CHAPTER 167

THE EFFECT OF GROUNDWATER ON SCOUR NEAR STRUCTURES

John H Loveless[1], Geoffrey T Grant[2] and Robert I Karlsson[2]

ABSTRACT

A previously unreported mechanism which is believed to be a key process in the formation of shingle beaches is identified. It is proposed that this mechanism be called "winnowing".

Several new considerations relating to the selection of appropriate model sediments for shingle beach models are discussed. It is shown that lightweight sediments are subject to a significant scale effect and a compromise solution is suggested.

The results of some experiments, never previously performed, of beach scour in front of sea walls resulting from various combinations of wave attack and groundwater flow in the beach are presented. These show that the presence of groundwater flow in the beach has a significant impact on the amount of toe scour to be expected.

INTRODUCTION

A thorough understanding of all the major mechanisms involved in the formation of beaches is necessary if effective remedies to coastal erosion problems are to be established. This paper suggests that the study of the movement of sediment on beaches has until recently tended to ignore or misjudge the effects of flow into and out of the beach. It has only recently been discovered that under-drainage can be used as an effective method of beach accretion and it would be highly surprising if we have nothing more to learn about how beaches behave.

Beach or seabed scour in front of and around coastal structures is possibly their most frequently occurring failure mechanism. However, the reliability of the advice that coastal engineering researchers can provide is dependent on how well these processes can be modelled.

---

1) Senior Lecturer, Dept of Civ. Eng. Univ. of Bristol, Bristol BS8 1TR
2) Research Asst., Dept. of Civ. Eng. Univ. of Bristol, Bristol BS8 1TR

The spectacular failure of several large breakwaters around the world and the discovery that scour is occurring near to many of them has led to increased interest in this area of research. Scour predictions are still usually derived from physical model studies with length scales of 1:20 or less. It is impossible to satisfy all the criteria for similarity in these models which are therefore subject to scale effect errors.

HOW SHINGLE BEACHES FORM

Coarse Material Transport

Broadly speaking the creation of a shingle beach is usually explained by reference to two mechanisms. First the movement of coarse material to the upper beach is explained on the assumption that coarse material moves as bed load and the peak bed velocity over each wave cycle is greater inshore than offshore. Also, since there is significant percolation into a shingle beach, the energy of the backwash is less than the energy of the swash. For example (Muir Wood, 1970) described this process admirably as:

"Whereas sand is moved by the sea predominantly in saltation and, near and inshore of the breaker line, in suspension, shingle is shifted by sliding and rolling along the bottom. The significance of this difference is that, whereas sand will tend to be moved in the direction of the vector representing residual wave velocity plus tidal velocity, shingle is only moved during that part of the wave cycle in which a certain threshold value is exceeded".

Beach Slope

He also showed that the local slope of a beach is given by;

$$\tan\alpha = \frac{(1-c)}{(1+c)}\tan\phi$$

where α is the local beach angle, ϕ the angle of repose of the local beach material and c the ratio of the energy flux E_2 of the backwash to the energy flux E_1 of the upwash. This equation results in the limiting conditions of $c = 0$ at the top of the beach giving $\alpha = \phi$ and far offshore where $c = 1$ giving $\alpha = 0$ between these limits the equation results in the prediction of a parabolic beach form.

Fine Material Transport

The second mechanism which has been adduced to explain the formation of shingle beaches is the well known theory of Dean (Dean 1973). The theory has been shown to give extremely good correspondence with field results and it is highly probable therefore that it is essentially correct. However, the theory starts with an assumption for which no explanation has yet been given, viz. "It is assumed that the action of breaking waves is sufficient to place sand into suspension over at least a portion of the water column".

Dean then goes on to explain how the relative fall times of the sediment lifted into suspension when compared to the wave period determines whether the sediment will move onshore or offshore.

Thus the analyses of both Dean and Muir Wood while both being clear and highly plausible do not provide a complete explanation. There is one piece missing from the jig-saw. How is the fine sediment carried into suspension not only from the surface, but also from within the beach? The jet caused by plunging waves creates a scour trench an associated bar and turbulence which could be deemed sufficient, but is there something else at work?

Winnowing

It is now suggested that there is a third mechanism at work which operates rather like the process of winnowing. As a wave approaches the breaking point the hydraulic gradient in the surface layers of the beach just in front of the wave reach a maximum. A number of experiments were carried out to investigate the nature and magnitude of these hydraulic gradients and to predict their possible consequences on sediment transport in the beach.

