CHAPTER 54

SOME SAND TRANSPORT PHENOMENA ON COASTS WITH BARS

M. Dyhr-Nielsen, Research Engineer
and
Torben Sørensen, Director
Danish Institute of Applied Hydraulics
Copenhagen, Denmark

1. INTRODUCTION

Longshore wave currents and their influence on the sand transport phenomena in the shore zone have attracted the attention of numerous researchers. Also the existence of transverse, secondary currents, superposing the longshore component, has been known for years, but less attention has been given to analysis of their effect on the sediment movement.

This paper presents some examples of the influence, these relatively weak transverse currents may have on the processes in the shore zone. They have a parallel in the effect of secondary currents in alluvial streams, which, although weak, give rise to such an impressive phenomenon as meandering.

All conclusions below are based on simple, qualitative considerations of the physics of the system. A strict mathematical, quantitative approach to the problem does not seem possible with the present knowledge of the fluid dynamics in the shore zone, and much further research into these complex phenomena remains, of course, necessary.

2. NET CURRENTS IN THE SHORE ZONE

Longshore currents

It is well known that the breaking of waves in shallow water exerts a force on the water body between the breaker zone and the shore. This is due to the existence of the wave thrust [Lundgren 1963], found by integrating the flux of momentum and the wave pressure over the water depth in a wave period. The wave thrust has the same direction as the wave orthogonals.

It is also known that the longshore component of the wave thrust generates longshore currents in the trough between breakers and shore. An equation of equilibrium of the forces in the longshore direction may in principle be established to yield an expression for the longshore velocity. This approach is physically sound, but lack of sufficient knowledge of the bed shear stress generated in the complex movement in and behind the breaker zone renders this approach impracticable at this moment. Furthermore the stochastic aspects of the problem are undoubtedly very important and cannot at present be grasped in mathemathical form.

Circulation currents

The component of the wave thrust parallel to the shore generates the longshore currents.

Similarly, the component perpendicular to the shore generates circulating currents in the cross section. These currents were first observed by Bagnold [Bagnold 1940] and have since been verified by many others. In the following a simple qualitative explanation of the generation of these currents is given, and their occurrence is related to specific properties of the wave motion.

Bottom currents under shoaling, nearly-breaking waves

The deformation of the waves approaching the breaker zone will increase the wave thrust I in the shoreward direction, so that the thrust I_2 in section 2 is greater that I_1 in section 1, see Fig. 1. Therefore the resulting thrust I_R on a control volume from section 1 to section 2 has an offshore direction. This force is compensated by a decrease in mean water level in onshore direction, creating a static water pressure reaction P_R against I_R.

The strong deformation of the orbital velocity profile of a wave immediately before breaking causes I_R to act at a higher level over the bottom than P_R. Hence an equilibrium in the moments can only be obtained if there is a resulting force along the bottom, i.e. a resulting shear stress T. T must act on the water body in a seaward direction, and in a shoreward direction on the bottom. The waves will contribute to this, as the resulting shear stress due to wave motion will have an onshore component, but near the breaker zone this appears not to be sufficient, and a shoreward bottom current will superpose the wave motion.

The existence of shoreward currents under nearly-breaking waves can clearly be observed in a laboratory flume.

Bottom currents under surfing waves

After breaking the wave proceeds for some wave lengths as a surfing wave. The heavy energy losses will reduce the wave height, and the wave thrust will decrease in the onshore direction, see Fig. 2. The resulting wave thrust I_R acting on the control volume will now have a shoreward direction. A rise in mean water level will give a static pressure reaction P_R, but due to the high particle velocities at the water surface, I_R will attack at a higher level than P_R.

Equilibrium in the moments again requires the existence of a resulting bottom shear stress T, but now acting shoreward on the water volume and seaward on the bottom. Hence under surfing waves the wave movement must be superposed by a resulting bottom current in a seaward direction.

This current can also be observed in a laboratory flume.

Circulating currents

Under the breaker line, the onshore and offshore bottom currents under the waves will meet. Observations in a flume have shown, that there is only a very small transport of water through the breaker zone near the bottom. Circulating cells are formed as shown in Fig. 3 whereby the return flows for the bottom currents are established. Fig. 3 shows a two-breaker zone where the surfing waves are regenerated and a secondary breaker zone is formed. Two circulating cells are formed between the breaker lines, preventing transport in the bottom zone from the inner to the outer cell.

