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Numerical modelling of consolidation of 2-D porous unsaturated seabed under a composite breakwater

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1. Introduction

Nowadays, more than two-thirds of the world's population is concentrated in the coastal zones, where the coastline generally is either the center of economic development, or the important port for transportation. In coastal zones, the breakwaters, such as composite breakwater are widely used to protect the coastline from damage and erosion; and also protect the people living in the zones near to the coastline from death and properties loss. However, the breakwaters built on seabed are vulnerable to the liquefaction and the shear failure of seabed foundation [1-2]. An inappropriate design of breakwater would result in the collapse of breakwater after construction, and further bring great economic loss. Therefore, the development of an effective analysis tool to evaluate the shear failure in seabed foundation under marine structures is necessary.

In recent three decades, more and more marine structures, such as breakwater, platform and turbine, have been constructed in offshore areas. A lot of investigations have been conducted on the offshore geotechnical mechanics. These previous works mainly pay their attentions on the dynamic response of seabed under ocean wave loading, including the analytical solutions [3-4], and numerical simulations [5-7]. However, the initial consolidation status of seabed with or without marine structures is not involved in these previous investigations. The initial displacements, pore pressure, velocity and acceleration in seabed foundation are all assumed as zero in these investigations. Obviously, this assumption is a negative factor for accurately evaluating the potential liquefaction and dynamic shear failure in seabed foundation under ocean wave loading. In real offshore environment, the seabed foundation on which a marine structure is built experiences the consolidation process under the weight of structure and the hydrostatic pressure. The final consolidation status of seabed foundation under marine structures should be the initial condition to evaluate the dynamic response of seabed foundation. At present, few works have been conducted to determine the consolidation status of seabed.

The first researcher investigating the consolidation problem was Terzagh [8] who proposed the analytical solution of 1D soil volume. Later Biot [9] presented a 3D general theory for the soil consolidation, which is widely adopted to understand the coupled phenomenon of the flow and deformation process in porous media. Generally, the exact solution of consolidation problems of soil is difficult to obtain due to the complex boundary conditions. In engineering, most problems are solved by numerical techniques. Most of previous investigations pay their attention on the methods of solving the Biot's consolidation equation, and the corresponding convergence and stability [10-12]. Little attention has been given to the application of these numerical methods proposed to determination of the consolidation status of large-scale seabed foundation under hydrostatic pressure and large-scale breakwater.

In this study, taking the dynamic Biot's equation as the governing equation, a finite element (FEM) program PORO-WSSI 2D is developed to investigate the consolidation of unsaturated porous seabed under a composite breakwater and hydrostatic water pressure.

2. Governing equations and boundary conditions

2.1. Governing equations

It is well known that the seabed is porous medium consisting of the soil particles, pore water and trapped air. The Biot's theory is widely adopted to describe the mechanical behaviour of porous medium. In this study, the seabed is treated as an elastic, isotropic and homogeneous porous medium. The dynamic Biot's equation known as "*u-p*" approximation proposed by Zienkiewicz (1980) [13] is used as the governing equation for porous seabed and the rubble mound. The relative displacements of pore water to the soil particles are ignored, however, the acceleration of the pore water is considered in the governing equation.

$$\frac{\partial \sigma'_x}{\partial x}+\frac{\partial \tau_{xz}}{\partial z}=-\frac{\partial p}{\partial x}+\rho\frac{\partial^2 u}{\partial t^2} \tag{1}$$

$$\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \sigma'_z}{\partial z}+\rho g=-\frac{\partial p}{\partial z}+\rho\frac{\partial^2 w}{\partial t^2} \tag{2}$$

$$k\nabla^2 p-\gamma_w n\beta\frac{\partial p}{\partial t}+k\rho_f\frac{\partial^2 \varepsilon}{\partial t^2}=\gamma_w\frac{\partial \varepsilon}{\partial t} \tag{3}$$