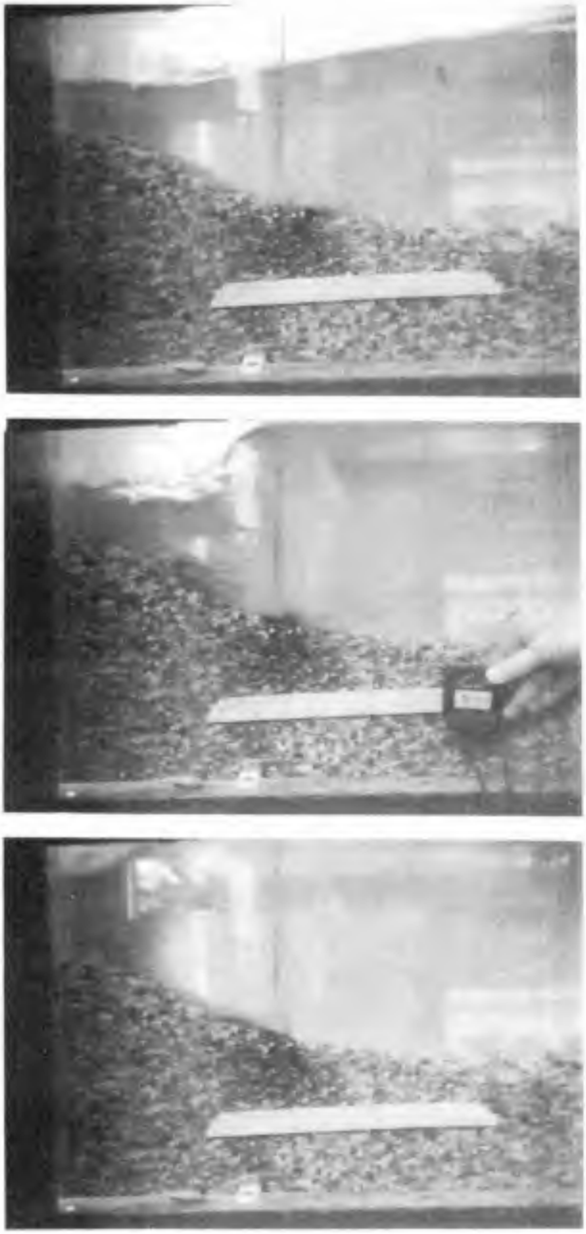
In one experiment dye was injected into a model shingle beach (D_{50} = 5.6 mm) near the breaker line. The movement of the dye indicated the direction of the instantaneous seepage velocity within the beach. The motion was seen to be rotary and in phase with the wave with the maximum velocity in the horizontal (onshore) direction just beneath the breaking wave. Just in front of the breaking wave the percolation velocity is vertically upwards and this was clearly visible as shown in Figures 1 & 2 as a jet of dye ejected into the flow. When the wave passes the dye cloud is swept forward up the beach.

Further experiments were carried out using a small probe inserted into the bed on which a cruciform of wire was fixed. Using electrolysis the wires were made to emit hydrogen bubbles as the waves passed and their movement was recorded on video. These experiments showed similar results and, because the probe could be moved about easily it was possible for a complete flow net to be constructed showing the hydraulic gradients in the beach beneath the breaking wave. Although these experiments proved that just in front of a breaking wave the upward direction of the seepage velocity in the bed is capable of squirting dye into the flow above the bed, it did not explain why this should preferentially eject the fine sediments.

In a third set of experiments some small pressure transducers were immersed in the bed. These showed that the hydraulic gradient in the bed frequently exceeded 1.0 in front of the breaking wave. This is the hydraulic gradient usually thought of as necessary to fluidise a soil sample.

Permeameter Tests

To investigate the hydraulic gradients needed to start soil migration a series of experiments was carried out using combinations of gravel and sand in a permeameter. These were reported briefly (Loveless & Grant, 1995) and showed conclusively that for gap-graded sediments the fine particles will start to migrate at very low hydraulic



Dye plume emerging from a shingle beach ($D_{10} = 4.0$ mm) under a breaking wave ($f = 0.5$ Hz).

