THE INFLUENCE OF OBLIQUE REFLECTION ON BREAKWATERS

by Richard Silvester M. ASCE*

ABSTRACT

The degree of reflection from rubble-mound breakwaters, even those comprising large pre-cast concrete armour units is greater than is usually thought. This is because the bulk of the face consists of smaller stones where water exchange in voids is minimal. Theory and experiment have shown that for 100% reflection of oblique waves the orbital motions are very complex, varying across the crest length of the short-crested system from rectilinear oscillation to circular or vortex motion. Also the influence of these high velocity orbital motions on a sedimentary bed have been shown to have a high scouring capacity. This has been exhibited in hydraulic models and in the field.

1. INTRODUCTION

In most cases of experiments on breakwaters of any form the flume is used to simplify the problem to two dimensions. They assume, therefore, that waves of any consequence are arriving normal to the structure, which often is not the case. For the purpose of discussing sediment transport it is not the short duration storm waves that create the problem but the more persistent swell, even though this varies in height and period continually. Where a structure is angled to the crests of such repetitve waves the scouring can be severe, which is not exhibited in a flume test. In fact, in this case, accretion will occur at the antinode of the standing wave adjacent to the toe (Xie 1981).

As the angle of obliquity increases so the scouring shifts from the nodal area to the antinodal area, next to the structure. Material can be removed until a trough is formed parallel to the face whose profile approaches the angle of repose for the sediment. In any subsequent storm the build-up of pore pressure can cause a slumping of this trough face and concomitant subsidence of the breakwater. It is the author's belief that this could have been the cause of the Sine's breakwater failure, which was sudden over the bulk of its length even with a less than design storm. In any case it behoves the engineer

* University of Western Australia, Nedlands, 6009, Western Australia.

involved in design of these massive structures to conduct 3 dimensional model investigations to observe the scouring that can occur.

2. REFLECTION FROM RUBBLE MOUND BREAKWATERS

Rubble-mound structures, especially those faced with large pre-cast concrete monoliths to just below the water line, appear to dissipate waves very effectively, from observation of the turbulence within the voids of these units. However these larger than normal blocks are not taken down the full depth of the face for economic and constructional reasons. As indicated in the cross-section of the Sines breakwater in Figure 1, the Dolos armour units extended down to only -15 m whereas the bed (which was not rock as indicated in the original figure (Edge et al 1982) but was sand for several metres) ranged down from -30 m to more than -45 m. Thus 5 m thickness of stone was 16-20 ton, another 5 m of 9-20 ton and 20 m of ½ to 6 ton. Hence the lower ½ to ⅔ of the wave action was impacting on rubble material with very small voids. Since the water orbits at these depths are virtually horizontal oscillations little or no energy is dissipated. This is the reason for substantial reflection being experienced.

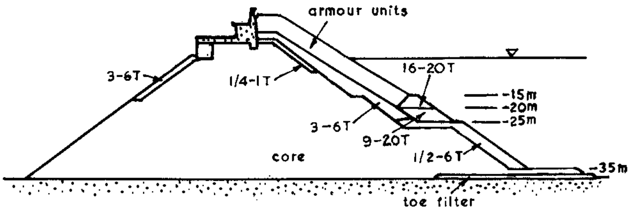


Fig. 1 Cross-section of the Sines breakwater (Edge et al 1982).

Tests have been carried out for normal waves, on breakwaters of differing materials (Gunback 1976, Sollitt & Cross 1972, Hyd. Res. Stn. Wallingford 1970) and summarised by Losada and Giménez-Curto (1981). The reflection coefficient was correlated with the Iribarren No. Ir = $\tan\alpha/\sqrt{H/L_0}$, where α is the face slope, H is the local wave height and L_0 is the deep-water wave length. The resulting curves, taking the maxima of the data points rather than the mean, are shown dotted in Figure 2. These data and I_r do not specify the size of the units involved which could make a difference to the degree of reflection. However, it is worthwhile substituting some reasonable values into I_r to see what readings are applicable. Assuming $\tan\alpha = 0.5$, H = 1 m (swell), T = 12 sec. then $I_r = 7.5$. Hence for rip-rap or dolos the reflection coefficent is 0.8.

It should be noted that Gunback (1976) had armour stone thickness to water depth at 0.18 whilst Sollitt and Cross (1972) used 0.36. Also the former had 0.82 of the depth taken up with these units whilst the latter had 0.57. In a prototype structure, as indicated in Figure

1 these proportions could vary significantly with resulting different reflections.

