CHAPTER 97

LOCAL SCOUR AROUND CYLINDRICAL PILES DUE TO WAVES AND CURRENTS COMBINED

by

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ABSTRACT

Local scour depth around a pile due to waves only is small, but under waves and weak currents combined it became large. If the flow velocity increases, the maximum scour depth increases and may approach to that by running water. In the processes of the scouring, Kármán vortex play an important role in deciding characteristics of a scour hole. In the case of the horseshoe vortex predominant, the maximum scour depth is found at the upstream end of a pile, but in the coupled field of waves and currents, the initial scouring position is a little apart from a pile in the offshore side and make an angle of about 45 degree in the shoreward direction. This depends on a vortex shedding from a pile. By using light weight aggregate, the effect of ripples on local scour depth is made clear.

1. INTRODUCTION

In recent year, we have a lot of various coastal structures in the shallow water, such as artificial reclaimed islands, access bridges, breakwaters and piers for fishing and field observation. When these structures are designed, many factors for desirable construction must be taken account. One of them is local scour around cylindrical piles of pier type structures.

Some studies on local scour due to waves have been made in hydraulic experiments and in field observations, as reviewed by Herbich et al.(1984). Local scour depth due to waves is not so large in comparison with that due to uni-directional flow. As to the experimental results obtained by Herbich et al. and through our preliminary tests, conditions of waves and weak currents combined makes scour depth large in comparison with that only by waves. The conditions can be usually seen in the nearshore zone in which several currents such as longshore currents, rip currents and undertow coexist with waves. The scouring mechanism is not so clear, therefore, it is very difficult to predict the scour depth and area around a cylindrical pile in the nearshore environment.

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Studies on local scour due to currents only have been made by Shen et al.(1969), Raudkive et al.(1983) and other many investigators in river engineering. The works show that the horseshoe vortex is a dominant factor to determine the characteristics of local scour around a pile in uni-directional flow. Moreover, two types of scour may be identified as follows: (1) Clear water scour where sediment is removed from the scour hole and not replenished by the approach flow; and (2) Live-bed scour where sediment is continuously supplied into the scour hole by the approach flow. Their experiments also suggested that the scour depth increases with increase in mean water velocity in the clear water regime and reaches a maximum at a velocity approximately equal to the threshold velocity with which bed sediment is no longer removable from the hole. With live-bed scour, an equilibrium is attained when the rate of sediment transport into the scour hole by the approach flow is equal to the rate of sediment removed from the hole. The equilibrium scour depth in the live-bed scour regime is usually smaller than the maximum scour depth in the clear water scour regime. These characteristics are not clear yet under the condition of waves and currents combined. Moreover, the enlargement of the scour hole with time have not studied in detail, so that the limitation of the data keeps the physical modelling of scouring incomplete.

The objectives of this investigation are to examine processes of local scour around a cylindrical pile due to waves and currents combined in the regimes of clear water scour and live-bed scour and to make clear the effect of ripples on the characteristics of scouring.

2. EXPERIMENTS ON LOCAL SCOUR

2.1 Experimental apparatus and methods

Hydraulic experiments on local scour around a cylindrical pile were carried out in a recirculating wave flume at the Ujigawa Hydraulics Laboratory, Disaster Prevention Research Institute, Kyoto University. The experimental apparatus is shown in Fig.1 . The flume used was 40m long , 50cm wide and 65cm deep with a piston type wave generator at the end. This is a double-deck type flume in which rate of mass transport in waves in the upper deck can return in the offshore

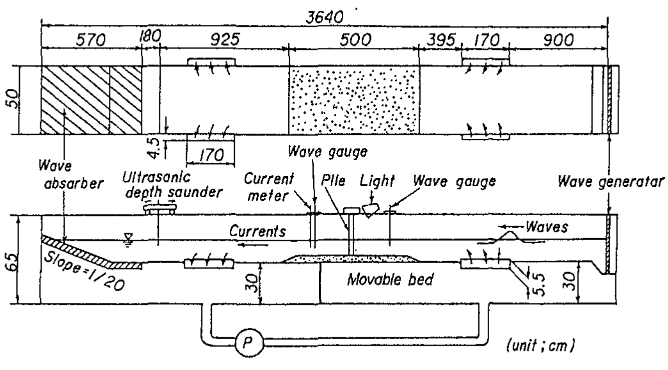


Fig. 1 Experimental apparatus and wave flume.