If the surfing waves reach the shore like in Fig. 4, only one cell is formed, and transport from the shore to the outer breaker line will occur. This has a very important effect on the coastal sediment transport as will be shown later.

3. EFFECTS ON SEDIMENT TRANSPORT

Formation of longshore bars

It has been shown above that waves breaking on a sloping plane will generate secondary currents directed towards the breaker line. This will have an accumulating effect on the grains on the bottom, moving them towards the breaker line where they build up a bar.

The shape will stabilize when the slope gets so steep that the bottom current cannot transport the sand up over it, or when there is equilibrium between the amount of sand carried up by the bottom current and the sand returned in suspension at higher levels. At present it is not possible to tell which of these two conditions is the governing factor.

The position of the bar is closely connected to the position of the breaker line. Therefore, on tidal shores where this position is changing rapidly with the tidal cycle, distinct bars can only be expected to occur under severe wave conditions. Hence the existence of bars is more likely to occur in the winter as a result of more frequent storms.

The lower waves in the summer will not break over the bar, so the accumulating effect is replaced by an onshore bottom current that will erode the bar configuration and change the winter-profile to a summer-profile.

Formation of transverse bars

In certain cases the situation with a two-breaker zone may change to a one-breaker zone, where the surfing waves from the outer breaker line are not regenerated but extends to the shore as shown in Fig. 4 and 5. It might for instance happen when the depth over the outer bar is increased by erosion or dredging.

In this case a shoreward bottom current extends from the shore to the outer breaker line, see Fig. 4. This current will carry at least a part of the material transported on the inner bar out to the outer bar. Studies of bottom topographies in the nature have shown, that in connection with this a transverse bar is formed.

The deficit in the near shore transport downstream of the transverse bar affects the stability of the beach profile. Erosion of the beach occurs in the downstream region in order to reduce the deficit and satisfy the transport capacity of waves and currents downstream of the transverse bar.

The stable beach

It has been shown in laboratory tests that the wave steepness, defined as the ratio between wave height and wave length, has a high influence on the stability of a beach. Waves steeper than a certain value were shown to erode the beach profile while waves below this steepness would build up the beach.

The existence of secondary currents seems to offer a simple explanation of this. Consider a plane beach with slope 1:n, see Fig. 6. A wave of height H will break at a depth approximately equal to H. Hence the distance from the shore to the breaker line will be approximately n H.

It is obvious that if this distance is large, surfing waves are formed and seaward bottom currents are generated. But if the breaker line is very close to the shore this is not the case and the breaker will instead form a swash wave on the beach. Surfing waves are able to remove sand from the shore, whereas swash can move sand up on the beach for the following reasons; Swash has the highest velocity and hence the highest transport capacity, when the water is moving shoreward, and seepage losses reduce the seaward transport capacity further when the water is running back.

Assuming that the change between surf and swash happens when the breaker line is distance k L from the shore, where L is the wave length. Now a simple similarity consideration gives the limiting wave steepness H/L for the stable beach as $H/L = k/n$.

It can be seen that the critical steepness depends on the slope of the beach. This may have some implications for model tests with movable bed and a distorted scale. The effect of distortion on the slope of a beach might change an eroding wave in the nature to an accumulating wave in the model.

Meandering in the shore zone

An interesting observation of some shore line configurations may be mentioned in this connection.

On a 10 km long reach south of Hvide Sande on the west coast of Denmark it is possible to detect a periodic fluctuation on the shore line and of the outer bar. The wave length of this fluctuation is about 3000 m, and the amplitude of the order 100 - 200 m. Hence with 3000 m interval the width of the beach is relatively large, and in between it is relatively narrow. This pattern has been remarkably stable in the 9 years for which this shore has been studied in detail, although it has been superposed by local erosions and accretions in connection with the formation and passage of transverse bars.

If the area between the bar and the shore is considered as a "river" carrying the longshore current, the ratio between the width of this river (about 300 m) and the length of its "meander" (about 3000 m) is the same as found for meanders in alluvial rivers. From this it seems possible that the longshore current in certain aspects is similar to an alluvial river. The observations of formation of dunes in the trough between bar and shore [Zenkovich 1967] further support this assumption.

A similar "meander" pattern in a smaller scale has been observed on other Danish coasts.

