

Study of Horizontal Bottom Velocities & Prediction of Sediment Transport behind a Submerged Breakwater

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Bottom horizontal velocity asymmetry and the resultant bottom sediment motion on the leeside of a submerged breakwater are examined. The laboratory tests are conducted with regular and irregular waves. In general the net bottom transport for the tested conditions is directed towards the shore behind the submerged breakwater. The sediment transport here is found to depend on the types of waves, whether they are regular or irregular, their height and the water level variation over the submerged breakwater. The use of irregular waves, which are closer to the real sea conditions, is recommended in similar investigations, as the information obtained from irregular and regular waves are different. The conditional total impulses method suggested by Longinov is found to be an effective tool in assessing the direction and intensity of net bottom water particle motion and the sediment transport.

Offshore breakwaters are increasingly used for the protection of natural and artificial beaches^{1,2}. Submerged offshore breakwaters are proved to have some definite advantages over the subaerial ones². The function of these breakwaters in the rebuilding of the beach depends on the wave kinematics in the leeside of the structure.

The process of beach-building is directly related to the sediment dynamics, which depends mainly on the maximum horizontal velocities generated by waves in the bottom boundary layer of the nearshore zone. In relatively deep water the shoreward and seaward components of the bottom velocities are equal. But in finite depth the waves become asymmetrical³, the crests of the wave profile becoming shorter and higher than the troughs. For the corresponding horizontal velocities, those under the crests are higher than under the troughs and the duration of crests are shorter than that of troughs. Asymmetry of waves and their bottom velocities on open beaches are studied in the field by Longinov³ and in the laboratory by Volkov⁴, Adeyemo⁵, etc. All these works are intended to determine the bottom horizontal velocities and their asymmetry up to the breaking point.

But by the construction of a submerged breakwater the waves are subjected to immature breaking on it, causing considerable changes in the wave and bottom velocity field behind the structure. Hence the theories put forward for the prediction of bottom velocities for open beaches are not applicable in this case. The kinematic structure of waves behind submerged structures especially at the bottom boundary layer has received very little attention^{4,6}. Wave action is always irregular in the field and for majority of the coasts the water level fluctuates due to tides. Studies on the

influence of irregular waves and tidal water level variations on the bottom velocities behind a submerged breakwater are totally missing in literature. Hence the present study looks into these 2 aspects for the assessment of beach building ability of a submerged breakwater.

Methods

Laboratory set-up—The tests were conducted in a wave flume ($29 \times 1.4 \times 1.2$ m). A concrete model coast with an underwater slope of 1:30 and subaerial beach slope of 1:5 at one end was constructed. An 'Odessa-type' submerged breakwater¹ with a seaward slope of 1:1.67 was built at a depth of 25 cm from the low water level. Four capacitance type wave gauges were used to monitor the wave profile; one near the wave paddle, another one in front of the breakwater and the rest behind the breakwater. The bottom velocities were measured at the 2 wave recording sites in the leeside of the breakwater (Fig.1). They represented the reformed waves after breaking over the submerged breakwater and the broken waves very close to the beach.

Bottom horizontal velocities were measured with electro-tensometric gauges, the sensor of which was a thin circular disc of about 15 mm diam. The horizontal displacement of this disc was sensed by an electronic circuit. The sensor element was kept very close to the bottom and directed against the wave approach. The wave and velocity gauges were calibrated⁷.

The tests were conducted with irregular and regular waves for three depths of submergence of breakwater (0, 3.8 and 7.5 cm). A spectrum suggested by Bao⁸ and reported in detail in Baba^{7,9,10} was used for the production of irregular waves. Statistical parameters of irregular waves incident on the submerged