direction in the lower one. Pump system equipped in the flume can generate recirculating currents. We set a cylindrical pile in the midst of the movable bed of 5m long. Two kinds of sediment were used, i.e., one is very fine sand with a mean diameter of 0.11mm and its density of 2.65gr/cm^3, and another is light weight aggregate whose diameter and density are 0.85mm and 1.81gr/cm^3 respectively. Under the usual experimental wave condition, ripples are not formed on the movable bed of the light weight aggregate. Two capacitance type wave gauges and an electro-magnetic current meter were used.

All experiments were run at a depth of 10cm on the movable bed and with a constant wave period of 1.4s. The wave heights were changed 0 to 6cm systematically and the mean flow velocities were 13.4, 12.1, 6.71, 0 and -12.0cm/s, in which sign minus means reverse flow. Cylindrical piles of diameter 1.6, 2.0, 2.4, and 3cm were used. The depth of the local scour was measured continuously with a hundred plastic optical fibers of diameter 0.5mm and a high speed VTR as shown in Fig.2 . The number of the lights which pass through the optical fibers is equal to the depth of the local scour in real time. We measured the local scour depth both at the offshore and onshore sides of a pile. When ripples were formed on the movable bed, their heights and lengths were measured with a ultra-sonic depth sounder.

2.2. SCOUR PROCESSES

At first, the scour processes due to waves in our experiments are as follows: The local scour did not occur when the wave height was smaller than about 2cm in every piles used. As the wave height increases, scour holes were formed in the clear water scour regime. The scour due to Karman vortexes was observed at the bed nearly 2cm away from a pile and at an angle of nearly 45 degrees in the direction of wave propagation. We observed sediment suspension due to formation of the vortexes which were formed along the surface of the pile, and after that shed behind it. The vortex moved upward and downward in accompany with wave motion. The sediment movement is not so active at first and thus the scour depth is very shallow. The scour depth at the onshore side was generally larger than that at the

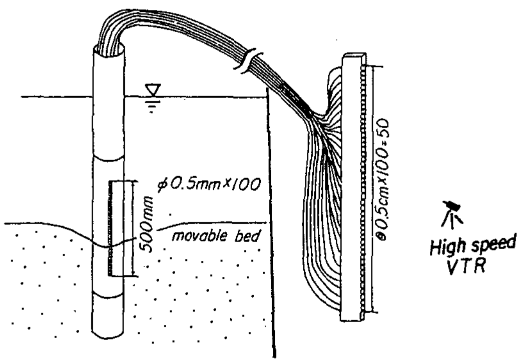


Fig. 2 Schematic diagram of a test pile with one hundred optical fibers and a high speed VTR.

offshore side because shoreward flow due to mass transport may strengthen a vorticity at the onshore side.

When the wave height was more than about 4cm, ripples were formed all over the surface of the movable bed. The depth of live-bed scour was nearly equivalent to the ripple height and the ripple length was usually of the same order of a pile diameter. Therefore, it was very difficult to estimate the scour depth. In this case, the sediment concentration near the bed generated by the vortex was very dense, but the scour depth is not so large.

Secondly, the scour processes due to currents are briefly explained. When the mean flow velocity was 6.71cm/s, local scour did not occur. When it was 13.4cm/s, scouring hole whose plan shape looked like a horseshoe was dug quickly. At the lee side of the pile, a slight accretion of sediment was recognized. When flow velocity was -12.0cm/s(reverse flow), the scour processes, of course, were very similar to the cases in which flow velocity was 13.4cm/s.

