CHAPTER 73

STABILITY AND BEARING CAPACITY OF BOTTOM SEDIMENTS

by

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The results of model testing show that the strength and stability of bottom sediments can be substantially reduced by the cyclic loading pulses induced by wave action. The minimum soil strength is approximately equal to the remoulded vane strength and the depth of wave remoulding appears to be mainly a function of the wave characteristics. The phenomenon of wave remoulding should be considered in the design of offshore foundations as reductions in bearing capacity and lateral shearing resistance can develop as a result of the action of storm waves.

Where bottom sediments are sloping such that the static factor of safety against slope failure is less than the soil sensitivity, severe storm conditions may lead to submarine landsliding. Wave induced submarine landsliding has been reproduced in model tests and the results are correlated with current analytical approaches to this problem.

INTRODUCTION

Most offshore construction and exploration activities are located in coastal waters where wave characteristics and water depths are such that the bottom sediments experience pressure pulses from passing waves. Under storm conditions these pressure pulses have been considered to induce catastrophic instabilities in soft gently sloping bottom sediments (see, for example, Bea, 1971). The role of wave action in causing submarine slope instabilities has been examined analytically by Henkel (1970) and by Wright and Dunham (1972). Henkel considers circular arc sliding from an upper bound moment equilibrium approach while Wright and Dunham carry out stress analyses appropriate to an infinite slope type of failure. These two possible modes of failure are shown on Figure 1. Both theoretical treatments attempt to evaluate the driving forces (or stresses) exerted in the soil mass by a standing wave. At failure, gravitational forces together with driving forces due to wave action are assumed to overcome the resisting forces derived from the undisturbed strength of the sediment.

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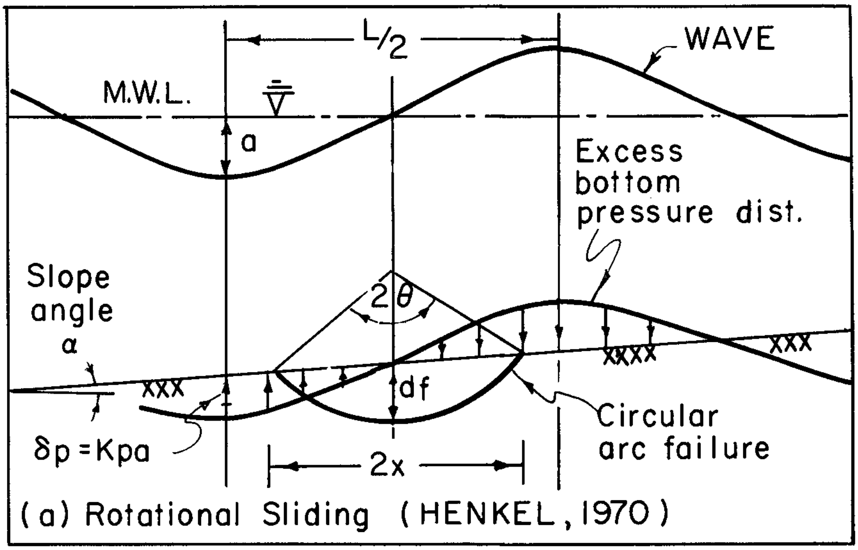


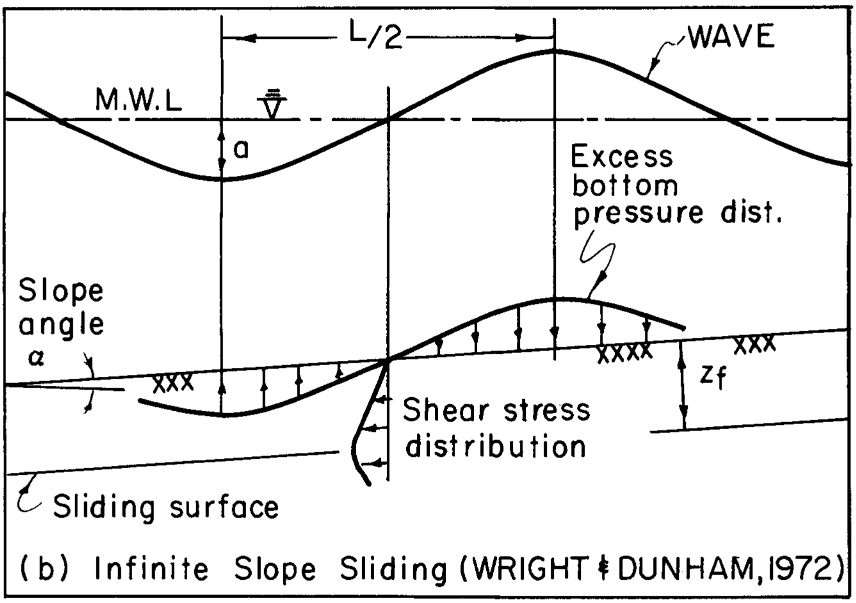


FIGURE 1 : STATIC REPRESENTATION OF FAILURE MODES

Mitchell et al (1972) demonstrated that wave action was instrumental in initiating mass movements of submarine sediments in model studies but indicated little correlation between the model test results and previous analytical predictions. They suggest, from analysis of the model test results, that the driving forces in submarine landslides are primarily gravitational and that a progressive wave train initiates failure by reducing the soil strength (remoulding the soil).

In the design of offshore foundations the bearing capacity, lateral resistance (for piles) and stability of the bottom sediments must generally be evaluated. If wave action causes loss of strength due to remoulding there will be an associated decrease in bearing capacity and lateral resistance as well as a potential for mass instability; these effects would be relatively independent of the direction of the storm wave progression. If waves produce only driving forces, stability against landsliding would be the main concern and the effect would vary depending on the direction of the wave train with respect to the dip of the sediment surface. The studies reported in this paper were carried out to investigate the effects of wave action on the strength of a marine sediment.

Strength of bottom sediments and depth of slope failures

Seasonal and long term variations in deposition rates and in the consistency of sedimenting materials complicates the problem of characterizing the strength-depth relations for marine sediments. In areas where sedimentation rates are relatively high, bottom sediments may remain unconsolidated (i.e. an excess pore water pressure gradient exists in the sediment due to high rates of accumulation and slow rates of consolidation) for long periods of time (see, for example, McClelland, 1967). Despite these complications, many marine sediments exhibit somewhat linear increases in undrained strength with depth although the upper portion of the profile often shows a nearly constant strength (see, for example, Sangrey, 1972).

