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A 3-DIMENSIONAL CONTINUUM ALE MODEL FOR ICE SCOUR – STUDY OF TRENCH EFFECTS

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ABSTRACT

A new Arbitrary Lagrangian Eulerian (ALE) Finite Element (FE) model of ice scour was recently developed by the authors. It is based on continuum representation of the soil. It was shown in recent papers that such a model can characterize the mechanics of the ice-soil-pipeline interaction without requiring any of the assumptions that the Winkler models depend on. The model utilizes soil properties obtained by conventional laboratory testing. In a recent paper, this model was used to show that the subscour deformations and ice-soil interaction forces are very sensitive to ice ridge geometries for shallow slope ice features. In this paper, the ALE FE ice scour model is utilized to study the effects of the pipeline trench on the scour process and the forces transmitted to the pipeline. Two different infill soil properties and two different ice ridge geometries are analyzed with a 36 inch diameter pipe buried to in a trench of 1.5 m cover.

It is shown that the scour process near and in the trench is significantly different than in the ambient seabed soils and the recognition of this may present some potential advantages for the protection of the pipelines not recognized by the Winkler models. It is also shown that the pipeline loads generated during the scour process are cyclic. They build slowly as the ice moves over the trench and then reverse as the ice ridge moves away from the trench. This is in contrast to monotonic and rapidly growing loads predicted by the Winkler models. The paper shows that the loads transferred to the pipeline depend on the infill soil properties placed in the trench. It is shown that loads experienced by the pipeline are less for the softer infill than stiffer soils.

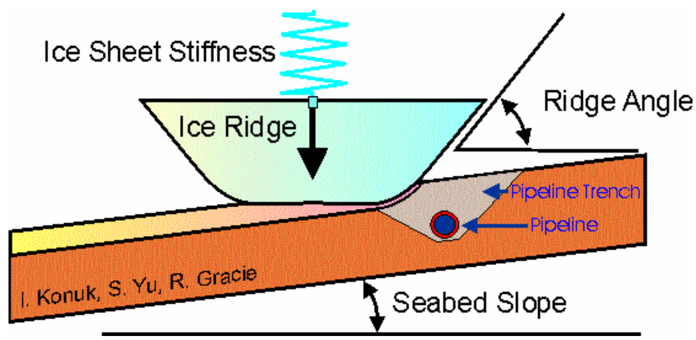

Figure 1. Illustration of Elevation View of Ice Scour Process

INTRODUCTION

Offshore pipelines in the Beafort Sea have to be designed against ice scour by ice ridges. Analysis of the scour process requires modeling of large deformations of the pipeline and the soils around it (Palmer et.al. [1]). Figure 1 illustrates the cross section of the scour process. As shown in that figure, pipeline would be normally placed and buried in a trench. The burial material may be the remolded or reworked soils removed originally from the trench or some other material brought from elsewhere.

As described by Palmer [1], many papers were published in the last decade or so that presented analysis models for design of pipelines against ice scour. Current design methods and most published work are based on Winkler models where the soils around the pipeline is idealized using inelastic springs and soil displacements arising during the scour process are

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modeled as prescribed displacement of the Winkler foundation supporting the pipe. Such models rely on empirical soil deformations functions and also employ numerous assumptions. One of the important assumptions required by the Winkler models is that the soils deformations are not effected by the presence of the pipeline or the pipeline trench. Other shortcomings of the Winkler models were illustrated in a paper by Konuk et.al. [2].

In recent years, several numerical models were published by different authors. A brief review of these models can be found in Konuk et.al [3]. As presented in [3], most of these models have serious shortcomings. Firstly, since the approach utilized in these models do not necessarily incorporate a rigorous advection algorithm incorporating equation of conservation of mass, the models may generate or vanish soil mass during the process. Secondly, the models are intrinsically static and allow only relatively short translation of the ice ridge. As a result, these models can not ensure that a mechanically admissible (satisfying conservation of momentum, conservation of mass, and equation of compatibility) steady state process is established. In fact, as shown in [3], an ice ridge travel distance of at least 5 times the scour width is required to generate a steady state scour simulation. As shown in recent papers by the authors [3, 4], ALE FE method can overcome these difficulties when applied in an explicit (time domain) dynamic framework.