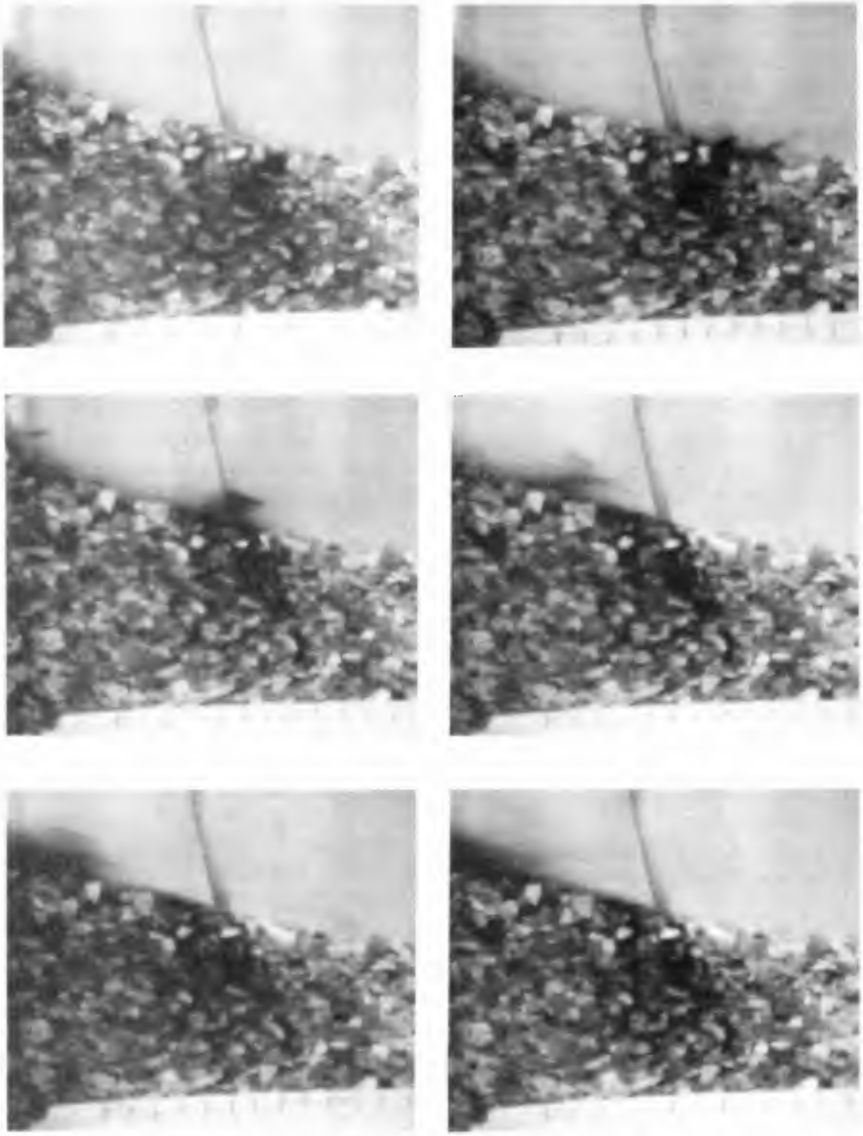


Figure 2: Detail of dye plume emerging from shingle beach under a breaking wave ($f = 0.5$ Hz).

gradients, as low as 0.2 or 0.25. The results of these (and other) experiments are shown on Figure 3. The Stability Index is a measure of how gap-graded the soil is. It is defined as the percentage of a soil sample passing at a diameter 4D minus the percentage passing at a diameter D all divided by the percentage passing at a diameter D. A Stability Index less than 1.0 is a potentially unstable soil. Where the soil is gap-graded, as in a shingle beach, the hydraulic gradient required to initiate fine soil migration is only around 0.2 not 1.0 as for a normal soil as shown in Figure 3.

The Dynamics of the Swash Zone

Finally, it is readily observed in the field and laboratory that the swash zone is a very dynamic environment for the sediment. During storm events the face of the beach, to a considerable depth, is being reworked and this reworking it is suggested provides the final element in the process which leads to marked size segregation which is the hallmark of a shingle beach.

Thus to summarise it is suggested that fine sediments are ejected from the bed just in front of breaking waves by a winnowing like process as vertical hydraulic gradients in excess of 0.5 act on a bed which is effectively being fully fluidised at the same time by peak horizontal hydraulic gradients in excess of 1.0. The finer particles are more mobile and are moved both upwards and downwards. The process naturally strengthens as segregation causes the beach to become more and more permeable.

The fine material carried to the surface can be carried both inshore and offshore. This leaves the part of the beach subjected to the highest hydraulic gradients to protect itself with a shingle beach and what nature chooses to defend itself may not be able to be bettered by man.

