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STABILITY OF UNDERWATER SLOPES INFLUENCED BY PORE-WATER PRESSURE

STABILITE DES TALUS SUBMERGES SOUMIS AUX PRESSIONS INTERSTITIELLES

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SYNOPSIS: Storm waves induce oscillations in the bottom hydrodynamic pressure at the seabed surface and simultaneously, as a consequence, within the soil matrix (*i.e.*, pore water pressure) which may be of sufficient magnitude to initiate a slip-surface mode of failure. Oscillations of the wave-induced pore water pressure within the seabed are responsible not only for the effective normal stresses in the soil but also for the effective shear stress. Assuming a circular shear surface, an analysis has been made, where the stability factor of the seabed against sliding is checked with respect to different parameters, namely: pore water pressure profile, wave loading characteristics, bottom slope angle, and size of sliding body. The loading characteristics, bottom slope angle, and size of sliding body formulate a geometry of the problem. Evaluation of the wave-induced pore water profile is based on an analytical solution derived for a finite seabed layer thickness. Pore pressure distribution is, among others, strongly dependent on soil saturation conditions; the influence of variations in the degree of saturation is investigated and discussed.

INTRODUCTION

The instability of an underwater slope due to surface wave action is an aspect of major importance with respect to the safety of some "on-shore" and "off-shore" structures like: rubble mound breakwaters, vertical monolithic breakwaters, artificial islands, submarine pipelines, anchors, gravity and pile supported oil platforms, which are built straight on the ocean floor which usually contains sandy depsits on top. Unstable sea bottom sediments itself can cause unexpected changes in a bathymetry that can be further developed into erosion and sediment transport problems. It is extremely demanding, engineering task to predict a place, time and extent of the sliding failure mechanism in seabed sediments. The interaction between an ocean environment and the seafloor is a very complex problem and all the methods used for assesing stability are based on strongly simplified assumptions.

The stability of underwater slopes was initially studied by Terzaghi with particular reference to the high pore water pressure which remains undissipated in an accumulating sediment. He concluded that the submarine landslides could be explained in terms of gravity forces and the very low shear strength of the underconsolidated sediments. A rewiew of the existing literature shows that the most works devoted to the problem of stability of seabed sediments were done with respect to soft clayey soils [*e.g.*: Henkel (1970), Doyle (1973), Dormieux (1988)]. In case of sandy sediments there is a limited number of information pertaining to a slip-surface mode of failure of an inclined seabed surface. Wright and Dunham (1972) considered this problem defining, however, a stability criterion in terms of the failure strain as a percentage of the maximum lateral displacements. Finn *et al.* (1982) presented, unfortunately, no calculation results from the proposed method with application to the stability of underwater slopes. Barends (1985) showed already a strong influence of the excess pore water pressure on the stability factor in a situation, however, of more steeper underwater slopes typical for the vicinity of the toe foundation for rubble mound breakwaters.

An intention of the Authors of the present paper was to perform a stability analysis, and to check the stability factor of a gently inclined sandy (non-cohesive) seabed sediments under storm wave conditions, incorporating the effect of cyclic oscillations of the wave-induced excess pore-water pressure.

DEFINITION OF THE PROBLEM AND SLIP-SURFACE FAILURE CRITERION

The geometry of the problem of a gently inclined underwater slope is shown in Fig. 1, and will be used in the following.

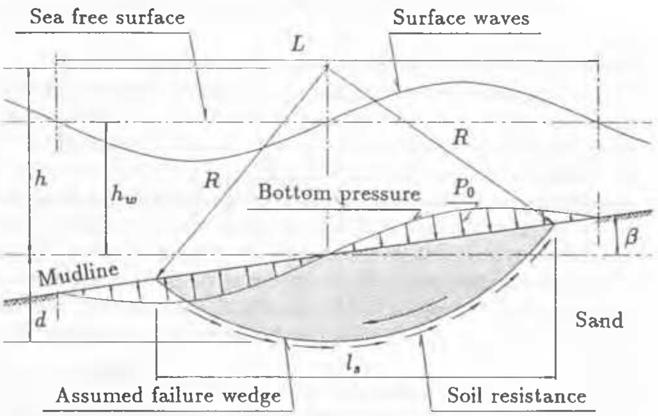

Fig. 1. Wave pressure profile superimposed over idealized slide model.