Neither the Winkler models nor the numerical models mentioned above consider the effects of the pipeline and the trench on the ice scour process. It can be easily visualized that steady state scour process will transform to a transient state when the soil mound accumulated in front of the ice ridge reaches to the pipeline trench and the subscour deformations interact with the pipeline. Explicit ALE FE method is well suited to model this transient process. This paper applies the explicit ALE FE model developed in [3] and [4] to study the effects of the trench and the pipeline.

FINITE ELEMENT MODEL DESCRIPTION

The ALE method was developed originally for solving fluid-structure interaction problems. It is recently recognized that ALE is one of the few rigorous numerical methods for solving problems combining large deformations and large mass movements along with significant density variations. In the ALE method, the analysis undergoes three major steps. In the first step, a standard Lagrangian FE analysis is conducted. In the second step, the FE mesh is remapped based on some smoothing criteria. The remapping algorithms can be based on the stresses and the deformations obtained in the previous time step or on the mesh topology. The third step in the ALE approach is the advection phase. In this step, the discretized strain, mass, and momentum parameters are computed for the nodes of the new mesh (or the original mesh if using Eulerian mesh such as in this paper) using laws of conservation of mass and momentum. In this paper, the ALE algorithm implemented in the LS-DYNA software (Hallquist [5]) is utilized to model the ice scour process. A detailed description of the algorithm can be found in Souli et al. [6] and Aquele et al. [7].

A special case of ALE FE method is chosen in this paper to model the ice scour process. In the special application of the ALE method adopted in the ice scour model, the mesh is kept stationary (Eulerian mesh), thus avoiding the second step of the ALE method. In order to provide space for the berm and the mound expected to accumulate in front of the ice ridge, a third component consist of "void" material is laid over the soil part.

Finite element discretization is done using LS-DYNA (Version 970) Explicit FE software (LSTC [8]). All analysis is conducted as a dynamics problem incorporating inertia effects. Ice ridge is represented by a conical rigid body. Typical finite element mesh used for implementing this model is illustrated in Figure 2. Two versions of the cone indentor are used in this paper with the ridge angle of 30 degrees and 45 degrees (See Figure 1). In all models presented in this paper, the ice scour width is 15 m.

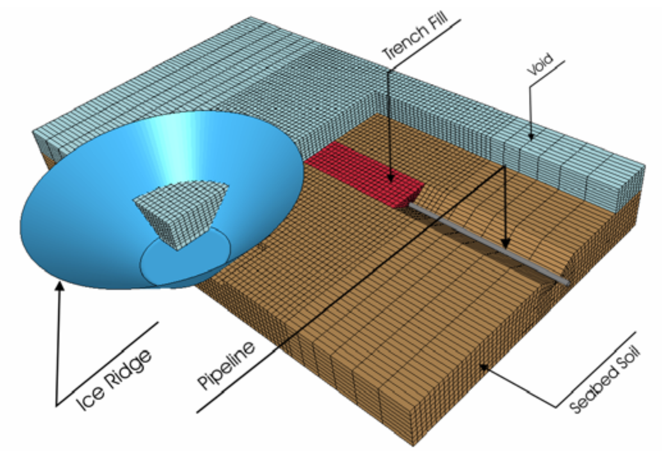

Figure 2. Illustration of the FE Model

The essential parts of the developed model are the seabed soil, the trench, the void, the ice ridge, and the pipeline. Soil in the seabed as well as the trench is modeled using 8 node constant stress (one point integration) solid elements. The void consists of solid 8 node constant stress elements that initially contain no material. The depth of the void layer is chosen to accommodate the berm on the sides of the ice ridge and the soil pile expected to develop in front of the ridge. The ice ridge motion is defined by prescribing its velocity. The soil and the void elements are defined as "Eulerian" elements. Thus, the soil and the void element nodes are fixed. Soil mass is allowed to move through both the soil and the void meshes. The ice indentor moves through these Eulerian meshes. A penalty based contact with friction between the soil and the ice indentor induces the dislocation (plowing) of the soil as the ice indentor moves through the soil and void elements.

The 36 inch diameter pipe is discretized using shell elements. In analyses conducted in this paper, the pipe is modeled as a rigid structure and kept stationary at its original position. Similar to the soil-ice contact, soil-pipe contact is defined using penalty functions. The vertical and horizontal forces acting on the pipe are recorded during the execution of the model.