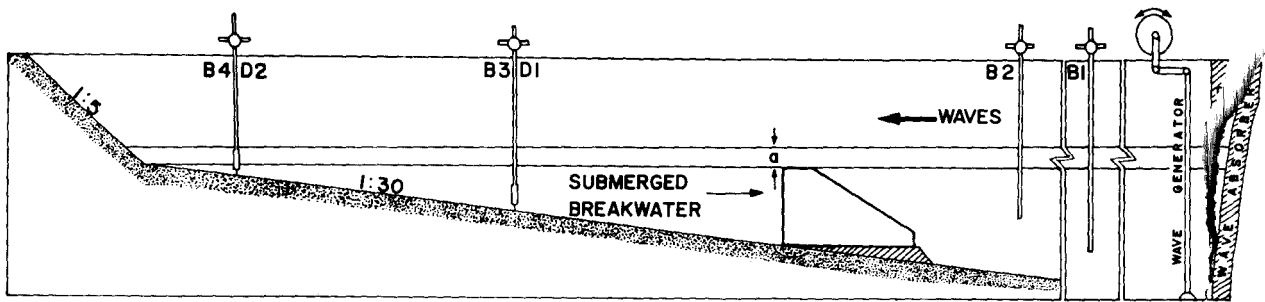


Fig. 1—Model of beach behind the submerged breakwater showing observation points (B1-B4-wave gauges; D1 & D2 - velocity gauges, a - depth of submergence of breakwater)

Table 1—Statistical Parameters of Incident Irregular Waves

Depth of submergence of breakwater top a (cm)	Mean period, $\bar{T}_i$ (sec)	Mean height, $\bar{H}_i$ (cm)	Maximum height H_{max_i} (cm)
0	1.31	7.8	18.5
3.8	1.24	7.4	16.6
7.5	1.31	6.5	15.1

breakwater are given in Table 1. The regular waves tested have heights in the range of 6-16 cm and period around 1.3 sec, which corresponds to the mean period of the irregular waves. Both the wave and velocity profiles were recorded in a photosensitive paper. In the velocity record (Fig. 2) crests correspond to the maximum horizontal velocities towards the shore (positive) and troughs to those towards the sea (negative).

Asymmetry of horizontal bottom velocities—To understand the actual displacement of water particles on the bottom layer and the corresponding sediment movement, it is essential to know not only the absolute bottom velocities, but also the dominant direction of transport. It is important to know the duration of positive and negative velocities, which differs considerably (Fig. 2), for a realistic assessment of the net particle motion. Longinov³ suggested a method known as 'conditional total impulses' (CTI) to explain the capability of bottom horizontal water particle velocities in transporting the sediment grains.

Conditional total impulses (CTI) method—This method is based on the assumption that the movement of sediments in the bottom layer is directly related to the horizontal wave pressure available very near to the water-sediment boundary layer. In this the mean mass sediment transport rate for a long duration of wave action is considered to be proportional to the mean impulse of pressure (product of pressure and duration), required to move the sediments. It is assumed that the pressure, which moves the sediment mass is the one, the value of which exceeds the critical pressure

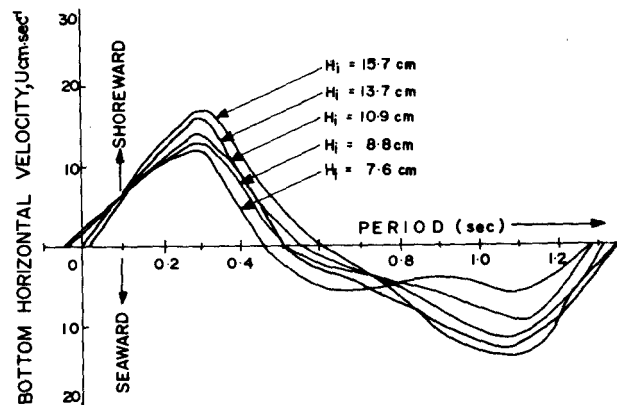


Fig. 2—Typical horizontal bottom velocity profiles at D1 for a wave period of 1.32 sec and different wave heights

required for the initiation of motion of a given sediment mass. Thus for computation of impulses of motion for long interval of time it is necessary to find for each sediment fraction the sum of mean impulses exceeding the critical velocity. The value of total impulses of motion, obtained for a given group of bottom pressure values, and subsequently for those sediment fractions, which are set-in-motion under the action of above group of pressures is known as 'conditional total impulses' and is presented as I_{Σ} . This will clearly demonstrate the behaviour of different sediment fractions at a given point on the sea bed for a given period of wave action.

