Wave-induced Mine Burial into Seabed;
Part 1: Cohesionless Seabed in Cyclic Liquefaction State

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LONG-TERM GOALS

1. Understand the physical insight into the mine burial process in the wave-induced cyclic liquefaction environment.
2. Develop a simple method to estimate burial depth of mines for engineering application.

OBJECTIVES

1. Develop numerical methods to simulate the behavior of wave-structure-seabed system in wave-induced cyclic liquefaction field, with special attention to liquefaction.
2. Develop centrifuge model test method for physical simulation of the behavior of wave-structure-seabed system in cyclic liquefaction field.
3. Study the mechanism of mine burial process in seabed that undergoes cyclic liquefaction compaction process due to wave-induced loading.
4. Develop a practical yet logical method to estimate burial depth of mine in the wave-induced cyclic liquefaction field.

APPROACH

This project is conducted in a joint effort of Defense Science and Technology Agency (DSTA) of Singapore and National University of Singapore (NUS).

Both physical and numerical simulations will be utilized to study the wave-induced mine burial mechanisms in wave-induced cyclic liquefaction field. The physical simulation will be carried out by centrifuge tests and one-dimensional column tests. The numerical simulation will be carried out at the

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micro- and macro-levels. The micro-level method will be based on the distinct element method (DEM) specially designed for liquefaction problem. The macro-level method will be the meshless method, which can easily consider the moving boundary and large deformation in the analysis. After understanding the behavior of seabed with or without an object in cyclic liquefaction field, main factors controlling the natural burial depth of a mine will be studied. In view of only the first order mechanism and effects, a simple method to predict rate of burial and the final burial depth will be developed with rational simplifications of the complex situation. Special attention will be paid to practicability and logicalness of the method.

Numerical simulations

The seabed may be cyclically liquefied within a shallow zone under severe wave loading. The condition of soil in this zone is transformed cyclically between fluidization status and regular soil status. Despite such complexity, the behavior of the medium may conveniently be handled by macro-scale Biot’s consolidation theory. The present problem requires a special consideration on the following factors in formulation: high nonlinearity of soil, large deformation, moving boundary at the interface of mine-seabed, interaction of wave and seabed, and anisotropy of hydraulic properties. Meshless methods will be developed to solve the boundary value problems with the Biot’s consolidation theory. This method uses only a cluster of nodes instead of elements to construct its shape functions, thus avoiding possible singularities that typically occur in the finite element method for large deformation and moving boundary problems. Therefore, the meshless method is especially useful for the present problem.

Cyclic liquefaction field undergoes both liquefaction and compaction cyclically. It is extremely difficult to use the Biot consolidation theory for such an environment because the theory does not have a rational basis to handle fluidization. On the other hand, the distinct element method (DEM) treats the soil mass as an assembly of solid particles and mass behavior is computed through the movements of an individual particle (Cundall and Stark 1979; Cundall et al. 1982; Ting et al. 1989). In view of such modeling, DEM may be more convenient to simulate the complex behavior that undergoes liquefaction-compaction process cyclically. Although its application to the analysis of soil behavior can be found just recently in this area (Sakaguchi and Muhlhaus 2000), the current DEM should be further developed to consider the effects of fluid in a more rational and computationally efficient manner.

Physical simulations

Liquefaction behavior is complicated. Its physical phenomenon will be observed scientifically in model tests under the controlled environment. Special attention will be paid to the soil behavior at / near the surface and mine-soil interface in liquefaction process. The soil behavior under nonlinear and liquefaction environment is highly dependent on the confining pressure that the soil is subjected to. It is therefore important to conduct the model tests under the realistic soil confining pressure.

A full-scale model test (1g) is difficult or even impossible to do for the ocean wave environment because of its size. A scaled-model test, on the other hand, is unfavorable for satisfying the scaling laws particularly for tests involving soils. This shortcoming can be improved to a significant extent by increasing the gravitational force in a centrifuge facility. In centrifuge model tests, the dynamic viscosity of pore water is typically adjusted because of inconsistency of the scaling laws between pore water diffusion rate and soil stress-strain behavior. This however may produce complexity in appropriate scaling for the drag force exerted to soil particles and wave loading to an object sitting in the seabed. In view of these, centrifuge experiments will be conducted at 50g and with carefully adjusted pore water viscosity with silicon oil in model. Centrifuge model tests were attempted just recently to study the behavior of seabed subjected to wave loading (Sekiguchi et al. 1995; 1999; 2001). However, these tests did not consider the effects of objects placed on seabed.

