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# An Investigation on the Formation of Submerged Bar Under Surges in Sandy Coastal Region*

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## ABSTRACT

Cross-shore sediment transport rate exposed to waves is very important for coastal morphology, the design of marine structures such as seawalls, jetties, breakwaters etc, and the prevention of coastal erosion and accretion due to on-off shore sediment transportation. In the present study, the experiments on cross-shore sediment transport are carried out in a laboratory wave channel with initial beach slopes of 1/8, 1/10 and 1/15. By using the regular waves with different deep-water wave steepnesses generated by a pedal-type wave generator, the geometrical characteristics of beach profiles under storm conditions and the parameters affecting on-off shore sediment transport are investigated for the beach materials with medium diameters of $d_{50}$=0.25, 0.32, 0.45, 0.62 and 0.80 mm. The offshore bar geometric characteristics are the horizontal distances from the shoreline to the bar beginning ($X_b$), crest ($X_t$), and ending ($X_s$) points, the depth from the bar crest to the still water level ($h_t$), and the bar volume ($V_{bar}$). The experimental results have indicated that when the deep-water steepness ($H_0/L_0$) increased, the net movement to seaside increased. With the increasing wave steepness, the bars moved to widen herewith the vertical distances from still water level to the bar beginning ($X_b$), crest ($X_t$) and ending ($X_s$) points and the horizontal distances from the coast line to the bar beginning, crest and ending points increased. It was also shown from experimental results that the horizontal distances from the bar beginning and ending points to the coast line increased with the decrease of the beach slope. The experimental results obtained from this study are compared with previous experimental work and found to be of the same magnitude as the experimental measurements and followed the expected basic trend.

**Key words:** *cross-shore sediment transport*; *beach profiles*; *bar parameters*; *experimental study*

## 1. Introduction

Cross-shore sediment transport in the surf zone plays a very important role in shoreline migration as well as in the transformation of beach profiles. Estimation of beach transformation requires the knowledge about the functional relationship of sediment transport rate to conditions of waves, currents, water depth, bottom configuration, sediment property, and so on.

Most problems of coastal engineering are dependent on a number of parameters. Therefore, the solution to these problems is usually obtained by physical modeling. Many theoretical and experimental studies have been carried out by researchers working on sediment movement in the onshore-offshore directions, and consequential coastal features of diverse factors (Dean, 1973; Gourlay, 1980; Sawaragi

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and Deguchi, 1980). There are many attempts to determine parameters classifying beach profiles, such as Nayak (1970) and Hattori and Kawamata (1980). Sunamura and Horikawa (1974) offered a model to describe onshore-offshore sand transport in the surf zone. They proposed beach classification based on displacement of topography from the initial beach slope. The dependence of grain size on the beach slope was investigated by geologists King (1972). Monotonic beach profile has been defined as $d(y)= Ay^{2/3}$, in which $d(y)$ is the water depth at a distance $y$, and $A$ is a scale parameter depending on sediment characteristics (Dean, 1991). Watanabe *et al*. (1980) developed a three-dimensional numerical model to estimate cross-shore sediment transport. The results of the model show a good agreement with those obtained by the formula for sediment transport caused by waves and currents. An attempt was made on the states concerned with the geometrical features of the bar parameter which occur in winter by evaluating the inventions from studies of other investigators (Silvester and Hsu, 1989). Quick *et al*. (1991) experimentally studied the discharge of longshore sediment transport along the beach profile, and they highlighted the fact that the bed slope and the mean particle diameter have an effect on sediment discharge. Zheng and Dean (1996) found out the divergence of the steady-state of the coast as the cause of the sediment transport and offered theoretical model for cross-shore sediment transport. Leont'yev (1996) studied the discharge of cross-shore sediment transport due to waves considering the total transport as the sum of sediment transport and wave run-up, and proposed a model for variation of beach profile by the discharge of sediment transport and showed that the model exhibits good agreements with experimental data and other results of previously developed models. Hsu (1998) carried out experimental and theoretical studies to determine the geometry of offshore bar. In his experiments, he studied the effects of cross-shore waves traveling with variable angles in three-dimensional wave basin. He concluded that cross-shore waves traveling with variable angles make the beach profile be in equilibrium. Ruessink *et al*. (2002) determined a long time variation of the bar crest location by use of remote sensing. They determined the beach profile by measuring water depth along with the beach profile and digitized the profile. Günaydın and Kabdaşlı (2003) carried out an experimental study on the characteristics of coastal erosion with a model in which the mean diameter of particles and the beach slope are 0.35 mm and 1/5 under regular and irregular wave conditions, respectively. Their investigation mainly focused on erosion length, erosion depth, the position of peak erosion, and the total erosion area. Kömürcü *et al*. (2007) investigated the cross-shore sediment movement by laboratory experiments. A regression analysis was made to establish the bar parameters which came out from the experiments and equations were constructed by use of the bar parameters. Özölçer (2008) carried out an experimental investigation of coastal erosion profile (storm profile) in a wave flume with regular waves, and the geometric characteristics of erosion profile were determined by the resultant erosion profile. Celikoğlu *et al*. (2004, 2006) experimentally studied the cross-shore and longshore sorting on a beach under wave action. The sorting of bed material and the formation of armor coats along beach profiles were defined by grain-size distribution and dimensionless parameters for sandy beaches.