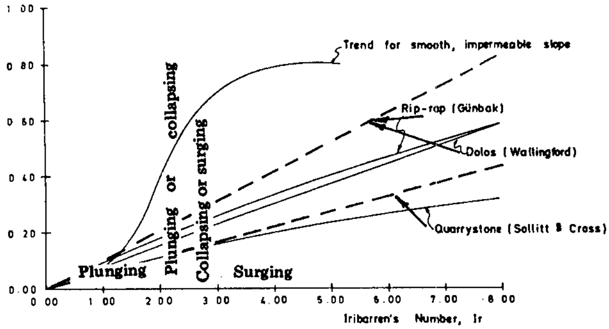


Fig. 2 Reflection coefficient I_r showing the wave type. (Losada and Giménez-Curto 1981).

3. COMPLETE SHORT-CRESTED SYSTEM

The theory of angled waves in which the components are of unequal height is too difficult to solve with the current state of the art. However for two oblique waves of equal height and period, solutions have been found for the kinematics and, also the mass-transport near the bed. (Hsu et al 1979, Hsu et al 1980). This theory to the 3rd order has been verified in a wave basin with a unique window in its bed. (Hsu 1979, Silvester 1977). Such waves might be termed "complete" as for standing waves where this term is used for opposing waves of equal height and period.

But inspite this simplification the orbital motions of the water particles are quite complex as depicted in Figure 3. (Silvester 1972). They vary from rectilinear oscillation to circular across the crest length L', which is finite and not infinite as in a progressive wave. The circular motions on alignments $Z/L' = \frac{1}{8}, \frac{3}{8}, \ldots$ are in a constant direction as dictated by their location. Such vortices, even if formed near the surface, as for deep water conditions, will expand along their axes to a boundary, which in this case is the bed. In so doing they exert a strong suction which draws sediment from the floor and throws it out radially into other zones of motion. These whirling bodies of water also generate secondary vortices which make for excessive macro-turbulence which helps keep particles in suspension.

Like any oscillatory motion of wave action short-crested systems have their own specific mass-transport or net motion per wave cycle. This is evident in Figure 4 from tests conductd by Hsu (1979). Even in the alignments ($Z/L' = \frac{1}{4}, \frac{3}{4}, \ldots$), where rectilinear motion is normal to the wall or path of the island crests, there is a net movement along the wall. Theory shows a distribution of mass transport across each quarter crest length as in Figure 5. (Silvester 1985) It is seen that along crest alignments this ratio is maximum

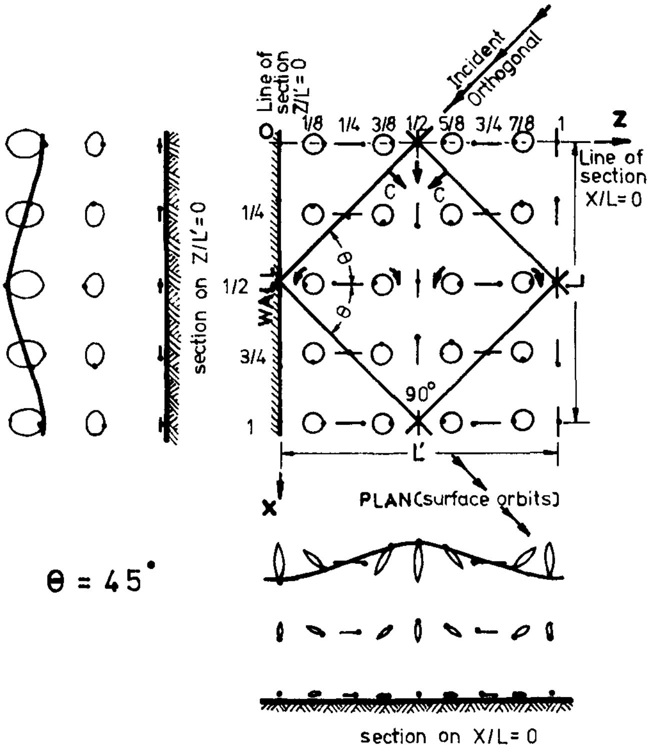


Fig. 3 Water particle motions in a complete short-crested wave system. (Silvester 1972).

and can be 2 or 3 times that of the incident wave. The shearing of material from the floor by the orbital motions at this alignment or half way between (i.e. Z/L' = $\frac{1}{4}$, $\frac{3}{4}$, ...) varies with the wave obliquity. For near standing waves the velocities and hence the scour are greater at Z/L' = $\frac{1}{4}$, $\frac{3}{4}$, ... but for greater obliquity it is excessive at Z/L' = $\frac{1}{2}$, 1, ...