All degrees of freedom for the nodes at the bottom of the model are fixed. The vertical degrees of freedom for nodes at the sides of the model are left free. The depth and width of the model are selected to ensure that the boundary effects are negligible. The location of the trench is determined such that the scour process can reach to a steady (almost periodic) state by the time the soil mound in front of the ice ridge riches to the trench or the subscour deformations connect with the pipeline. In order to determine the steady state condition, berm geometry is monitored along with the ice-soil contact forces and the soil particle trajectories.

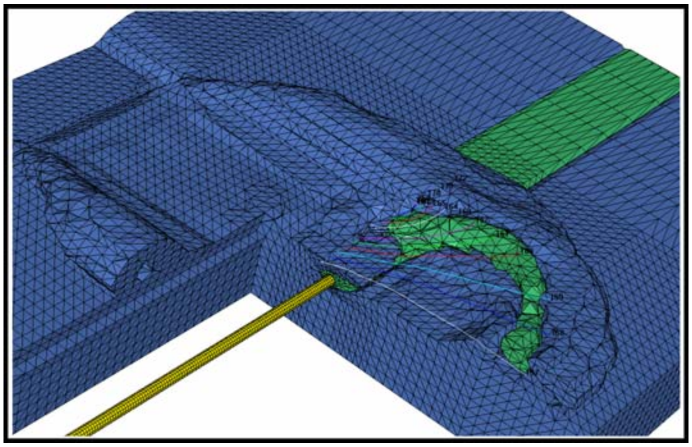

Figure 3. Visualization of Typical Output from the ALE FE Model – 45 Degree ice ridge, 1 m deep scour, pipe burial depth 1.5 m, Trench Soil#2 – Ice travels from the upper left to lower right corner.

Soil mass is initially taken to be stress free. However, in order to prevent artificial hardening, the CAP position is moved forward for each layer corresponding to the surcharge load due to the weight of the soil layers on top. The loads and displacements are imposed in three stages. In the first step, gravitational acceleration is applied. Sufficient time is allowed to ensure that the soil stresses reach a stationary state. This step ensures that the stress state in the seabed soil is representative of the natural conditions and is mechanically admissible with the soil constitutive model used in the analysis. Initially, ice ridge is kept outside the top soil layers. In the second step, the ice ridge is accelerated following a sinusoidal ramping function starting with zero velocity. In the third step, after the ice ridge reaches to the soil boundary, its velocity is kept is constant and it moves across the model at a constant speed until a steady state condition is reached. All translational and rotational degrees of freedom of the indentor, other than translation in the direction of the scour, are constrained. In all analysis presented in this paper, ice ridge speed is taken to be 1 m/s.

The CAP soil constitutive model used in this paper was originally developed by Simo et al. [9]. The soil is assumed to be a single phase material in this paper. Detailed discussion of choice of CAP constitutive model can be found in [3] and [4]. The soil parameters used in the ALE FE model is given in the Appendix. Two types of soils somewhat softer than the ambient seabed soils are used to cover the pipeline and fill the trench. The Trench Soil#1 is taken to be softer than the Soil#2.

DISCUSSION OF RESULTS – SCOUR PROCESS NEAR THE TRENCH

Typical graphical outputs from the model are illustrated in Figure 3. In this figure, the blue color elements indicate ambient seabed soil and the trench soil is designated by green color. Empty void elements are removed, and only partially or completely full soil elements are shown. This figure also contains the trajectory of the Trace particles that were placed at 0.5 m depth and at a location 1 m ahead of the pipe axis.

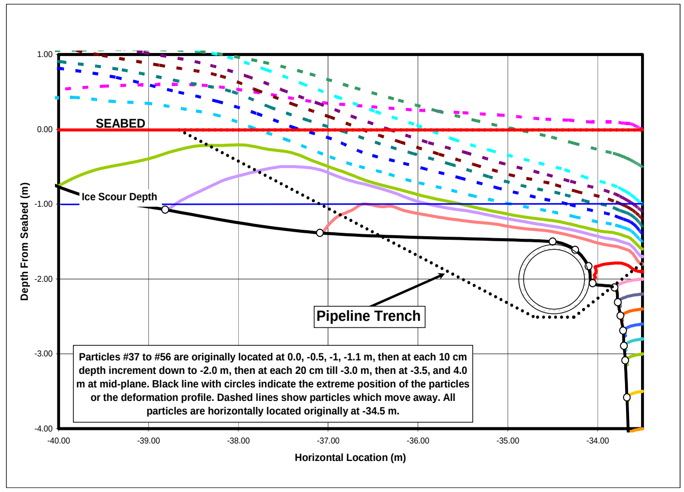

Figure 4. Example of Particle Trajectories and Sub-scour Deformation – 30 Degree ice ridge, 1 m deep scour, pipe burial depth 1.5 m, Trench Soil#1.