Cross-shore sediment transport has been studied since the beginning of 1950s both in the laboratories and fields. But the physical process has not been fully understood. The aim of this study is to obtain a better understanding of the mechanism governing cross-shore sediment transport and the transformation of beach profiles resulted from sediment transport across the surf zone. In this study, the experiments on cross-shore sediment transport are carried out and the parameters affecting onshore-offshore sediment transport are investigated for five different beach materials with a medium diameter.

## 2. Methods

Laboratory experiments were carried out for investigation of cross-shore sediment transport under the storm conditions and the geometrical features of the beach profiles in a wave channel of 12 m in length, 0.40 m in width and 0.60 m in depth with a glazed wall at the Department of Civil Engineering, Cukurova University, Adana, Turkey. A series of laboratory experiments have been performed to investigate the variation of coastal profile under different scenarios (64 tests). Each experiment was performed in a series of runs. The sloping beach and the wave generator were located in the wave channel. Waves in the channel were produced by use of the pedal-type wave generator. Wave conditions chosen between the maximum and the minimum originate erosion profiles would be in nature in order to examine the considered parameters. The characteristic features of produced waves could be adjusted by the speed of the electrical engine twisting the pedal and the crank length of the engine. Therefore, waves with periods from 0.47 s to 0.76 s could be produced. In this work, three different beach slopes were used and the values of these slopes both represent slopes in nature and make laboratory conditions easy. Bed slopes were 1/8, 1/10 and 1/15, respectively. Determination of material properties in the proposed model was considered as a significant problem. There has been a certain method to choose model scaling of bed materials, although several investigations have been carried out recently. On the contrary, materials with different densities are proposed in experimental and theoretical studies, but there is still an ongoing discussion about this approach (Noda, 1972; Ito and Tsuchiya, 1984; Trenhaile and Lakhan, 1989; Wang *et al*., 1994). In the present study, five different materials with mean diameters ($d_{50}$) of 0.25, 0.32, 0.46, 0.62 and 0.80 mm were used. A detailed information about the experimental procedure can be found in Demirci (2006).

For the investigation of the sediment movement which occurs after the storm conditions and resultant geometrical features of the beach profiles, the experimental conditions were arranged. Parameter $C$ in Eq. (1) given by Sunamura and Horikawa (1974) is larger than 8.

$$C = \frac{H_0}{L_0}(\tan\beta)^{0.27}\left(\frac{d_{50}}{L_0}\right)^{-0.67}, \tag{1}$$

where $C$ is the profile parameter, $H_0$ is the deep-water wave height, $L_0$ is the deep-water wave length, $\tan\beta$ is the bottom slope, and $d_{50}$ is the grain size. It is classified in this form according to the value of $C$ as follows.

$C < 4$ accretion-summer profile;

$4 < C < 8$ equilibrium profile;

$8 < C$ erosion-winter profile.

Wave heights produced by pedal-type wave generator were acquired by the records of a video camera. Therefore, the scaling was made onto the glazed wall of the wave channel and the altitude of wave was determined by averaging the certain wave levels passing through this scaling. In similar way, the passing time of waves on the vertical indicator located on the glazed wall of the wave channel was determined by a chronometer and it was divided by the number of wave passing to determine the period of wave. This procedure was repeated in a certain amount. Consequently, the period was determined for a particular wave. Experimental conditions are shown in Table 1.