4. EXPERIMENTAL EVIDENCE OF SCOUR

The movement of sedimentary material on the sea floor can be considered in 3 stages. Firstly, ripples are formed whose orientations and characteristics are dictated by the water particle orbits in the vicinity. (Silvester 1974) Secondly, erosion occurs in alignments parallel to the wall where velocities are excessive. Thirdly the complete region of the ribbon of reflected waves is scoured after accretion has occurred firstly at the downcoast end due to the passage of material from the upcoast end. This last phenomenon requires sufficient duration in model studies for this to be exhibited. Prior to this stage erosion occurs in selected zones for monochromatic waves but is less evident for irregular waves.

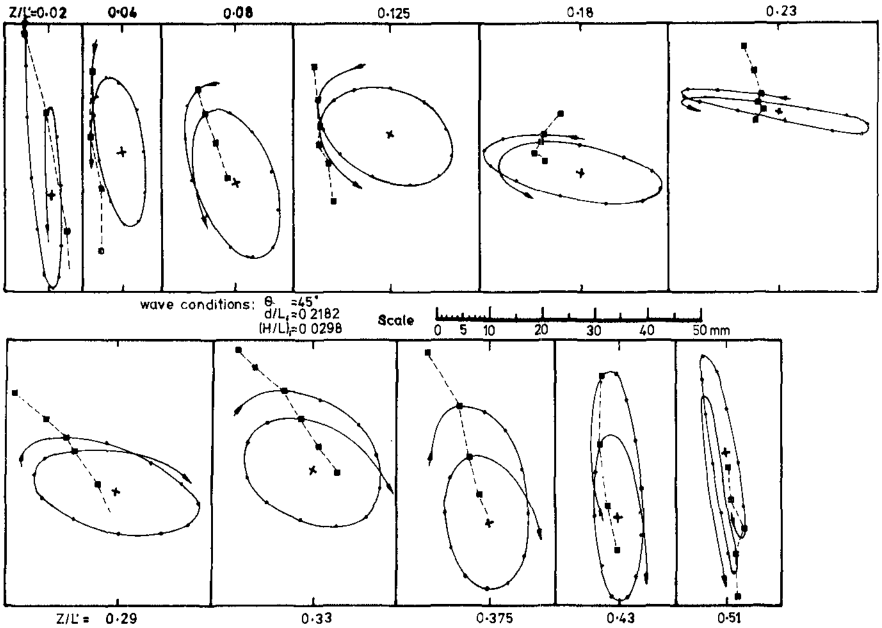


Fig. 4 Orbital motions recorded at the bed for a short-crested system showing the mass transport per wave cycle. (Hsu et al 1979)

Since the persistent swell wave, with its longer periods and good reflection, is the culprit in this removal of sediment, its orbital motions in a short-crested system need to be studied. A factor to be remembered is that such waves are changing in period continually as they travel at different speeds in a dispersal or so-called decay area. (Silvester 1974). These produce variations in orbital amplitudes and hence crest lengths of bed ripples. During such changes more sediment is placed in suspension, which then is subject to the mass-transport of the water in the wave motion.

The crests of any ripple formation will be normal to the water oscillation creating it. Thus those adjacent to the wall and at crest alignments $Z/L' = \frac{1}{2}, 1, \ldots$ will be normal to the wall; whereas those half way between ($Z/L' = \frac{1}{4}, \frac{3}{4}, \ldots.$) will be parallel to it. Along alignments between again ($Z/L' = \frac{1}{8}, \frac{3}{8}, \ldots$) the vortices will create circular mounds which make for a snake-like undulation. These are exhibited in Figure 6, where waves have reflected at 45° to the wall on the right of the figure, with the Z/L' distances marked. The slight deviations from these alignments in the figure are due to the partial transport that has occurred which introduced changes in water depth and concomitant refraction.

After some time the zones of high velocity water oscillation causes them to be eroded first which is evident in Figure 7 where