SEDIMENT SELECTION AND SCALING FOR MODELS OF SHINGLE BEACHES

Since laboratory models of shingle beaches are still the ultimate source of design guidance for both physical and mathematical models it is very important that the best possible physical models should be constructed and the greatest care be taken to identify the various mechanisms at work.

It has recently been shown (Loveless 1994), that for normal wave approach, there are nine separate mechanisms which can produce scour near to the toe of a coastal structure. It has also been shown (Loveless & Grant 1995) that certain aspects of model sediment selection are commonly misunderstood or ignored.

Lightweight sediments

In the UK lightweight sediments have been used for over 30 years to construct models of shingle beaches. It has been shown however (Loveless 1994) that this means that one of the important forces is in error by a factor of six for an upward hydraulic gradient in the beach. Figure 4 is a diagram (not draw to scale) of the main forces acting on a particle on a beach under the trough of a wave. The upward percolation force is significant when the upward hydraulic gradient is large as it is just

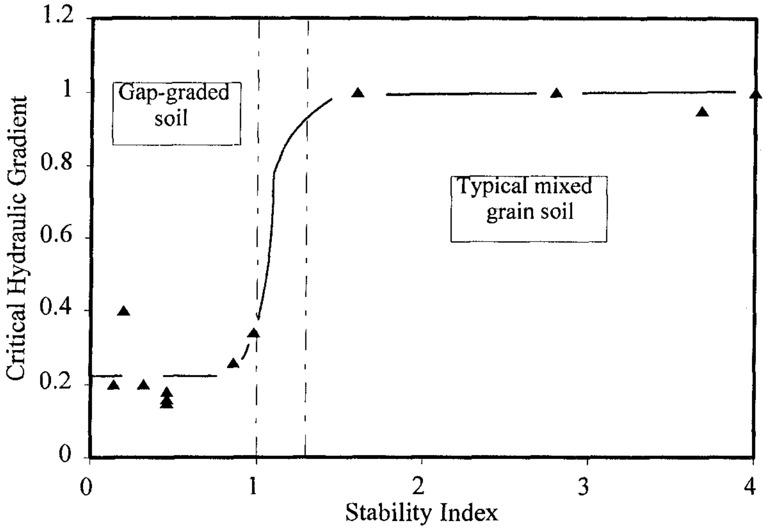
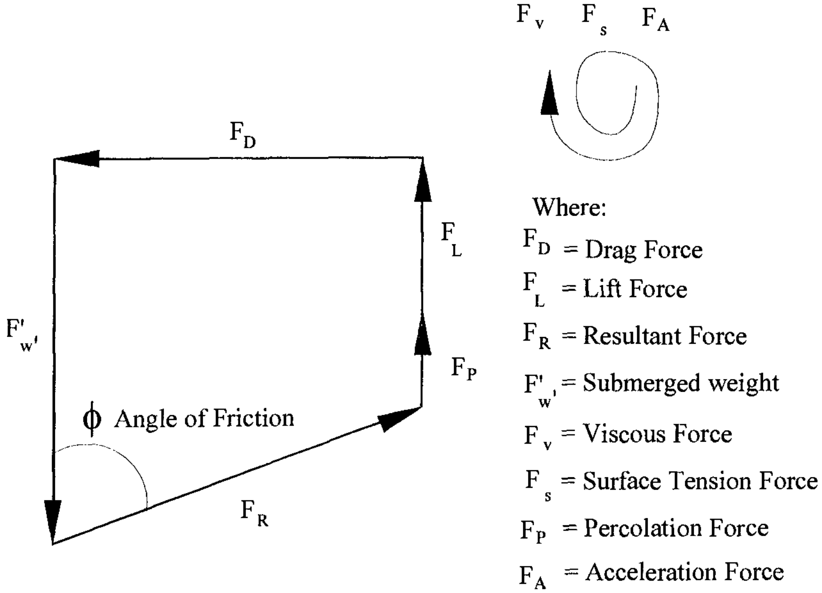


Figure 3: Critical hydraulic gradient against Stability Index.



Where:

F_D = Drag Force

F_L = Lift Force

F_R = Resultant Force

$F'_{w'}$ = Submerged weight

F_v = Viscous Force

F_s = Surface Tension Force

F_P = Percolation Force

F_A = Acceleration Force

Figure 4: Forces on a sediment particle beneath a wave trough.

in front of a breaking wave. For similarity the ratio of the submerged weight and the upward percolation force should be the same in model and prototype. The ratio is given by,

$$\frac{F_{w'}}{F_p} = \frac{i}{(1-n)(s-1)}$$

where i is the hydraulic gradient, n is the porosity of the soil and s is the specific gravity. If i and n remain the same, but s (model) equals say, 1.27 then a scale effect error of 6.1 would result if the prototype sediment had a specific gravity $s = 2.65$. Hence lightweight sediments will grossly overpredict scour at the toe of coastal structures.