An underwater slope can be a part of an original seabed in a coastal zone or man-constructed sand bodies in seas and estuaries by hydraulic fill to serve as breakwaters, harbour extensions, artificial islands, closure dams, etc. As far as the original seabed floor is concerned, a stability against sliding failure mechanism can be endangered when the slope has a certain inclination, and severe wave conditions exist. For other than exeptional wave loading seabed sediments seem to be safe because of already existing stable slope profile and relatively compacted soils. The hydraulic fill method, however, produces sand bodies which are normally not yet adjusted to possible, local water wave conditions and also the low relative density of the soil introduces the risk of flow slides. A comparison of the slope inclination data, from 'in-situ' measurements on Norderney Island (Magda and Davidov, 1990) and from few location of hydraulic filling in the Netherlands (de Groot *et al.*, 1988) indicates that the seabed surface inclination can vary from $\beta = 0°$ up to ca. $\beta = 15°$, where higher values are reached when the hydraulic fill method is used to form a seabed deposit artificially.

A potential failure surface is assumed and the equilibrium of the sliding mass of unit thickness bounded by the failure surface and the surface of the slope is investigated. In rotational slips the slope of the failure surface may be a circular arc or a non-circular curve. In general, circular slips are associated with homogeneous soil conditions (Craig, 1983).

In case of cohesive soils the water pressure changes are considered to act as an external force (the couple of forces) on an almost impermeable soil block, only at the seabed surface [*e.g.*: Henkel (1970), Dormieux (1988)]. Assuming, however, an existence of non-cohesive, sandy seabed sediments, a propagation of the hydrodynamic, wave-induced bottom pressure into the soil has also to be taken into account. Using a modified model of Fellenius solution to the method of slices, the slope stability factor for such a situation can be defined in terms of effective stress by the following general equation (Craig, 1983):

$$F = \frac{\tan\phi' \sum(W\cos\alpha - \bar{p}l)}{\sum(W\sin\alpha)} \tag{1}$$

where: F is the stability factor, ϕ' is the angle of soil internal friction, W is the total weight of slice, α is the inclination of slice base to the horizontal, $\bar{p}$ is the excess pore water pressure at central point of slice base, and l is the length of slice base.

In the present analysis the failure surface is assumed to have any dimensions (the ratio h/d can vary, see Fig. 1) keeping, however, a circular shape all the time.

WAVE-INDUCED WATER PRESSURE

The active force system consists of gravity loading and pore water pressure acting on the failure surface. Dissipation capabilities of the seabed sediment are assumed to be large enough to preserve from build-up pressure (residual pressure) and allowing therefore only transient pore water pressure oscillations within the soil sediment.

The term in Eq. (1) containing the pore water pressure, $\bar{p}$, represents in fact the difference between the instantaneously changing hydrodynamic bottom pressure and the pore water pressure at the slip surface, which indirectly results also from a wave passage over the seabed. This pressure difference is computed with respect to the hydrostatic pore water pressure distribution in the soil. The problem considered is schematically illustrated in Fig. 2. And thus,

$$\bar{p} \equiv p_d - p_u = P_0 - \bar{p}_d \tag{2a}$$

$$\bar{p}_{max} \equiv p_d^{(max)} - p_u = P_0 + \bar{p}_d \tag{2b}$$

where: $\bar{p}$ is the pore water pressure difference, $\bar{p}_{max}$ is the maximum pore water pressure difference, P_0 is the bottom pressure amplitude, and $\bar{p}_d$ is the wave-induced excess pore water pressure at depth d in soil.