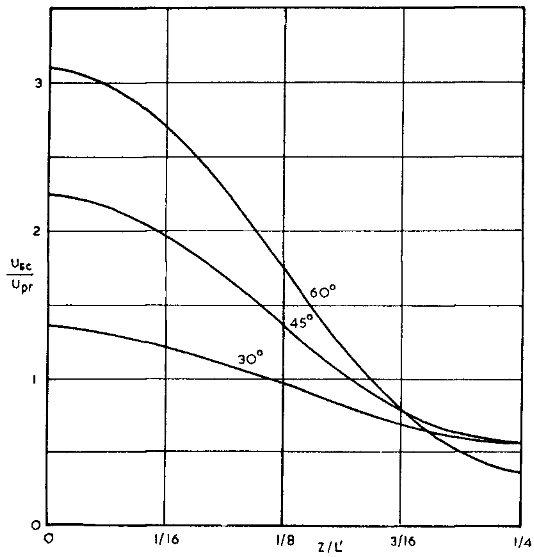
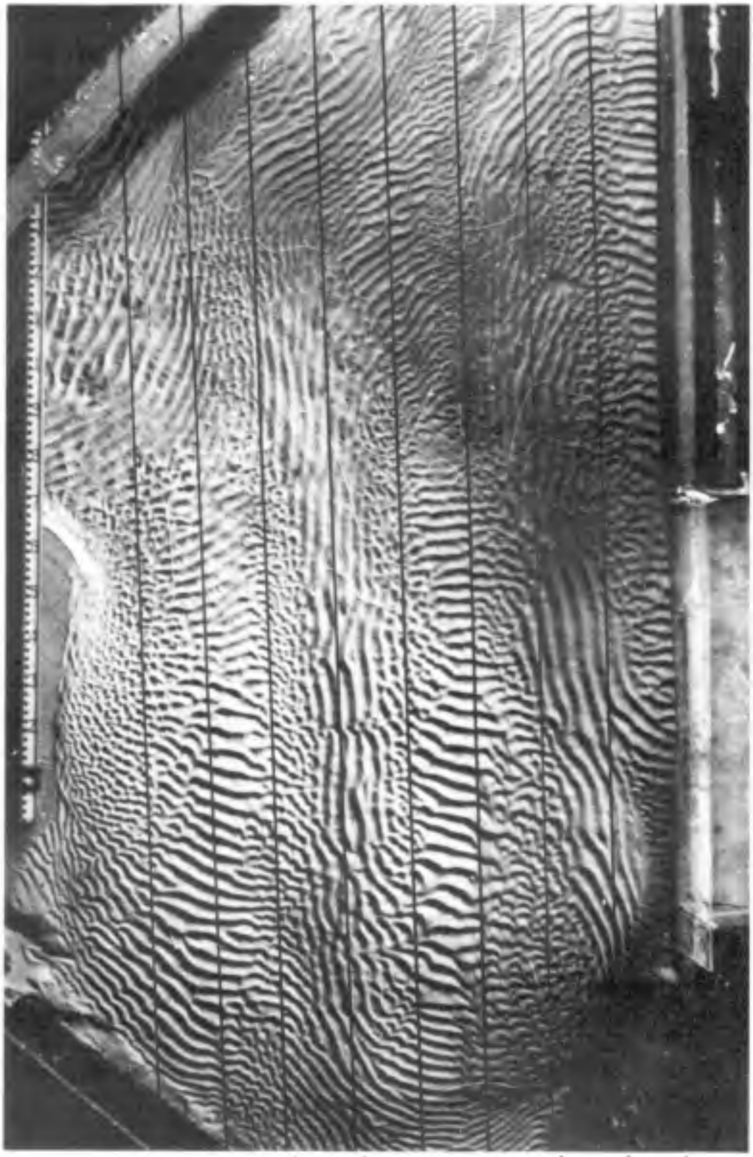


Fig. 5 Ratio of mass-transport in a short-crested wave (U_{sc}) to that in a progressive wave (U_{pr}) for various angles of incident to a reflecting wall. Z is measured normal to the wall across the crest length L'.

removal has occurred at Z/L' = $\frac{1}{4}$, $\frac{3}{4}$, ... where ripple crests are parallel to the wall. It is seen that for this approach angle of 25° scour has taken place for more than 3 crest lengths from the structure. The orthogonal of the reflected wave through the upcoast tip of the reflecting wall is shown. To the right of this these waves are diffracting, so suffering a curved crest pattern and reducing in height. Even so, the short-crested system still exists as exemplified in the scouring that has occurred beyond this ribbon of reflected wave. In other photos a similar expansion occurred from the downcoast limiting orthogonal. (Silvester 1985).

This is not to imply that the reflected wave height remains the same in its propagation from the wall. Its passage can be likened to transmission through a breakwater gap as in Figure 8, the diffraction of which has been determined experimentally for no reflection from adjacent breakwater arms. (Silvester 1981) As the wave travels along multiples of the non-dimensional width B/L its energy is absorbed in diffraction beyond the limiting orthogonals. As seen in Figure 9 the diffraction coefficient reduces so that on the centre-line at R/B = 4 the height has been reduced to half. Thus the incident wave will be double the height of the reflected and will therefore have more effect on the movement of sediment. The water particle orbits will be very complex but still conducive to bed scour.



L'/8's = 8 7 6 5 4 3 2 1 0

Fig. 6 Bed ripple formations in a short-crested system. (Silvester 1972).

Fig. 7 Differential erosion occurring at quarter crest lengths from the wall.

