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MODELLING EXPERIMENTS ON SEA-BED STABILITY UNDER THE ACTION OF WATER WAVES

FABRICATION DE MAQUETTES POUR LA STABILITE DE FOND SOUSMARIN SOUS L'ACTION DES VAGUES

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SYNOPSIS: The responses of sandbed subjected to water waves were investigated in a scale model experiment. Wave-induced pore water pressure, total vertical and horizontal normal stresses were directly measured. Horizontal shear stress was calculated from the measurement of normal stress on the 45° inclination of soil element. A microscope was used to monitor the particle displacements in the sandbed. The sandbed exhibited a nearly elastic behavior. The elastic theory can provide a reasonable method of estimating wave induced stresses in a sandbed. Phase reversal between the vertical and horizontal effective stresses was observed in the tests. The shear slip surface is likely to occur around $|2z/L|=0.08-0.10$. The normally and over consolidated sea sandbed is stable in that the pore water pressure accumulation is small provided that the local drainage is not impeded, and in that the residual movements have almost ceased after numerous previous cyclic loadings. However, water waves can produce significant residual displacements in the newly deposited sandbeds with inclined surfaces, imposing the possibility of instability of sandbed slopes in oceanic situations.

INTRODUCTION

The dynamic response of seabed layers under the action of water waves is a rather complicated issue. At present, the various theoretical computations are based on some simplifying assumptions which do not take into the considerations of some significant factors. Field observations are necessary to characterize the responses of pore pressures and displacements. However, due to the technical and financial difficulties, the field measurement may not always be possible. The scale model experiment is a desirable alternative for studying the seabed stability and verifying the present theories.

CRITERIA OF SIMILITUDE

In order for laboratory experiments to be applicable to prototype situations, similitude laws must be satisfied between the two physical conditions. It is required that (1) the produced wave loads are similar to the dangerous storms in real sea waters; (2) the stress conditions and boundary conditions are identical to those of the prototype. Theoretically, it is required that the similarities of both fluid movements and dynamic responses of soil layers between the model and prototype should be satisfied.

1. Similarity of fluid movement

If "a" represents the scale ratio of a physical quantity between the prototype and the model and the subscript V, L, T, g, D, ..H represent the wave velocity, wave length, wave period, gravity acceleration, water depth and wave height respectively, the similitude criteria are stated as follows:

a) The characteristic of fluid movement mainly depends on the gravity. The effect of fluid viscosity is considered negligible. Therefore the scale ratio should follow the Froude law:

$$a_v^2 = a_L \quad (1)$$

b) The similitude of the wave propagation in shallow

waters:

$$a_v = a_T = a_H^{1/2} = a_L^{1/2} \quad (2)$$

c) The similitude of the wave steepness

$$a_H = a_L = a_D \quad (3)$$

2. Similarity of the dynamic responses of soils

According to the Coulomb-damped poro-elastic theory, there exists three kinds of stress waves in seabed: the compressional wave of fluid and soil skeleton movement, the compressional wave of fluid movement relative to soil skeleton and the shear wave. These waves are represented by three characteristic values ζ_1 , ζ_2 and ζ_3 , which are usually called Mach numbers in the stress wave equations. The Mach numbers for the model and the prototype should be the same or close. However, it is almost impossible to fully satisfy this requirement if the model employs the same materials as the real seabed. Fortunately, the value of ζ_1 is very small, particularly for the sandbed. Therefore, ζ_1 can be considered approximately identical for the model and the prototype. ζ_2 represents a secondary wave. Its effects on the sandbed responses is very limited and negligible due to its short travelling distance and the small amount of energy it carries. Consequently, its effect on the sandbed response is very limited and negligible. The values of ζ_3 are quite different for a sandbed and a claybed. In a sandbed ζ_3 is very small and can be considered identical for the model and the prototype. However ζ_3 is close to 1 for the soft clay bed and its influences on stress waves are significant.

In summary, the model and the prototype can be considered approximately similar for sandbed as long as the Froude law is satisfied. For the soft claybed, ζ_3 should be made the same for the model and the prototype. This requirement indicates that the shear strength gradients for the model and the prototype should be identical or close since many earlier studies indicated the proportionality between the shear modulus G and shear strength S_u of soilbed:

$$G = CS_u$$

MODELLING SETUP

The modelling system is illustrated in Fig.1. Basically the system consists of five sections: 1. Water wave generator; 2. Plume in which plane strain condition was assumed; 3. Soilbed tank; 4. Sample-falling wagon from which the sand sample automatically and uniformly fell through water and sunk in the sandbed tank; 5. Dumping slope where waves were absorbed and the reflection was acceptably small.