In the coupled field of waves and currents (u=6.71 cm/s), much sediment was easily swirled up with the vortexes generated behind a pile (onshore side), and the initial scouring position is slightly apart from a pile in the onshore side and make an angle of 45 degrees in the onshore direction as shown in Fig.3. This depends on the vortex shedding from a pile. The size and the depth of the hole were much larger than those due to waves only. As time went by, the scouring also occurred at the offshore side. After this stage, sediment which was swirled up at the offshore side of the pile was carried away due to currents, but some suspended sediment inside a scour hole can not be carried out with currents. Therefore, the former leads to net loss of sediment from the hole. This is a typical process of local scour enlargement at the offshore side of the pile. At the onshore side, the process of scouring is similar to that at the offshore side. However, some sediment which was flew up over the hole at the onshore side deposited on the edge of the scour hole at the onshore side. Behind the holes (onshore side), small ripples were formed.

In an equilibrium stage of live-bed scour, the shape of the scour hole was semicircular at the offshore side, and trapezoidal at the onshore side. When the wave height becomes larger than that at the beginning of ripple formation, it was very difficult to distinguish

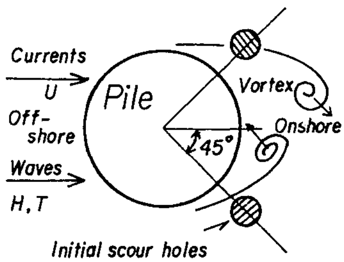


Fig. 3 Vortex shedding with a vertical axis and location of initial scouring.

between the trough of the ripple and the scour hole. The scouring processes in u=13.4cm/s resembled those in the cases of u=6.71cm/s, but the horizontal scales and the depth of the scour holes were much larger than the latter case. In the first stage, the vortex which looks like a horseshoe one contributes to local scour as well as the scouring process due to currents only. After this stage, the scouring advanced as same as that in the case of u=6.71cm/s. In some experiments, small ripples were formed at the onshore side of the scour hole. When wave height was larger, ripples were formed all over the bed. With the reverse flow (u= -12.0cm/s), the scour processes were very similar to the cases of those at the velocity of 13.4cm/s. The the shape of the scour hole in the former case, of course, was almost opposite to that in the latter case.

3. CHARACTERISTICS OF LOCAL SCOUR

Characteristics of local scour around a pile due to waves and currents combined are very different from those due to currents only. Using the data obtained in our experiments, we analyzed them with traditional method of dimensionless expressions.

3.1 Bottom topography of scour hole

Figure 4 shows the bottom topography of the scour hole given under the condition of wave period of 1.4s, wave height of 3.0cm, pile diameter of 3.0cm and current velocity of 13.4cm/s in the live-bed scour regime. At the offshore side of the pile, a hole like a reverse-circular corn is formed, and the offshore slope of the hole is an angle of 43 degrees and very uniform. This value is a little smaller than the angle of repose of the sand. At the onshore side, however, the plan shape of the scour hole looks like a trapezoid, and a narrow and flat zone of accretion is formed behind the pile (in the onshore side). In this area the shedding vortexes are being developed and bottom sediment are easily flown up. Mild bottom slope continues from this area to onshore side and at further onshore area, deposition of some sediment makes the bed flat and on the surface, small ripples are

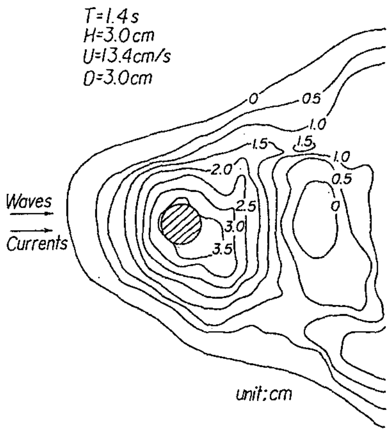


Fig. 4 Bottom topography of a typical scour hole.

generated. The lateral width of the scour hole increases shorewards with the distance from the pile. These characteristics depend on moving trajectories of the vortexes which shed from the pile and moves to onshore at an angle of 45 degrees in the onshore direction.

Figure 5 is a cross section of the scour hole along the longitudinal axis of the flume. The experimental conditions are as same as in the case of those in Fig. 4. At the offshore side of the pile , the angle of the bed slope is about 45 degrees. At the onshore side, the slope close to the pile is gentle, and with increase of the distance from the pile, it becomes steeper and approaches to 45 degrees. Fig. 6 shows a cross section of the scour hole along the transverse direction. The mean bed slopes both on the right and left sides of the pile make an angle of about 45 degrees to the horizontal bed and their shapes are nearly symmetric. It is found from our experiments that the bed slope of the scour hole is nearly equal to an angle of repose (it is about 45 degrees), but along the lines which make an angle of about 45 degrees in the shoreward direction as already shown in Fig.3, the slope is a little small due to active movement of sediment by vortexes.