Tests carried out for 60 hours with waves angled 30° to a wall in water depth of 25 cms, wave period 1.0 sec. and sand bed thickness of 5 cms, resulted in scour as seen in Figure 10. During this limited duration material removed from the RHS is in transit through the area to the left so causing shoaling in that region. Had the experiment been carried out for longer this accretion would ultimately disappear. A similar test has been carried out by Tanaka et al (1972) where sediment 10 cms in thickness and water depth 5.5 cms waves of 2.8 cm height and 0.52 seconds period caused progressive erosion at the upcoast end of a breakwater with approach angle of 30°. As seen in Figure 11 accretion occurred in the downcoast region after 10 hours duration. It is seen, as in Figure 10, that the bed is affected even outside the limiting orthogonal through the upcoast tip of the

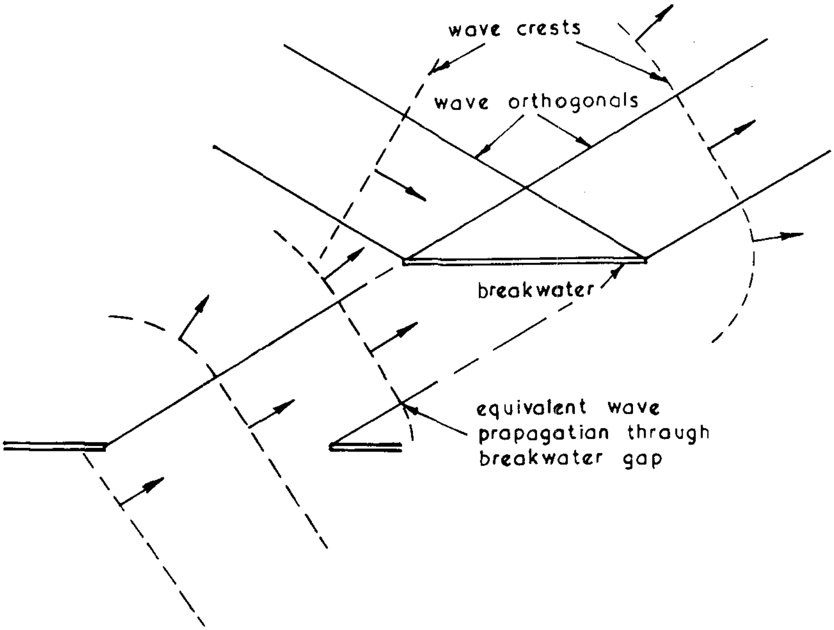


Fig. 8 Comparison of reflected waves to diffraction through a breakwater gap.

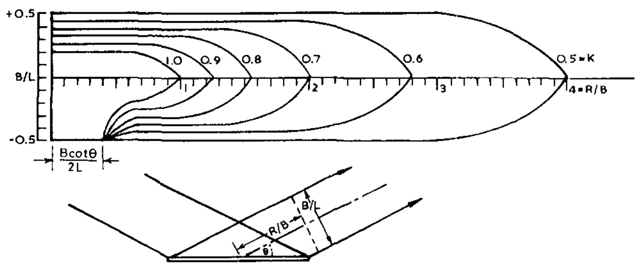


Fig. 9 Diffraction coefficient distribution in front of a reflecting wall.

breakwater. The variations in bed level in the figure are based upon the assumption that a profile recorder had a distance to the original bed of 25 cms in the data provided by the authors. Irie and Nadaoka (1984) have conducted model tests on a breakwater where the bed was sloping upwards towards the downcoast end as seen in Figure 12. The final contours after 11 hours duration are shown from which zones of erosion and accretion can be identified. It is seen that these zones vary across the normal to the breakwater.

More recently Irie et al (1985) have conducted further experiments with angled waves both regular and irregular. The

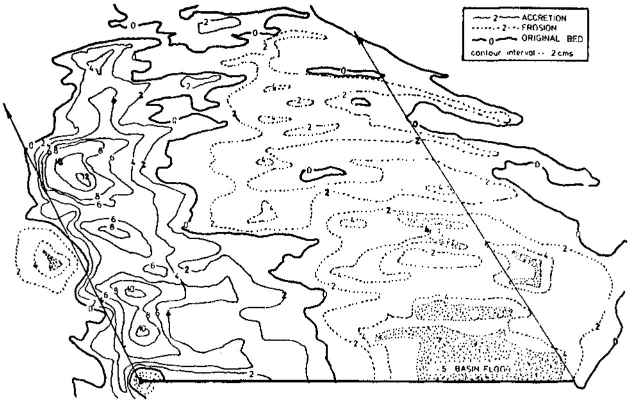


Fig. 10 Scour of bed to concrete floor after 60 hours duration.