As in the present investigations, instead of bottom pressure, velocity is measured for the computation of CTI and is presented as I_{Σ} ; the recorded bottom velocity profiles are used directly. As Longinov³ points out, the use of velocity impulses in the place of pressure impulses does not cause any considerable difference in the direction or intensity of CTI. Examples for computation of CTI are given in Fig. 3 and Table 2 for both regular and irregular waves.

According to Volkov⁴ critical velocity for sand motion initiation under waves depends on sediment size, specific gravity of sediment grains and wave period. If latter 2 factors are kept constant, this critical

velocity will depend only on sediment size. An empirical relationship between them for the case of quartz grains is given by Volkov⁴ as

$$U_s = k(gD)^{1/3} \quad \text{where}$$

U_s - critical velocity of sediment motion initiation; D - diameter of sediment grains; g - acceleration due to gravity and k - an empirical coefficient given by $k = 8 + 5.6 D$.

From this relationship it is possible to predict the bottom velocity required to move the sediment of any grain size. The CTI in turn will predict the direction and intensity of motion of the sediment mass as a whole for a given period of wave activity. The information regarding the movement of individual grain sizes from the whole sediment mass for a given bottom velocity condition may also be obtained using this method.

Results

Results of computation of CTI (further referred only as impulses) at the 2 observation points (D1 and D2) for different regular wave heights, keeping the period constant at $T_i = 1.32$ sec for 3 depths of submergence

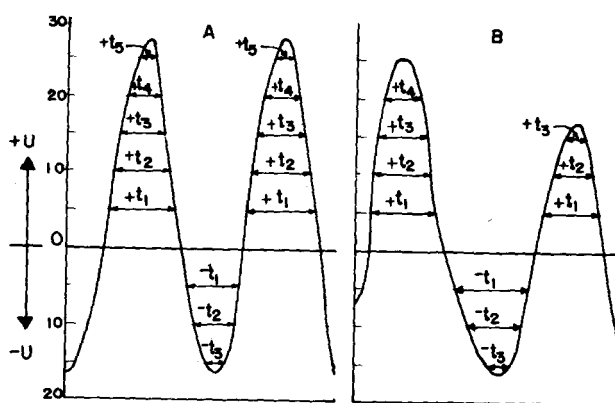


Fig. 3—Examples of analysis of horizontal bottom velocity records for the computation of conditional total impulses [A - regular waves, B - irregular waves; $t_1, t_2, t_3, \dots$ —duration of velocities $U = 5, 10, 15, \dots$ cm.sec⁻¹]

of breakwater are presented in Fig.4. The results of tests with irregular waves with a mean period of $\bar{T} = 1.31$ sec are also superimposed on these diagrams. The grain sizes of bottom sediment, which could be set in motion by their corresponding horizontal bottom velocities are also reproduced on these diagrams.

For $a=0$ near D1, the impulses are directed exclusively towards the shore for all the tests conducted with the regular and irregular waves (Fig.4A). The intensity of impulses for different regular wave heights does not vary considerably. However the resulting water motion is not capable of moving sandsize sediments ($D = 0.1$ to 1.0 mm) at the bottom. As the waves move towards the shore the intensity of bottom water motion increases (Fig.4A). Here the 2 smaller regular waves tested gave negative impulses, leading to a net bottom water motion towards the breakwater. But the higher waves tested have positive impulses. The smaller waves after transmission over the breakwater, travel right up to the shoreline, where they break. Hence the negative impulses observed at D2 might have been due to the influence of backwash from the beach. But the 3 higher waves tested, break just in front of D2 leading to a mass transport towards the shore. The intensity of bottom transport increases with the wave height, causing the transportation of bottom sediments of larger and larger size.

Under irregular waves the bottom impulses are directed towards the shore with almost constant intensity for the entire protected zone (Fig.4A). But just near the breakwater these waves are capable of moving sediments of 0.5 mm or less, but near the shoreline they are capable of transporting the complete range of sand fractions. On a comparison with the regular waves near the breakwater they contain stronger impulse than the irregular waves. But near the shoreline the impulses generated by irregular waves are closer to that of a regular wave of height equal to 11.1 cm.