In laboratory studies it is convenient to prepare a simply sedimented soil and it is necessary to examine the form of the strength vs. depth relation in such model sediments. Morgenstern (1967) suggests that the undrained strength profile for a simply sedimented soil may be approximated by

$$C_u = A\,\sigma'_v = AZ\,\overline{\gamma}' \qquad 1$$

where C_u = the undrained strength at depth Z

A is a soil constant related primarily to the effective stress strength parameter ϕ' of the soil

σ'_v = $Z\,\overline{\gamma}'$ is the effective vertical stress at depth Z

$\overline{\gamma}'$ is the average effective unit weight of the overburden above depth Z .

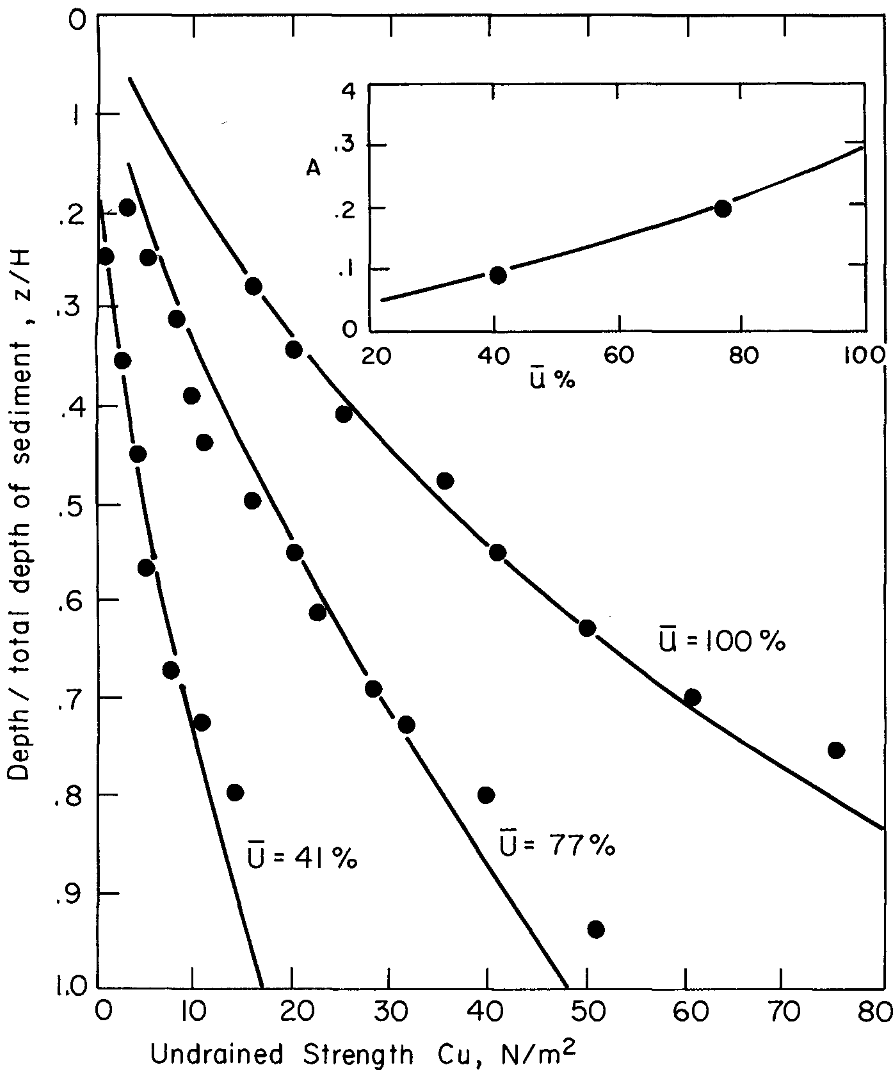


FIGURE 2 : UNDRAINED STRENGTH PROFILES (DATA FROM TSUI, 1972)

Detailed density and pore water pressure measurements carried out by Tsui (1970) and Hull (1973) show that laboratory sedimentation of a bentonite slurry results in the following characteristics:

$$\text{Unit weight, } \gamma = B + C Z$$

and excess pore water pressure, $\Delta u = D Z$

where B, C and D are constants depending on the degree of consolidation.

From equation 1, the undrained strength profile is then predicted as:

$$C_u = A\,[B - (D + \gamma_\omega)]\,Z + \frac{CZ^2}{2} \qquad 2$$

Using experimental values of the constants B, C and D at various average degrees of consolidation, $\bar{U}\%$, equation 2 is fitted in Figure 2 to the vane strength data published by Mitchell et al (1972). The form of the profiles agrees with equation 2 and numerical correlation is obtained by using $A = F(\bar{U}\%)$ as shown inset on Figure 2. The value of A at $\bar{U} = 100\%$ agrees with the Mohr-Coulomb value $A = \sin\phi'/(1 + \sin\phi')$, for $\phi' = 24°$, a reasonable value for this clay. Since A does not remain constant it is concluded that the strength of underconsolidated sediments cannot be predicted from effective stress considerations alone; a more fundamental strength gain develops as the soil consolidates.

In prototype situations the gravitational stresses are proportionally higher (according to the linear scaling factor λ) and variations in density over the depth of the profile are likely to be less pronounced. Prototype strength profiles would then be expected to be more linear than those at the model scale.

The short term (undrained) factor of safety against gravitational failure of submerged slopes can be shown to be directly proportional to the C_u/σ'_v ratio (Gibson and Morgenstern, 1962) and for infinite slope sliding this factor of safety is given by

$$F.S. = \frac{2\,C_u}{\bar{\gamma}' Z \sin 2\alpha} \qquad 3$$

where α is the slope angle. Thus at any given degree of consolidation the depth of failure is independent of the strength vs. depth relation providing it is of the form given in equation 1. Any contribution of wave characteristics to depth of failure should then be related in the model and prototype situations.