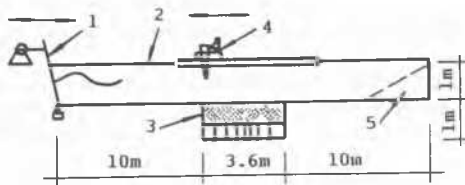


Fig. 1 Modelling setup (not to scale)

A model with dimensions $D=0.4\text{m}$, $H=0.15\text{m}$, $T=2\text{s}$ and the desired $a_v=100$ would correspond to a prototype with $D=40\text{m}$, $H=15\text{m}$, and $T=20\text{s}$, which is similar to the offshore conditions in the South China Sea.

The sandbed was constructed in four subsequent layers with the thickness of each layers being 10cm. The falling heights through water were made equal for each layer so that a uniform soil profile could be obtained.

The sand used was of medium size, relative density $D=0.353$, permeability $k=1.27 \times 10^{-5}\text{m/s}$, compressibility coefficient $a_v=4 \times 10^{-7}\text{m}^2/\text{kN}$, angle of internal friction $\phi=32.5^\circ$.

A total of 18 pressure transducers which were used to measure the changes of total normal stresses and pore water pressure were attached to two vertical bars which were anchored to the bottom of the soil tank (Fig.2). The transducers, 6mm in diameter and 10mm in length, had an output ranging from $1.00\mu\text{E}$ to $2.5\mu\text{E}$ per millimeter change in water pressure head. The degree of linearity was around 5%.

A coordinate-tracing system was set up. It consisted of a glass window on a side of the soil tank and two rigid steel bars to which a microscope was attached to measure the displacements of several tiny T needle heads which were positioned during the sandbed sedimentations (Fig.2).

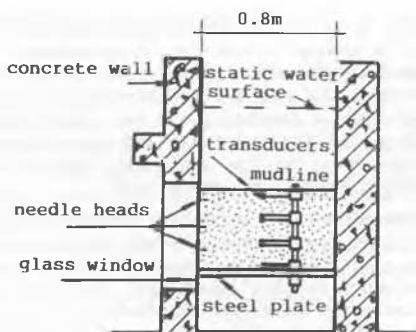


Fig. 2 Cross section of soil tank (not to scale)

ANALYSES OF TESTS RESULTS

Two groups of tests were conducted shortly after sedimentations. The parameters and measured items in each group are summarized in Table 1 and Table 2. In the group B tests, the surface of sandbed was constructed with an initial slope of 1.5% to investigate the effects of initial shear stress.

Table 1 Group A tests

Tests	R1	R2	R3	R4	R5
D(cm)	42	38	41	41	41
H(cm)	16.5	15	5.5	10	16
T(s)	1.5	1.6	2.3	2.3	2.2
Time (min)	18	18	39	32	30

Table 2 Group B tests

Tests	T1	T2	T3	T4	T5
D(cm)	35	33	32	32	32
H(cm)	8.9	15.6	17.2	18.0	24
T(s)	4.1	3.0	3.6	2.7	2.2
Time (min)	18	18	39	32	30

Typical outputs of pore pressure and normal stress transducers are shown in Fig.3 which corresponded to three stages in which pore pressures and stresses were changed during a single loading and unloading process: (a) Soil was densified and pore pressure increases were in excess of local pore pressure dissipations. This resulted in pore pressure accumulation; (b) The pore pressure accumulation stopped when the dissipations were equal to the pore pressure increases. Stable stress fields were established at which pore pressure oscillated at constant amplitudes; (c) The wave generator was stopped. As the water waves quickly attenuated, the stress field and the accumulated pore pressure rapidly diminished to zero.

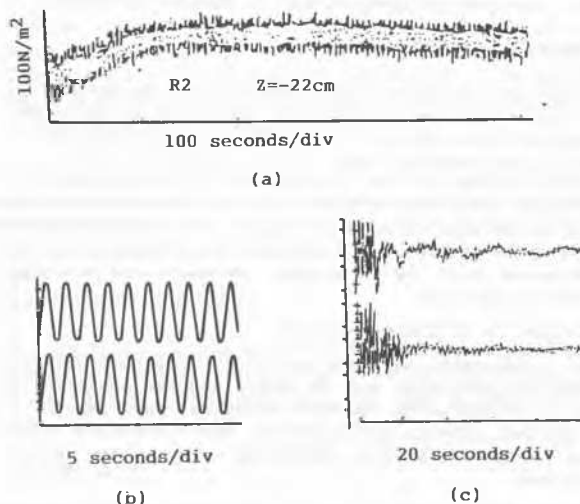


Fig. 3 Typical output of pore pressure transducers

- (a) Pore pressure accumulation during initial loading
- (b) Stable oscillatory pore pressures
- (c) Pore pressure dissipation