3.2 Time development of scouring

Figure 6 illustrates some examples of the time development of scour depth z with time t in the case of a 3cm diameter pile with the parameter of wave height. The data may be each composed of three straight-line segments on a semilog graph paper. The first segment is associated with the slow scouring by the shedding vortexes. The middle segment describes the development of the scour hole as the vortexes move away from the pile and grow in strength. The last segment indicates an equilibrium stage. The development of scour in clear water scour is essentially as same as that in live-bed scour.

In the case of scour due to waves only, accretion of sediment is found at the offshore side of the pile. In the case of scour due to waves and currents at the velocity of 6.71cm/s, local scouring around a pile is so small that the effect of currents on local scour is very weak. This is due to a small amount of suspended sediment which is picked up by small waves. At a flow velocity of 13.4cm/s, local scour advanced much more in comparison with the other cases. This means that under the waves and currents combined, the local scour depth around a pile chiefly depends on the flow velocity.

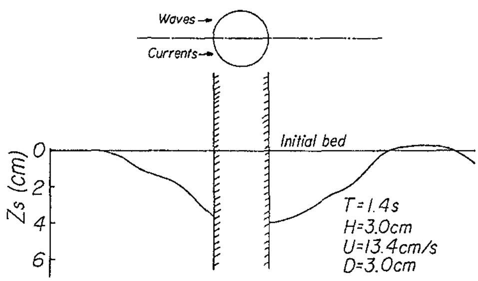


Fig. 5 Cross section of a scour hole in the longitudinal direction of the flume.

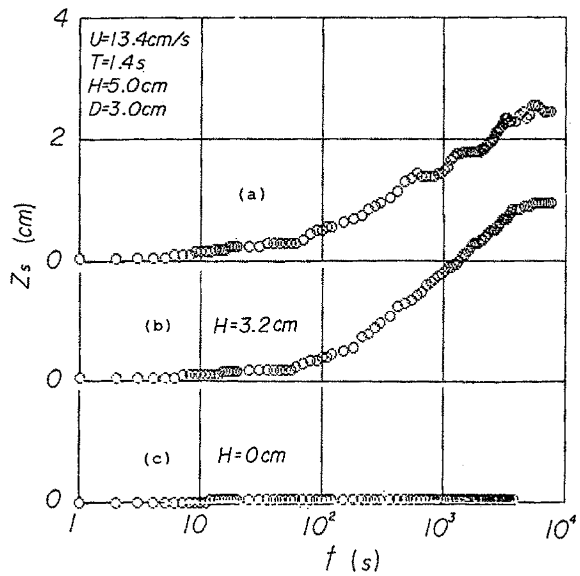
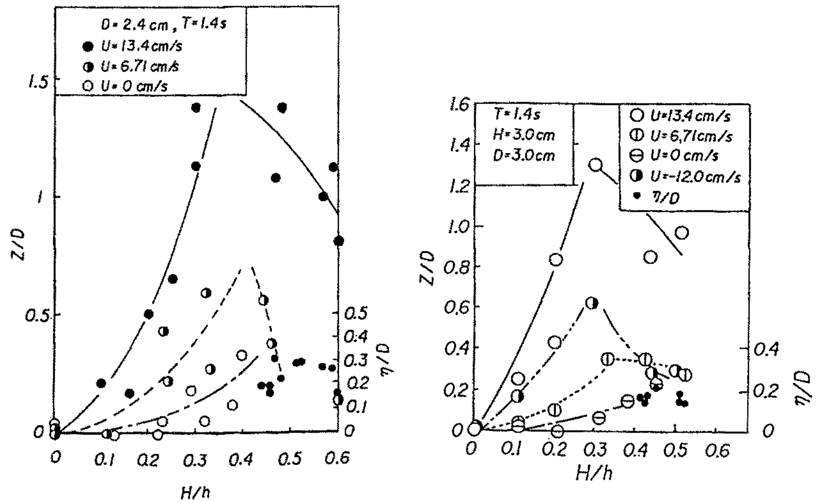


Fig. 6 Some examples of time development of clear water scour.



