, according to discussion in section 8.6.3.

Finally, it is also found the elastic-plastic properties of the pipe will affect the design temperature and buckle force to some extent. The results given by the elastic pipe model will always give conservative results for design. Therefore it is wise to take the elastic-plastic material properties into consideration.