Fig.4 presents the amplitude profiles of the vertical and horizontal cyclic effective stress. $\Delta\sigma'_z$ was increased with depth. At $z=-2\text{cm}$, the minimum net vertical effective stress was 31 N/m^2 , which was far from the initial liquefaction state. $\Delta\sigma'_x$ demonstrated a reverse in phases within the upper profile ($z=-12\text{cm}-0\text{cm}$) as compared to the phases in the deeper profile. The reversal point moves upward as wave height increases. Within the reversal region, the soil skeleton is subjected to compression in the vertical direction while in the horizontal direction the soil skeleton undergoes tension and vice versa. Such behavior increases the deformations in the vertical and horizontal directions. It is easy to imagine that such stress state may produce unfavorable settlements of structures in a offshore foundation.

The computed stress fields are also plotted in Fig.4. The computations were based on the Biot stress wave theory on viscous-elastic fluid-filled porous media for seabed response to the action of sine-oscillatory water waves. Soil anisotropy and coupled effect of water-soilbed interaction were considered. A nonlinear numerical model was developed to compute the response of a finite, layered soilbed. The computations in accordance with the modelling conditions indicate that $p, \Delta\sigma'_z, \Delta\sigma'_x$ and $\Delta\sigma'_x$ follow the synchronous changes whereas they are in reverse to $\Delta\sigma'_x$ in the upper layer. The reversal point goes up as H increases. These results are in agreement with the experimental results.

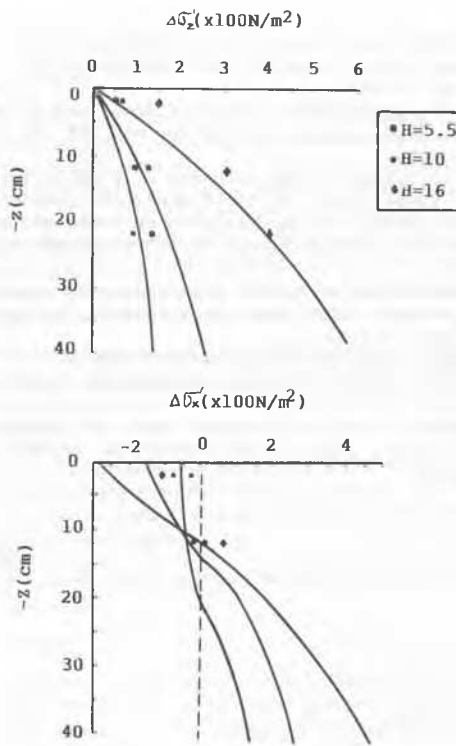


Fig. 4 Effective stress amplitude profiles(Group A tests)

Fig.5 summarizes the pore-water pressures and effective vertical stresses from the Group A tests by way of normalization. The agreement between the experimental results and the computed values from the linear theory indicates that the sandbed demonstrates a near linear-elastic behavior.

Shear stress in the soilbed is of important concern in assessing the seabed stability. The horizontal shear stress induced can be calculated from the measurements of vertical, horizontal stresses and normal stress on the 45° inclination, which was obtained from the Group B tests. The normalized results are presented in Fig.6. The close agreement between the measured shear stress profile and the linearly computed shear stress profile may imply the shear stress waves for model sandbeds and real sandbeds could better satisfy the similitude requirement.