**Table 1** Experimental conditions

| Total experiment number | Experiment number | Medium sediment diameter $d_{50}$ (mm) | Beach slope | Wave period $T$ (s) | Wave steepness ($H_0/L_0$) |
|---|---|---|---|---|---|
| 5 | No.1~5 | | 1/8 | 0.60~0.83 | 0.070~0.232 |
| 5 | No.6~10 | 0.25 | 1/10 | 0.60~0.83 | 0.070~0.232 |
| 5 | No.11~15 | | 1/15 | 0.60~0.83 | 0.070~0.232 |
| 6 | No.16~21 | | 1/8 | 0.52~0.83 | 0.070~0.214 |
| 6 | No.22~27 | 0.32 | 1/10 | 0.52~0.83 | 0.070~0.214 |
| 4 | No.28~31 | | 1/15 | 0.60~0.76 | 0.130~0.232 |
| 4 | No.32~35 | | 1/8 | 0.60~0.76 | 0.130~0.232 |
| 4 | No.36~39 | 0.45 | 1/10 | 0.60~0.76 | 0.130~0.232 |
| 4 | No.40~43 | | 1/15 | 0.60~0.76 | 0.130~0.232 |
| 4 | No.44~47 | | 1/8 | 0.60~0.76 | 0.130~0.232 |
| 4 | No.48~51 | 0.62 | 1/10 | 0.60~0.76 | 0.130~0.232 |
| 3 | No.52~54 | | 1/15 | 0.60~0.76 | 0.130~0.232 |
| 5 | No.55~59 | | 1/8 | 0.47~0.76 | 0.130~0.262 |
| 3 | No.60~62 | 0.80 | 1/10 | 0.47~0.63 | 0.257~0.263 |
| 2 | No.63~64 | | 1/15 | 0.52~0.63 | 0.232~0.263 |

In the present study, cross-shore sediment transport under the storm conditions is investigated. The geometrical features of the beach profile which came out in different sediment diameters, coast slopes and parameters affecting the formation of profiles are investigated. The characteristics of the beach erosion geometry investigated are given in Fig. 1, in which $X_b$ is the horizontal distance between the original point of the shoreline and the bar starting point, $X_t$ is the horizontal distance between the original point of the shoreline and the bar crest point, $X_s$ is the horizontal distance between the original point of the shoreline and the bar ending point, $h_t$ is the vertical distance between the bar crest point and the still water level (SWL), and $V_{bar}$ is the volume of the erosion.

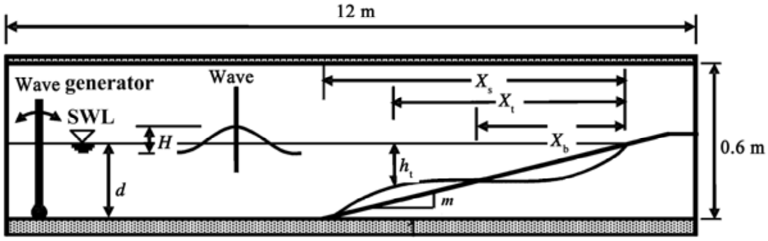


**Fig. 1.** Wave channel and bar parameters.

## 3. Experimental Results

Winter profiles occurred under storm conditions are shown in Figs. 2, 3 and 4. It can be seen in these figures, when the deep-water wave steepness increased, the net movement towards the sea and consequently the volume of the bar coming out from the sea increased.