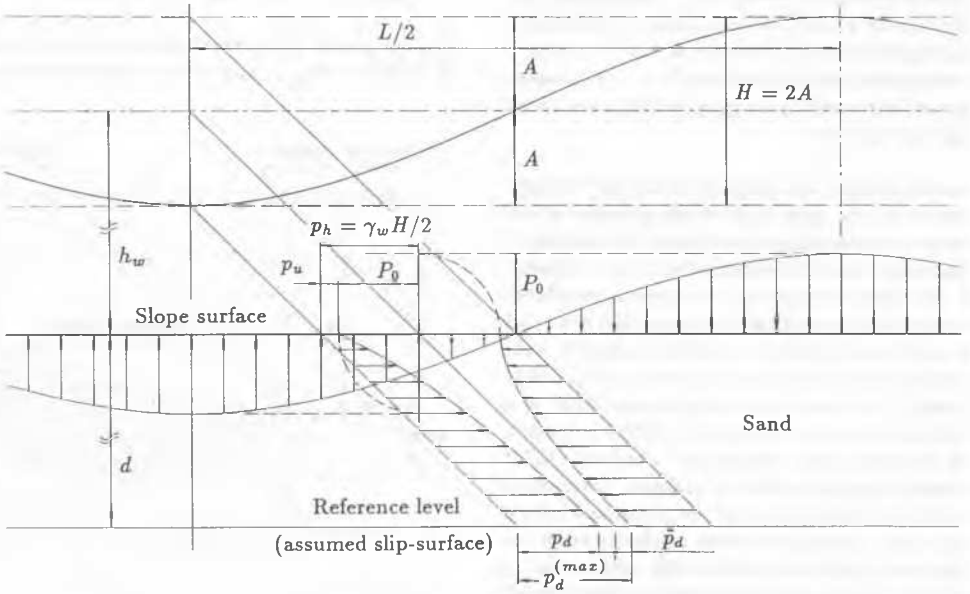

Fig. 2. Wave-induced pore water pressure oscillations in seabed sediments.

Wave Conditions and Bottom Pressure

The maximum possible wave height, H, as a main parameter responsible for the bottom pressure magnitude, was analysed using two principle wave-breaking criteria, *i.e.*:

- wave steepness limit

$$\sigma \equiv \frac{H}{L} \leq \frac{1}{7} \tanh\left(\frac{2\pi h_w}{L}\right) \tag{3a}$$

- breaking limit

$$\frac{H}{h_w} \leq 0.78 \qquad \left(\text{in practice} \quad \frac{H}{h_w} \leq 0.6\right) \tag{3b}$$

where: σ is the wave steepness, H is the wave height, L is the wave length, and h_w is the water depth.

The bottom pressure amplitude, P_0, can be described using, for instance, the linear (Airy's) theory of small-amplitude waves:

$$P_0 = \gamma_w \frac{H}{2} \frac{1}{\cosh\left(\frac{2\pi h_w}{L}\right)} \tag{4}$$

where: P_0 is the bottom pressure amplitude, and γ_w is the unit weight of sea water. Having results from large-scale experiments, Magda (1989) showed that the above relationship [Eq. (4)] is a very good approximation for the bottom pressure generated over a sandy sediment layer. Assuming the wave period up to 12s, and using Eqs. (3), Fig. 3 shows the result for the maximum possible bottom pressure in case of intermediate and shallow water conditions ($h_w/L < 0.5$). It has also to be noted that the hydrostatic pressure that comes as a result of oscillations in the free water surface elevation (*i.e.*, waves) is always in its value higher than the bottom pressure being a dynamic consequence of the water particle motion (see Fig. 2).

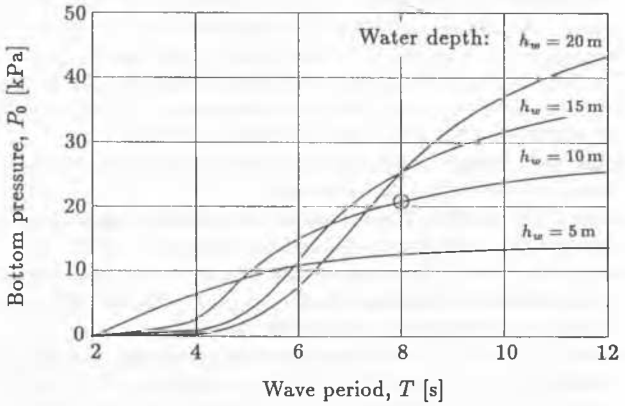

Fig. 3. Bottom pressure amplitude induced by storm waves, for shallow and intermediate water conditions.