Figure 4 show the trajectories of the soil particles for particles from the scour surface to a depth of 4 m in the mid-vertical-plane in the direction of the scour at 1 m ahead of the pipeline axis. Several general aspects of the soil deformation field in the sub-scour region may be observed from Figure 4. Similar to the soil particle traces presented in [3] and [4], the soil (particles) underneath the scour initially moves slightly down. However, this movement is much smaller than in the case of the ambient seabed soils and almost unnoticeable in the figure. Immediately afterwards, the soil particles in the trench start moving upwards at a faster rate than the ambient soil and appear to follow the trench and the seabed soil interface. As can bee seen from Figures 3 and 4, the soil particles that are pushed up the trench are eventually pushed down and trapped between the ambient seabed soils mass. In the process, significant amount of soil is pushed out of the pipeline trench. This is illustrated in Figure 5 which shows the trench soil material for three different cases. In this figure, the ambient seabed soil material is removed. In some of the cases illustrated in Figure 5, the original infill or cover soil is totally removed from around the pipeline. This however does not mean that the pipe is exposed after the ice ridge passes over. In fact, the ambient seabed material brought in front of the ice ridge is pushed over the pipeline.

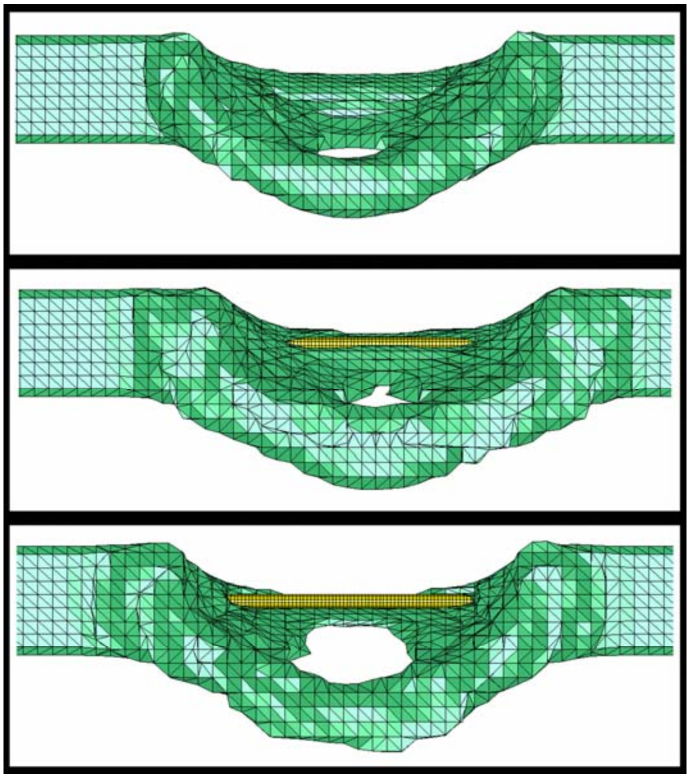

Figure 5. Three Examples of the Trench Soil after Ice Ridge moves over the Trench – a) Trench Soil#2, 45 Degree Ice Ridge, b) Trench Soil#1, 45 Degree Ice Ridge, c) Trench Soil#1, 30 Degree Ice Ridge.

Most important and distinct aspect of the soil particle traces for soils in line with the pipeline axis is that when they reach to the pipeline surface, they either turn down or up depending on their elevation with respect to the pipe axis, therefore, being pushed around the pipe. It is clear that the pipe generates a discontinuity in the soil deformation profile which is very different then the soil deformation profile if the pipeline and trench were not there. This is illustrated in Figure 6 where different soil deformation profiles are shown. In Figure 6, the soil deformation profiles for the particles behind the pipe show that the pipe acts as a shield for soil particles directly behind it.

