

Experimental investigation of cross-shore sandbar volumes

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Abstract Sandbars are critical to the cross-shore movement of sediment. Prediction of cross-shore sandbar volumes requires knowledge about the functional relationship of sediment transport rate conditions with waves, currents, base slope, sediment property and water depth. In this study, experiments on cross-shore sediment transport were carried out in a laboratory wave channel for initial base slopes of 1/8, 1/10 and 1/15. Using regular waves with different deep-water wave steepness generated by a pedal-type wave generator, bar volumes caused by cross-shore sediment transport are investigated for beach materials with the medium diameter of $d_{50}=0.25, 0.32, 0.45, 0.62$ and 0.80 mm. A non-dimensional equation for sandbar volume was obtained by using linear and non-linear regression methods through the experimental data and was compared with previously developed equations in the literature. The results have shown that the experimental data fitted well to the proposed equation with respect to the previously developed equations.

Keywords Cross-shore sediment transport · Bar volumes · Regression analysis · Experimental study

Introduction

The nearshore environment is very dynamic and complex with wave action, circulation due to currents, movements of sediment on the ocean bottom and the interaction between all of them. Some of the most common morphological features in

the nearshore region are cross-shore sandbars. The nearshore processes are sensitive to the location and volume of a sandbars. As the sandbar moves onshore or as the bar height decreases, the beach becomes more prone to wave attack as well as to storm damage and erosion (Cambazoglu 2009). Sandbar volumes caused by cross-shore sediment transport are very important for design of coastal structures. The generation and evolution of nearshore sandbars have been under investigation for several decades. Field and laboratory studies have been conducted in order to observe bar formation and migration events. Laboratory studies including the effect of undertow showed that it is one of the main mechanisms causing offshore sediment transport and sandbar migration (Stive 1987; Roelvink and Stive 1989). Field measurements support this hypothesis in the nearshore regions of natural beaches (Trowbridge and Young 1989; Gallagher et al. 1998; Elgar et al. 2001). Thornton et al. (1996) investigated the bar/trough generation over a natural beach using an energetics-based sediment transport formula. The model was observed to perform well for the offshore bar migration case but gave inconsistent results for the onshore bar migration cases under mild conditions. Gallagher et al. (1998) used a similar model for modeling sandbar evolution. The model performed well for an offshore bar migration case but could not predict the observed onshore bar migration in the field. The reason for the failure to predict the onshore bar migration cases was predicted to be either not including the fluid accelerations or neglecting the phase lag between the fluid and sediment flow. Sunamura and Horikawa (1974), presented a model to describe cross-shore transport in the surf zone. The model was based on the physical consideration that the net transport attains a state of equilibrium. They proposed beach classification based on displacement of topography from the initial beach slope. Watanabe et al. (1980) developed a three-dimensional numerical model to estimate cross-shore sediment transport. Larson and Kraus (1989), studied erosion and deposition profiles and proposed a formula for bar parameters using experimental data as well as for erosion and deposition criteria. The proposed formula for bar volume is given in

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Table 1. Silvester and Hsu (1997), determined beach profile parameters by non-linear regression techniques using various experimental data obtained from previous works. In this study, equation for bar volume is also given in Table 1. Larson (1996) developed a numerical model to compute cross-shore sediment transport and the beach profile under effects of regular waves and in this modeling, three cases of variation of profiles were studied. Hsu (1998) carried out experimental and theoretical works to determine the geometry of offshore bar. In his experiments, he studied the effects of cross-shore waves traveling with variable angles in a three-dimensional wave basin. Ruessink et al. (2002) determined long time variation of the bar crest location by the method of remote sensing. They determined the beach profile by measuring water depth along with the beach profile and digitized the profile. An experimental study of Günaydın and Kabdaşlı (2003) was carried out by studying the characteristics of coastal erosion using 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. Cambazoglu et al. (2006) studied the effect of velocity skewness on sandbar migration. An energetics-based sediment transport formula is used to isolate the effect of velocity skewness. Kömürçü et al. (2007) carried out laboratory experiments to investigate cross-shore sediment transport. A regression analysis was made to establish the bar parameters which came out of the experiments and equations were constructed for the bar parameters. Proposed equation for bar volume is also given in Table 1. Özölçer (2008) carried out an experimental study in a wave flume using regular waves, and geometric characteristics of erosion profile were determined by the resultant erosion profile. The results have shown that the experimental data fitted well to the proposed equations with respect to the previously developed equations. Demirci and Aköz (2012), carried out an experimental study to investigate the geometrical characteristics of beach profiles under storm conditions and the parameters affecting on-off shore sediment transport for the different beach materials. Experimental results showed that the bar parameters were formed by the breaking waves and the bar parameters migrated with the increasing wave steepness. Demirci and Aköz (2013) investigated bar parameters occurred by cross-shore sediment transport and proposed nondimensional equations for bar parameters.