Pore-Water Pressure and Geometry of the Problem

As far as a non-cohesive, sandy soil is concerned, the wave-induced excess pore water pressure, acting at the slip-surface, is of interest to us. The most critical situation will occur when the excess pore water pressure, firstly, reaches its maximum, and secondly, has a character of overpressure, *i.e.* forcing a soil element to lift it up, and thus enlarging the risk of failure. These unfavourable loading conditions will appear when the slip soil body of a certain width, l_s, is "covered" by the wave trough. The problem of relevant position between the wave trough and the considered soil body has to be optimalize during a parameter study where the slip soil body width, l_s, engaged in the sliding process, is being varied with respect to the wave length, L.

Considering the pore water pressure distribution with depth in the seabed sediments, the factors responsible for the most critical case are ruled by some of soil and pore fluid parameters (*e.g.*: saturation, soil permeability) as well as by geometry of the problem (*i.e.*: wave length, thickness of the seabed sediment layer). A question of the pore water pressure theory has been studied by many researchers; in the present work a theory proposed by Madsen (1978) and checked in large- and small-scale laboratory experiments (Magda, 1989, 1990) was used. Both the soil skeleton and the pore water are assumed to be compressible.

A phase lag in the pore pressure with depth associates always the pore pressure oscillations in soil sediments. Simplifying and excluding the influence of the phase lag ($\delta = 0°$) in the whole soil vertical profile, it becomes obvious that the highest value of the uplift force will be produced if the excess pore water pressure at the point of question (*i.e.*, on the slip-surface) stays unchanged during the entire period of oscillations ($\bar{p}_d = 0$, see Fig. 2). Introducing, however, effects of the phase lag ($\delta \neq 0°$), it is possible that the excess pore water pressure at a considered point of the slip-surface will be even larger than the initial (no waves) hydrostatic pressure ($\bar{p}_d > 0$, see Fig. 2). An extreme case happens when $\delta = 180°$, *i.e.* one half of the oscillation period. This is practically possible, especially when the seabed sediment is treated as unsaturated.

It can be seen now that detection of the most critical state, from the stability point of view, requires very wide coupled-parameter studies where changes in geometry and soil and pore fluid parameters are simultaneously controlled and analysed in repeated calculation procedure (trial-and-error method).

CALCULATION EXAMPLE AND DISCUSSION

The following data was used for the illustrative calculations: soil and pore fluid parameters (angle of internal friction $\phi' = 35°$, permeability $k = 0.0001\,\mathrm{m/s}$, porosity $n = 0.4$, shear modulus $G = 10^6\,\mathrm{kN/m^2}$, Poisson ratio $\mu = 0.33$, compressibility of pore fluid $\alpha = 4 \times 10^{-7}\,\mathrm{m^2/kN}$, degree of saturation $S = 1.00$ and $S = 0.98$, infinite soil layer thickness), and water and wave parameters (wave height $H = 6\,\mathrm{m}$, wave period $T = 8\,\mathrm{s}$, water depth $h_w = 10\,\mathrm{m}$). The soil parameters correspond with these typical for a medium sand in a loose state. The wave parameter were chosen to represent severe storm conditions (after the former discussion on wave conditions and bottom pressure).

First of all, the calculations were performed assuming only the hydrostatic pore water pressure distribution in the soil, and three different inclinations of the underwater slope surface, *i.e.* $\beta = 5, 10, 15°$. The stability factor F, compared versus different geometry (flattening) of the slip soil body, ruled by the ratio h/d, indicates stable conditions ($F > 1$) in all the considered cases.