where u, w are the soil displacements in the x, z directions, respectively; n is soil porosity; σ'_x and σ'_z are the effective normal stresses in the horizontal and vertical directions, respectively; τ_{xz} is the shear stress; p is the pore pressure in porous medium; $\rho = n\rho_f + (1 - n)\rho_s$ is the average density of porous medium; ρ_f is the fluid density; ρ_s is solid density; k is the Darcy's permeability (the seabed in this study is treated as isotropic); g is the gravitational acceleration and γ_w is the unit water weight. ε is the volumetric strain. In Eq. (3), the compressibility of pore fluid (β) and the volume strain (ε) are defined as

$$\varepsilon = \frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} \tag{4}$$

$$\beta = \frac{1}{K_f} + \frac{n(1-S_r)}{p_{w0}} \tag{5}$$

where S_r is the degree of saturation of seabed, p_{w0} is the absolute static pressure and K_f is the bulk modulus of pore water.

2.2. Boundary conditions

In this study, the consolidation of 2-D porous unsaturated seabed under a composite breakwater is numerically investigated. The configuration of seabed and composite breakwater in computational domain is shown in Fig. 1. In order to solve the governing Eqs. (1) to (3), the following boundary conditions are applied to the computational domain.

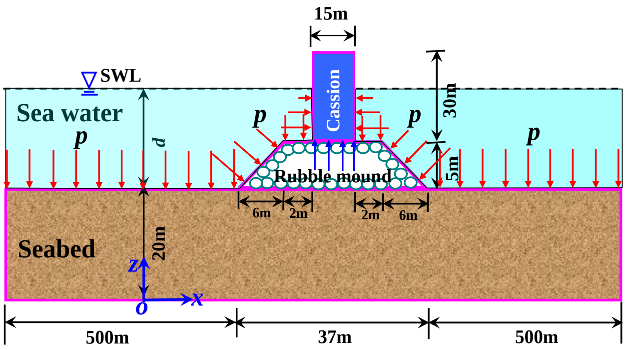


Fig. 1 The configuration of seabed and composite breakwater in computational domain

First, the bottom of seabed is considered as rigid and impermeable

$$u = w = 0 \text{ and } \frac{\partial p}{\partial z} = 0 \tag{6}$$

Second, due to the fact that the computational domain is basically symmetrical along x direction and the computational domain is truncated from the infinite seabed. In this study, the periodical boundary condition is applied to the left and right lateral boundary. It means that the displacements and pore pressure on left and right lateral sides of seabed are equal to each other at any time.

Third, in real offshore environment, the seabed and the part of composite breakwater under the static water level (SWL) are all applied by the hydrostatic water pressure (Fig. 1). Therefore, the surface of seabed and the outer surface of composite breakwater are applied by the hydrostatic water pressure expressed as

$$p = \rho_f g(h + d - z) \tag{7}$$

where h is the thickness of seabed, d is the water depth, z is the vertical coordinate. It is noted that the hydrostatic water pressure acting on seabed and the composite breakwater is perpendicular with the surfaces of seabed and composite breakwater. Additionally, the pore pressure at seabed surface and the outer surfaces of composite breakwater must be equal to the corresponding hydrostatic water pressure, to satisfy the continuity condition of water pressure at the interfaces. On the part of composite breakwater over the SWL, there is no force applying, and the water pressure is 0.

Fourth, the composite breakwater consists of a rubble mound and a rigid and impermeable caisson. The caisson not only is applied by the hydrostatic water pressure at two lateral sides, but also is applied by the floating force on the bottom. Therefore, the floating force acting on the bottom of impermeable caisson is also taken into consideration in computation.

In this study, in order to solve the above boundary value problem, a 2D FEM program (PORO-WSSI 2D) is developed, in which the Generalized Newmark method [14] is adopted to determine the time integration. The unconditional stability could be reached by using this method. More detail information about PORO-WSSI 2D can be found in [15].

3. Verification of numerical model

The FEM program PORO-WSSI 2D contains two models: dynamic model and consolidation model. Ye and Jeng [14] has verified the dynamic model in PORO-WSSI 2D by using the dynamic response of a sandy bed to a fifth-order wave and cnoidal wave in laboratory. The consolidation model in PORO-WSSI 2D has not been verified.

