WAVE SCOUR AROUND A VERTICAL CIRCULAR PILE IN SILT*

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This paper summarizes the results of an experimental investigation on wave scour around a circular pile in three different soils, namely in dense silt, in loose silt and in loose sand. The dense silt was achieved by wave liquefaction. Upon the completion of the liquefaction/compaction process, the pile was subjected to wave induced scour. Scour in all three cases was in the live-bed regime. The scour depth was increased by a factor of 1.6-2 when the bed soil was changed from loose silt/sand to dense silt. The angle of friction may be one "candidate" to cause large scour depths in the case of the dense soil. The time scale of scour also was influenced by the density of the soil. The time scale was largest for the dense-silt case, and the smallest for the sand case in the experiments.

1 Introduction

Scour is a threat to the stability of marine structures. Quite a substantial knowledge of scour around piles in waves has accumulated over the past decade. Sumer et al. (1992a, 1993) and Kobayashi and Oda (1994) demonstrated that the Keulegan-Carpenter number, KC, is the main parameter governing the scour process (and thereby the scour depth) on a live bed. In a follow-up publication Sumer and Fredsøe (2001) reported on the influence of combined waves (regular/irregular) and current, contributing to the already existing knowledge of scour in combined waves and current reported in a series of publications by Herbich and his co-workers (Wang and Herbich, 1983, Herbich et al., 1984, and Eadie and Herbich, 1986). Recent reviews of the subject can be found in Whitehouse (1998), Sumer, Whitehouse and Tørum (2001) and Sumer and Fredsøe (2002).

The sediment used in the above mentioned studies was fine to medium sand. To the authors' knowledge, no study is yet available investigating the scour in waves in very fine sand and silt. Field observations show that very fine sand/silt can be present on the ocean floor in various densities, from very loose to very dense states. The question is whether

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or not the existing knowledge of scour obtained in the case of fine-to-medium sand is applicable to dense, very fine sand and silt; particularly, does the density of the soil play any role in the scour process? If it does, how are the properties of scour, such as the equilibrium scour depth and the time scale of scour, influenced by this parameter? The purpose of the present work is to address this question.

2 Experimental set-up

The experiments were carried out in a wave flume, 0.6 m in width, 0.8 m in depth and 26.5 m in length. Waves were produced by a piston-type wave generator. The water depth was maintained at 42 cm. The soil (silt or sand) was placed in a 0.175 m deep, 0.59 m wide and 0.9 m long perspex box (with transparent walls), located at a distance of 12 m from the wave generator. The box was placed in the flume so that the soil surface was flush with the false bottom of the flume. Two kinds of soil were used in the experiments: (1) Silt with d_{50} = 0.060 mm (with the geometric standard deviation of 1.8); and (2) Sand with d_{50} = 0.147 mm (with the geometric standard deviation of 1.2). The sand experiments were conducted for reference purpose. Two kinds of silt were used in the experiments: (1) Loose silt with D_r = 0.38; and (2) Dense silt with D_r = 0.73 in which D_r is the relative density defined by $D_r = (e_{max} - e)/(e_{max} - e_{min})$, e being the void ratio.

The dense silt was achieved by wave liquefaction in which the soil was subjected to waves. The waves were large enough to cause liquefaction, which was followed by compaction. This technique proved very effective to compact the soil. When a "fresh" soil with no history of liquefaction is exposed to a wave, and when it is "undrained" as in the case of very fine sand or silt, it goes through a number of different stages/regimes (Sumer et al., 2004): With the introduction of waves, (1) first the pore pressure begins to build up; (2) When the "accumulated" pore pressure reaches the overburden pressure value, the soil is liquefied; (3) With the soil liquefied, an upward-directed pressure gradient is generated in the soil. This pressure gradient drives the water in the liquefied soil upwards while the soil grains "settle", leading to a progressive compaction of the soil; (4) This compaction process first begins at the impermeable base and gradually progresses in the upward direction as the pore water is drained out of the soil; and (5) When the compaction "front" arrives at the mud line, the compaction process is completed.

In the case of the silt exposed to waves larger than a critical value of wave height, H_{cr} (the critical value of H corresponding to the onset of liquefaction, Sumer et al., 1999), the soil undergoes the previously mentioned liquefaction/compaction processes. The present tests reveal that the scour begins to occur upon the completion of the compaction process. These tests are designated as the **dense-silt tests**. In the case of the silt exposed to waves smaller than H_{cr}, the soil is not liquefied. The tests show that the scour in the latter case begins to occur immediately after the waves are switched on. These tests are designated as the **loose-silt tests**. In the case of the sand, the soil was not liquefied (no matter what the wave height was) because the sand was too coarse.