The significance of the trench is also observed in the forces encountered by the pipeline. In Figure 7, solid green line shows the total horizontal force encountered by the pipe. As can bee seen there, this force gradually increases until the front of the ice ridge reaches to the pipeline axis. Then, the force decreases at the same rate as it increases and eventually becomes negative. This means that the pipeline is first pushed forward and then backward by horizontal forces of about the same magnitude. The peak average force per unit length of pipe is about 1 Ton/m. Figure 7 shows that the horizontal forces derived from the ALE FE model are very different than the forces calculated by the Winkler models [2]. Although in this paper, the pipe is fixed and rigid which means that the loads calculated here are an upper limit, depending on the soil properties, the peak load values calculated by the ALE FE model is somewhat lower than the Winkler models.

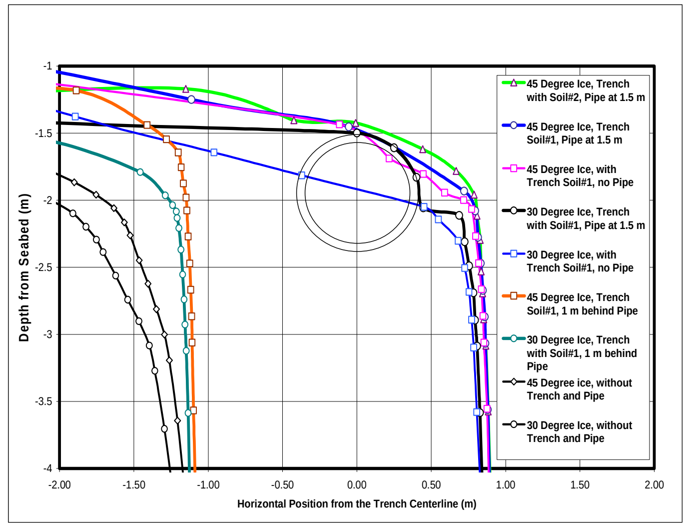

Figure 6. Comparison of Soil Deformation Profiles

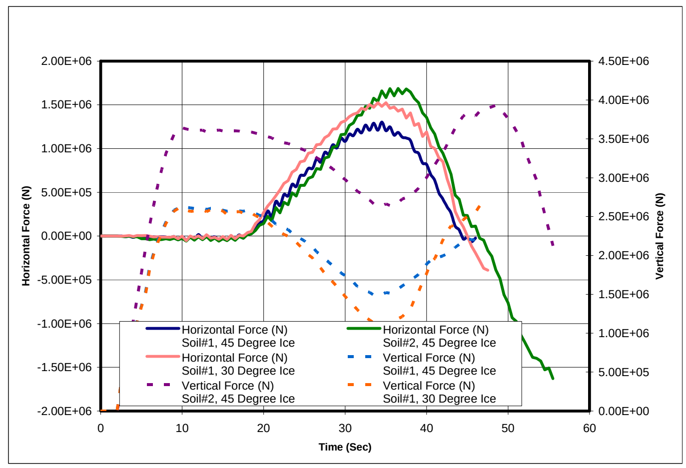

Figure 7. Vertical and Horizontal Pipe Forces

However, the two most important aspect of the pattern shown in Figure 7 is that the horizontal loads vary gradually and they are cyclic. It can be seen that the pipe is first pushed forward and then pushed back by forces of similar magnitude. Both of these aspects conflict with the Winkler model outputs. Due to bearing failure concept, the loads would rapidly increase in Winkler models and level off after a small soil-pipe displacement. It would be logical to conclude that the soil loads on the pipeline in the Winler models would be more uniformly distributed than the ALE FE model. Although pipe stresses are beyond the scope of this paper, this would result with higher pipe stresses near the scour edge in the Winkler models. In addition, since the Winkler models are monotonic, the loads either continue to increase or level off. The load reversal can, therefore, not be captured in Winkler models.

It is shown in this section that the presence of the trench and the pipe significantly modify the deformation pattern in the soil and the loads applied to the pipe are cyclic. Both the load reversal and the gradual application of scour loads on the pipeline can be beneficially utilized by the pipeline designer.

The effects of these factors on the pipeline stresses will be studied in more detail in a future paper.