Table 1 Currently used equations for determination of bar volumes

Authors	Bar volume equation	Eq. no
Larson and Kraus (1989)	$V_{bar}=0.088H_0^{2.26}T_w^{-1.36}T^{0.55}$	(1)
Silvester and Hsu (1997)	$V_{bar}/(H_o/L_o)=160(H_o/L_o)\tan \beta + 11560[(H_o/L_o)\tan \beta]^2$	(2)
Kömürçü et al. (2007)	$V_{bar}/d_{50}^2=0.0627m^{-0.1233}(H_o/L_o)^{-0.8938}(H_o/d_{50})^{2.2587}$	(3)

Sediment transport on beaches is an active research field with many unknowns and uncertainties. Even with the most sophisticated sediment transport models, many empirical relations are used to predict or simulate field or laboratory observations. As a result, it is important for coastal engineers to be able to predict sandbar movements for recreational, environmental, economical purposes as well as storm damage reduction. Researchers have been working hard to fully understand the physics of the nearshore environment. In this study, experiments are carried out on cross-shore sediment transport in order to investigate the affecting bar volumes cross-shore sediment transport for five different beach materials of mean grain diameter d_{50} equal to 0.25, 0.32, 0.45, 0.62 and 0.80 mm.

Methods

Under the storm conditions and experiments were carried out 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 Department of Civil Engineering, Cukurova University, Adana, Turkey (Demirci 2006). A series of laboratory experiments have been performed to investigate cross-shore sandbar volume under different scenarios (64 tests). The sloping beach and wave producer were located in the wave channel. Waves in the channel were produced by using the pedal type wave producer. Wave conditions chosen between maximum and minimum to originate erosion profile as would be in nature in order to examine considered parameters. The characteristic features of the waves produced could be adjusted by the speed of the electrical engine twisting the pedal and the crank length of the engine. Therefore, waves having periods between 0.47 and 0.76 s could be produced. In this work, three different beach slopes were used and 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.

In order to investigate cross-shore sandbar volumes under storm conditions, the experimental conditions were arranged according to the parameter C (it would be greater than 8). C parameter is in Eq. (4) given by Sunamura and Horikawa (1974)

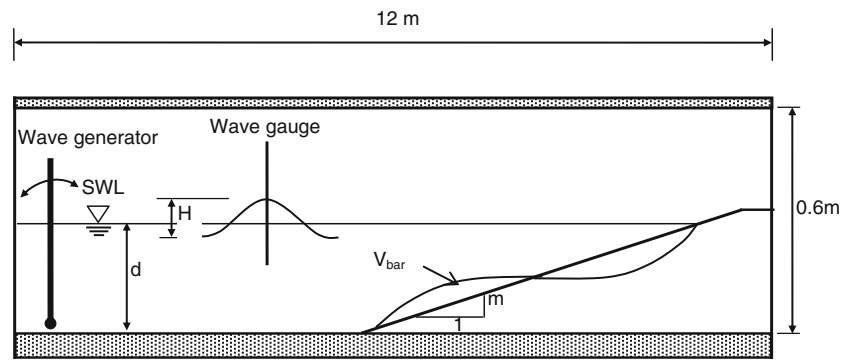
$$C = \frac{H_0}{L_0}(\tan \beta)^{0.27} \left(\frac{d_{50}}{L_0}\right)^{-0.67} \tag{4}$$

where C is profile parameter, H_0 is deep water wave height, L_0 is deep water wave length, $\tan \beta$ is bottom slope, d_{50} is grain size. C is classified as follows.

- $C < 4$ accretion-summer profile
- $4 < C < 8$ equilibrium profile
- $8 < C$ erosion-winter profile

In the current study, cross-shore sandbar volumes under the storm conditions were investigated. Bar volumes which

Fig. 1 Wave channel and experimental parameters



occurs as results of the beach erosion are investigated and given in Fig. 1.

In the figure, V_{bar} is the volume of the erosion and, H is the wave height, d is the water depth, still-water level (SWL).