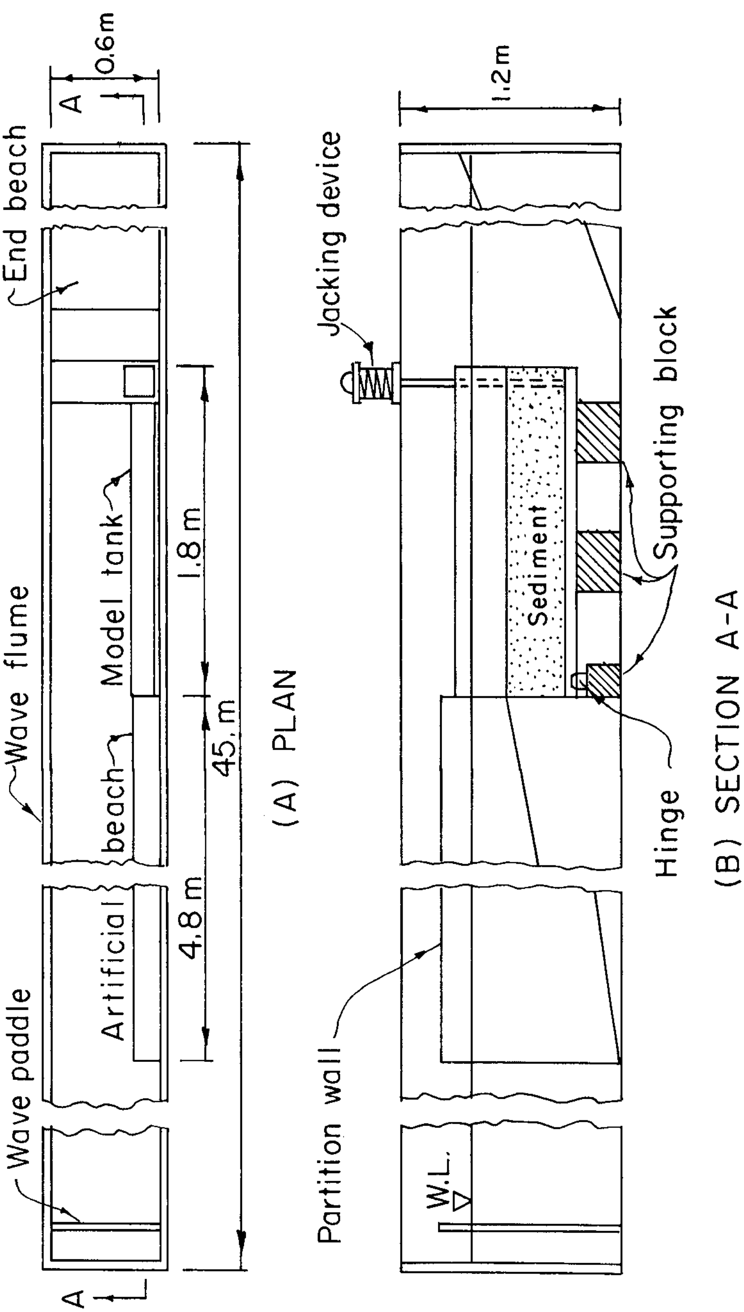


FIGURE 3 : MODEL TANK IN WAVE FLUME

MODEL STUDIES

Model studies were carried out using the physical facilities described by Mitchell et al (1972) to determine the effect of wave action on the strength and stability of a bentonite clay sedimented in a marine environment. Figure 3 shows the physical arrangements with the model tank dimensions being 6 ft. long by 2 ft. deep by 0.5 ft. wide. A commercial bentonite was used as the sediment and was prepared as a 10 percent by weight suspension. Sea water was represented in the sediment and in the flume by a mixture of 35 parts sodium chloride per thousand parts of water. Soil movements were documented by sequential photographs of plastic markers embedded in the sediment and visible through the plastic wall of the model tank. For further details of the sediment preparation techniques the reader is referred to Mitchell et al (1972) and Hull (1973).

The current model studies incorporated more variations in test conditions than earlier studies. In addition to passing progressive wave trains over sediments tilted at various inclinations, static tilting tests were carried out on sediments that had previously been subjected to wave action. Laboratory vane strength measurements were carried out on the sediments before and following wave action and/or tilting experiments. Model tests were carried out under two different deep water wave lengths and the depth of water to wave length ratio was varied between the limits of practical influence.

The bentonite used in these model studies differed from that used in earlier model studies; sediment strengths were an order less in magnitude than those reported by Mitchell et al (1972) and the sediment exhibited a constant strength over the upper portion of the profile. A typical strength profile from the sediment used in this study is shown in Figure 4 for comparison to those in Figure 2.

Effect of wave action on the strength of bottom sediments

The effect of wave action on reducing the strength of bottom sediments was investigated by two methods: direct measurement using the vane apparatus and indirect measurement in static tilting tests. Series of vane strength measurements were carried out on sediments consolidated to a given degree of consolidation. Undisturbed and remoulded vane strength measurements were made prior to passing waves and following sequential application of waves of different heights (wave length constant). Each wave was allowed to act on the soil for several minutes prior to taking strength measurements. It was found that progressive increases in wave energy (wave height) remoulded the soil to increasing depths. Sinking of the near surface plastic markers ($G_s = 1.05$) accompanied the remoulding of the soil by wave action. Figure 5 shows typical undisturbed and remoulded vane shear strength measurements.

Static tilting tests were carried out by tilting the tank at a rate of 3 degrees per minute. Displacement of the plastic markers during a typical test are shown in Figure 6. Failure angles from static tilting tests