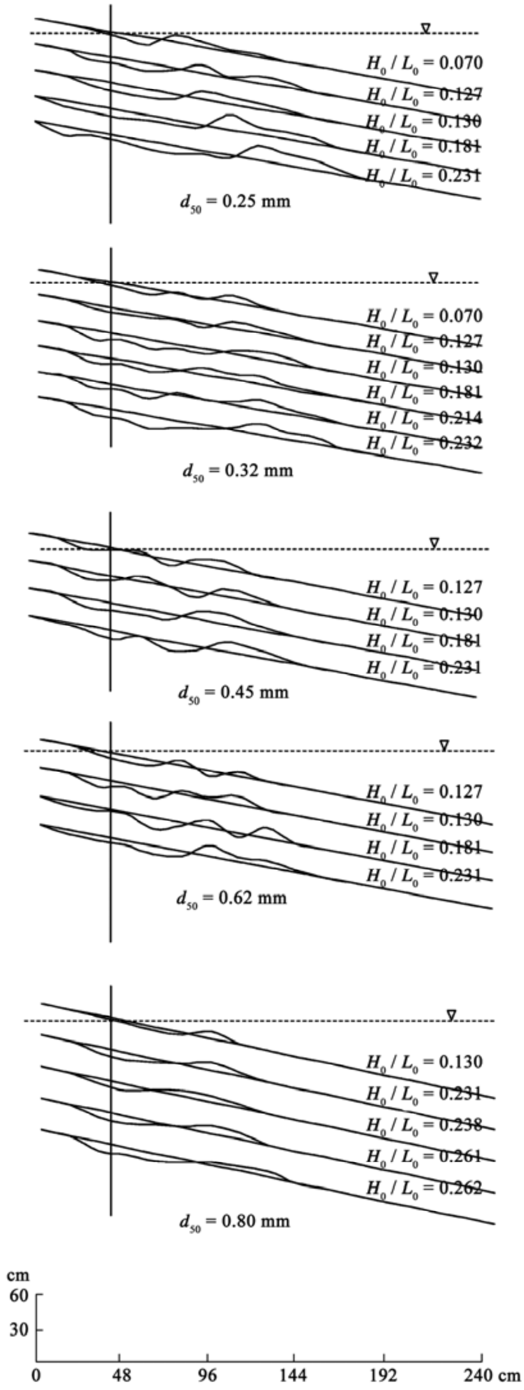


**Fig. 2.** Winter profiles in equilibrium, $m$ =1/8.

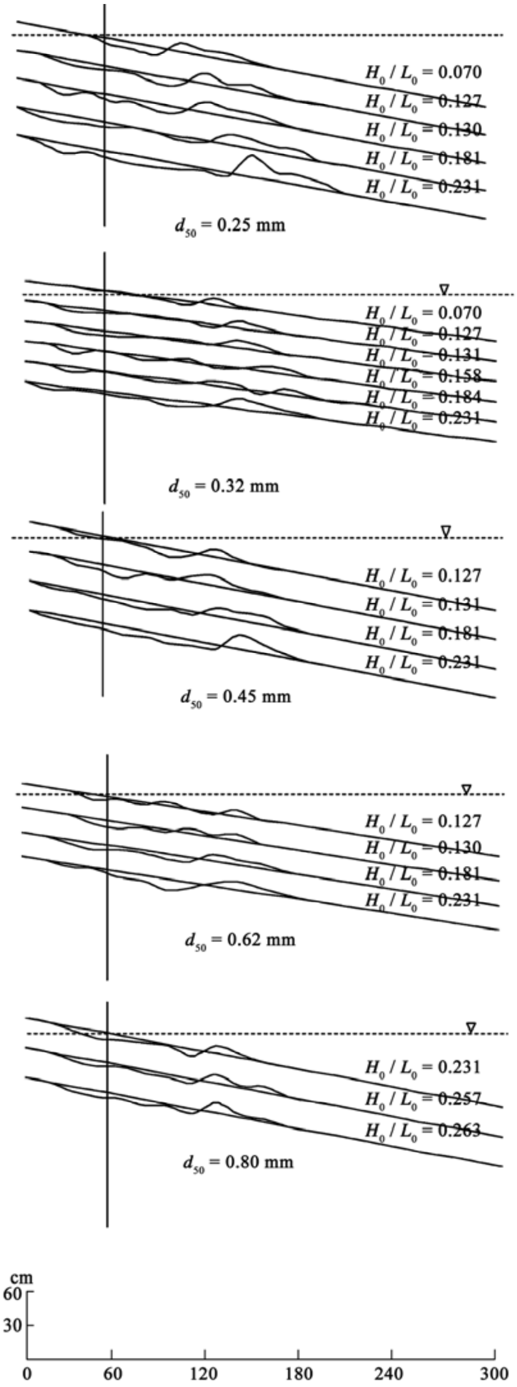


**Fig. 3.** Winter profiles in equilibrium, $m$ =1/10.

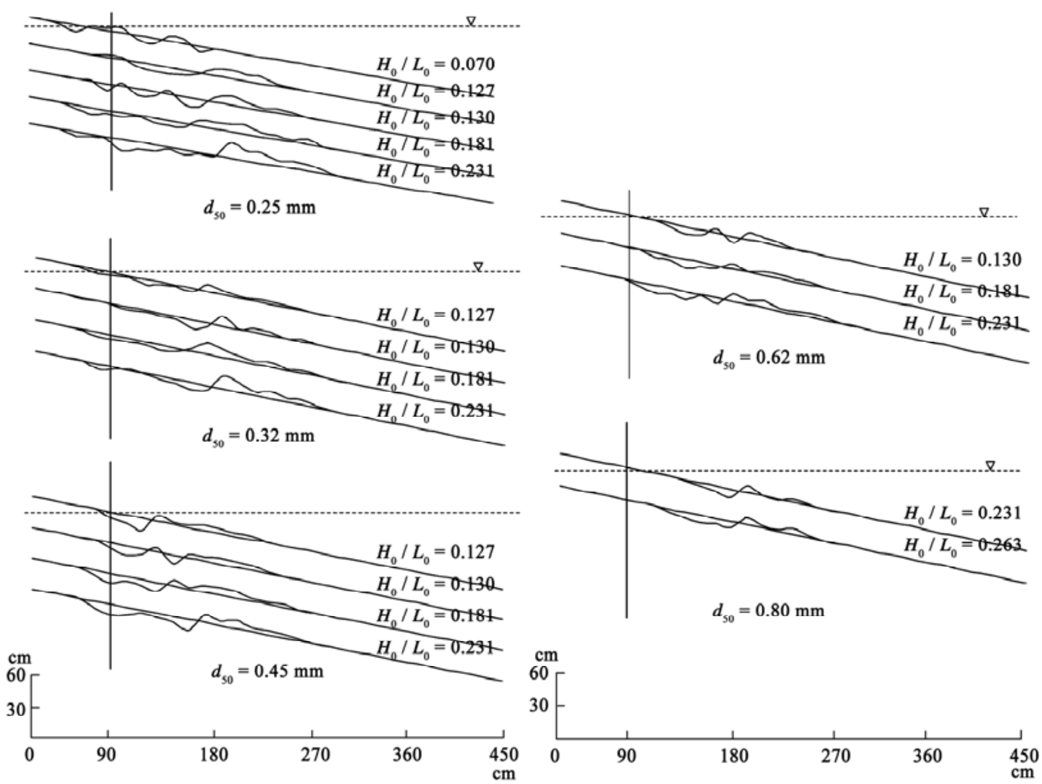


**Fig. 4.** Winter profiles in equilibrium, *m* =1/15.

Experiments also showed that winter profiles formed under relatively large wave steepness conditions, showing systematic increase in bar size with the increase of wave steepness ($H_0/L_0$).

Similarly, the increasing $H_0/L_0$ values are positively correlated with the vertical distance from the bar peak point to the still water level, the horizontal distances from the coast line to the bar beginning and ending points.

İt can be seen from the experimental results that the break position also moved with the bar. On the other hand, sand outside the surf zone was shifted offshore. Owing to the sand transport, water depth around the breaking position increased progressively, and beach slope in the surf zone became steeper. Experimental results obtained by Hattori and Kawamata (1980) indicate similar phenomena.

When the sediment movement related to the beach material was examined, medium sediment diameter decreased with higher sediment movement has occurred to the seaside and as a result more scour has come out in the regions close to the coast line. Coast line decreased in the consequence of the erosion brought about by the material movement to the seaside. When assumed that the beach profiles came out under the experimental conditions, it was evidently realized that larger sediment may cause steeper coast slope ($d_{50}$ > 0.5 mm).

Differences in the sediment movement which occurred on the coast bases with the same slope but different sediments are discussed below.