(a) D=2.4cm

(b) D=3.0cm

Fig. 7 Maximum scour depth and ripple height vs. wave height.

3.3 Equilibrium maximum scour depth

Figure 7 shows the relationship between the dimensionless maximum scour depth and the dimensionless wave height in the cases of a pile diameter of 2.4 and 3.0cm respectively. Measuring point of the maximum scour depth is onshore side of a pile. In this figure, the dimensionless height of ripples which are formed in the dimensionless wave height of more than about 0.3 to 0.4 is also shown with small circles. With our experiments, the maximum scour depth is the largest under the conditions of the limit of beginning of ripple formation, i.e., the initial stage of live-bed scour regime. In clear water scour, the scour depth increases with increase of H/h. When H/h is more than about 0.3 (In live-bed scour regime in which movable bed is covered with ripples.), the maximum scour depth is as large as or slightly larger than the height of ripples except for the case of u=13.4cm/s. Our experiments shows that the length of ripples are larger than a diameter of a pile. Therefore, it is difficult to take away the local depression corresponding to trough of ripples from local scour depth. In the case of u=13.4cm/s, the scour process quickly advances due to large flow velocity, and thus the outflow rate of sediment transport from the scour hole is larger than those in other cases. Therefore, the maximum scour depth becomes large.

In Fig.8, the relationship between dimensionless radii of scour hole both in the onshore and offshore directions. The line in this figure indicates empirical relationship corresponding to each flow velocity. From Fig.8, the dimensionless radius of scour hole in the onshore direction is generally greater than that in the offshore direction. As the flow velocity increases, the horizontal size of the scour hole becomes large, as shown in Fig.4 and also the asymmetry of the plan shape of the scour hole in the longitudinal direction advances. This phenomenon can be explained with the characteristics of a vortex around a pile. The vortex which firstly sheds at the offshore side of the pile in a half cycle of wave period, moves to the onshore

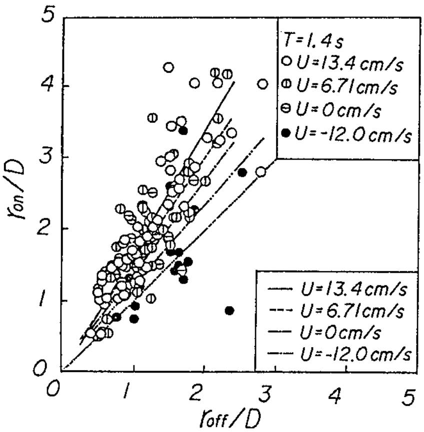


Fig. 8 Relationships between onshore and offshore radii of a scour hole.

side with growth in the next half cycle. Therefore, pick up rate of sediment at the onshore side of a pile is larger than that in the offshore side. In the case of waves only as shown in Fig.7, the onshore radius of a scour hole is also larger than the offshore one, though the scour hole is smaller than that under waves and currents combined. In the case of reverse flow at a velocity of -12.0cm/s, the data are much scattered in comparison with other cases. Experimental observation shows that difference between shoreward water particle velocity and seaward one under wave motion (nonlinear waves) contributes to this small asymmetry of the scour hole.

Figure 9 reveals the relationship between the dimensionless mean radius of the scour hole and the dimensionless wave height with the value of flow velocity as a parameter. The mean radius is defined as a half of the sum of the onshore and offshore radii of the scour hole. In this figure, the dimensionless ripple length is also shown. From the figure, it is found that the radius of the scour hole increases with increase of the wave height and the flow velocity. When wave height becomes larger and ripples are formed, the ripple length is as large as the mean diameter of a scour hole, and changes of ripple length with H/h is approximately equal to those in a scour hole. Therefore, in any case, the ripple length is larger than a diameter of a pile. Under these conditions, it is very difficult to estimate quantitatively a real scour depth. Taking scales of ripple length and a pile diameter in the field into account, their relationship is quite different from the experimental one, even if a ripple length depends on sediment diameter and an amplitude of water particle velocity. When it is necessary to predict a local scour depth around a pile in the field, the effect of ripples on local scouring process in the experiment should be made clear.