4. THE "HVIDE SANDE" STUDY

Investigations in the prototype

Hvide Sande is a small harbour town on the west coast of Denmark. It is located on a narrow sand spit in a tidal outlet which is now controlled by sluices. The undisturbed coast profile at Hvide Sande has two parallel bars and the resulting sand transport along the shore has a southward direction.

To stabilize the outlet two 100 m long groynes were constructed in 1931, but these had no significant influence on the outer bar. In the fifties the depth over the outer bar was considered too shallow for safe navigation and in order to improve the conditions a 400 m long groyne was constructed about 100 m north of the outlet, see Fig. 7.

This groyne crossed the outer bar and forced it to move seaward. Furthermore a strong erosion took place on the outer bar at least up to 3 km south of the new groyne in the following 3 - 4 years as the supply from north was temporarily cut.

Hence in October 1966 the original bar was significantly reduced over long reaches south of the groyne. In the same period a severe erosion of the beach occurred at a point about 3 km south of Hvide Sande. (Similar attacks were reported 6 and 10 km to the south, in places where the "meandering" had narrowed the beach.) In connection with this soundings in April 1967 showed that transverse bars had been formed in the winter of 1967 connecting the near-shore bar with the remnants of the outer bar, see Fig. 8. Just south of these bars the severe erosions were observed. The transverse bars migrated towards south with a velocity of about 600 m/year, changing the points of attack on the beach so that the erosion in a point decreased or was substituted by a temporary accretion after the passage of the bar.

South of the transverse bars the outer bar was built up again, which indicates that the outer bar was supplied with sand from the shore zone as mentioned above. The erosion of the outer bar in connection with the groyne construction changed the breaker regime from a two-breaker zone to a one-breaker zone causing the formation of the transverse bar.

It should be mentioned that transverse bars have been observed at many other locations, for example at the upstream side of a groyne where the beach transport has to leave the shore to get around the groyne. They are also found on coasts without manmade interference, but again in connection with local erosion of the beach.

Model tests

With the purpose of studying the effect of the groyne constructions on the wave current patterns during storms three fixed bed models were built. The horizontal scale was 1:300, the vertical scale 1:100. The models illustrated the situation in 1927 before any groynes were built, in 1961 with the two small groynes just before construction of the big groyne, and in 1967 3 years after the big groyne was completed.

As the bottom currents were of major interest they were traced by plastic balls having a diameter of 1 cm and a settling velocity of 7 cm/sec. These balls were shown to be light enough to follow the wave current but heavy enough to stay at the bottom.

The movement of the balls showed clearly the existence of resulting transverse bottom currents as mentioned in section 2, as they always had a velocity component towards the breaker zone. But an even more convincing demonstration came from the injection of small (1 mm ϕ) polystyrol grains which were transported seaward under surfing waves and shoreward under nearly-breaking waves. The accumulating effect of the circulation currents concentrated the grains under the breaker lines where they were transported downstream in very narrow bands parallel to the shore.

That something similar happens in the nature has been demonstrated by Ingle in his studies of the movement of dyed grains on beaches in California [Ingle 1966].

The only exception from the pattern above was found in the region where the beach erosion had been reported. Here the relatively low outer bar caused a change from a two-breaker zone to a one-breaker zone, and the grains were transported from the bar near the shore out to the outer bar. In the two other models where the outer bar was undisturbed this did not occur.

Hence it was concluded that the heavy beach erosions were a secondary effect of the groyne construction. The erosion of the outer bar and the change in the breaker zone regime, caused by temporary cutting of the sand transport from north, gave rise to the formation of transverse bars, and these in turn were responsible for the erosion of the beach.

REFERENCES

Bagnold, R. A. (1940). Beach formation by waves; some model experiments in a wave tank. J. Inst. Civ. Engrs., London, 15, 27-52.

Ingle, J. C. (1966). The movement of beach sand. Elsevier, Amsterdam.

Lundgren, H. (1963). Wave thrust and wave energy level. Internat. Assoc. Hydr. Res., 10th Congr., London, I.20, 147-151.

Zenkovich, V. (1967). Processes of coastal development. Interscience Publishers, New York.