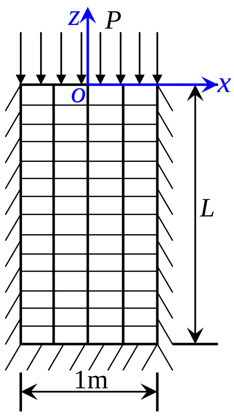


Fig. 2 The mesh generated in the 1-D soil volume in Terzaghi's consolidation theory

Here, the 1-D Terzaghi's consolidation theory is adopted to verify the developed 2D soil model. A 1-D poro-elastic, isotropic, homogeneous and fully saturated soil volume with length L = 20 m is applied by a constant stress P = 10 kPa (Fig. 2). The 1-D soil volume consolidates under the constant stress. The drainage is only allowed through the surface on which the constant stress applying. The bottom of soil volume is fixed and impermeable. The properties of soil volume are: Elasticity modulus E = 100 MPa, Poisson's ratio μ = 0.25, Permeability $k = 1.0 \times 10^{-5}$ m/s. The analytical solution for the pore pressure and displacement variation in consolidation process developed by Wang [16] is adopted to verify the consolidation model in PORO-WSSI 2D.

The pore pressure, displacement in 1-D soil volume, and the settlement of the surface on which the constant stress P is applied are monitored in consolidation process. The comparison for the results between present FEM numerical model PORO-WSSI 2D and the analytical solution [16] are shown in Figs. 3-5. It is found that the numerical results determined by present model agree very well with analytical solution [16].

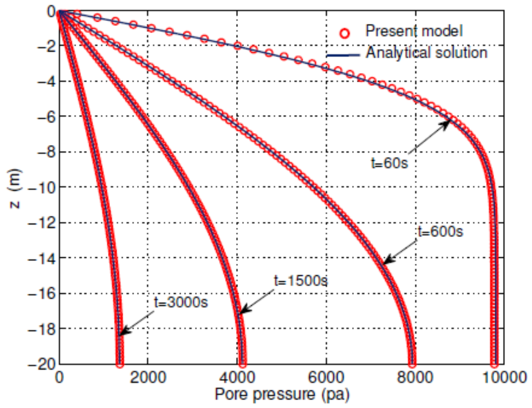


Fig. 3 The distribution of pore pressure along the 1-D soil volume at different times in consolidation process

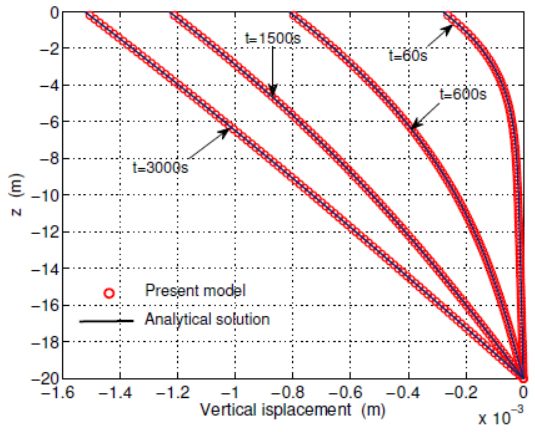


Fig. 4 The distribution of vertical displacement along the 1-D soil volume at different times in consolidation process

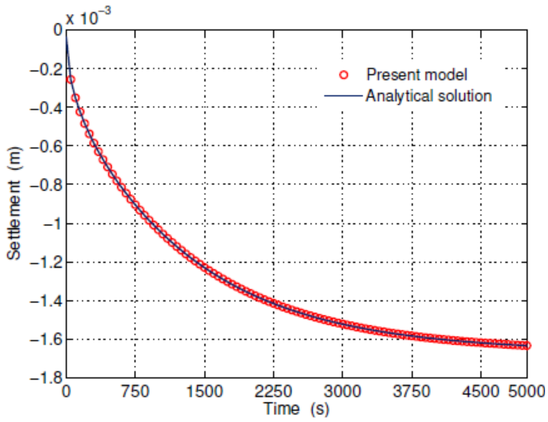


Fig. 5 The historical curve of the settlement of surface on which the force is applied

4. Results and discussion

The developed FEM program PORO-WSSI 2D is used to investigate the consolidation of 2-D porous unsaturated seabed under a composite breakwater. The seabed, rubble mound and caisson are all discretized by the 8-nodes iso-parametric elements. The length of seabed foundation in computational domain is 1037 m, which is enough to eliminate the effect of the two lateral boundaries on the stress fields in the seabed near to the composite breakwater [14]. The properties of porous seabed, rubble mound and caisson used in calculation are listed in Table. The seabed thickness h and the water depth d are both 20 m.