In the project, 1D soil-water column tests will also be carried out for observing mine burial process and soil liquefaction. An approximate wave-induced cyclic liquefaction field in seabed can be created conveniently in a 1D column test. Because of the one-dimensional condition, such test setting enables us to conduct the model tests on a portion of a full-scale or nearly full-scale seabed model without modification of the gravitational force. This allows us to observe more conveniently micro-level behavior particularly important at the seabed surface and interface at the seabed and mine.

Research team

Following list is the key individuals and their roles in the research team for this project:

Toyoaki Nogami, Ph.D. (PI) :	Principal Investigator
Ganeswara Rao Dasari, Ph.D. (Co-PI):	Experimental measurements and analysis
Pengzhi Lin, Ph.D. (Co-PI):	Experimental measurements and analysis
Jianguo Wang, Ph.D.:	Numerical simulations
Md. Rezaul Karim:	Numerical simulations
Chen Cheng, Bishwajit Chowdhury:	Graduate students working on this project

WORK COMPLETED

Although the ONR grant document is dated as February 2001, the funding was not received by National University of Singapore until June 2001. Furthermore, the funds from DSTA and NUS have not been received yet as of the time preparing this report. Thus, it is difficult to make a full effort at the present time. Despite the current situation, we have managed to form a research team and accomplish the following work.

Experiment device design

The problem of interest is to find interaction between seabed and mine placed on it due to wave loading (see Figure 1). The experimental investigation consists of two sections (i) Centrifuge Test, and (ii) One-Dimensional Soil-Water Column Model Test. The equipment necessary for the centrifuge testing has been designed, while that for one-dimensional soil-water column test is being designed. The principle and key apparatus are shown in Figure 1 and 2.

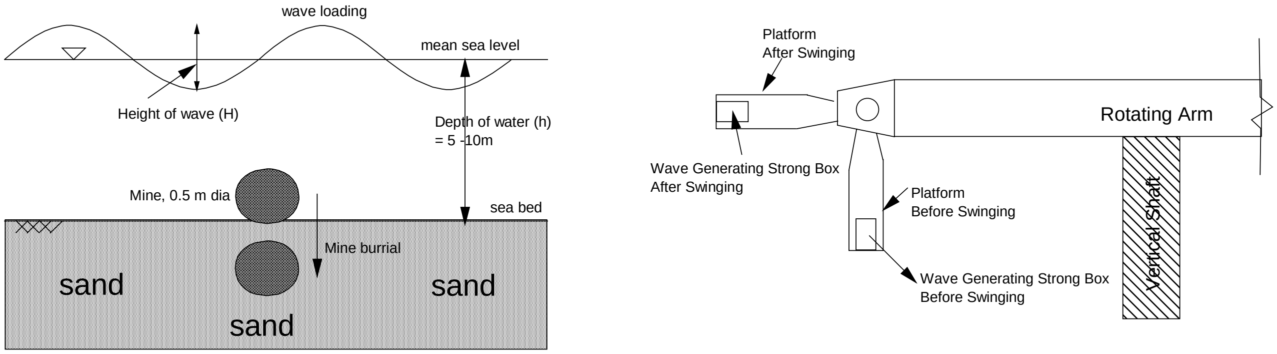

Figure 1 Schematic diagrams of (a) seabed-object interaction problem and object settlement process under wave-induced loading; (b) main components in centrifuge facility

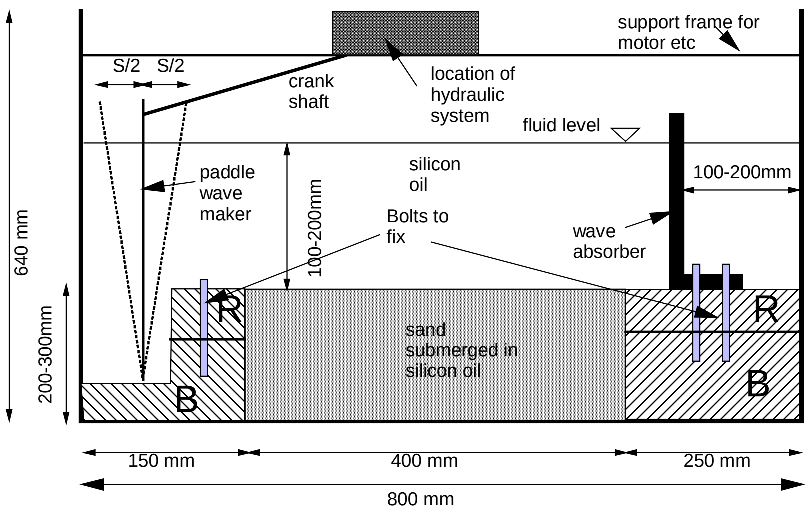

Figure 2 Strong box with wave maker and wave absorber to generate traveling wave

Numerical algorithm

1, Development of meshless method for wave-induced response analysis of seabed. The soil is assumed to be linearly elastic under traveling-wave and wave loading is directly applied on seabed surface. The algorithm is now being extended to consider the anisotropy of seabed soils, mechanical and hydraulic properties with depths, nonlineaity of soil, moving seabed surface etc.