If the sediment diameter decreases, the movement to seaside increases and therefore the volume of the bar increases. In other words, in the coastal regions with materials of finer sediment, the amount of sediment movement increases on account of more erosion in the front of the coast. Furthermore, the horizontal distances from the coast line to the bar beginning and ending points increase.

When the materials have the same medium sediment diameter on different bottom slopes, the horizontal distances from the coast line to the bar beginning and ending points increase. As well, when the bottom slope decreases, the volume of the bar increases. These results agree with that of Sunamura and Horikawa (1974). As a matter of fact, there is no consensus in literature on the certain causes of offshore bars. It is generally believed that the undertow associated with breaking waves is responsible. Seasonal shoreline changes are usually considered to be related to the larger incidence of storms during winter and associated with seaward sand transport and storage in nearshore bar features.

### 3.1 Dimensionless Bar Beginning Distance $X_b/L_0$

The dimensionless distance from the coast line to the bar which formed after the beach profile had reached the equilibrium position was investigated with deep-water wave steepness for the bases with medium diameters of 0.25, 0.32, 0.45, 0.62, and 0.80 mm. It can be seen from experiments that the breaking position moved with the bar. Hattori and Kawamata (1980) pointed out that when the migrating bar reached the beach face, the shoreline advanced considerably and the beach profile transformed to winter profile. In Fig. 5, this variation was obtained for the 1/8, 1/10 and 1/15 beach slopes. With the increase of the deep-water wave steepness for the three slopes, the dimensionless bar beginning distance increases.