As the depth of submergence of the breakwater increases ($a = 3.8$ cm) the influence of regular waves on

Table 2—Example for the Calculation of Conditional Total Impulses (I_{Σ})

Bottom velocity U cm.sec ⁻¹	Duration		Percentage		Difference $\pm \Delta t$ %	$U \cdot \Delta t$	I_{Σ}
	+ t sec	- t sec	+ t	- t			
5	20.15	18.91	30.36	28.49	+1.87	+ 9.35	+45.15
10	9.53	8.85	14.36	13.33	+1.03	+10.30	+35.80
15	3.56	3.55	5.36	5.35	+0.01	+ 0.15	+25.50
20	1.25	0.50	1.88	0.75	+1.13	+22.60	+25.35
25	0.07	0	0.11	0	+0.11	+ 2.75	+ 2.75
	34.56	31.81	52.07	49.93			
	$\Sigma t = 66.37$		$\Sigma t\% = 100$				

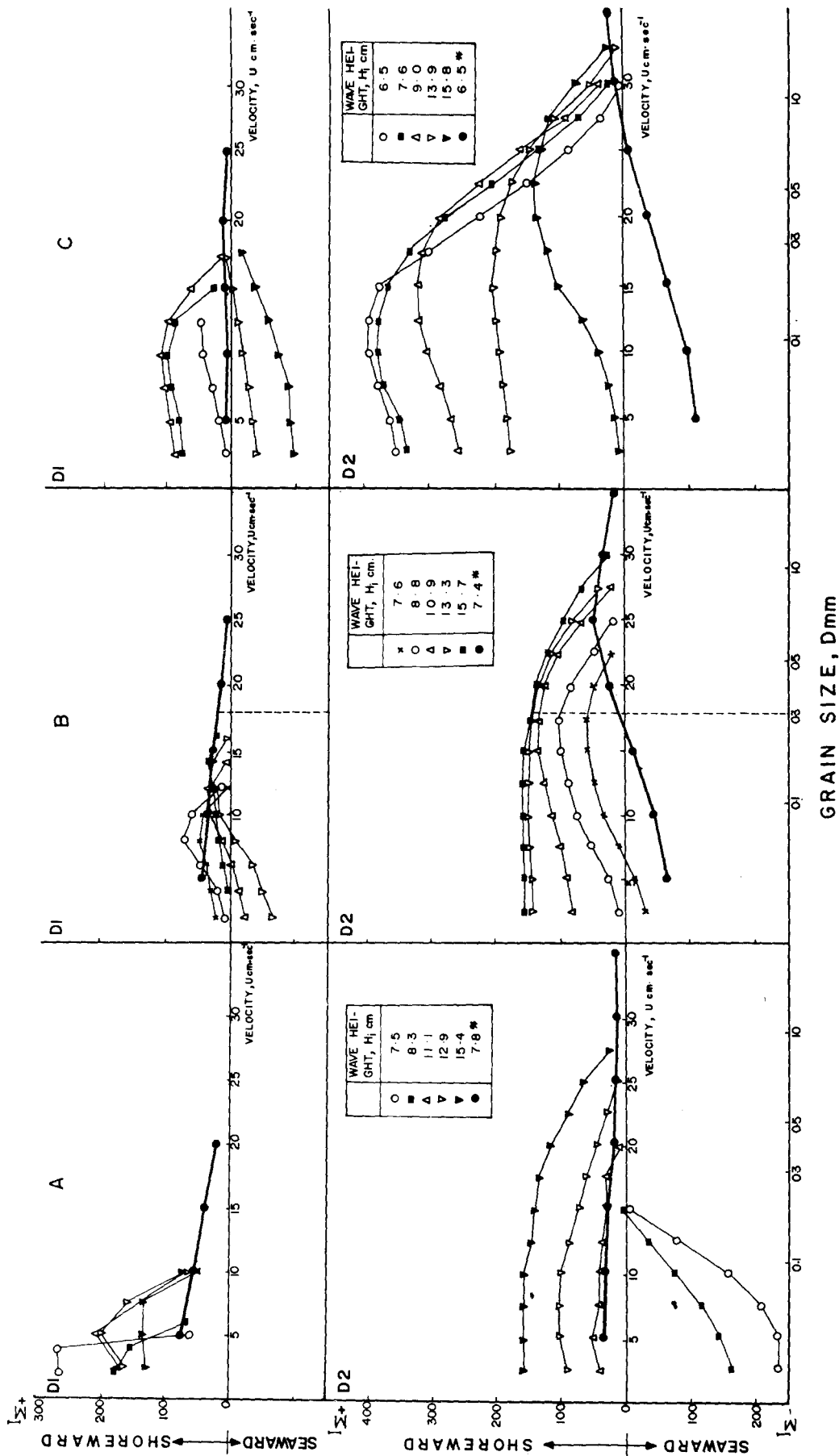


Fig. 4—Horizontal bottom velocity impulses of regular and irregular waves for depth of submergence of breakwater crest, (A) 0, (B) 3.8, (C) 7.5 cm [D1 & D2 are observation points, * mean wave heights correspond to regular waves]

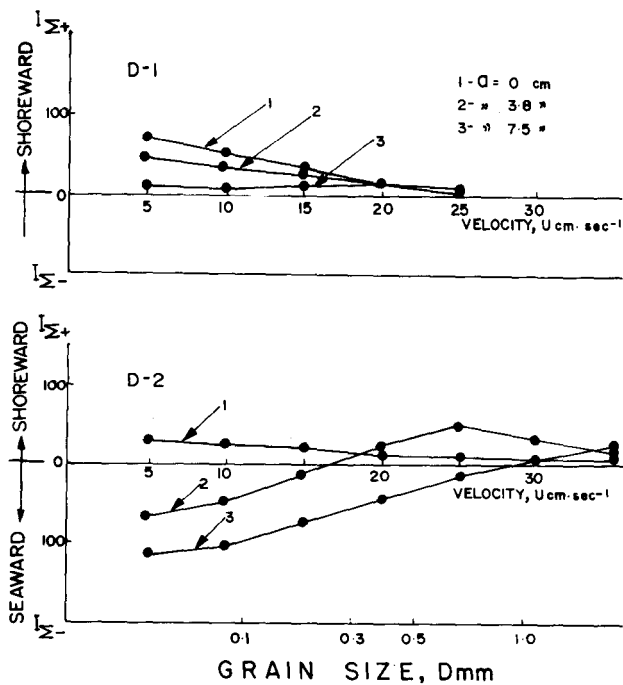


Fig. 5—Impulses due to irregular waves for varying depths of submergence of breakwater

the bottom near the structure is reduced (Fig. 4B). As a result, even negative impulses are observed, especially for higher waves at this point. But these impulses are sufficient only to move the smallest of the sand particles. However, near the shore the impulses under all the tested regular waves are directed towards the shore and the intensity increases with wave height. Here these impulses have the capacity to move all the sand size particles towards the shore, which may lead to the accretion of the beach.

The impulses under the irregular waves in the deeper portions of the protected zone are directed towards the shore. These are capable of carrying the fine and medium sand grains. As the waves approach the shore it is found that the grain sizes with $D < 0.25$ mm move seaward and the larger ones - shoreward.

With a further increase in the water level ($a = 7.5$ cm) the intensity of impulses increases (Fig. 4C). At the seaward side of the protected zone, the larger regular waves take the sediments seaward and the shorter ones - shoreward. At the shoreward side the impulse curves show 2 different trends. The intensity of sediment movement decreases with an increase in regular wave heights for smaller fractions; but for fractions > 0.5 mm it increases with the wave heights. However, for all regular waves tested the shoreward direction of sediment transport is maintained.

Irregular waves for this depth at the first section give uniform positive impulses, for the entire range of grain sizes, even though the intensity is too small to move any