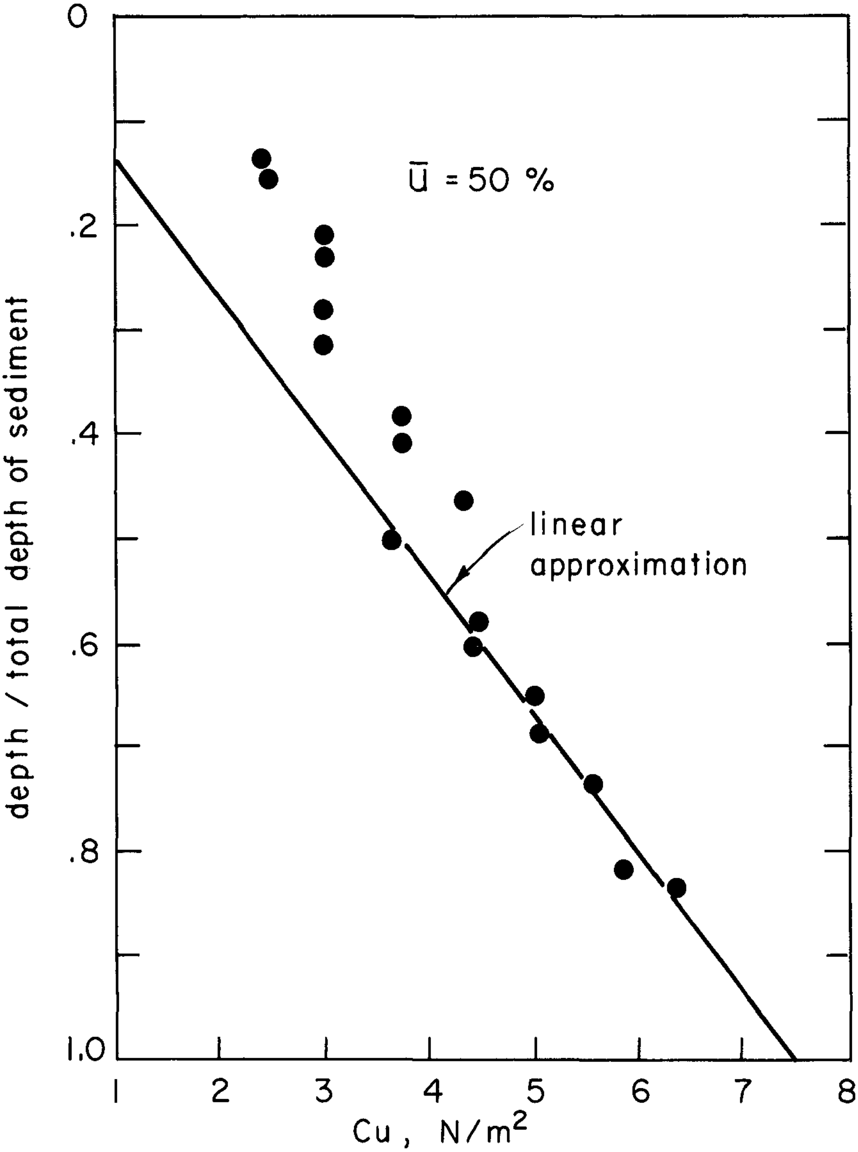


FIGURE 4 : UNDRAINED STRENGTH PROFILE, $\bar{U}$ = 50%

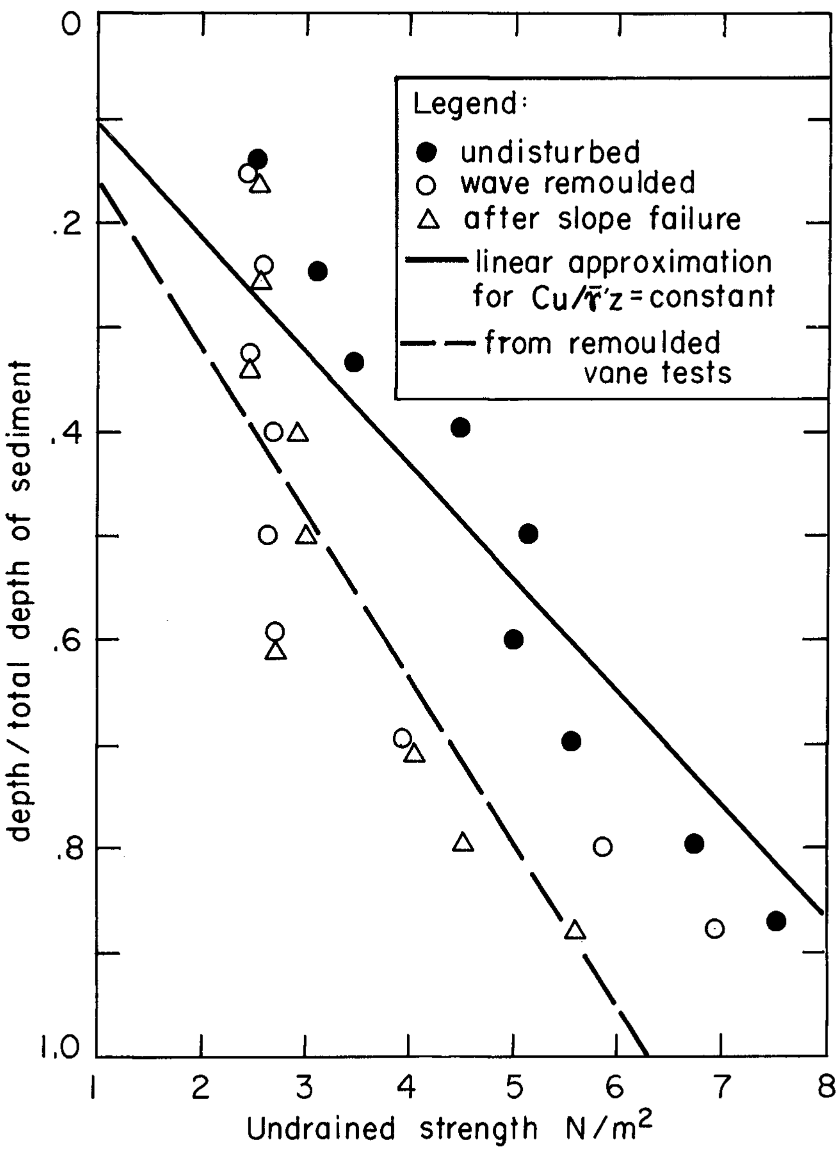
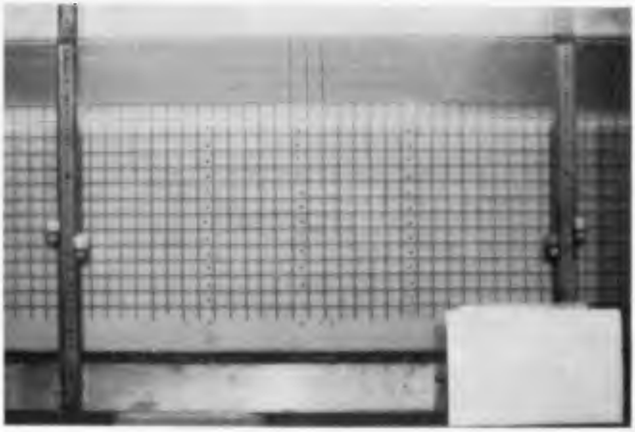
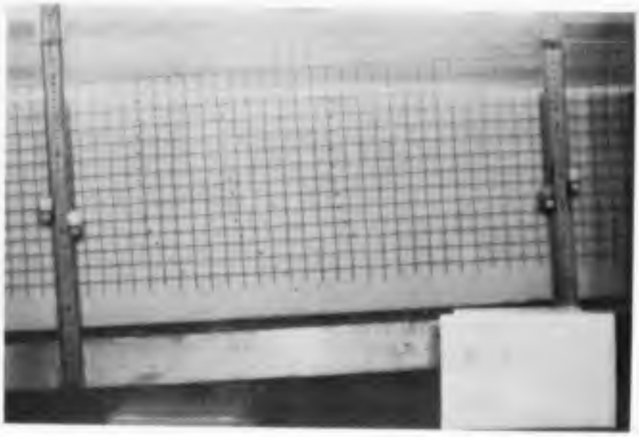