Analysis method of experimental results

Experimental results were examined using linear and non-linear regression methods to obtain equations defining the bar volumes. Two equation types were determined in regression analyses, power (PF) and linear (LF). These functions are given respectively as follows:

$$y_0 = b_0x_1^{b_1}x_2^{b_2}x_3^{b_3}x_4^{b_4} \dots x_n^{b_n} \tag{5}$$

$$y_o = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + \dots + b_nx_n \tag{6}$$

Experimental results were examined in detail and used to obtain best-fit equations for bar volumes using non-linear regression method. Different regression analyses were applied on V_{bar} .

Dimensional and non-dimensional variables

In most of engineering applications, experimental results are made non-dimensional to minimize measurement errors due to laboratory conditions. In this study, non-dimensional bar parameters were used for estimation process. V_{bar} considered as an independent variable becomes an area (m^3/m) and was obtained by dividing by L_o^2 , H_o^2 and d_{50}^2 . In constructing non-dimensional equations, independent variables, m , H_o/L_o , H_o/d_{50} and H_o/wT were used in various combinations, in final expression w is the sediment fall velocity.

Results and discussion

In this study, bar volumes under storm conditions were investigated and experimental conditions are shown in Table 2. As a result of experimental study, bar volumes for each experiment were calculated. Regression analysis was implemented for bar volumes and non-dimensional equations are presented.

Table 2 Experimental conditions

Total Experiment number	Experiment number	Medium sediment diameter d_{50} (mm)	Beach slope	Wave period T (s)	Wave steepness (H_o/L_o)
5	NO.1~5	0.25	1/8	0.60~0.83	0.070~0.232
5	NO.6~10		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	0.32	1/8	0.52~0.83	0.070~0.214
6	NO.22~27		1/10	0.52~0.83	0.070~0.214
4	NO.28~31	0.45	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		1/10	0.60~0.76	0.130~0.232
4	NO.40~43	0.62	1/15	0.60~0.76	0.130~0.232
4	NO44~47		1/8	0.60~0.76	0.130~0.232
4	NO48~51		1/10	0.60~0.76	0.130~0.232
3	NO52~54	0.80	1/15	0.60~0.76	0.130~0.232
5	No55~59		1/8	0.47~0.76	0.13~0.262
3	NO60~62		1/10	0.47~0.63	0.257~0.263
2	NO63~64		1/15	0.52~0.63	0.232~0.263

Non-dimensional regression analysis was applied using results obtained from 64 experiments for V_{bar} . The determined coefficient for non-dimensional dependent and independent variable alternatives were computed by non-dimensional regression techniques using various function types.

Regression analysis for V_{bar} dimensionless

The dimensionless dependent variables used in regression analysis for bar volume (V_{bar}) are V_{bar}/L_0^2 , and V_{bar}/d_{50}^2 , V_{bar}/H_0^2 , the independent variables are m , H_0/L_0 , and H_0/d_{50} , H_0/wT . Determination coefficients for alternatives of dimensionless dependent and independent variables for V_{bar} are calculated and it is shown in Table 3.

As seen from the Table 3 that, the maximum value of determination coefficient for linear function occurs in the case of V_{bar}/L_0^2 as dependent variable and m , H_0/L_0 , H_0/d_{50} , H_0/wT as independent variables. In the multi-hyperbolic function, the maximum value of determination coefficient is reached in the case of V_{bar}/d_{50}^2 as dependent variables and m , H_0/L_0 , and H_0/d_{50} , H_0/wT as dependent variables in the linear functions. Changing of R^2 with the reduction in the number of independent variables is also examined and presented in Table. 4.

When Table 4 is examined, it is seen that value of determination coefficient decreases with decreasing number of independent variables. Moreover, if V_{bar}/L_0^2 is considered as the dependent variable in linear function and V_{bar}/d_{50}^2 is considered as dependent variable in the hyperbolic function r^2 takes the maximum value. In addition, in the case of absence of H_0/d_{50} and H_0/L_0 for the linear function the maximum reduction in value of determination coefficient is seen. The bottom slope is a variable which has minimal impact. For multi hyperbolic function, absence of H_0/d_{50} variable causes maximum decreasing in the determination coefficient.