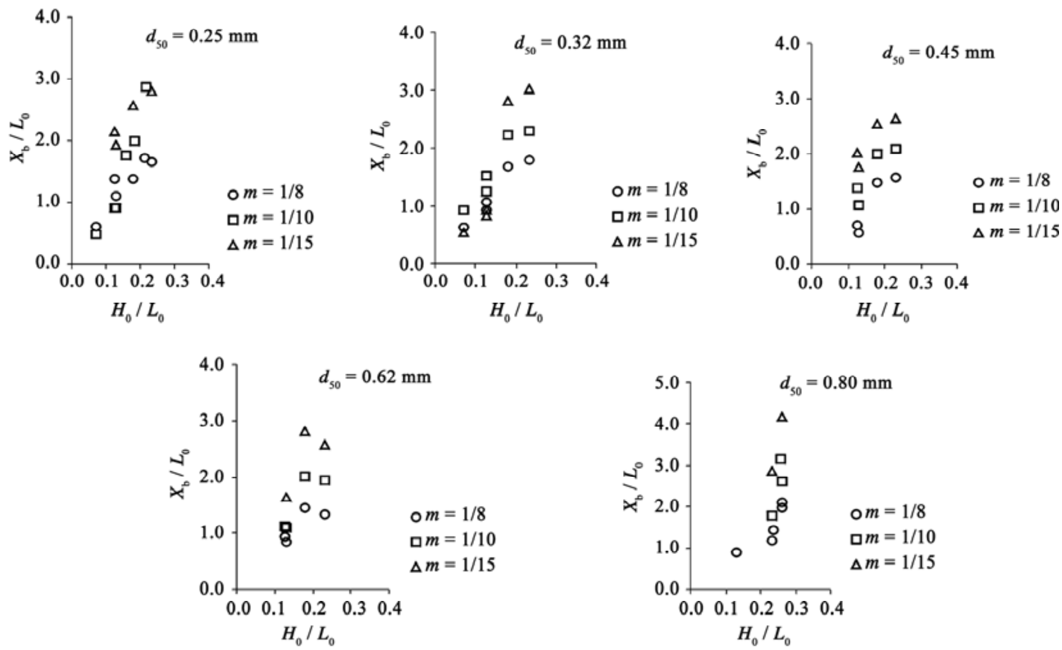


**Fig. 5.** Dimensionless bar beginning distances at different base slopes for $d_{50}$=0.25, 0.32, 0.45, 0.62 and 0.80 mm.

### 3.2 Dimensionless Bar Crest Distance $X_t/L_0$

In Fig. 6, with the beach slopes of 1/8, 1/10, and 1/15, the variation of the dimensionless bar crest distance to the coast line with $H_0/L_0$ was settled for the medium sediment diameters of 0.25, 0.32, 0.45, 0.62 and 0.80 mm. It can be realized from the figure that the dimensionless bar crest increases with the increasing wave steepness and it is the same for the three slopes. For all sediment diameters considered in the experiments, the dimensionless bar crest distance increases with the increase of deep-water wave steepness.

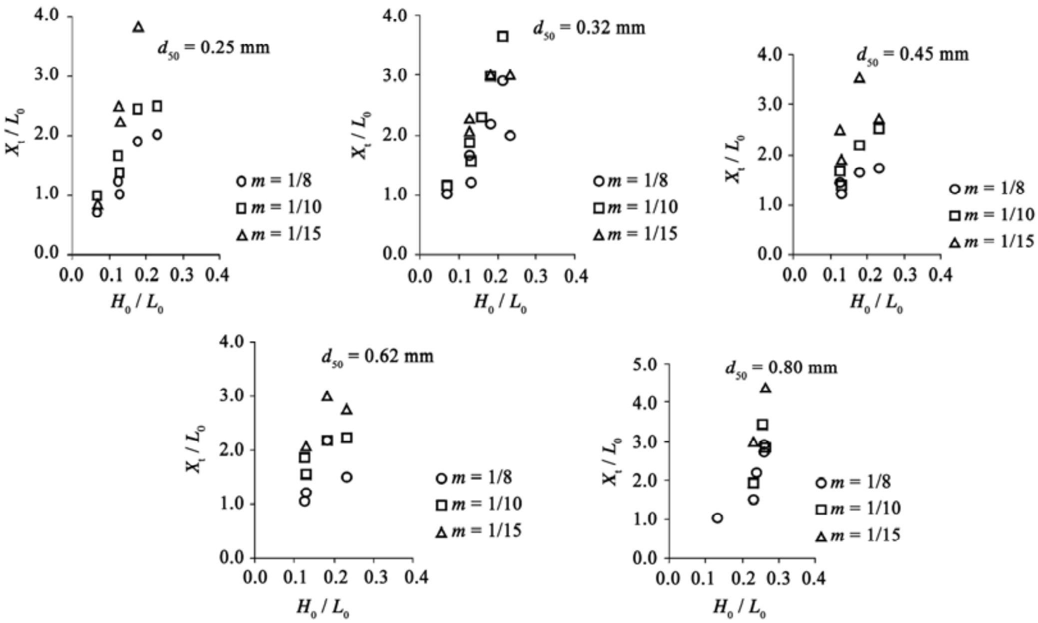


**Fig. 6.** Dimensionless bar crest distances at different base slopes for $d_{50}$=0.25, 0.32, 0.45, 0.62 and 0.80 mm.

### 3.3 Dimensionless Bar Ending Distance $X_s/L_0$

The variation of the dimensionless bar ending distance at the equilibrium position of the beach profile with the deep-water wave steepness is shown in Fig. 7. The dimensionless bar ending distance increases as the deep water wave steepness increases for the three slopes. As a result, this coastal erosion increases with the increasing wave steepness. From the experimental results, King (1972) mentioned that the bar moved shoreward gradually and the breaking position also moved with the bar. Results of the present study are compatible with the results of King (1972).

### 3.4 Relative Bar Crest Height $h_t/L_0$

The variation of the vertical distance from still water level to the bar crest with deep-water wave steepness is given in Fig. 8. Under given experimental conditions, relative bar crest height $h_t/L_0$ increases with the increasing $H_0/L_0$ for all slopes and sediment diameters except for the relative crest height of the bars forming on the sloping beach. For $d_{50}$= 0.32 mm and $m$=1/15, $H_0/L_0$ increases but $h_t/L_0$ decreases.