FIGURE 5 : VANE TEST RESULTS FOR $\bar{U}$ = 70%



(A) PRIOR TO TILTING



(B) AT FAILURE

FIGURE 6 : MARKER DISPLACEMENTS IN STATIC TILT TEST, $\overline{U}$ = 30%

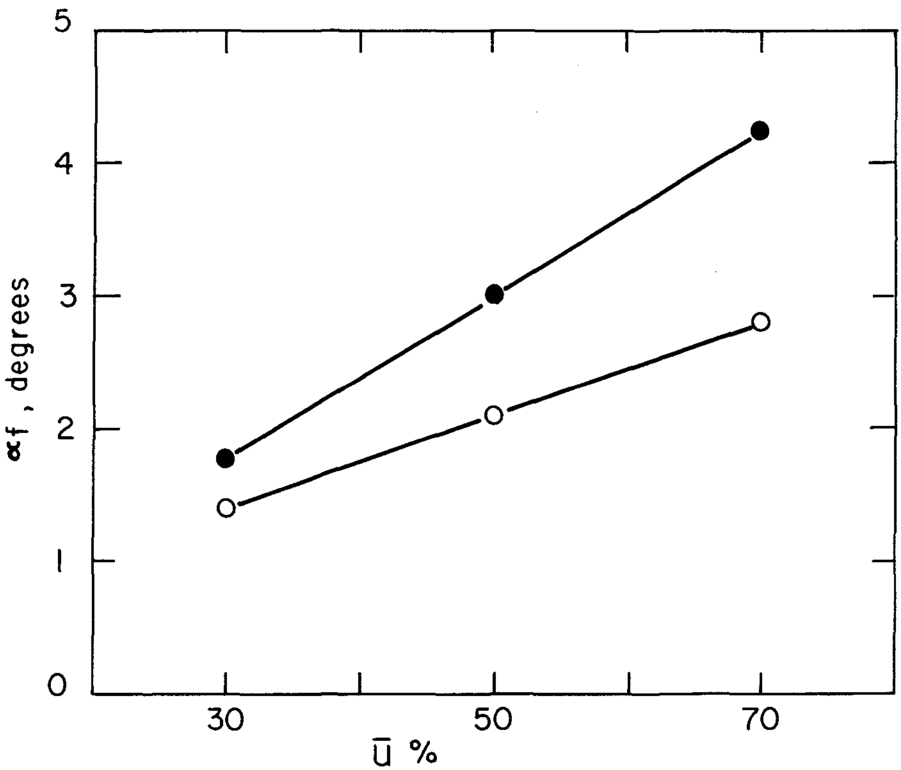


FIGURE 7 : FAILURE ANGLES IN STATIC TILTING TESTS

carried out without wave remoulding and after wave remoulding are shown in Figure 7. These measured angles were found to give a factor of safety approximately equal to unity in equation 3 for the undisturbed and remoulded strength profiles respectively.

From the data in Figure 7 and correlations such as shown in Figure 5 it is concluded that progressive waves can cause loss of strength in consolidating sediments. The minimum strength of the sediment after wave remoulding was found to be approximately equal to the remoulded vane strength. The ratio of undisturbed to remoulded strength (soil sensitivity) averaged about 1.5 in the laboratory sediments. In prototype situations soil sensitivities may be in the order of 10 (see, for example, Sangrey, 1972).

Effect of wave action on slope stability

Tilted sediments at known average degrees of consolidation and gravitational factors of safety, F.S., were subjected to incremented increases in wave height until failure of the slope occurred (wave length constant). These experiments were similar to those reported by Mitchell et al (1972) except that the depth of water to wave length ratio (d/L_o) was varied over a wide range and the sediment was substantially weaker. The subsurface pressure initiating a slope failure, δp_c, and the depth of failure, z_f, were of primary interest in each experiment. Movements of the plastic markers and pore water pressure changes were recorded after each wave train had acted on the sediment until an equilibrium was established. The time duration of each successive increment in wave height varied from about 3 minutes for initial waves to about 10 minutes for the penultimate wave. The wave defining the critical subsurface pressure, δp_c, was that wave under which continual downslope movements occurred.

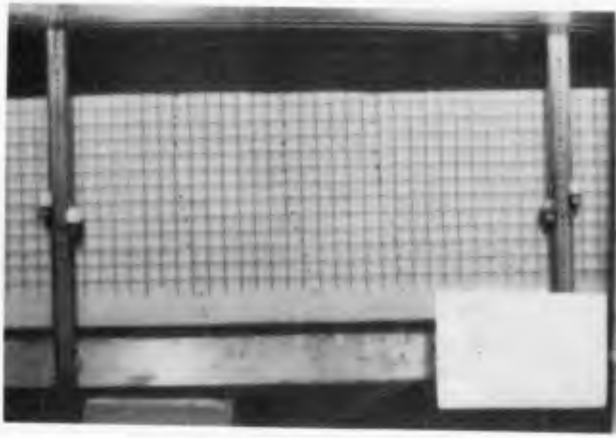
Figure 8 shows typical marker displacement between successive increments of a test. For d/L_o ratios less than about 0.45 the marker displacements generally showed a well defined failure zone similar to earlier experiments; for d/L_o ratios greater than 0.45 the failure was usually poorly defined and extended to the sediment surface. Figures 9 and 10 show the marker displacement sequences for typical tests.