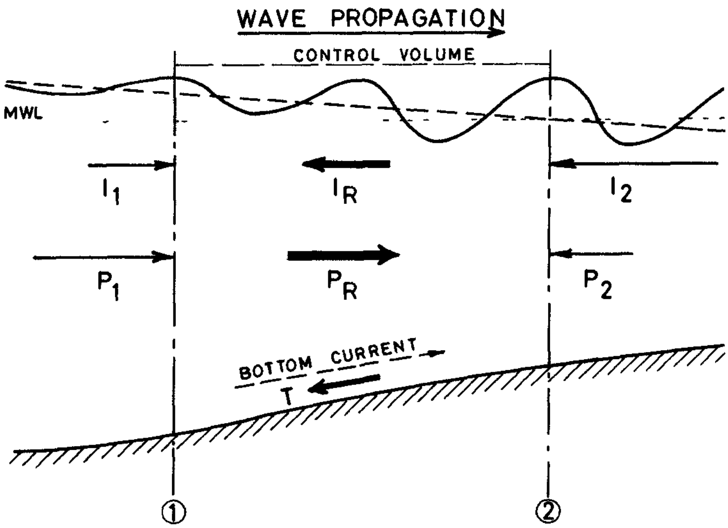

FIG 1 WAVES NEAR BREAKER ZONE

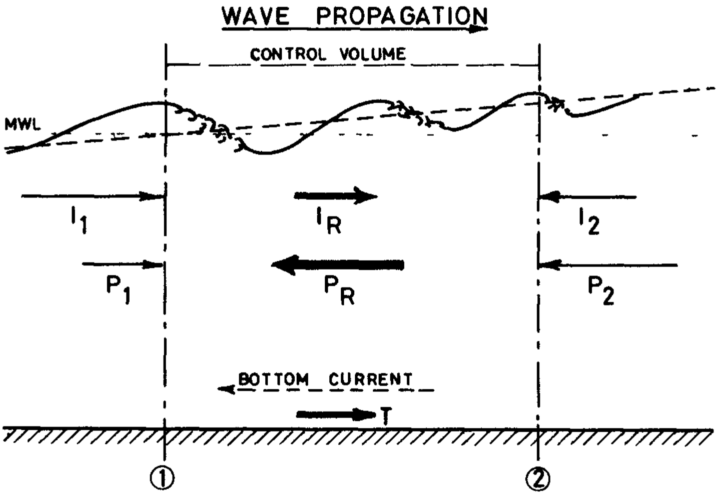

FIG 2 SURFING WAVES

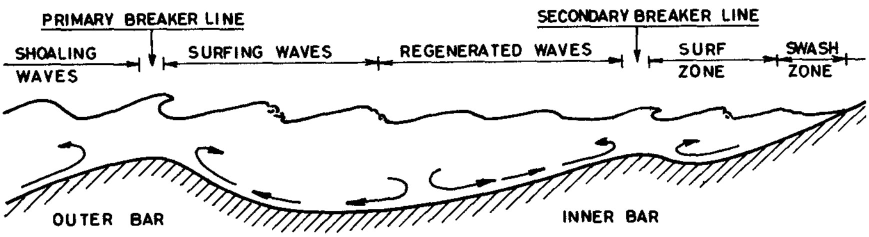

FIG 3 BOTTOM CURRENTS IN A TWO-BREAKER ZONE

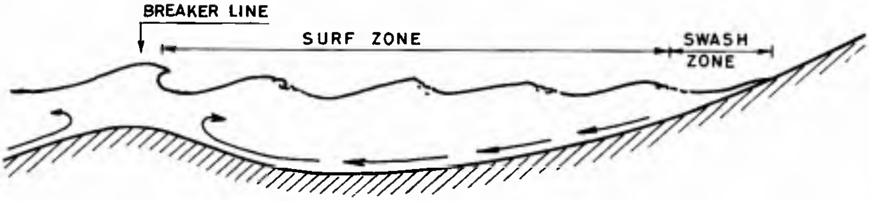