DISCUSSION OF RESULTS – EFFECTS OF INFILL PROPERTIES AND ICE RIDGE ANGLE

Figure 6 contain soil deformation profiles for different combinations of soils and ice ridge angle with pipe and without it. First, the effect of the ridge angle will be discussed. As was observed in [4], the soil deformation profiles obtained by the ALE FE model indicate boundary layer type behavior. It was concluded in [3] that the thickness and shape of this boundary layer depends greatly on the ice ridge angle especially for shallow ridges (less than 30 Degrees). This is confirmed again here and appears to be more pronounced in the trench area. As it can be seen from the comparison of the soil profiles in the trench without the pipe, the thickness of the boundary layer for the 45 Degree ice ridge is about 0.5 m. The boundary layer thickness for 30 Degrees is about 1 m. This difference in boundary layer thickness is less pronounced in the profiles for the ambient seabed soils. From Figure 6, one can see that the influence of the pipe on the soil deformation profile is dependent on the pipeline burial depth with respect to the boundary layer thickness or location. It is seen in that figure that the soil profile is hardly affected for 45 Degree ice ridge as the boundary layer nicely fit over the pipe. However, in the case of 30 Degrees ice ridge, the ambient boundary layer in the trench cuts across the pipe axis and a discontinuity is generated when the pipe is introduced. These patterns would be expected to be slightly different for a flexible pipe. However, since the soil particle movements are much larger than the pipe deformations, the difference is not expected to be significant.

A study of the horizontal forces concludes that the pipe loads are not significantly affected by the ridge angle. It appears that simple presence of the trench provides protection to the pipeline. However, the study of the same figures for different soil types show that the stiffer the infill soil, the higher the horizontal loads experienced by the pipeline. It can bee seen in Figure 7 that the vertical pipeline loads are significantly higher for the stiffer Soil#2. More detailed study of infill properties can be beneficial in the design of the pipelines. In fact, no-infill may provide the optimum design choice for ice scour protection purposes. However this is beyond the scope of this paper as the analysis of unburied flexible pipe will be presented in a future paper.

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REFERENCES

[1] A.C. Palmer, I. Konuk, A.W. Niedoroda, K. Been, K.R. Croasdale, Arctic Seabed Ice Gouging and Large Sub-gouge Deformations, The International Symposium on Frontiers in Offshore Geotechnics, Perth, Western Australia, September 19 to 21, 2005.

[2] Konuk, I, Fredj, A., A FEM model for Pipeline Analysis of Ice Scour, Offshore Mechanics and Arctic Engineering Conference, Vancouver, Canada, 20-25 June 2004, paper OMAE2004-51477.

[3] I. Konuk, S. Yu, R. Gracie, An ALE FEM Model of Ice Scour, accepted for publication to the 11th International Conference of the International Association of Computer Methods and Advances in Geomechanics, Turin, Italy, June 19-21, 2005.

[4] I. Konuk, R. Gracie, A 3-Dimensional Eulerian FE Model for Ice Scour, International Pipeline Conference, Calgary, Alberta, October 2004, paper IPC04-0075.

[5] LS-DYNA Theoretical Manual, Livermore Software Technology Corporation, compiled by John O. Hallquist, May 1998.

[6] M. Souli, A. Ouahsine, L. Lewin, "Arbitrary Lagrangian Eulerian Formulation for Fluid-Structure Interaction Problems", Computer Methods in Applied Mechanics and Engineering , Volume 190, Pages 659-675, (2000).

[7] Aquelet, N., Souli, M., "A new ALE Formulation for Sloshing Analysis", Structural Engineering and Mechanics, Volume 16, Number 4, (2003).

[8] LS-DYNA Keyword User's manual – Version 970, Livermore Software Technology Corporation, Livermore, California, April 2003.

[9] Simo, J.C., J.W. Ju, K.S. Pister, and R.L. Taylor, "Assessment of Cap Model: Consistent Return Algorithms and Rate-Dependent Extension", Journal of Engineering Mechanics, Volume 114, Number 2, Pages 191-218, (1988).

APPENDIX: SOIL CAP CONSTITUTIVE PARAMETERS

The following constitutive model parameters define the soil used in the model for the ambient seabed soil:

K = 10 MPa
G = 1 MPa
α = 500 Pa
γ = 0.0 Pa
β = 0.0 Pa-1
θ = 0.2
R = 4
W = 0.06
D = 1.26 E-06 Pa-1
ρ = 1400 kg/m3

The Trench soil properties differ from the ambient soil by only one parameter. For Soil#1, the parameter θ is taken to be 0.05 and for Soil#2, it is assumed to be 0.1. The notation used here is similar to the one used by Simo [9].