If however a lightweight sediment is not used it is not possible to model the rate of percolation into the beach correctly for a sediment which satisfies similarity of the threshold of motion condition. In recent research we have found that a sediment having a specific gravity of about 2.0 would give scale effect errors not exceeding 3.0 for both percolation rate and percolation force. This may be the ideal compromise if such a material can be obtained at a reasonable price.

Angle of Repose

Another factor which appears to be ignored by researchers, but which is nevertheless important is the angle of repose of the sediment in model and prototype. To obtain similarity of the threshold of motion between model and prototype it can be shown that the following condition must be satisfied.

$$\frac{\lambda U_b}{\lambda_{W_s} \lambda_{\tan\phi}} = 1$$

where λ is the scale factor, U_b the near bed velocity, W_s the fall velocity of the sediment and ϕ the angle of repose. Hence ϕ directly affects one of the key similarity parameters and therefore must not be ignored.

A further important aspect of the variable ϕ is that it is reduced when a finer material is added to a gravel even when only 50% of the sample is sand. This effect was measured in the laboratory and a typical result is shown in Figure 5.

SCOUR EXPERIMENTS WITH GROUNDWATER FLOWS SUPERIMPOSED

A sea wall that is subjected to waves breaking near the toe of the structure, may at the same time experience a seaward groundwater flow under it. The experiments reported here show that the severity of scour is dramatically increased when these two scour mechanisms are combined. Similarly, if on the other hand the groundwater flow is reversed, accretion can be made to occur even under storm wave conditions and where, with no groundwater flow, a considerable scour hole would be formed. Although an experiment of this kind, with ground water flow being taken into account, is obviously a more realistic one than one which only considers waves we have not been able to trace a report of any such experiment having been performed

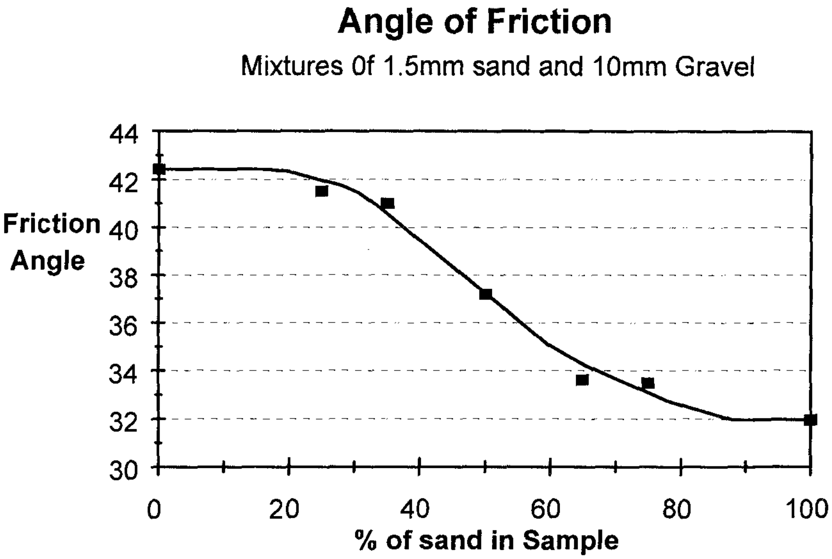


Figure 5: Value of ϕ for various combinations of sand and gravel.

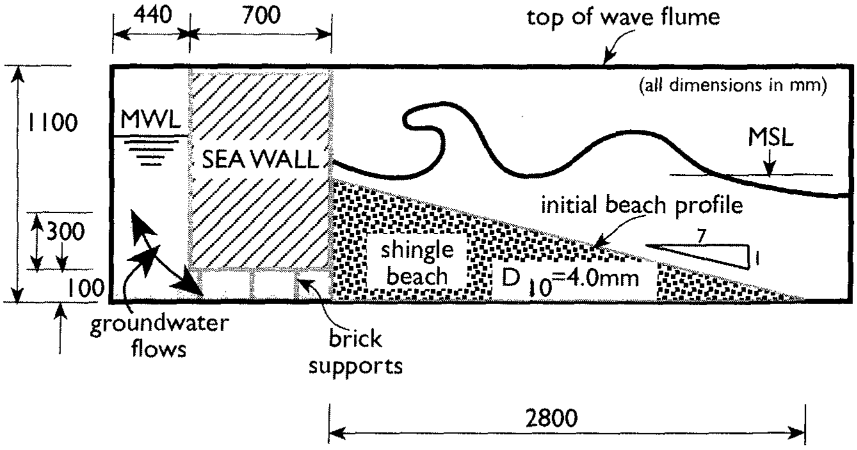


Figure 6: Cross-section of the arrangement of the model beach and sea wall.