2, Preliminary study on soil liquefaction and sediment re-suspension on seabed due to wave-current interaction.

RESULTS

A two-dimensional numerical approach is developed to analyze the transient response of saturated porous elastic seabed under cyclic loading. The approach is based on the element-free Galerkin method (EFGM) in which only nodes are used to discretize equations. Shape functions are constructed by moving least-square method, and essential boundary conditions are implemented through Lagrange multipliers. The model is applied to a typical two-dimensional transient problem as shown in Figure 3.

It is found that the present approach is simple and efficient in predicting the response of soil under cyclic load accurately.

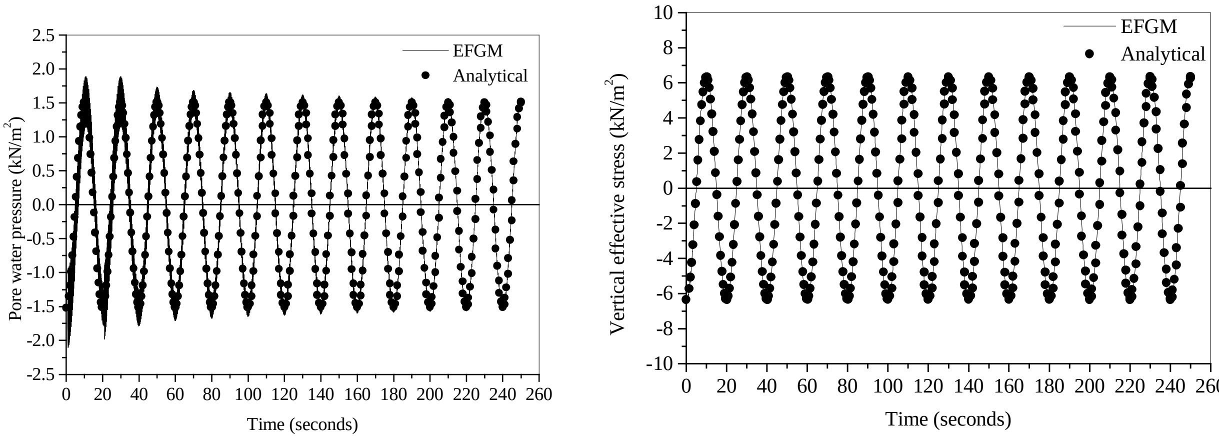

Figure 3 Comparison of wave-induced pore water pressure and vertical effective stress obtained by element-free Galerkin method and closed-form solution

A new liquefaction parameter is proposed that can be used to characterize the initiation of soil liquefaction in seabed. In general, the maximum value of liquefaction parameter is the function of wave parameters (e.g., wave height, wave number *k*, and water depth *h*) and soil properties (soil density, permeability, and elasticity). For saturated soils, however, the liquefaction criterion depends on wave parameters and soil density only. When the horizontal shear force and lift force contribution to liquefaction is neglected, soil will become liquefied when the liquefaction parameter exceeds 1.0. However, it is found that the liquefaction is most likely to occur when *kh=1.20*.

IMPACT/APPLICATIONS

The present research will develop numerical and physical methods to simulate the cyclic liquefaction behavior. As of today, no satisfactory numerical model and method are available for such a simulation. A centrifuge modeling method will be developed for physical simulation of wave-structure-seabed interaction and cyclic liquefaction behaviors. This will be the first carefully calibrated centrifuge modeling method for such physical simulation. The engineering method to estimate the mine burial depth will be developed for wave-induced cyclic liquefaction. The expected method is based on scientific understanding of the mechanism. If the cyclic liquefaction is a major role for burying a mine, such an engineering method will be of great value to the Navy community.

TRANSITIONS

The physical simulation method and numerical method to be developed will have a wide application to the problems related to soil liquefaction and ocean engineering.

RELATED PROJECTS

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PUBLICATIONS

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"Soil liquefaction and sediment re-suspension on seabed due to wave-current interaction". Proc. Of Asian and Pacific Coastal Engineering 2001, Dalian, China

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