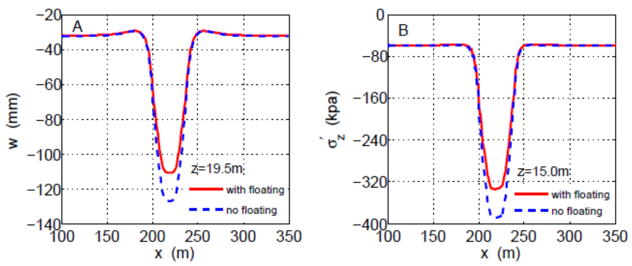
Table

Properties of porous seabed, rubble mound and caisson used in calculation

Medium	φ,°	E, MPa	ν	k, m/s	S_r, %	n	G_s, kg/m^3
Seabed	30	50	0.33	10^{-5}	98	0.25	2650
Rubble mound	35	1000	0.33	0.2	99	0.35	2650
Caisson	40	10000	0.25	0	0	0	2650

4.1. Effect of floating force

Due to that the caisson is rigid and impermeable, the caisson built on rubble mound is applied by the hydrostatic water pressure not only on the two lateral sides, but also on the bottom. It means that the caisson is applied by an upward floating force on the bottom. The consideration of this floating force on bottom of caisson is important to determine the displacement and stress fields in seabed foundation.



a b

Fig. 6 The comparison of results in which the floating force is considered and is not considered. a) is the vertical displacement on line z = 19.5 m; b) is the vertical effective stress on line z = 15.0 m

Fig. 6 illustrates the effect of the floating force acting on the bottom of caisson on the displacement and effective stress. It is found that the vertical displacement (it is positive if the displacement is in the same direction with axis) and effective stresses (compression is taken as negative) in seabed foundation are all overestimated greatly if the floating force is not taken into consideration in numerical calculation. Therefore, the consideration of the floating force acting on the bottom of caisson is compulsory when determining the consolidation status of seabed under a composite breakwater.

4.2. Consolidation process

It is well known that the seabed generally has experienced the consolidation process under the hydrostatic pressure and the self-gravity in the geological history in the offshore environment. In engineering, after the construction of a breakwater on seabed, the weight of breakwater is initially transferred to the pore water in seabed foundation, resulting in the generation of excess pore pressure and pressure gradient (Fig. 7, t = 1000 s). As time passing, the pore water permeates driven by the pressure gradient through the void between soil particles, promoting the pore pressure dissipate gradually (Fig. 7, t = 4000 s and Fig. 8 (A)). In this process, the weight of breakwater gradually is transferred from the pore water to the soil particles (Fig. 8 (B)); and the breakwater subsides correspondingly (Fig. 8 (C)). Finally, the seabed foundation reaches a new consolidation status, in which the excess pore pressure and pressure gradients disappear (Fig. 7, t = 15000 s). This newly reached consolidation status should be the initial status for the evaluation of the dynamic response of seabed foundation and breakwater under ocean wave loading.

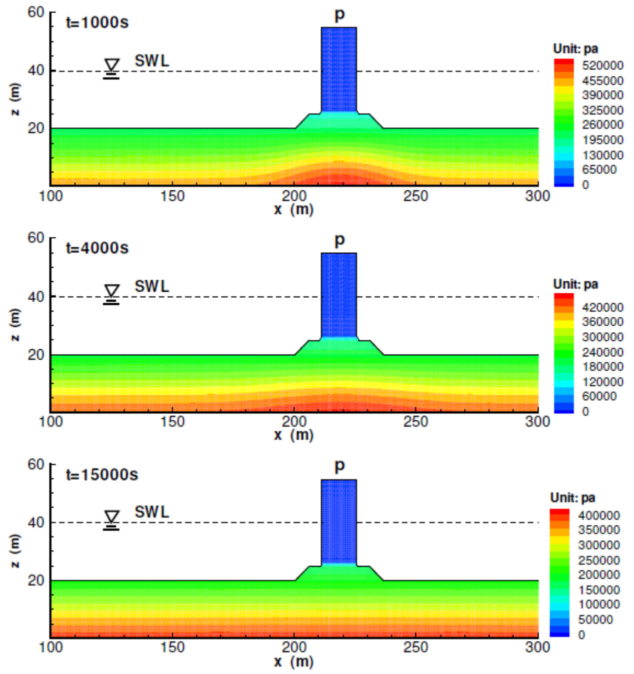


Fig. 7 The distribution of pore pressure in seabed foundation at different times in consolidation process