### 3.5 Dimensionless Bar Volume $V_{bar}/L_0^2$

In Fig. 9, the variation of the bar volumes, which formed after medium sediment diameters had reached the equilibrium position under 1/8, 1/10, and 1/15 coast slopes with the deep-water wave steepness, is presented. It can be seen from the figure that, when the deep-water wave steepness increases for the three slopes, the dimensionless bar volume increases. And erosion in front of the coast increases with the increasing $H_0/L_0$. Watanabe *et al*. (1980) pointed out that winter profiles formed under relatively large wave steepness conditions, showing systematic increase of bar volume with the increasing wave steepness. Results of the present study agree with their view. Furthermore, in the wave conditions that coastal slope and deep-water wave steepness are likewise, more sediment movement to the seaside occurred and the dimensionless bar volume had a higher value.

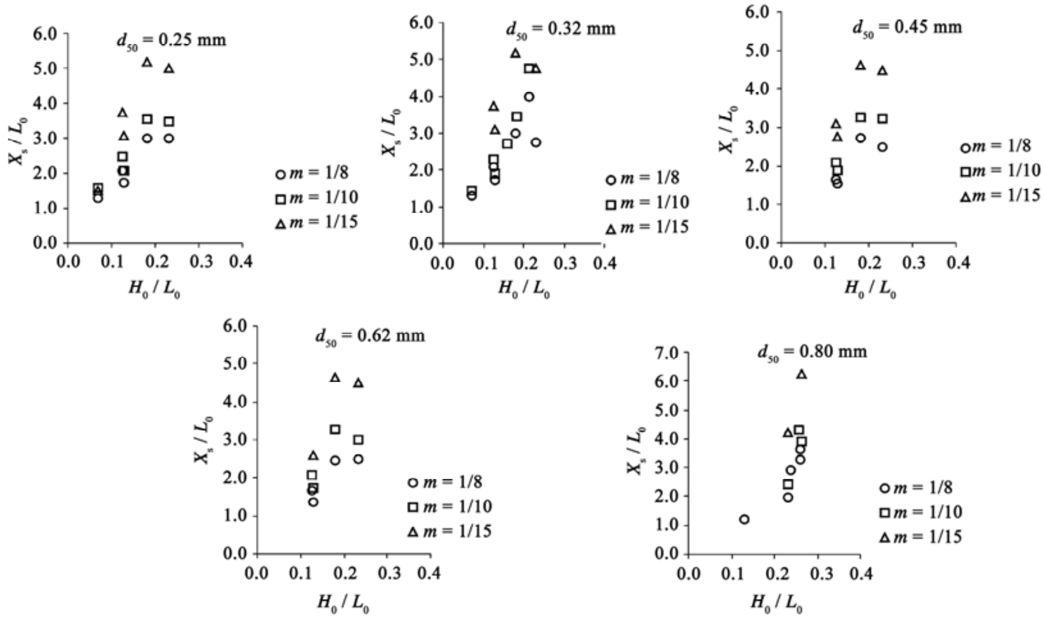


**Fig. 7.** Dimensionless bar ending distances at different base slopes for $d_{50}$=0.25, 0.32, 0.45, 0.62 and 0.80 mm.

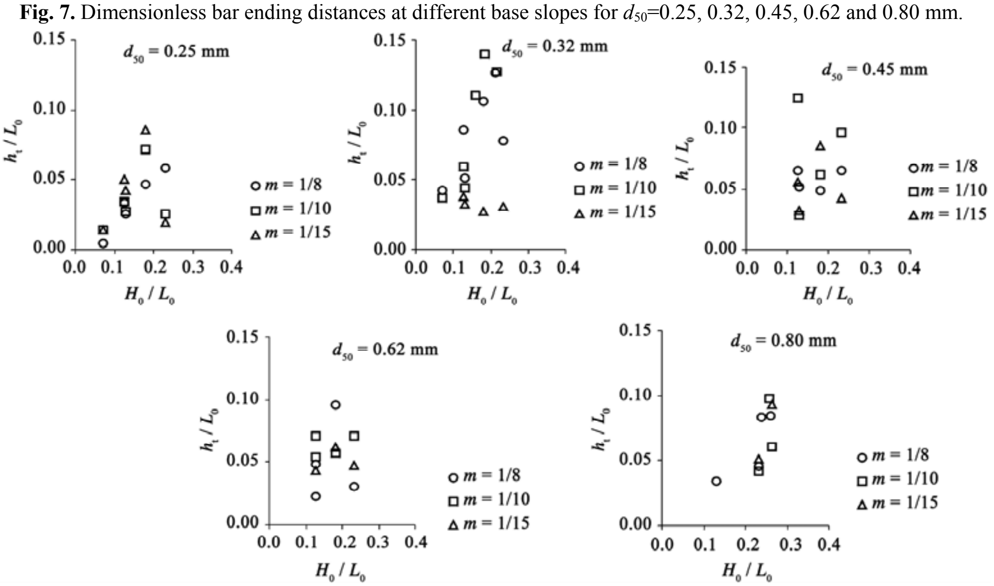


**Fig. 8.** Relative bar crest deepnesses at different base slopes for $d_{50}$=0.25, 0.32, 0.45, 0.62 and 0.80 mm.

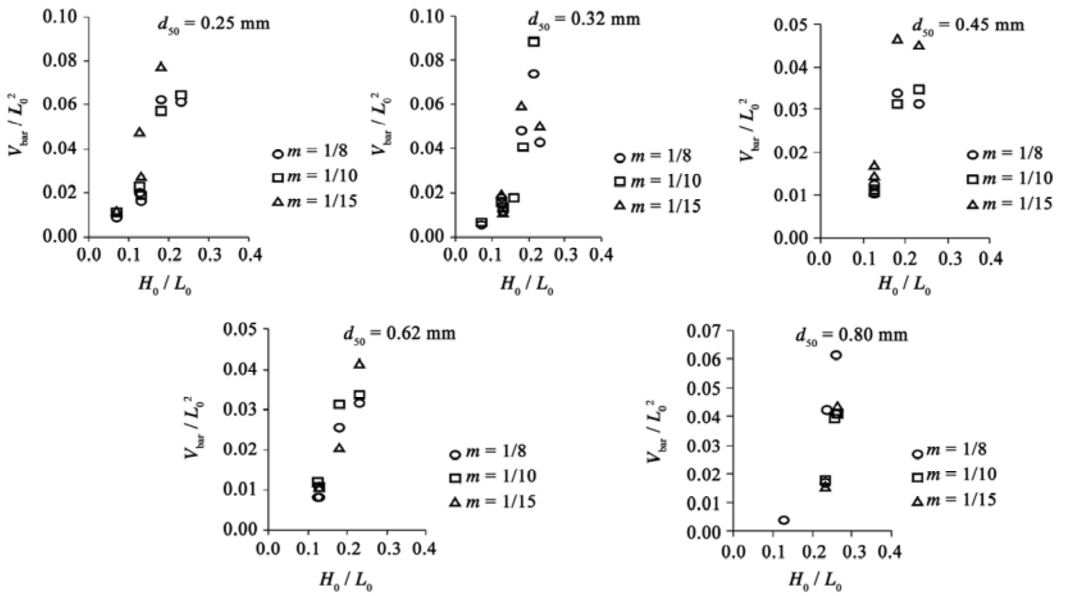


**Fig. 9.** Dimensionless bar volumes at different base slopes for $d_{50}$=0.25, 0.32, 0.45, 0.62 and 0.80 mm.

## 4. Conclusions

In the present study, cross-shore sediment transport on the basements with 1/8, 1/10, and 1/15 coast slopes and the geometrical features of the beach profiles were investigated. In addition, parameters affecting these profiles were investigated. 64 tests were performed in physical model. Experiments were carried out under the storm conditions and five different medium sediment diameters (0.25, 0.32, 0.45, 0.62 and 0.80 mm) were used as the basement material. The results of this study reveal the following conclusions.