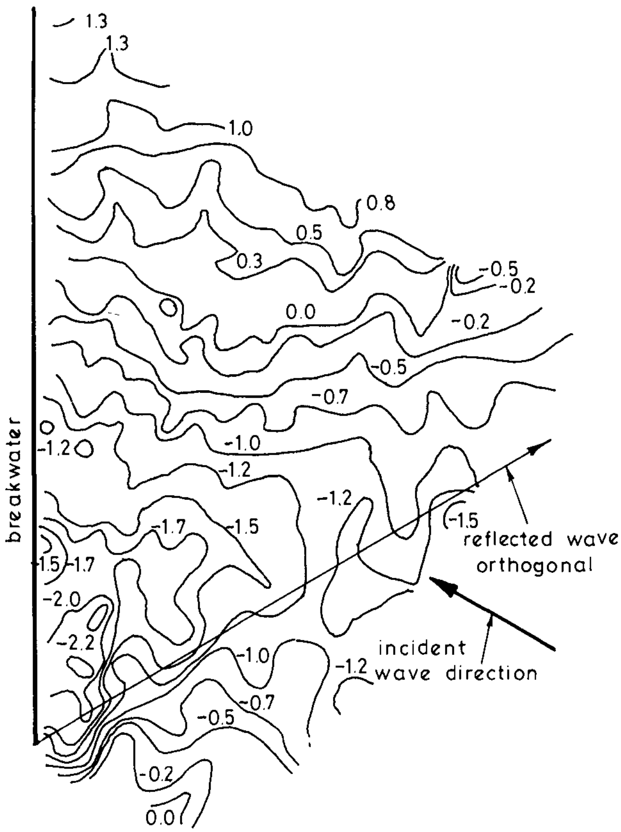


Fig. 11 Contours after 10 hours duration. (Tanaka et al 1972).

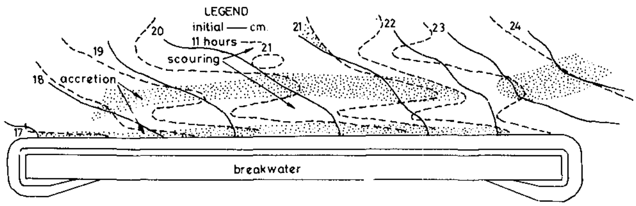


Fig. 12 Tests showing differential erosion and accretion for a duration of 11 hours with irregular waves. (Irie & Nadoaka 1984).

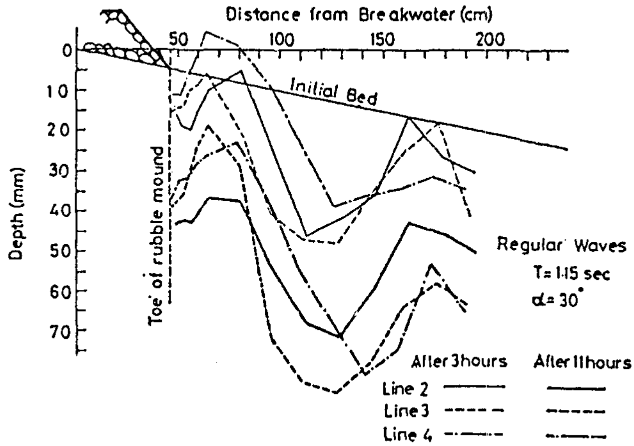


Fig. 13 Profiles normal to the breakwater for regular waves at 30° after specified durations. (Irie et al 1985).

breakwaters were of caisson type with a trapezoidal rock mound on the sea side. Profiles normal to the breakwater at the point of greatest scour were measured after 3 and 11 hours the results of which are reproduced in Figure 13. A significant feature of these profiles is the steep slope of the near side of the major trough which is 1:3.4, even after such a short duration. From tests with irregular waves (Figure 14) the same steep slopes exist near the toe of the rubble mound. In this case the scour is more uniform across the bed. Irie also plotted profiles parallel to the breakwater over certain durations which showed severe erosion at the upcoast end and accretion at the downcast tip. The progressive deepening is illustrated in Figure 15, where it is seen that scouring is rapid over the first hour but slows down with time. An optimum had not been reached for the regular waves after 11 hours duration.

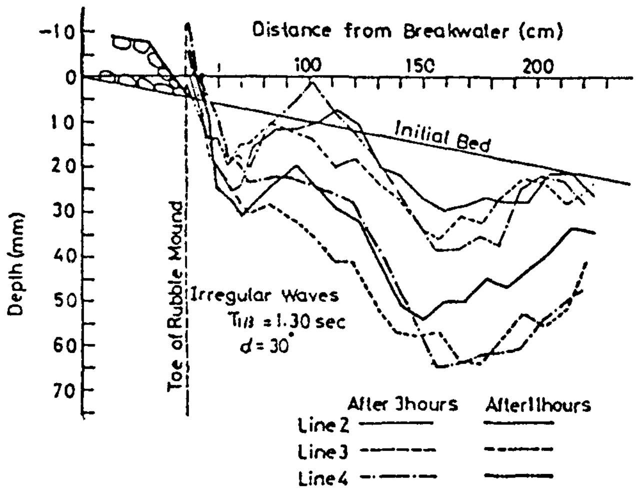


Fig. 14 Profiles normal to the breakwater for irregular waves at 30° after specified durations. (Irie et al 1985).