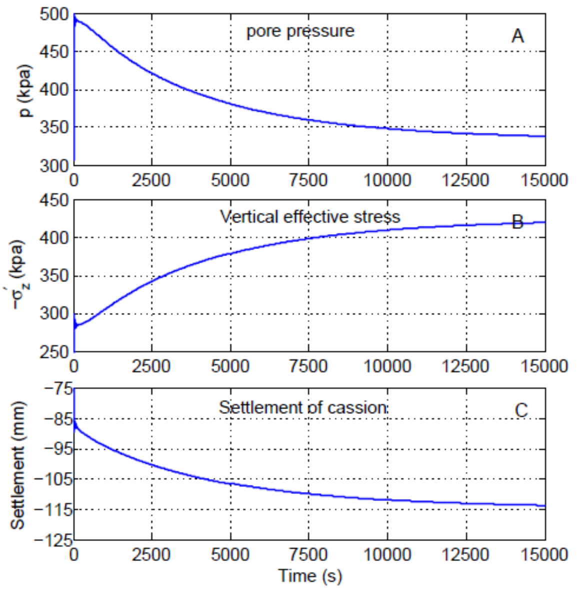


Fig. 8 (A) and (B): the historical curves of the pore pressure dissipation and the growth of effective stress at point (x = 218.5 m, z = 60 m); (C): the process of subsiding of the caisson

It is noted that the pore pressure in the caisson is always zero in the consolidation process due to that it is treated as rigid and impermeable medium in computation.

4.3. Distribution of effective stresses and displacements

Fig. 9 shows the distribution of stress fields in seabed foundation and the composite breakwater. As illustrated in Fig. 9. The construction of a composite breakwater on seabed has significant effect on the stress fields in seabed foundation. The effective stresses σ'_x and σ'_z increase greatly in the zone beneath the composite breakwater, to support the weight of the composite breakwater. In the zone far away the composite breakwater, the effect of the breakwater on the stress fields disappears gradually.
The shear failure is the main reason for the instability of seabed foundation, and the collapse of composite breakwater in engineering. From the distribution of shear stress τ_{xz} in seabed foundation and rubble mound in Fig. 9, it is found that the shear stress τ_{xz} concentrates in the zones beneath the two foots of rubble mound in seabed; and concentrates in the zones near to the two lateral sloped sides in rubble mound. These concentrations of shear stress in seabed foundation and rubble mound frequently are the direct reason for the shear failure of seabed foundation and breakwater.

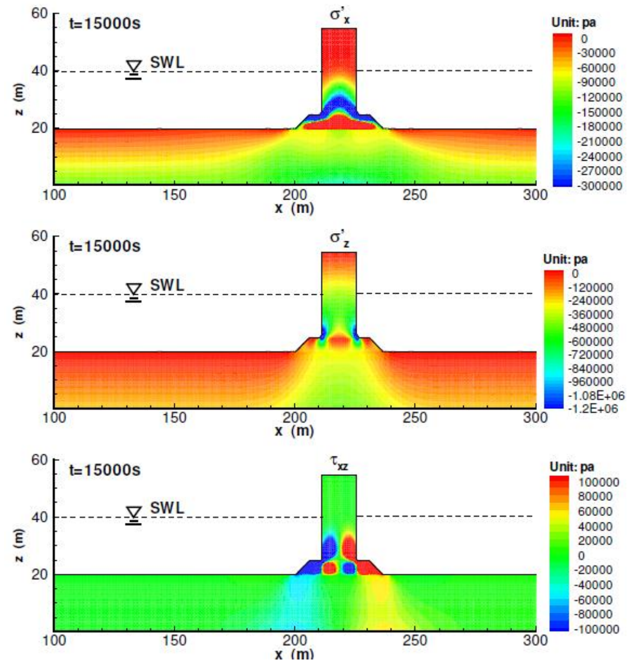


Fig. 9 The distribution of stress fields in seabed foundation and composite breakwater