The model test results presented by Mitchell et al (1972) were carried out at a nearly constant value of $d/L_o = 0.35$ and indicated that the critical subsurface pressure, δp_c, (calculated from linear wave theory) was given by

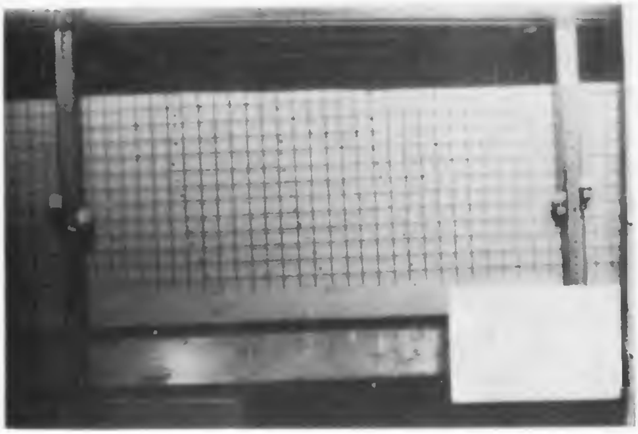
$$\delta p_c = 2.40\ S_r \qquad 4$$

where S_r is the reserve strength and is given by

$$S_r = (\text{F.S.} - 1)\ \bar{\gamma}'\ z\ \frac{\text{Sin } 2\alpha}{2} = C_u\ (1 - \frac{1}{\text{F.S.}}) \qquad 5$$