Table 3 Determination coefficients for dimensionless alternatives variables for V_{bar}

Status of the dimensionless variables		For multi-linear function R^2	For multi-hyperbolic function R^2
Dependent variable	Independent variable		
V_{bar}/L_0^2	$m, H_0/L_0, H_0/wT, H_0/d_{50}$	0.784	0.816
	$m, H_0/L_0, H_0/d_{50}$	0.608	0.578
	$m, H_0/d_{50}, H_0/wT$	0.438	0.428
V_{bar}/H_0^2	$m, H_0/L_0, H_0/wT, H_0/d_{50}$	0.675	0.748
	$m, H_0/L_0, H_0/d_{50}$	0.388	0.759
	$m, H_0/d_{50}, H_0/wT$	0.503	0.426
V_{bar}/d_{50}^2	$m, H_0/L_0, H_0/wT, H_0/d_{50}$	0.733	0.969
	$m, H_0/L_0, H_0/d_{50}$	0.643	0.682
	$m, H_0/d_{50}, H_0/wT$	0.664	0.682

Table 4 Reduction rates in determination coefficient according to dimensionless independent variables for V_{bar}

Multi-linear function	Multi-hyperbolic function		Reduction rates in R^2 (%)	R^2	Reduction rates in R^2 (%)		
	Status of dimensionless variable						
	Dependent	Independent					
V_{bar}/L_0^2	Presence	$m, H_0/L_0, H_0/wT, H_0/d_{50}$	$m, H_0/L_0, H_0/wT, H_0/d_{50}$	0.784	0.969		
		$m, H_0/L_0, H_0/wT$	$m, H_0/L_0, H_0/wT, H_0/d_{50}$	0.457	0.126		
		$m, H_0/L_0, H_0/d_{50}$	$m, H_0/L_0, H_0/wT$	0.608	0.897		
	Absence	H_0/d_{50}	$m, H_0/L_0, H_0/wT, H_0/d_{50}$	0.438	0.915		
		H_0/wT	$m, H_0/L_0, H_0/d_{50}$	0.757	0.941		
		m	$m, H_0/L_0, H_0/wT, H_0/d_{50}$	0.430	0.090		
	V_{bar}/d_{50}^2	Presence	$m, H_0/wT, H_0/d_{50}$	$m, H_0/wT, H_0/d_{50}$	0.430	0.090	
			$H_0/L_0, H_0/d_{50}$	$m, H_0/wT, H_0/d_{50}$	0.327	0.067	
			$m, H_0/wT$	$m, H_0/wT, H_0/d_{50}$	0.432	0.102	
		Absence	$H_0/L_0, H_0/wT$	$m, H_0/wT, H_0/d_{50}$	0.600	0.892	
			$m, H_0/d_{50}$	$m, H_0/wT, H_0/d_{50}$	0.018	0.032	
			m	$m, H_0/wT, H_0/d_{50}$	0.411	0.056	
		V_{bar}/H_0^2	Presence	$m, H_0/L_0, H_0/wT, H_0/d_{50}$	$m, H_0/L_0, H_0/wT, H_0/d_{50}$	0.315	0.031
				$m, H_0/wT, H_0/d_{50}$	$m, H_0/L_0, H_0/wT, H_0/d_{50}$	0.168	0.873
				$m, H_0/d_{50}, H_0/wT$	$m, H_0/L_0, H_0/wT, H_0/d_{50}$	0.478	0.968
Absence	H_0/L_0	$m, H_0/wT, H_0/d_{50}$	0.478	0.968			
	H_0/wT	$m, H_0/wT, H_0/d_{50}$	0.315	0.031			
	H_0/d_{50}	$m, H_0/wT, H_0/d_{50}$	0.168	0.873			

Table 5 Regression coefficients obtained from dimensionless regression analysis for V_{bar}

Multi linear function		Multi hyperbolic function	
$\frac{V_{bar}}{L_0^2} = b_0 + b_1 m + b_2 \frac{H_0}{L_0} + b_3 \frac{H_0}{wT} + b_4 \frac{H_0}{d_{50}}$		$\frac{V_{bar}}{d_{50}^2} = b_0 m^{b_1} \left(\frac{H_0}{L_0}\right)^{b_2} \left(\frac{H_0}{wT}\right)^{b_3} \left(\frac{H_0}{d_{50}}\right)^{b_4}$	
$R^2=0.787$		$R^2=0.969$	
Coefficients	Values	Coefficients	Values
b_0	0.00274	b_0	0.268
b_1	-0.122	b_1	-0.430
b_2	0.813	b_2	3.63
b_3	-0.144	b_3	2.2587
b_4	0.000127	b_4	3.12

The base slope (m) and deep-water wave steepness (H_0/L_0) are two parameters which have minimal impact. In the case of the maximum value of the coefficient of determination, the regression coefficients are presented in Table 5 for multi linear and hyperbolic functions.