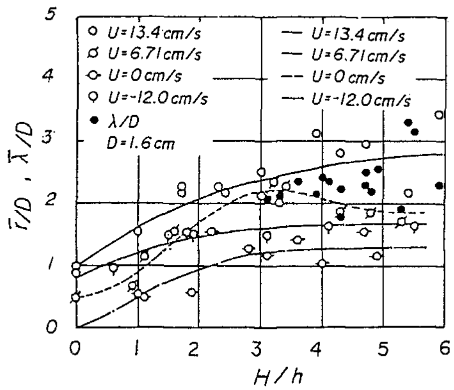


Fig. 9 Radius of scour hole and ripple length vs. wave height.

4. EFFECT OF RIPPLES ON LOCAL SCOUR

In our experiment with sand, ripples are always formed in live-bed scour regime. In order to obtain real local scour depth, it is necessary to exclude the contribution of ripple height. In the field, the pile diameter of a pier-type coastal structure is usually larger than a length of ripples which are appeared on the sea bottom, so that a local scour depth is larger than a ripple height. Therefore, there is a scale effect in the experimental data. In this chapter, we discuss the effect of ripples on local scour with the experimental data in no-ripple and live-bed scour regime which is obtained by using light weight aggregate.

Figure 10 shows the relationship between dimensionless local scour depth and dimensionless wave height at a velocity of 13.4cm/s in no-ripple regime. The critical dimensionless wave height between clear water scour and live-bed scour is around 0.35. After over this value, the scour depth also increases and rapidly decreases in the range of more than 0.42. In this figure it is not recognized the effect of wave period on local scour depth.

Figure 11 also shows the local scour depth in the two cases of no-ripple and ripple regime. In ripple regime, the data(open circle) are scattered within the area which is get between two dotted curves. The changes of local scour depth with wave height is similar to those of ripple height. Therefore, the scattering of the data might be not due to experimental error but due to existence of ripples. If the crest of ripples coincides with the location of a pile, local scour depth nominally becomes small. On the contrary, the trough comes, it increases. On the basis of our experiment, the effect of ripples on local scour is appeared due to following two mechanisms:

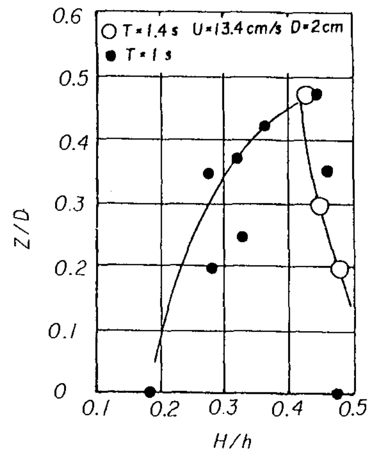
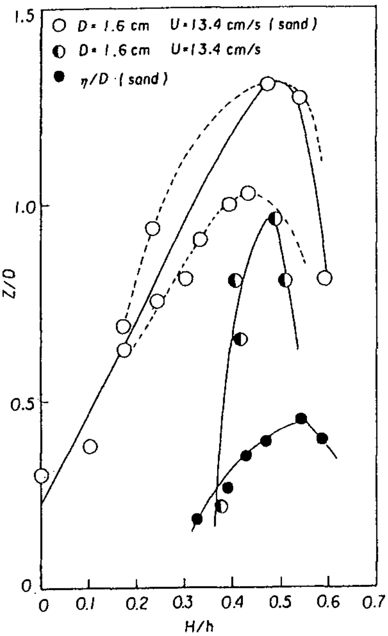
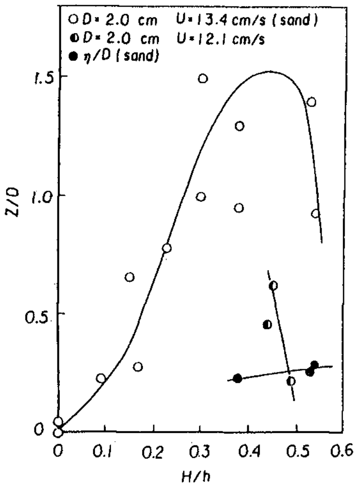


Fig. 10 Maximum scour depth vs. wave height in no-ripple regime.