before. Figure 6 shows the arrangement that was used to test these conditions for both shingle and sand beaches. The experiments were conducted in a large 1.5m wide wave flume at the end of which there was a test section of 0.5m width. The dimensions of the shingle beach were as shown in Figure 6, giving an initial beach slope of 1:7. The sand beach however was arranged with a gap beneath the sea wall of 70 mm and a depth above this of 230 mm giving a total depth of sand of 300 mm at the sea wall. The beach extended for 800mm giving a beach slope of 1:26.7. The gravel used in the model had a $D_{10} = 4.0$ mm and a $\phi = 36°$. It was selected to model, at a scale of 1:20, a shingle beach having a $D_{10} = 14$ mm. The reasons for this selection have been reported earlier (Loveless & Grant, 1995). The sand used in the model had a $D_{50} = 0.33$ mm and $\phi = 30°$. It was used to model a beach sand having D_{50}=1.5mm and $\phi = 32°$.

The beaches were subjected to regular waves except that, for the sand beach only, the beach was exposed to a JONSWAP Spectrum with the following characteristics for two hours: $f_p = 0.7$ Hz, $H_s = 7.4$ cm, σ_1, left = 0.7, σ_1, right = 0.09; water level, $h_o = 0$ or 170 mm above datum at the flume floor level.

The groundwater flows in the beach were created by means of a small submersible pump. To create an offshore flow the pump was placed in the main flume and water was pumped to the back of the sea wall. To create an onshore flow the pump was instead placed behind the sea wall. The maximum capacity of the pump was 2.0 ℓ / s and with the gravel beach this flow created a difference in mean water levels of 80 mm in both directions. The sand beach was exposed to an increasing hydraulic gradient until at a difference of 280 mm it failed by boiling. During the tests it was subjected to water level differences of +20, +10 and -20 cms. These corresponded to pumping rates of +0.30, +0.15 and -0.30 ℓ / s.

The range of tests completed is shown in Tables 1 & 2. In these tables, h_o represents the mean sea level at the sea wall above the level of the beach. The scour depth, Y is measured at the structure and H_i is the offshore wave height incident on the beach and structure.

Figure 7 is a summary of the gravel beach results and shows clearly that the presence of a groundwater flow in the beach has a significant impact on scour at the structure. The most dramatic difference was obtained with Test 15 and the resulting profiles for this test are shown in Figure 8.

The toe scour occurring with offshore flow was much greater than the no flow case and the onshore flow actually caused accretion. Figure 9 again shows the significant difference in the resulting beach profile. The results for sand beaches, while not showing such dramatic changes in scour near to the toe of the structure nevertheless resulted in very different beach profiles as shown in Figure 10.

CONCLUSIONS

The paper has identified a new mechanism which it is believed is a fundamental mechanism in the formation of shingle beaches. It is proposed to call this mechanism “winnowing”.

Test	Freq.	Hydraulic difference	Toe water depth	Incom. wave height	Steepness	Rel. depth	Rel. scour	No. of waves
	f (Hz)	Δh (cm)	h_0 (cm)	H_i (cm)	H_i/L	h_0/H_i	Y/H_i	
4	0.7	+8	0	5.5	0.017	0	0.41	-
4	0.7	0	0	5.5	0.017	0	0.69	1260
11	0.7	+8	+5	9.0	0.028	0.56	-0.25	-
11	0.7	0	+5	9.0	0.028	0.56	-0.21	1092
12	1.0	+8	-3	12.5	0.080	-0.24	-0.32	-
12	1.0	0	-3	12.5	0.080	-0.24	0.15	-
15	0.7	+8	+5	18.4	0.058	0.27	-0.43	-
15	0.7	0	+5	18.4	0.058	0.27	-0.24	-
15	0.7	-8	+5	18.4	0.058	0.27	0.14	-
18	1.0	+8	+10	11.5	0.074	0.87	-0.36	-
18	1.0	0	+10	11.5	0.074	0.87	-0.26	-
21	0.7	+8	+10	18.7	0.059	0.53	-0.21	-
21	0.7	0	+10	18.7	0.059	0.53	-0.11	812
21	0.7	-8	+10	18.7	0.059	0.53	-0.03	-

Table 1 Comparator scour test results for a gravel beach ($\phi = 36°$).