According to the values in Table 5, for bar volume (V_{bar}), equation obtained from the dimensionless hyperbolic functions is presented below

$$\frac{V_{bar}}{d_{50}^2} = 0.268m^{-0.430} \left(\frac{H_0}{L_0}\right)^{3.63} \left(\frac{H_0}{wT}\right)^{-5.73} \left(\frac{H_0}{d_{50}}\right)^{3.12} \quad (7)$$

Equation 7, shows function obtained from results of multi-linear regression. In this study, Eq. 7 is proposed as equation of dimensionless of bar volume.

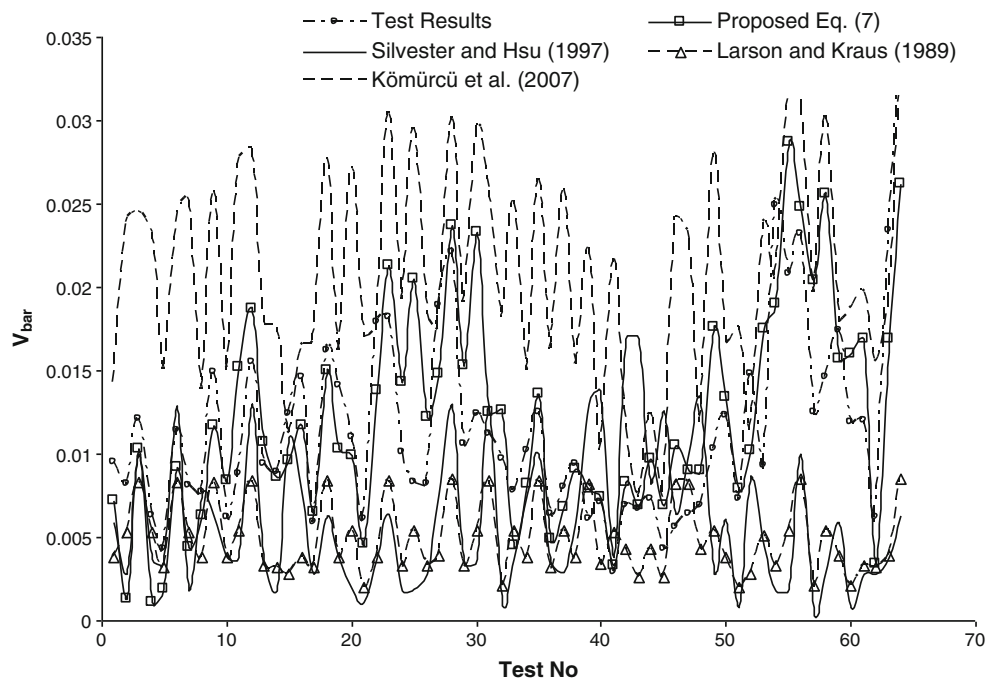
A comparison was made for V_{bar} with the expressions proposed by other researchers. Comparisons of the experimental results, the best equation (Eq. (7)) and previously developed equations (Eqs. (1), (2) and (3)) by Silvester and Hsu (1997), Larson and Kraus (1989) and K m rc  et al. (2007) are shown in Fig. 2.

When Fig. 2 is examined, a good fit is observed between obtained values from equations proposed by Silvester and Hsu (1997) and current Eq. 7 and experimental values. Considering the equations and the results given in Table 1, the best results are obtained from the non-dimensional Eq. 7. On the other hand, discussing previously developed equations, Silvester and Hsu’s equation (Eq. 2) produces better results than Larson and Kraus’s equation (Eq. 1) and K m rc  et al. (2007) (Eq. 3). As seen in Fig. 2, the proposed equation (Eq. 7) gives best results for given experimental data. Also results of Silvester and Hsu’s equation (Eq. 2) are close to experimental results with respect to Larson and Kraus’s equation (Eq. 1) and both equations exhibit similar trends with experimental results.

Conclusions

Cross shore sediment transport on the sea beds with 1/8, 1/10, 1/15 slopes and sandbar volumes were investigated. In the experiments carried out under storm conditions, the sand

Fig. 2 Comparison of the test results and equations for V_{bar}



material having 5 different mean sediment diameters were used as the bed material. The mean sediment diameter of the sands used in the experiments was equal to 0.25, 0.32, 0.45, 0.62 and 0.80 mm. The results of this study revealed the following:

According to the regression analysis results, proposed equation for V_{bar} is (7). The most effective parameter for erosion volume is deep sea wave height (H_0/L_0) (44.13 %), but the effect of beach slope (m) (3.44 %) is insignificant. A good fit is observed between obtained values from equations proposed by Silvester and Hsu (1997). It should also be emphasized that the number of experimental datasets used in this study is greater than those obtained from previous works, hence this helps obtain better results in terms of reliability and reproducibility.

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