Circular model piles with diameters D = 1.5; 2; 2.4; 3; 4; 5 and 8 cm were implemented in the tests. The 4 and 8 cm diameter piles were transparent. This enabled the scour process to be monitored by a mini video camera placed inside the pile. The latter was achieved with the help of a 45^0 mirror placed in front of the camera. The camera-and-mirror system could be moved up and down as the scour developed. In the silt experiments, the water around the pile was so "murky" (because of the silt) that videotaping the scour process from outside the pile proved practically impossible, and therefore we resorted to this set-up. Nine tests were made for the dense silt and seven tests were made for the loose silt. Two experiments in the case of the dense silt and four experiments in the case of the loose silt were made with non-transparent piles. In these tests, the scour process was not monitored. Rather the equilibrium scour depth was measured after the completion of the test. Regarding the sand tests, thirty two tests were made in this case.

Pore-water pressure measurements were made during the course of the tests. These measurements were made at four depths, z = 5.5, 7.5, 12.5 and 17 cm in the case of the silt, and at z = 17 cm in the case of the sand, in which z is the vertical distance measured downwards from the mud line. Only one measurement point, z =17 cm, was implemented in the sand case just to check if there was any buildup of pore-water pressure at all. Rosemount, model 1151 DP Alphaline pressure transducers were used to measure the pore-water pressure. More information about the pressure measurements can be found in Sumer et al. (1999) and Sumer et al. (2004).

The process of liquefaction and subsequent compaction in the case of the silt was videotaped from the side. This and the videotaping from inside the pile were made simultaneously with the pressure and surface-elevation measurements in a synchronized manner. Using the video records taken from inside the pile and those taken from the side of the flume, the time series of the "net" scour depth (at the pile) was obtained. These time series were then analyzed to obtain the equilibrium scour depth and the time scale of the scour process. In the case of the non-transparent piles, only the equilibrium scour depth was measured, as mentioned previously.

The orbital velocity of water particles at the bed was measured in another wave flume (which was identical to that used in the actual experiments) with a rigid, smooth bed and glass side walls. A one-component Laser Doppler Anemometer was used to measure the velocity. The velocity measurements were made under exactly the same test conditions as in the actual scour experiments.

The test conditions are as follows. **Dense-silt tests**: Pile diameter, D = 2-8 cm; Wave height, H = 11-17 cm; Wave period, T = 1.2-2.5 s; Keulegan-Carpenter number, KC = 7-19; Shields Parameter, θ = 0.3-0.6 in which the KC number and the Shields parameter are

$$KC = \frac{U_m T}{D} \quad \text{and} \quad \theta = \frac{U_{fm}^{\,2}}{g(s-1)d_{50}} \qquad (1), (2)$$

in which T is the wave period, U_m the maximum value of the orbital velocity at the bed, U_{fm} the maximum friction velocity, s the specific gravity of soil grains and g the acceleration due to gravity. **Loose-silt tests**: Pile diameter, D = 1.5-8 cm; Wave height, H = 7-9 cm; Wave period, T = 1.6-2.5 s; Keulegan-Carpenter number, KC = 7-22; Shields Parameter, θ = 0.2-0.4. **Sand tests**: Pile diameter, D = 2.4-8 cm; Wave height, H = 5-17.5 cm; Wave period, T = 1.2-2.5 s; Keulegan-Carpenter number, KC = 9-19; Shields Parameter, θ = 0.05-0.26.

3 Results and discussion

Fig. 1a shows the time series of the pore water pressure at four depths (at z =5.5, 7.5, 12.5 and 17 cm) in the case of the silt where the silt was "hardened" by wave liquefaction (the dense-silt case). In the same figure, the time development of scour depth in this test also is plotted (Fig. 1b). The quantity p in Fig. 1 is the pore-water pressure in excess of static pore water pressure at the same depth, γ the specific weight of water and S_t the scour depth measured at the pile. In this test, the wave height (H=17 cm) was large enough to liquefy the soil. As seen from Fig. 1a, the pore-water pressure first builds up. The onset of liquefaction occurs when the accumulated pore water pressure reaches the overburden pressure value, which may be calculated from