Fig. 10 demonstrates the distribution of displacements in seabed foundation and composite breakwater under hydrostatic water pressure and the composite breakwater loading. From Fig. 10, it can be seen that the seabed beneath the composite breakwater moves toward two lateral sides. The maximum movement reaches up to 20 mm. Under the loading of composite breakwater and the self-gravity of seabed, the seabed beneath the rubble mound is compressed, and moves downward. Correspondingly, the composite breakwater subsides. The maximum settlement of caisson reaches up to 120 mm. In the zone far away the composite breakwater, the effect of breakwater on stresses and displacement gradually disappears. The seabed in that zone subsides about 30 mm under the hydrostatic water pressure and itself weight.

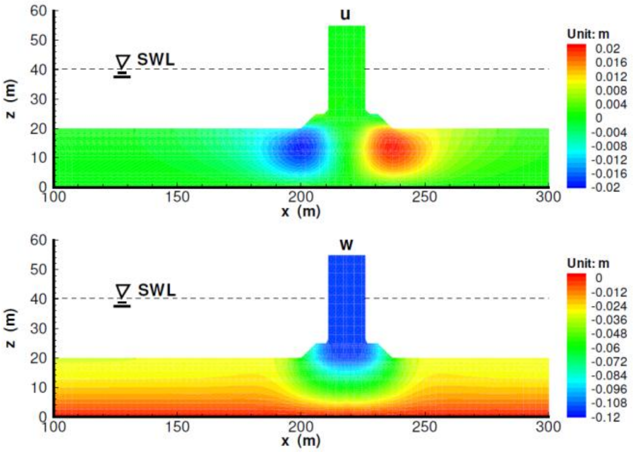


Fig. 10 The distribution of displacement fields in seabed foundation and composite breakwater at t = 15000 s

Figs. 11 and 12 quantitatively illustrate the distribution of effective stresses, shear stress, pore pressure and the displacements along the line z = 15.0 m in seabed foundation. From Fig. 11, it can be clearly observed that effective stresses σ'_x and σ'_z increase greatly in seabed foundation due to the compression induced by the weight of composite breakwater. The maximum magnitude of σ'_x and σ'_z reaches up to 90 MPa and 330 MPa respectively. The shear stress τ_{xz} concentrates in the zone under the foots of composite breakwater. The maximum magnitude of τ_{xz} reaches up to 50 MPa. This is a potential dangerous factor for the instability of seabed foundation due to the shear failure. The distribution of pore pressure along the line z = 15.0 m indicates that the excess pore pressure in seabed has dissipated sufficiently. The seabed basically reaches its new consolidation status under the composite breakwater at time t = 15000 s.

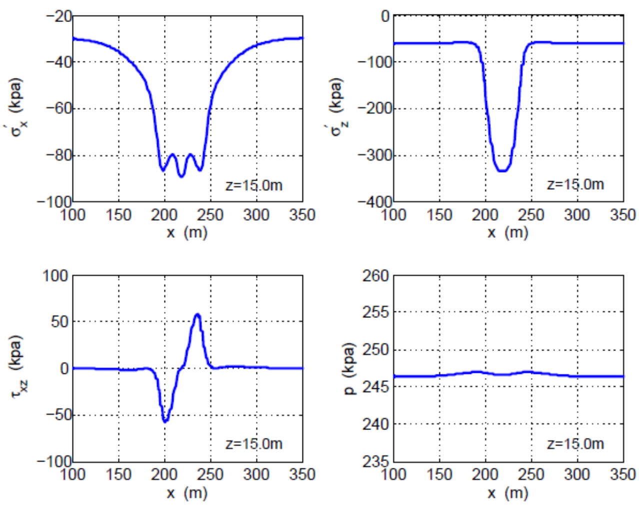


Fig. 11 The distribution of stresses and pore pressure along the line z = 15.0 m in seabed foundation

From Fig. 12, it can be observed that the seabed foundation moves toward the two lateral sides. The maximum horizontal displacement to left and right sides is nearly 20 mm. Furthermore, the seabed foundation moves downward due to the compression of composite breakwater and itself gravity. This trend also has been observed in Fig. 10.