(A) PEN-ULTIMATE WAVE



(A) FAILURE WAVE

FIGURE 8 : MARKER DISPLACEMENTS DURING WAVE INCREMENT, $\overline{U}$ = 50%, d/Lo = 0.28

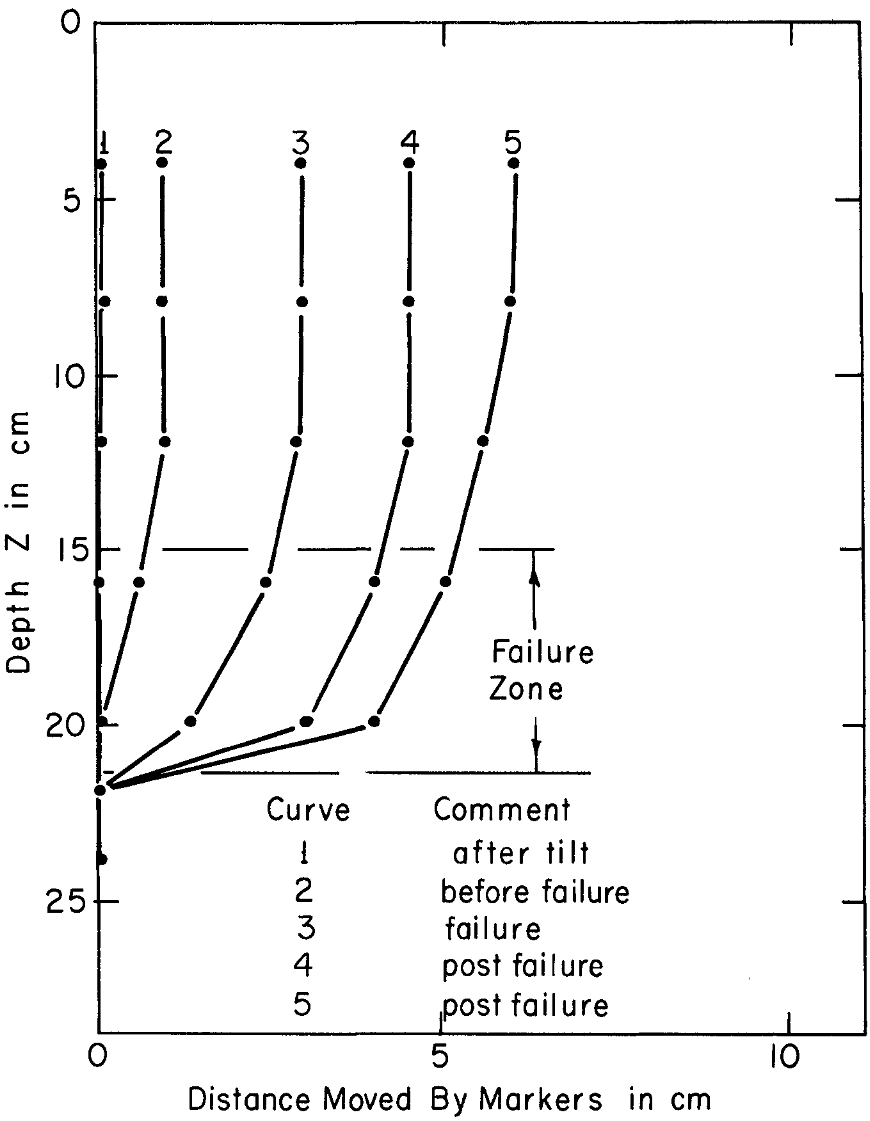


FIGURE 9 : MARKER DISPLACEMENTS, $d/L_o < 0.45$

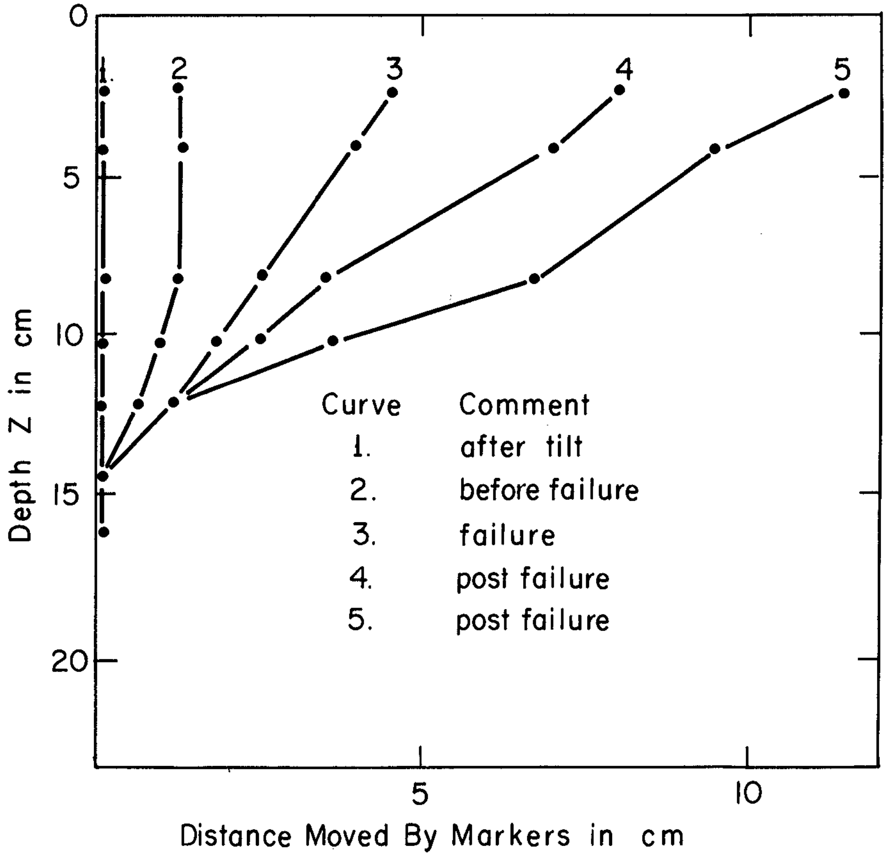


FIGURE 10 : MARKER DISPLACEMENTS, $d/L_o > 0.45$

The reserve strength, S_r , may be considered as the strength remaining after the shearing stresses due to gravitational forces have been deducted from the soil strength. A summary of the tests in which wave induced failure occurred is contained in table 1. The values of $\delta p_c/S_r$ given in table 1 generally increase with increased depth of failure. The average value $\delta p_c = 2.5\ S_r$ compares favourably with the earlier correlation. For static factors of safety in excess of 2.0 no well defined slope failures occurred but, under relatively high subsurface pressures the sediment surface gradually flattened by downslope movement of near surface materials. This observation supports the suggestion (Mitchell et al, 1972) that no mass failure will be initiated by waves if the static factor of safety is in excess of the sensitivity of the soil (this criterion follows directly from the concept that the slope failures are gravitational phenomenon and the wave action acts only to reduce the soil strength by remoulding).

Depth of slope failures

Theoretical analyses indicate that the depth of failure, Z_f , in all cases will increase as the bottom pressure, δp , increases. Wright and Dunham (1972) conclude that failure will be limited to shallow depths and indicate a maximum failure depth of 0.19 L_o for soils of constant strength. Henkel (1970) produces a non-dimensional plot relating the depth of failure to wave length ratio, (Z_f/L) , to certain wave characteristics and the static factor of safety. Using reserve strength, S_r , to eliminate the variations in F.S. a plot similar to that produced by Henkel is shown in Figure 11. While earlier data (Tsui, 1972) supported the suggestion that the depth of failure is limited to about 0.2 L_o , the current tests show that the depth of failure does increase with the $\delta p_c/S_r$ ratio in general agreement with the relation derived by Henkel (1970). Tests conducted by Tsui (1972) were restricted to $0.32 < d/L_o < 0.42$; extension of this range of d/L_o also indicates that depth of failure decreases with increasing water depth as shown on Figure 12. The lack of precise agreement between the two series of model studies, particularly with regard to failure depths, may be due to differences in the form of the strength profiles (compare Figures 2 and 4) and it must be concluded that the form of the in situ strength profile may influence the depth of failure in prototype situations.

As noted earlier, failures where $d/L_o > 0.45$ developed by gradual slope flattening with maximum movement at the mud line. This type of failure also developed in test No. 8 (see Table 1), where $d/L_o < 0.45$ but the factor of safety was large (F.S. = 2.0). In tests where $d/L_o < 0.45$ and F.S. < 2.0 zonal failures occurred (see Figure 10). Cyclic movements and fissure patterns approaching circular arcs were visible in the sediment just prior to the development of a zonal failure. This type of failure can

TEST No.	$\overline{U}$%	α_f	F.S.	d/L_o	z_f/L_o	δ_{pc}/S_r
1	33	1.8	2.0	.52	.23	3.0
2	70	4.4	1.4	.616	.255	1.1
3	50	3.0	1.7	.566	.333	1.0
4	30	1.8	2.0	.510	.360	2.0
6	50	3.0	1.7	.41	.31	2.24
8	42	2.5	2.0	.294	.41	2.7
9	75	4.5	1.4	.368	.525	2.35
10	50	3.0	1.7	.315	.23	1.85
11	85	5.1	1.0	.338	.50	1.70
12	70	4.2	1.4	.333	.475	2.24
13	50	3.0	1.7	.28	.575	4.3
14	70	4.2	1.7	.324	.49	2.85
15	70	4.2	1.7	.282	.46	3.1
16	70	4.2	1.3	.195	.565	4.1