(a) D=1.6cm



(b) D=2cm

Fig. 11 Comparison of maximum scour depth in ripple and no-ripple regime.

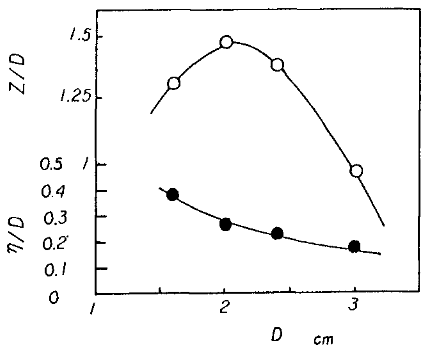


Fig. 12 Changes of scour depth and ripple height with a pile diameter.

(1) When ripples are generated on the bottom, the inflow rate of sediment transport into the scour hole reduces in comparison with that on a plane bed, because ripples spend certain energy of waves and currents.
(2) Suspended sediment cloud over ripples is easily spread out in the downstream area, therefore, transported sediment can not always be trapped with the scour hole.

From Fig.11, it is found that the dimensionless maximum local scour depth increases with increase of a pile diameter in ripple regime, but in no-ripple regime, this tendency become opposite. Moreover, the formation and characteristics of shedding vortexes are much affected with a pile diameter. Figure 12 show the changes of maximum scour depth and ripple height with a pile diameter.

5. MODELING OF LOCAL SCOUR

The most successive expression to explain mechanism of local scour around a cylindrical pile by running water was given by Shen et al.(1969) who introduced the concept of circulation. According to the conservation law of circulation, changes of bed shear stress in horse-shoe vortex region were obtained with development of scouring. This model have been modified by many researchers and some formulae are proposed to estimate the maximum scour depth under clear water scour. The horseshoe vortex with a almost horizontal axis is continuously generated along the sides of a pier.

Under wave motion, however, the horseshoe vortex is not clearly formed around a pile and the scour depth is not so large in comparison with that by running water. In the research field of wave forces, effects of a vortex formed with a vertical axis on lift force have been investigated. Through our experimental observation, Kármán vortex is a dominant factor to decide mechanism of local scour around a pile. Bottom sediment is easily picked up by the vortex and scoring process advances. Our physical model of local scour due to waves and currents combined introduces the effects of the vortex on sediment transport from scour hole by us(1987). Numerical simulation can roughly estimate the maximum scour depth. However, our model introduces many assumptions to predict the maximum scour depth due to incomplete knowledges about circulation of karman vortex and the formula of rate of sediment transport in the coupled field of waves and currents. We will reserve it for another occasion.

6. CONCLUSIONS

We investigated experimentally the characteristics of local scour around a cylindrical pile due to waves and currents combined, and made clear the effect of ripples in both clear water scour and live-bed scour regimes.

The main conclusions in our study can be summerized as follows:

1. Local scour depth around a pile due to waves only is small, but under waves and currents combined it became larger. If the flow velocity increases, the maximum scour depth increases and may come up to that in the steady flow. In the processes of the scouring, a vor-

tex with a vertical axis (Karman vortex) is dominant to decide characteristics of a scour hole. In the case of the horseshoe vortex in the steady flow, the maximum scour depth is found at upstream end of a pile, but in the coupled field of waves and currents, the initial scouring position is a little apart from a pile in the offshore side and make an angle of about 45 degree in the shoreward direction. This depends on a vortex shedding from a pile. It is found that the equilibrium scour depth around a pile in clear water scour is generally larger than that in live-bed scour.

2. By using light weight aggregate, the effect of ripples on local scour depth is made clear. In no-ripple regime, the scour depth suddenly decreases over a critical wave height due to increase of inflow rate of sediment transport. On the contrary, in ripple regime, suspended sediment cloud is not always trapped by a scour hole, so that its depth remains to be a certain value. The scattering of the data about scour hole depth might depend on the existence of crest and trough of ripples.

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