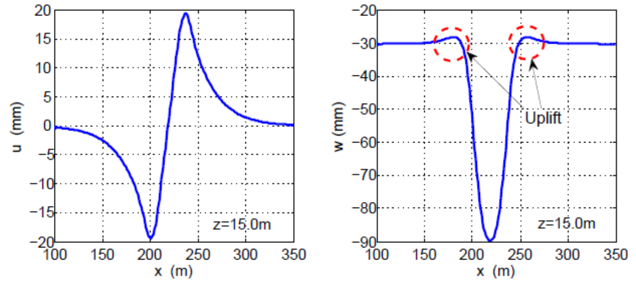


Fig. 12 The distribution of displacement along the line z = 15.0 m in seabed foundation

4.4. Shear failure in seabed foundation

In offshore engineering, it is important for coastal engineers involved in the design of a breakwater to predict the instability of seabed foundation due to shear failure. In the study, the developed FEM program PORO-WSSI 2D could provide the coastal engineers with a powerful analysis tool to evaluate the potential instability of seabed foundation due to shear failure under the marine structures loading, such as breakwater, pipeline, turbine and oil platform.

The Mohr-Coulomb criterion is widely used to judge the occurrence of shear failure in seabed foundation in offshore engineering. In Fig. 13, if the angle θ (known as stress angle) of the tangent AB of a Mohr circle (the measurement of the stress status at one point) is greater or equal to the friction angle φ of sandy seabed foundation, the shear failure occurs at this point

$$\theta = arcsin\left(\frac{\frac{\sigma_1-\sigma_3}{2}}{\frac{c}{tan\varphi}+\frac{\sigma_1+\sigma_3}{2}}\right) \geq \varphi \qquad (8)$$

where c and φ are the cohesion and friction angle of sand soil; σ_1 and σ_3 are the maximum and minimum principal effective stresses.

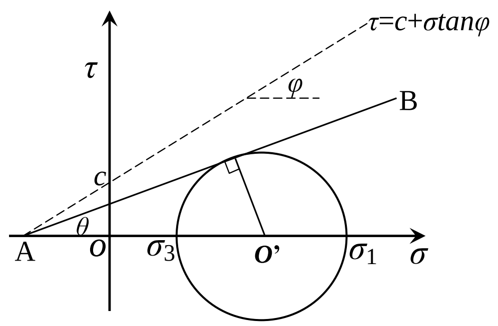


Fig. 13 The Mohr-Coulomb criterion

Fig. 14 shows the distribution of the stress angle θ in seabed foundation at time t = 15000 s. It is clearly observed that there is a large area where the stress angle θ is greater than the friction angle φ = 30° in the zone of seabed under the composite breakwater. It means that the shear failure in the seabed foundation will occur if the composite breakwater is built on the seabed whose properties is listed in Table 1. The predicted shear failure zone in seabed foundation is shown in Fig. 15 based on the Mohr-Coulomb criterion, and the numerical results determined by PORO-WSSI 2D. From Fig. 15, it is found that the seabed foundation beneath the composite breakwater fails in a large extent due to the shear stress concentration. The seabed soil near to the foot of rubble mound uplifts obviously due to the excessive shear deformation (Fig. 12). In engineering, some methods, such as replacement with hard materials, should be adopted to treat the soft seabed foundation if the shear failure is expected to occur.