Experiments showed that the bar parameters were formed by the breaking waves. And the bar parameters migrated with the increasing wave steepness. When deep-water steepness increased, the net movement to seaside increased. For this reason, the bar volume formed in the seaside increased. With the increasing $H_0/L_0$, the bars moved to widen herewith the vertical distances from the still water level to the bar beginning ($X_b$), crest ($X_t$) and ending ($X_s$) points and the horizontal distances from the coast line to the bar beginning, crest and ending points increase. Additionally, the relative bar crest deepness ($h_t/L_0$) increases with the increasing $H_0/L_0$ for all slopes and sediment diameters except for the relative crest height of the bars which formed on the sloping beach. With larger wave steepness associated with storms, the bar formed farther offshore where the wave steepness was higher and the entire scale of the bars similarly increased.

As the movement of sediments with different medium diameters on same beach slopes was examined, the medium sediment diameter decreased with higher sediment movement to the sea, and material accretion from the front of the coast was observed. As a result, the bar volume ($V_{bar}$) increased. When the sediment with the same medium diameters on different beach slopes was considered, the horizontal distances from the bar beginning ($X_b$) and ending ($X_s$) points to the coast line increased with the decrease of the beach slope. Moreover, the bar volume increased with the decrease of the beach slope.

It should also be emphasized that the experimental data used in this study is much more than those obtained from previous works, hence this can help to obtain better results in terms of reliability and reproducibility.

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