FIG. 4 BOTTOM CURRENTS IN A ONE-BREAKER ZONE

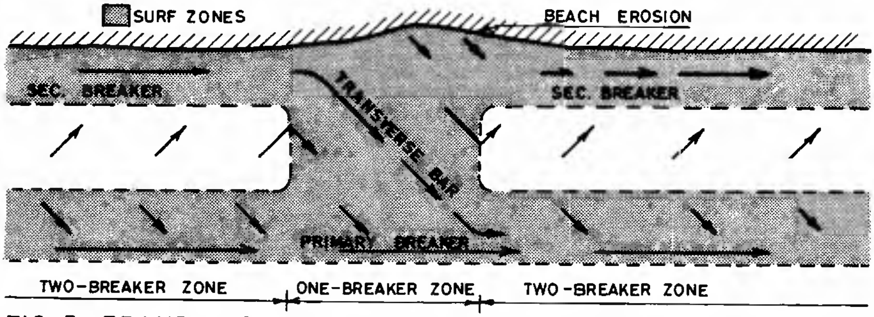

FIG. 5 TRANSVERSE BAR

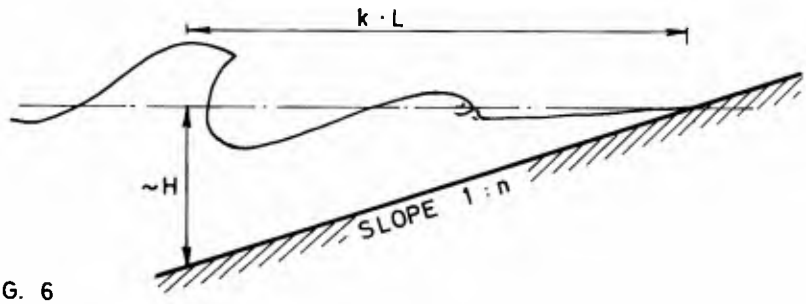

FIG. 6

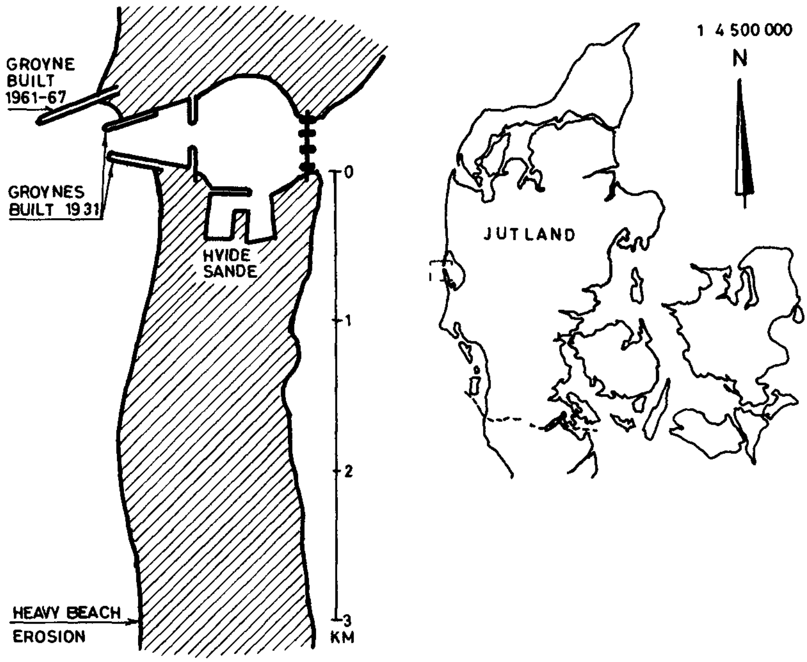

FIG 7 STUDY AREA

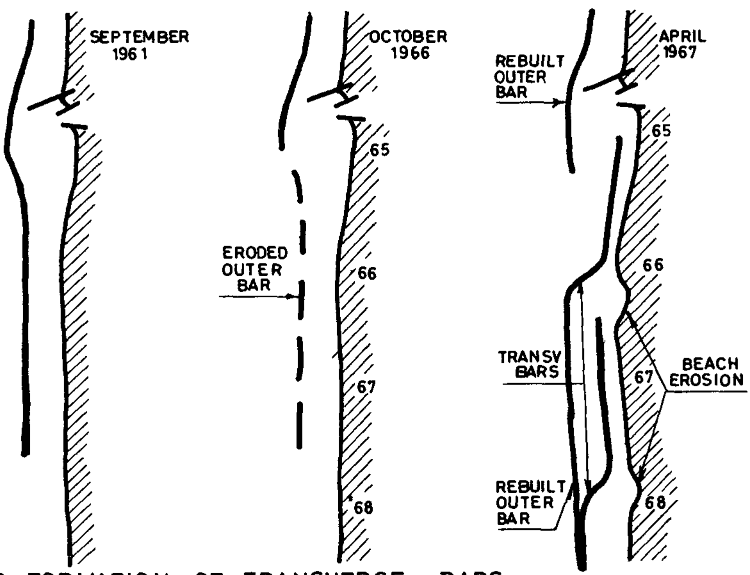

FIG 8 FORMATION OF TRANSVERSE BARS