$$\sigma_0' = \gamma' z \frac{1+2k_0}{3} \qquad (3)$$

in which γ' is the submerged specific weight of the soil, z the depth from the mud line, k_0 the lateral earth pressure coefficient, measured as 0.41 for the present silt. (The values calculated from the latter expression are σ_0'/γ = 11 cm for z = 17 cm; 8 cm for z = 12.5 cm; 4.8 cm for z = 7.5 cm; and 3.5 cm for z = 5.5 cm). Subsequently the liquefaction sets in, which is followed by the compaction process. The simultaneous measurements of pore-water pressure (Fig. 1a) and video recording of the soil behaviour reveal that the liquefaction/compaction process ends at t = 14 minutes (Fig. 1a). With the completion of the liquefaction/compaction process, the relative density of the silt was increased from its initial value D_r = 0.38 to the value D_r = 0.73.

A detailed description of the sequence of events from the buildup of pore-water pressure to liquefaction and to compaction is given in Sumer et al. (2004). It may be mentioned that great many works have been devoted to the theoretical and experimental investigation of buildup of pore pressure and the resulting liquefaction, starting with the work of Seed and Rahman (1978). Sumer and Fredsøe (2002) may be consulted for a detailed account of the topic.

Returning to Fig. 1, the figure shows that the scour begins to occur (Fig. 1b) only after the liquefaction/compaction process is completed (at t = 14 minutes, Fig. 1a). In the case when the wave height was small (smaller than H_{cr} =10.2 cm) (i.e., when the silt was not liquefied/compacted and therefore remained loose), the scour began immediately after the waves were introduced.

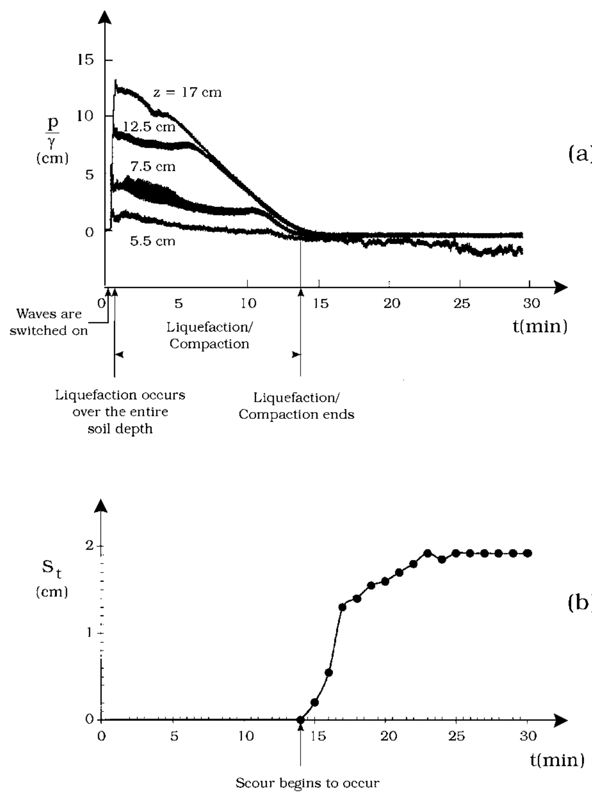

Figure 1. Time series of pore-water pressure (a) and scour depth (b). Dense silt. H=17 cm.

Fig. 1b shows that the scour develops towards its equilibrium stage through a transitional period, the usual behaviour known from sand experiments (e.g., Melville and Coleman, 2000 and Sumer and Fredsøe, 2002).

Symbol	Soil	Relative density D_r	Shields parameter θ
●	Dense silt	0.73	0.3-0.6
○	Loose silt	0.38	0.2-0.4
Δ	Sand	0.23	0.2-0.3

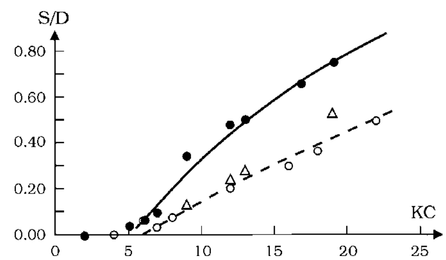

Figure 2. Equilibrium scour depth. Live bed. Dashed line: Curve representing Sumer et al. (1992a) data.

Fig. 2 presents the equilibrium scour depths obtained in the present experiments, plotted as a function of the KC number similar to the previous sand studies. Three kinds of data are plotted in Fig. 2: (1) Dense-silt data; (2) Loose-silt data; and (3) Sand data. In Fig. 2 is also plotted the empirical expression

$$\frac{S}{D} = 1.3\left[1 - \exp(-0.03(KC - 6))\right] \quad (4)$$

representing the sand data obtained in Sumer et al.'s study (1992a) for the live-bed scour regime (the dashed line). Finally it maybe noted that the data plotted in Fig. 2 all represent the live-bed scour regime.