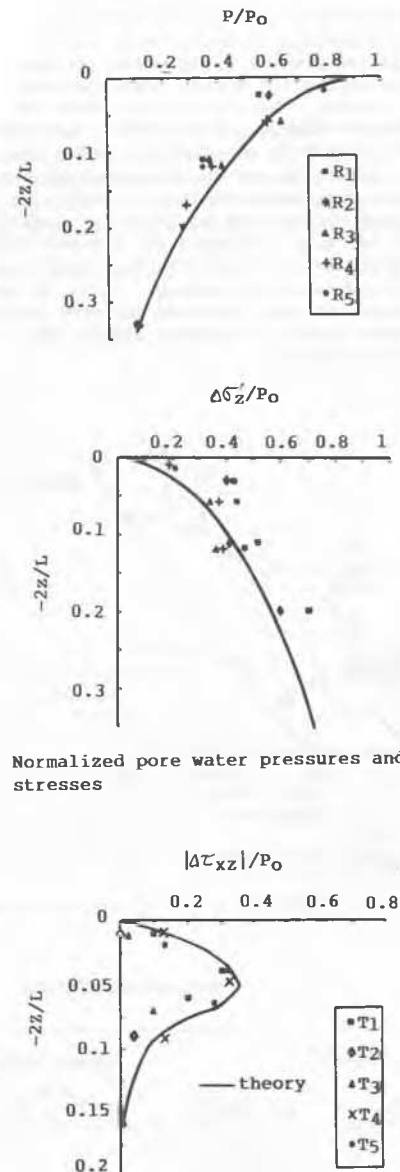


Fig. 5 Normalized pore water pressures and effective stresses

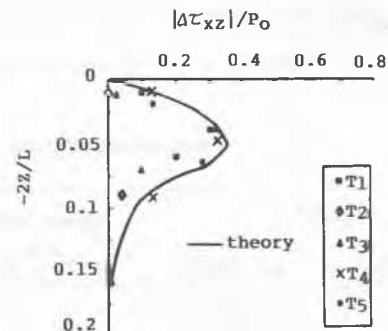


Fig. 6 Normalized horizontal shear stresses(Group B tests)

In all these tests, no oscillatory displacements were observed. Since the resolution of the microscope was 0.01mm , it can be inferred that the oscillatory displacements

ments in the sandbed were less than 10^{-2} mm. The computed oscillatory displacements are in the order of 10-3mm.

Although no residual displacements were observed in Group A tests, apparent residual displacements in vertical and horizontal directions were indeed observed in Group B tests. Fig.7 and Fig.8 give the measured developments of displacements at $z=-2.25$ cm. Upon initial loading, displacements increases rapidly and then gradually attained a stable value. The residual displacement in the vertical direction was twice that in the horizontal direction. Slight rebound occurred at the end of each loading. Creep between two consecutive loadings were very small. An interesting thing is that each of the first few loadings can produce significant residual displacements, indicating the strong remolding capability of the sandbed. However, the remolding effects decreased with further unloading-loading repetitions. The movements of soil particles eventually stopped even under the action of higher waves. It may be inferred that the normally and over consolidated sandbeds in real sea situations, in which the soilbed surfaces are usually slightly inclined and have undergone the actions of many years of water waves may not yield further significant displacements and thus are very stable. It is in the newly-deposited sandbeds with inclined surfaces that the water waves are most likely to produce significant settlements and deformations.

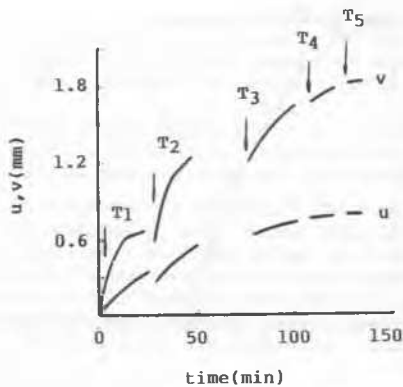


Fig. 7 Displacements at $z=-2.25$ cm

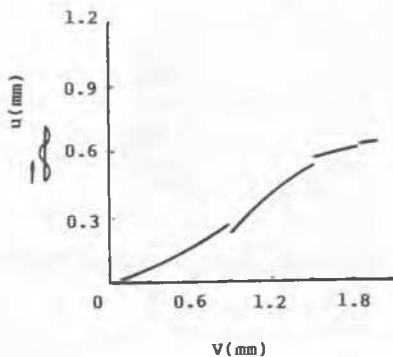


Fig. 8 Locus of particle movement at $z=-2.25$ cm

CONCLUSIONS

In sea-sand-bed of medium density, stable stress fields can be established within relatively short period of time. Under the action of shorter, higher frequency water waves, pore water pressure accumulation may occur in deep regions.

Elastic theory can provide a reasonable method of estimating wave-induced stresses in sandbed. In shallow soil layers, the phase reversal between the cyclic vertical and horizontal effective stresses can increase the vertical settlements and dorizontal deformations of sandbed.

The maximum shear stress ratio ($|\Delta\tau_{xz}|/P_0$) is about 0.35 and occurs around $|2z|/L = 0.08-0.10$. It is therefore predicted that the shear slip surface in real seabed is likely to occur around $|2z|/L = 0.08-0.10$.

Water waves can produce significant residual displacements in newly deposited-sandbed with inclined surface. However, the soilbed will eventually become stable. Under most oceanic conditions, displacements will be trivial in over-consolidated sandbed except when the pore-water accumulation is significant.

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