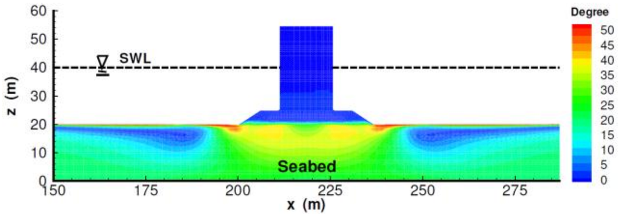


Fig. 14 The distribution of stress angle θ in seabed foundation at t = 15000 s

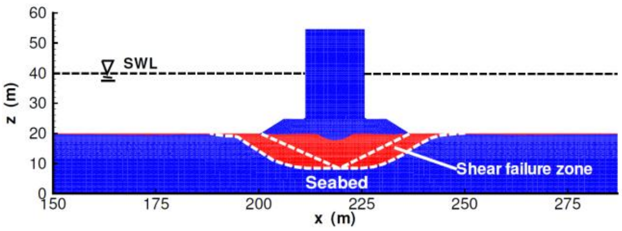


Fig. 15 The shear failure zone in seabed foundation under the composite breakwater loading at t = 15000 s

5. Conclusion

In this study, taking the Biot's dynamic equation "*u-p*" approximation as the governing equations, a FEM program PORO-WSSI 2D is developed based on SWANDYNE II. The consolidation model in PORO-WSSI 2D is verified by the 1D Terzaghi's consolidation theory. The developed numerical model could provide coastal engineers with an effective analysis tool to understand the stress/displacement fields, and to evaluate the shear failure in seabed foundation.

By adopting this developed FEM program, the consolidation of 2D unsaturated seabed under a composite breakwater is investigated. From the numerical results, following conclusions are draw:

1. The floating force acting on the bottom of caisson must be taken into consideration in calculation.

2. After the construction of a composite breakwater, the induced excess pore pressure in seabed foundation dissipates; and the weight of breakwater gradually is transferred to the soil skeleton in the consolidation process. Finally, the built breakwater makes the effective stresses in seabed foundation increase significantly.

3. In the zone beneath the foot of rubble mound, the shear stress highly concentrates. This is the direct potential dangerous factor for the instability of seabed foundation due to shear failure.

4. Under the compression of composite breakwater, the seabed foundation moves downward. Correspondingly, the composite breakwater subsides about 120mm. Additionally, the seabed also subsides under the hydrostatic pressure and self-weight about 30mm. It is noted that the final settlement of breakwater and seabed mainly depend on the stiffness of seabed.

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PURAUS NEPRISOTINTO JŪROS DUGNO PO SUDĖTINGU BANGOLAUŽIU SUTVIRTINIMO 2D MODELIAVIMAS

R e z i u m ė

Literatūroje nėra paskelbta tyrimų apie jūros dugno sutvirtinimą po bangolaužiu. Šiame straipsnyje, naudojant Bioto lygybes, kurios yra žinomos kaip pagrindinės lygties "*u-p*" supaprastinimas, BEM programa PORO-WSS1 2D yra pritaikyta įvertinti purios aplinkos sutvirtinimo savybes ir nustatyti jos dinamines charakteristikas. Pritaikius PORO-WSSI 2D, tyrinėtas neprisotinto jūros dugno po sudėtingu bangolaužiu sutvirtinimas veikiant hidrostatiniam slėgiui. Skaitiniu būdu buvo nustatyta bangolaužio dugną veikianti srovės jėga. Pasiūlytu būdu galima kontroliuoti grężinio slėgio sklaidos perteklių, efektyviųjų įtempių didėjimą, bangolaužio grimzdimą ir šlyties įtempių koncentraciją jūros dugne.

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NUMERICAL MODELLING OF CONSOLIDATION OF 2-D POROUS UNSATURATED SEABED UNDER A COMPOSITE BREAKWATER

S u m m a r y

The investigation of seabed consolidation under a breakwater is not available in previous literatures. In this study, taking the dynamic Biot's equation known as "*u-p*" approximation as the governing equation, a FEM program PORO-WSSI 2D is developed for the consolidation and dynamic response of porous medium. By adopting PORO-WSSI 2D, the consolidation of unsaturated seabed under a composite breakwater and hydrostatic pressure is investigated. The floating force acting on the bottom of caisson has been considered in numerical computation. The excess pore pressure dissipation, growth of effective stresses, settlement of breakwater and the shear stress concentration in seabed foundation all can be monitored. The developed FEM program provides coastal engineers with an effective analysis tool to predict the shear failure in seabed foundation.

Keywords: numerical modelling, consolidation of 2-D porous unsaturated seabed, breakwater.

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