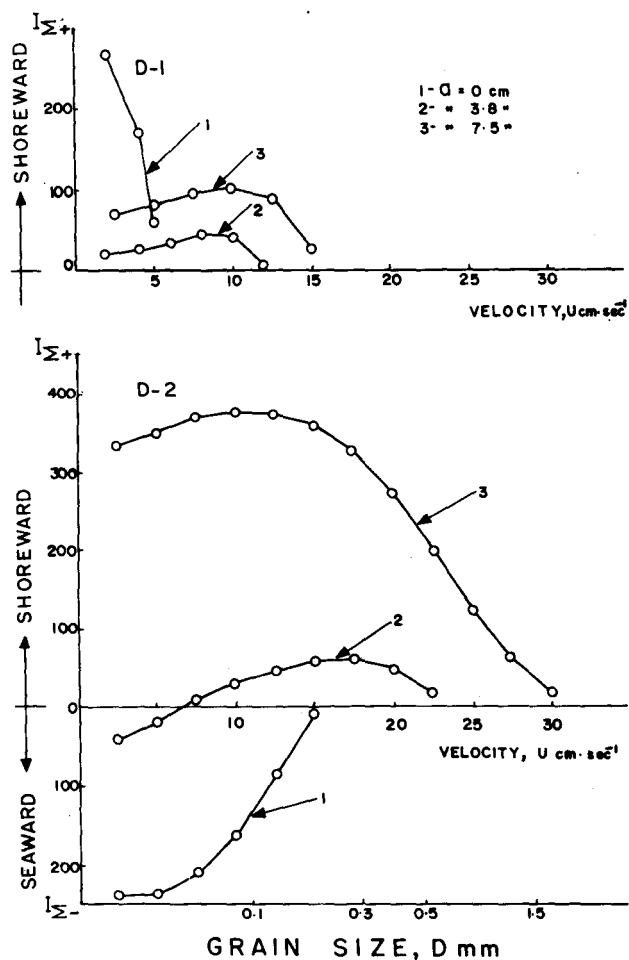


Fig. 6—Impulses due to a regular wave ($H_i = 7.6$ cm) for varying depths of submergence of breakwater

sediments. At the same time the total impulses near the shore are directed mainly towards the sea.

Discussion

Comparison of impulses of bottom velocities behind the submerged breakwater under irregular waves for different stages of water level (Fig. 5) reveals that the intensity of bottom water motion decreases with an increase in the water level. The direction of transport just behind the breakwater is shoreward and close to the shore, the transport takes a seaward direction, with the increasing water level. But in the latter case the larger sand grains are still transported towards the shore.

At higher levels larger sediment particles ($D \geq 0.8$ mm) are transported towards the shore and smaller ones are taken towards the breakwater. During a decrease in water level from high to low all the bottom sediments are transported towards the beach.

Under regular waves the picture is different from that of irregular waves. If we take an individual regular wave, (eg. $H_i = 7.6$ cm) it may be seen that the intensity of impulses increases with the water depth (Fig. 6). In

general higher values are obtained when compared to irregular waves and the transport is directed towards the shore. Near the breakwater the regular waves, irrespective of the height or water level, are capable of moving the finer or median sands. At the shoreline these waves, especially the higher ones, transport the complete range of sand grains towards the shore.

Thus the present investigation shows that the shore protective capacity of submerged breakwater is greatly influenced by the tidal level fluctuations. Also the behaviour of the bottom impulses and the sediment transport differs considerably between the regular and irregular waves. With an increase in water level, under the irregular waves the impulses change their direction from positive to negative, but the regular waves give an exactly opposite picture. This difference on the bottom transport for regular and irregular waves may be due to the fact that for irregular waves this transport depends mainly on the relatively larger waves. The picture of bottom transport with the increase in water level under the relatively larger regular waves (Fig.4; eg: $H_i = 15.7$ cm) is closer to that observed under the irregular waves, justifying the above assumption.

The picture obtained with the total impulses method is compared with the results obtained from tests conducted in the same flume for similar wave conditions with a movable bed. The concrete bed is replaced with sand of 0.3 mm mean diam. and a sorting coefficient of 1.4. The tests and results obtained are reported in detail in Baba^{7,9}. The sediment transport and resultant beach reformation under both the regular and irregular waves compare satisfactorily with the predicted picture for $a = 3.8$ cm and for a sand size of $D = 0.3$ mm (Fig. 4B).

Thus the laboratory tests with the submerged breakwater show that the sediment transport on the protected beach depends on the type of waves (regular or irregular), wave heights, and to a great extent on the tidal level fluctuations and the subsequent variations in the depths of submergence of the breakwater crest. The application of irregular waves, which are closer to

the real sea conditions, in similar studies are recommended as they give a totally different picture when compared with the regular waves. CTI method suggested by Longinov⁴ is found to be an effective tool in predicting the bottom sediment transport when the bottom horizontal velocity profiles are known. This method is more useful when the performance of different grains of the given sediment mass is to be understood.

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