The following conclusions can be drawn from Fig. 2.

1. The scour depth in the case of the sand (D_r = 0.23) of the present experiments (triangles) is in fairly good agreement with Sumer et al.'s (1992a) sand data (dashed line) although the last data point of the present experiments indicates a scour depth 17% larger than the Sumer et al.'s (1992a) data. This is, however, within the scatter of the data given in Sumer et al. (1992a).
2. The loose silt (D_r =0.38) data (circles) also agrees with Sumer et al.'s (1992a) sand data (dashed line).
3. The scour depth in the case of the dense silt (D_r = 0.73) (triangles) is markedly larger than those of Sumer et al.'s (1992a) sand experiments (dashed line), the present sand experiments (triangles) and the present loose-silt experiments.
4. The scour in the case of the dense silt begins to occur when the Keulegan-Carpenter number exceeds KC = 5, approximately the same value of KC corresponding to the onset of scour for the case of the sand and that of the loose silt.

The increase in the scour depth for the dense silt (larger D_r) may be related to the increase in the angle of friction. This is explained as follows. The flow agents responsible for scour (i.e., the lee-wake flow and the horseshoe vortex flow) will remain practically the same when the soil is changed from loose sand/silt to dense silt. Hence the plan-view extent of these flow agents will remain unchanged, irrespective of the bed soil (dense or loose). However, the angle of friction will increase when the soil is changed from loose sand/silt to dense silt. Thus, the scour depth should also increase when the soil is changed to dense silt.

Although the scour in both the dense silt and the loose silt/sand cases was in the live-bed regime ($\theta > \theta_{cr}$), the Shields parameter in the former case is generally larger (θ = 0.3-0.6) than in the case of the loose silt (θ = 0.2-0.4) and in the case of the sand (θ = 0.2-0.3) (Table 1). Hence it may be argued that the increase in the value of the Shields parameter in the case of the dense silt may also have contributed to the increase in the scour depth exhibited in Fig. 2. To observe whether or not the Shields parameter played any role in the increase of the scour depth for the dense silt, an extensive series of scour experiments have been carried out with the present sand where the Shields parameter was changed over a broad range of θ (from the clear-water scour regime to the live-bed scour regime). These experiments were conducted for two KC numbers, KC = 9 and 12. The results, when plotted together with the corresponding silt results, showed that the increase in the scour depth for the dense silt is not due to the increase in the Shields parameter.

The scour depth develops towards its equilibrium stage through a transitional period, as depicted in Fig. 1b. It is seen from the figure that the time variation of the scour depth can be approximately represented by the following relation

$$S_t = S(1 - \exp(-\frac{t}{T_{scour}})) \qquad (5)$$

in which S is the equilibrium scour depth. The quantity T_{scour} may be defined as the time scale of the scour process, representing the time period during which a substantial amount of scour develops (Sumer et al., 1992b and 1993). The time scale can be predicted from the scour-depth-versus-time information by integrating S_t over time. The normalized time scale (following Sumer et al., 1992b, 1993) is

$$T^* = \frac{(g(s-1)d_{50}{}^3)^{1/2}}{D^2} T_{scour} \qquad (6)$$

The normalized time scale was calculated, using the present scour depth time series. The data will not be shown here for reasons of space. However, the results show that the time scale, for a given value of KC and for a given value of θ, is largest for the dense silt and smallest for the sand. (Two orders of magnitude difference has been observed between the dense-silt time scale and the sand time scale). The time scale is largest for the dense silt because (1) the sediment transport takes place in a slower "pace" in the case of the dense silt, and (2) the equilibrium scour depth in this latter case is also larger (Fig. 7), which implies that larger times are required for scour. Hence these two effects make the time scale increase tremendously in the case of the dense silt.

4 Conclusions

The scour depth at a pile subject to waves is influenced by the soil density, represented by the relative density, D_r. The scour depth was increased by a factor of 1.6-2 when the bed soil was changed from loose silt/sand (D_r = 0.23 for sand and D_r = 0.38 for loose silt) to dense silt (D_r = 0.73) in the present experiments. This may partially be explained in terms of the angle of friction. The time scale of scour is also influenced by the density of the soil. The time scale was largest for the dense-silt case, and the smallest for the sand case of the experiments.

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