Test	Freq.	Hydraulic difference	Toe water depth	Incom. wave height	Steepness	Rel. depth	Rel. scour	No. of waves
	f (Hz)	Δh (cm)	h_0 (cm)	H_i (cm)	H_i/L_0	h_0/H_i	Y/H_i	
5	1.0	+10	+5	7.0	0.045	0.71	0	1500
5	1.0	+20	+5	7.0	0.045	0.71	-0.43	3300
5	1.0	0	+5	7.0	0.045	0.71	-0.61	2820
8	0.5	+10	+8	10.5	0.017	0.76	-0.95	1500
8	0.5	+20	+8	10.5	0.017	0.76	-1.29	1500
8	0.5	0	+8	10.5	0.017	0.76	-1.27	1500
8	0.5	-20	+8	10.5	0.017	0.76	-0.95	1500
14	1.0	+10	+10	11.0	0.070	0.91	-0.50	2100
14	1.0	+20	+10	11.0	0.070	0.91	-0.73	1800
14	1.0	0	+10	11.0	0.070	0.91	-0.70	1800
14	1.0	-20	+10	11.0	0.070	0.91	-0.45	1800

Table 2: Comparator scour test results for a sand beach ($\phi = 30°$).

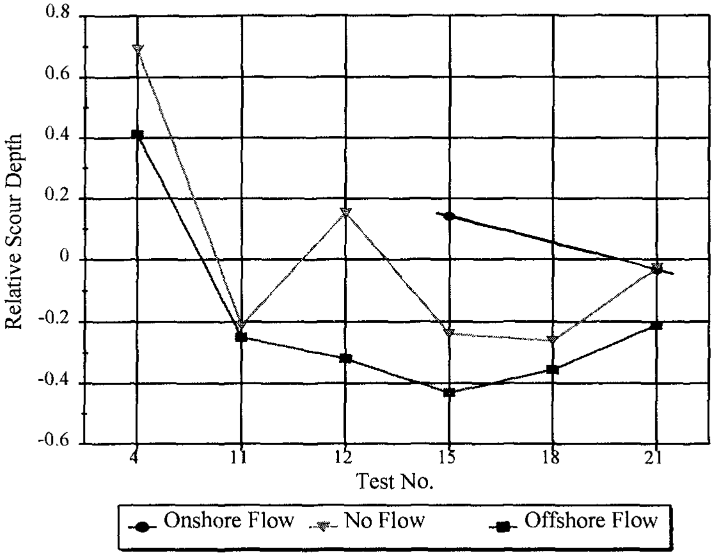


Figure 7: Relative scour depth (scour at toe/wave height) for various tests on a gravel beach.

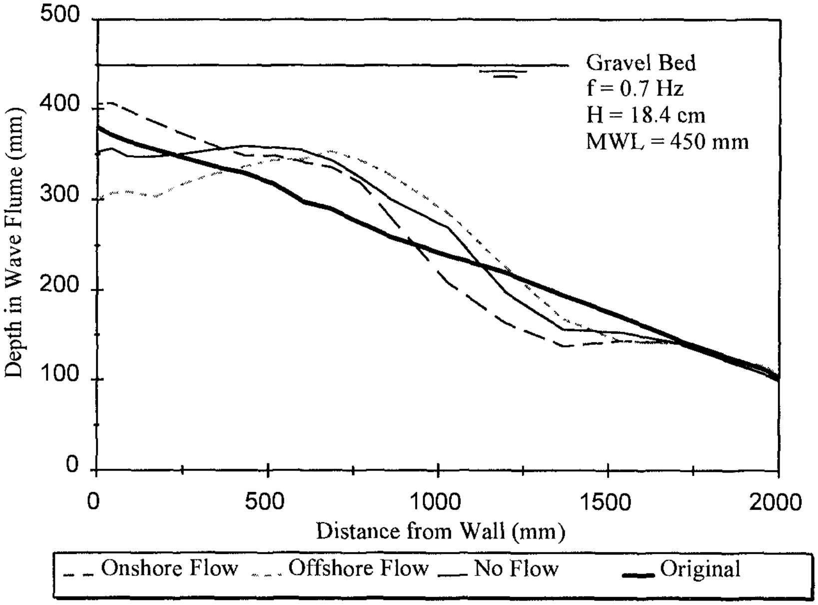


Figure 8: Resulting beach profiles after Test 15 (gravel beach).