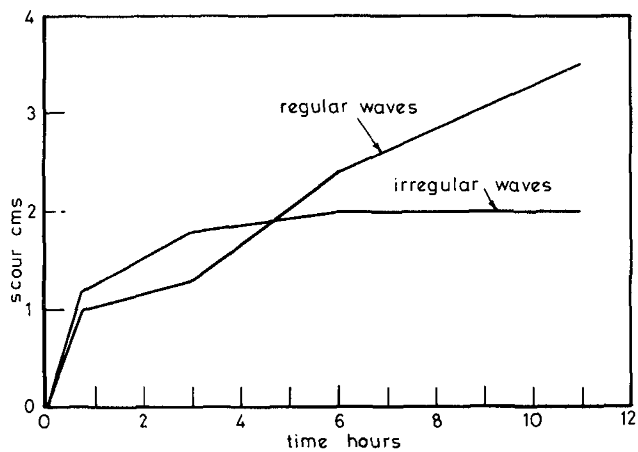


Fig. 15 Progressive scouring at zone of deepest hole for regular and irregular waves. (Irie et al 1985).

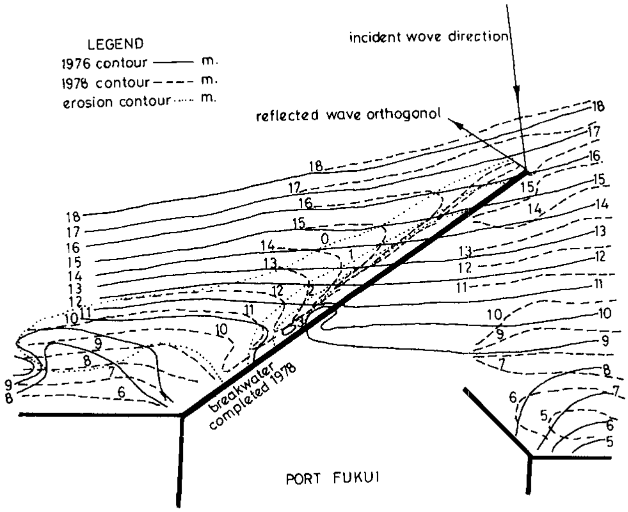


Fig. 16 Contours at the port of Forkui, Japan in 1976 and 1978 showing zones of scour. (Irie & Nadoaka 1984)

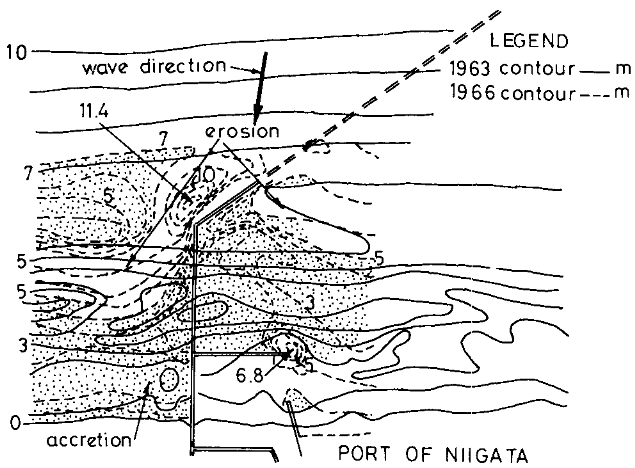


Fig. 17 Erosion and accretion at Niigata between 1963 and 1966. Sato et al 1969, Sato & Irie 1970).

5. FIELD EVIDENCE OF SCOUR

Scouring has been observed by Irie and Nadaoka (1984) in prototype situations. The port of Forkui is angled to the shoreline and to the bulk of the waves arriving. It was completed in 1978 when a hydrographic survey was conducted, which can be compared to the 1976 contours as in Figure 16, showing the zones of erosion and accretion. Scouring down to 3 metres over a large length of this breakwater took place in a matter of months. It would be interesting to see the contours some eight years later.