When the shape of the slip body approaches semi-circle ($h \to 0$, $h/d \to 0$) the stability factor tends to its maximum value. Making the slip soil body flatter and thus stretching the slip body over large areas ($h \to \infty$, $h/d \to \infty$), the stability curves approach asymptoticly values for the case of an infinite-slope stability analysis, whereas the factor of stability is defined as $F = \tan\phi' / \tan\beta$.

In order to investigate the influence of the excess pore water pressure on the stability of an inclined seabed, the knowledge of the pore water pressure oscillations within the seabed sediments is strongly required. Figs. 4 present the results of the pore water pressure calculations in terms of the pore pressure amplitude (Fig. 4a) and the phase lag (Fig. 4b), using the above assumed soil, pore fluid, and wave data. It is very characteristic to note how large the influence of different saturation conditions ($S = 1.00$ and $S = 0.98$) on the damping ratio of the pore water pressure is. The general tendency can be constituted, namely: the lower degree of saturation is the smaller depth in the seabed is where a certain value of the pore pressure gradient is reached.

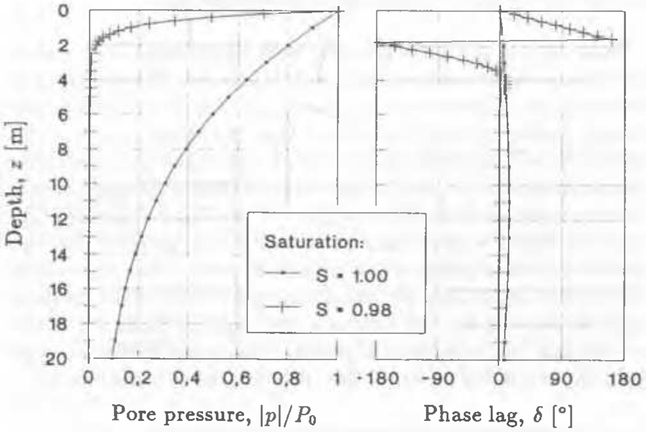

Fig. 4. Input pore pressure data for different saturation conditions; (a) amplitude, (b) phase lag.

Using the results of the pore water pressure distribution, further calculations were possible, taking the excess pore water pressure into account. Figure 5 illustrates the results of calculatons of the slope stability factor, F, for the case where the slope inclination $\beta = 15°$, and the maximum thickness of the slip soil body $d = 3.0\,\mathrm{m}$. Assuming unsaturated soil conditions ($S = 0.98$), the stability factor differs significantly from that one obtained for saturated conditions ($S = 1.00$); a much higher pore water pressure gradient, induced by a certain amount of air entrapped in the pore fluid, creates less stable conditions. Fig. 5 indicates also that, in case of fully saturated sediments, the stability factor F stays almost constant without any respect to the ratio h/d when $h/d > 5$. However, introducing unsaturated soil conditions, an optimum value of the ratio exists (here: $h/d \simeq 2$) where a respective value of the stability factor becomes minimum (here: $F \simeq 1$).

The analysis presented in the paper documents the possibility of the slip-circle mode of failure of underwater slopes formed by unsaturated sandy sediments, under severe storm wave conditions.

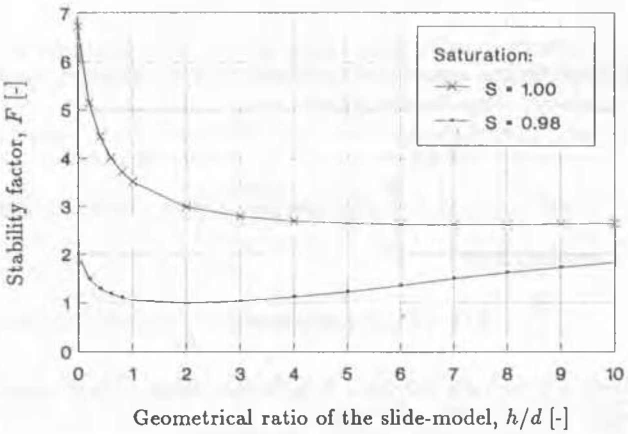

Fig. 5. Stability factor of inclined seabed under unsaturated soil conditions ($S = 0.98$), and slope inclination $\beta = 15°$.

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