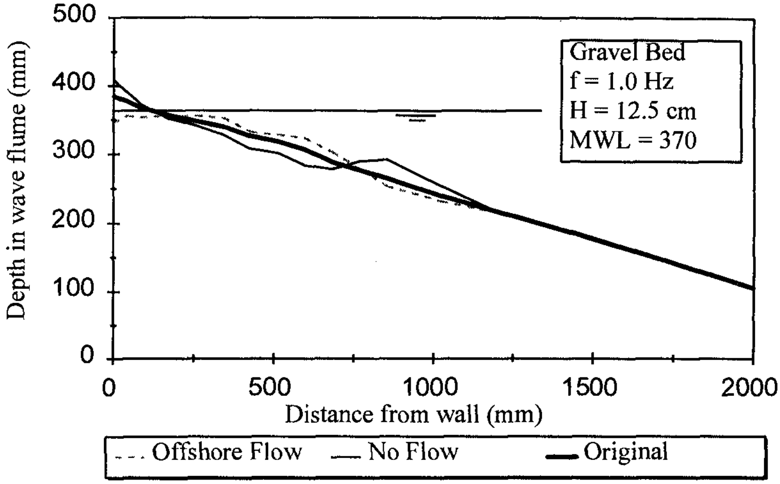


Figure 9: Resulting beach profiles after Test 12 (gravel beach).

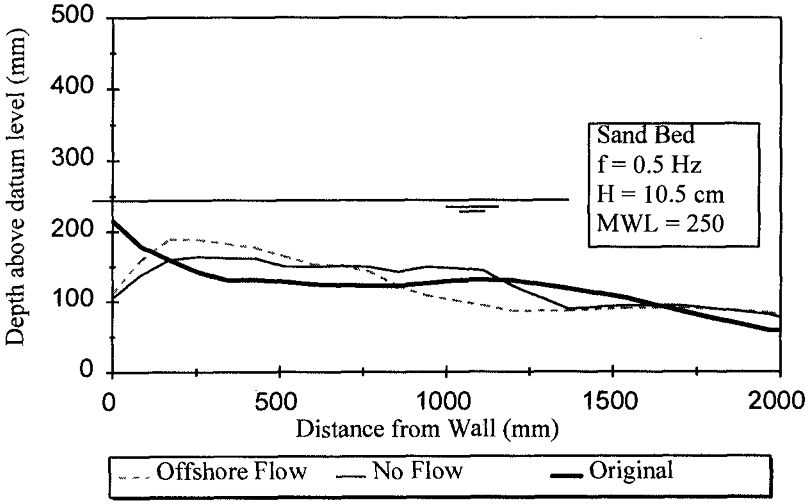


Figure 10: Resulting beach profiles after Test 8 (sand beach).

The paper has also suggested that aspects of the selection of model beach sediments which have tended to be ignored, such as the percolation force and the angle of repose of the sediment, should be taken into account when designing models.

The paper has reported on experiments which have shown how toe scour and beach profiles in the vicinity of coastal structures are affected by groundwater flows in the beach.

ACKNOWLEDGEMENT

Much of this research was conducted with the assistance of a grant from the UK Engineering and Physical Sciences Research Council for which the authors are grateful.

REFERENCES

1 Dean R G. "Heuristic models of sand transport in the surf zone." Conf. on Engg. Dynamics in the Coastal Zone. 1973. Inst. of Engineers of Australia.
2 Loveless J H. "Modelling toe scour at coastal structures." 2nd International Conference on Hydraulic Modelling, June 1994. BHR Group.England.
3 Loveless J H and Grant G T. "Physical Modelling of Scour at Coastal Structures." 26th Congress, Int.Ass. for Hydraulic Res. , London, UK. Sept. 1995.
4 Loveless J H and Grant G T. "Discussion of Skempton A W and Brogan J M. Experiments on piping in Sandy soils." Geotechnique 45, No 3. Sept 1995 p565-567.
5 Muir Wood A M. "Characteristics of shingle beaches: The solution to some Practical Problems." Proc. 12th Conf. on Coastal Engineering 1970 Chapter 68, p1059-1075.