Another example of erosion is given by Sato et al (1969) who give contours in 1966 for the port of Niigata, Japan, presumably soon after the completion of the breakwater to this stage. (Figure 17) These bed profiles are compared to those in 1963 provided by Sato and Irie. (1970). Zones of erosion and accretion are hatched and stippled respectively. It is seen that near the corner a depression of 11.4 m has been scoured in an original depth of 6.5 m. In the second reference (Sato & Irie 1970) contours are shown for a slight extension of the breakwater in 1967 and the installation of a rubble mound base for caisson units to the limit shown in Figure 17. These show some accretion in the region previously scoured, probably due to the transmission of sediment along the submerged mound during this short time period. It would be instructive to see hydrographic data for the current situation after some years of completion.

6. CONCLUSIONS

1. The degree of reflection from rubble-mound structures is significant enough in oblique wave approach to generate short-crested wave systems which are conducive to scour.

2. Consultants should not depend solely on flume tests if erosion of a sedimentary bed is possible as these imply normal approach for both storm and swell waves.

3. Theory and experiment have shown that the water particle orbits in a complete short-crested system (equal heights and periods of component waves) to be quite complex and severe in their erosive capacity.

4. Besides high velocity orbital motions the water particles experience a strong mass transport, greatest along the alignment of the island wave crests, which can interact with tidal currents to remove suspended material.

5. Model experiments with obliquely reflected waves have shown their ability to form trenches parallel to a structure that have profiles approaching the angle of repose of the sediment which could cause subsidence if pore pressure is built up during even moderate storm action.

6. Field measurements of scour adjacent to breakwaters have only been carried out soon after construction but even so have exhibited severe erosion which is being blamed on currents rather than waves.

8. REFERENCES

Edge B.L. et al (1982) Failure of the breakwater at Port Sines, Portugal, ASCE, Coastal Eng. Res. Council.

Gunback A.R. (1976) The stability of rubble-mound breakwaters in relation to wave breaking and run-down characteristics and to the $\xi = \tan\alpha\ T/\sqrt{H/L_o}$ number. Divn. Port and Ocean Eng. Norwegian Inst. Tech, Trondheim, Rep. 1-1976.
Hsu J.R.C. (1979) Short-crested water waves. Ph.D Thesis, University of Western Australia.
Hsu J.R.C., Y. Tsuchiya and R. Silvester (1979) Third order approximation to short-crested waves, J. Fluid Mech, 90(1), 179-196.
Hsu J.R.C., R. Silvester and Y. Tsuchiya (1980) Boundary-layer velocities and mass-transport in short-crested waves, J. Fluid Mech. 99(2), 321-342.
Hyd. Res. Stn. (Wallingford) (1970) High island water scheme, Hong Kong, Rep. EX 532.
Irie I. and K. Nadaoka (1984) Laboratory reproduction of seabed scour in front of breakwaters, Proc. 19th Inter. Conf. Coastal Eng. ASCE, Vol. II, 1715-1731.
Irie I. et al (1985) On the protection methods of scour in front of breakwaters, Proc. 32nd Coastal Eng. Conf. of Japan, 445-449 (In Japanese).
Losada M.A. and L.A. Giménez-Curto (1981) Flow characteristics on rough permeable slopes under wave action, Coastal Eng., 4, 187-206.
Losada M.A. and L.A. Giménez-Curto (1982) Mound breakwaters under oblique wave attack; a working hypothesis. Coastal Eng. 6, 83-92.
Sato S., N. Tanaka and I. Irie (1969) Study on scouring at the foot of coastal structures, Coastal Eng. in Japan 12, 83-98.
Sato S. and I Irie (1970) Variation of topography of sea-bed caused by the construction of breakwaters, Proc. 12th Inter. Conf. Coastal Eng. Vol. II, 1301-1319.
Silvester R. (1972) Wave reflection at seawalls and breakwaters, Proc. Instn. Civil Engrs. 51, 123-131.
Silvester R. (1974) Coastal Engineering Vol. 1, Elsevier Publ. Co., Amsterdam.
Silvester R. (1977) The role of wave reflection in coastal processes, Proc. Coastal Sediments Conf. 1977, ASCE, 639-654.
Silvester R. (1981) Diffraction through a breakwater gap, Trans. Instn. Engrs. Aust. CE23(2), 114-117.
Silvester R. (1985) Sediment by-passing across coastal inlets by natural means, Coastal Eng. 9, 327-346.
Sollitt C.K. and R.H. Cross (1972) Wave transmission through permeable breakwaters, Proc. 13th Conf. Coastal Eng., Vol. III, 1827-1846.
Tanaka N., I. Irie and H. Ozasa (1972) Report Port and Harbour Res. Inst. Vol. II, No. 3, 112-140 (In Japanese).
Xie S.L. (1981) Scouring patterns in front of vertical breakwaters and their influence on the stability of the foundations of the breakwaters. Rep. Coastal Eng. Group, Delft Univ, of Tech.