TABLE 1 - List of Slope Stability Tests

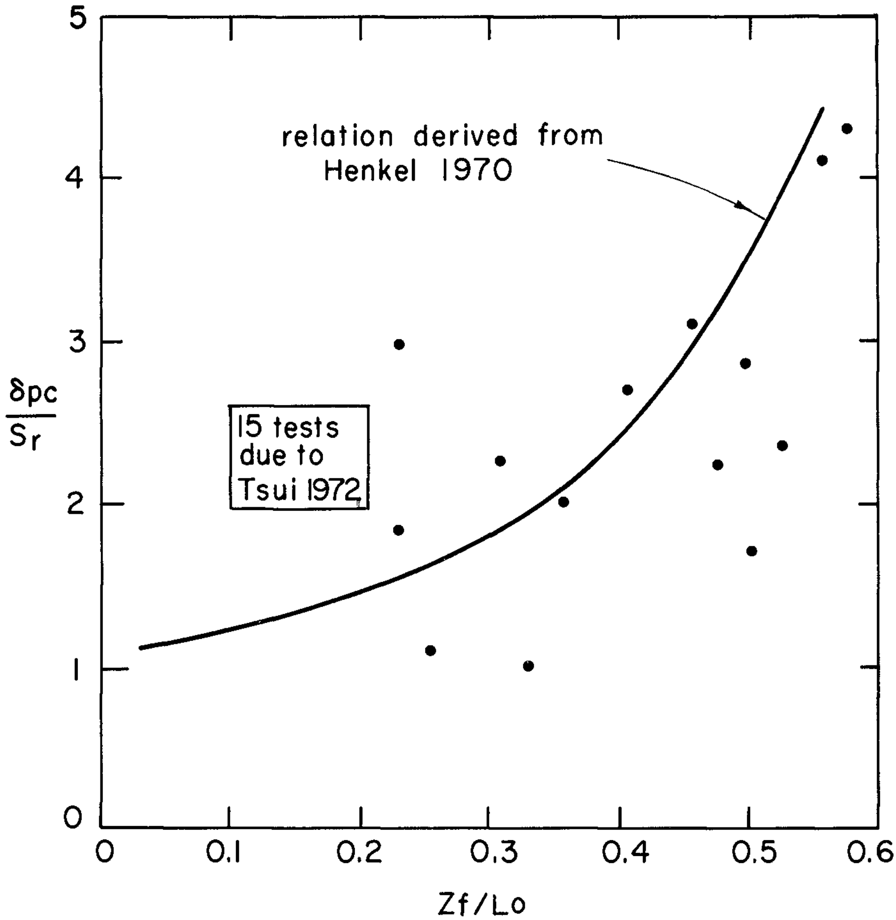


FIGURE 11 : RELATION BETWEEN BOTTOM PRESSURE, SOIL STRENGTH AND FAILURE DEPTH

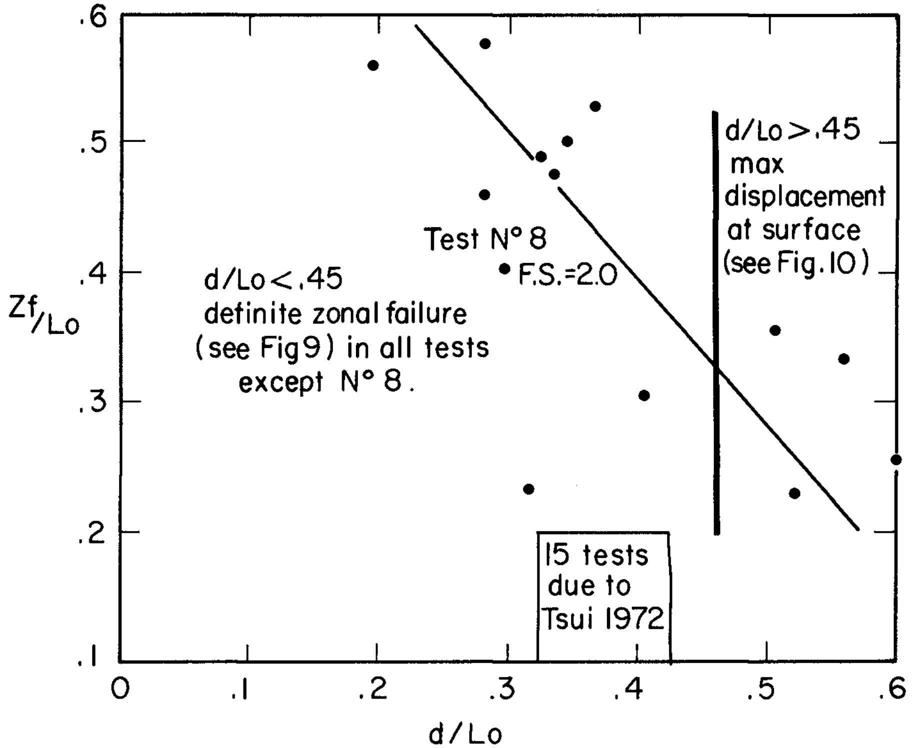


FIGURE 12 : RELATION BETWEEN WATER DEPTH AND FAILURE DEPTH FOR CRITICAL WAVE CONDITIONS

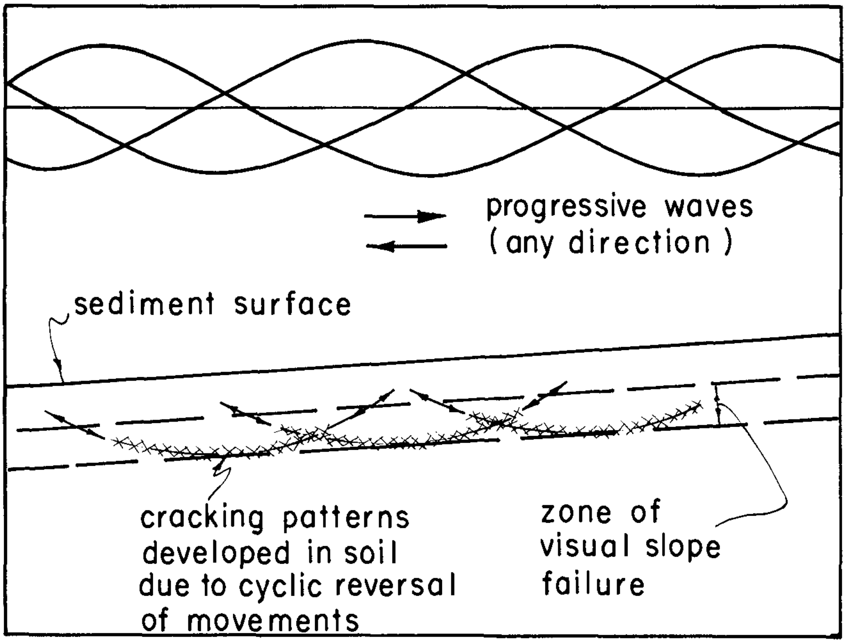


FIGURE 13 : FORMATION OF ZONAL FAILURE IN A SLOPE WHEN $d/L_o < 0.45$

be associated with an extension of the static rotational analysis (see Figure 1) to the progressive wave situation as depicted in Figure 13.

Slight increases in pore water pressure were noted on the standpipes (see Figure 8) when the sediment was subjected to wave action but marked decreases in pore water pressures accompanied the actual slope failure. Pore water pressure decreases were associated with the development of zonal failure as shown on Figure 13. From these visual observations it is concluded that the reversals in shearing strain (reversals in rotational movements) causes remoulding of the soil. The depth of remoulding was observed to increase with increasing subsurface pressure in general agreement with the relations shown in Figures 11 and 12.

Conclusions

From the model tests and correlations presented in this paper the following conclusions are advanced:

1. Cyclic subsurface pressures due to wave action can cause remoulding and loss of strength in fine grained submarine sediments. The depth of remoulding generally increases with increased subsurface pressure.

2. In sloping offshore sediments the remoulding due to wave action may lead to slope instabilities. The depth of potential slope failures increases with increased subsurface pressure in general accordance with the relation proposed by Henkel (1970). Deep failures are not considered possible unless the sensitivity of the soil is in excess of the static factor of safety of the slope.

While many advances in offshore sampling and in situ testing techniques are being made in order to measure the undisturbed strength of submerged soils, it is suggested that in situ measurement of remoulded strength profiles should be considered an essential part of all offshore subsurface investigations where water depths are less than the water wave lengths during storm conditions. The possibility of wave action reducing the sediment strength should be considered in the design of all permanent offshore structures.

Acknowledgements

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