Journal of Korean Society of
Coastal and Ocean Engineers
Vol. 11, No. 2, pp. 75~86, June 1999

Experimental Study of Beach Nourishment Fronting Seawalls
호안 전면에서의 양빈계획: 수리실험연구

Chul-Hee Yoo* and Robert G. Dean**
유철희* · 로버트 딘**

Abstract ☐ The behavior of beach nourishment fronting a seawall is investigated and compared to that on shorelines with compatible sand. Six different conditions of nourishment characteristics are studied and repeatability tests are conducted for each case. Experimental conditions include both sandy and seawalled shorelines and normal and oblique wave incidence. The effects of sediment size are also studied for a seawalled coast. Transport rates near the ends of the project in which all of the nourished sand is submerged are quantified for normal and oblique wave incidence for a seawalled shoreline. Two different sets of transport relationships are suggested and tested. Although there are some variations, comparisons between the predicted and the measured transport rate for the all cases tested show reasonably good agreement.

Keywords : beach nourishment, seawalls, longshore transport, beach evolution, shoreline stabilization

要 旨 : 호안전면에서의 양빈의 거동이 연구, 조사되며 모래로 이루어진 해변에서의 양빈과 비교하였다. 조건이 서로 다른 6개의 양빈 특성이 연구되며 각 조건에 대하여 반복실험이 수행된다. 실험조건에는 모래해변, 호안을 가진 해변, 해안에 직각인 파랑, 그리고 해안에 비스듬한 파랑을 포함한다. 호안을 가진 해안인 경우, 모래입경의 영향이 연구에 포함된다. 또한 호안을 가진 해안에서 모래가 완전히 물에 잠기는 양빈구역의 양단에서 표사이동율을 각각 해변에 직각인 파랑, 해변과 일정한 각도를 이루는 파랑에 대하여 정량화 하였다. 각기 다른 두 개의 표사이동 관계식이 제시되고 검사된다. 비록 약간의 차이가 있더라도 모델에 의한 표사이동율은 실측한 표사이동율과 비교적 잘 일치함을 보여준다.

핵심용어 : 양빈, 호안, 연안류에 의한 토사이동, 해변변화과정, 해안선 안정

1. INTRODUCTION

Since the first beach nourishment project at Coney Island of the States in 1992, more than 70 beach nourishment projects have been constructed to protect the nation's eroding beaches (Davison *et al.*, 1992). Methods have been proposed by a number of investigators to predict their performance by analytical, numerical, and empirical methods (Larson *et al.*, 1987; Hanson and Kraus, 1989; Verhagen, 1992). Numerical approaches can treat more complicated problems, such as the contribution of background erosion, the effect of shore-perpendicular structures designed to extend project life, and the effect of fill material of different character than the native (Dean and Yoo, 1992).

In some cases, earlier erosion control efforts have utilized armoring such as seawalls and there may be little sand remaining in the nearshore. Due in part to the cost of beach nourishment, it is essential to be able to predict project performance under the particular conditions at the project site. For projects constructed on a long unperturbed shoreline of compatible sand, it can be shown that the centroid of the planform anomaly remains relatively unchanged under the action of both normal and oblique wave attack. Also, under the action of constant wave energy, the rate of increase of planform variance is constant and relatively insensitive to wave direction.

*주식회사 세광종합기술단 (Se-Kwang Engineering Consultants, Co. Ltd., 179-44 Dongkyo-Dong, Mapo-Ku, Seoul 121-200, Korea)
**플로리다대학교 (University of Florida, Gainesville, FL 32611, USA)

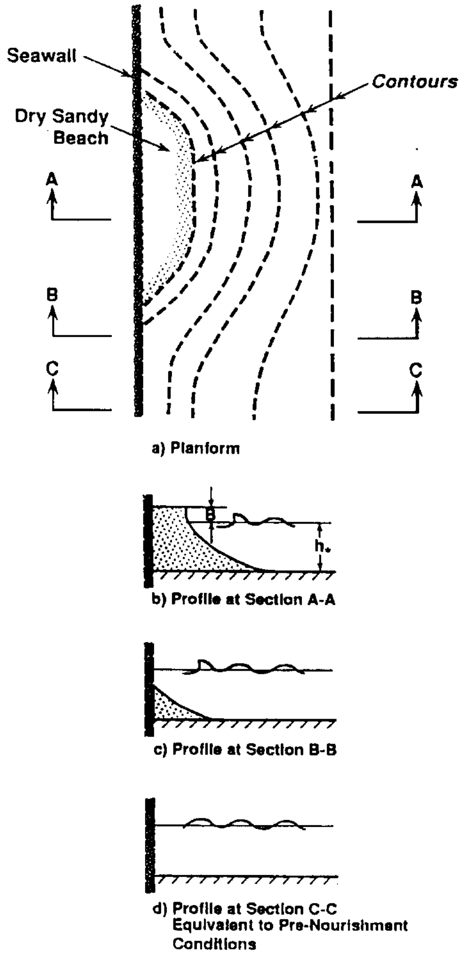

Fig. 1. Definition sketch for beach nourishment in presence of seawall (Dean and Yoo, 1994).

Dean and Yoo (1994) investigated the behavior of a beach nourishment project fronting a seawall (see Fig. 1) and found that when acted upon by oblique waves, the centroid of the planform anomaly migrated downdrift. They also found that the spreading rate of the planform anomaly was different from that on a long beach composed of compatible sand. It was shown rather qualitatively that the transport near the ends of the project, where all the nourishment sand is submerged, can affect results significantly.

In this paper, the actual transport near the ends of the project will be explored through a series of experiments and empirical transport reduction relationship near the ends of the project will be examined.

2. BACKGROUND

The bases for predicting the effects of longshore spreading are the equations of longshore transport and continuity which may be expressed in the "one--line form" as given by

$$Q=\frac{KH_b^{2.5}\sqrt{g/k}}{8(s-1)(1-p)}\sin(\beta_s-\alpha_b)\cos(\beta_s-\alpha_b) \quad (1)$$

and

$$\frac{\partial v}{\partial t}+\frac{\partial Q}{\partial x}=0 \quad (2)$$

in which Q = the transport rate, v = sand volume per unit beach length, s = the ratio of mass density of sediment to water, g = gravitational acceleration, p = in-place sediment porosity, H = wave height, κ = a wave breaking criterion, β_s = azimuth of the outward shoreline normal, α = azimuth from which the wave originates, K = proportional constant, and the subscript "b" denotes that the subscripted variable is to be evaluated at the breaker position.

Under the most idealized considerations for which the shoreline displacement is given by $y(x, y)$, the velocity of the centroid, U_c, of the planform anomaly was shown to be (Dean and Yoo, 1994).

$$U_c = \frac{\partial x_c}{\partial t} = \frac{1}{V}\int_{-\infty}^{\infty} Q\,dx \approx \frac{Q_o l_e}{V} \quad (3)$$

in which x_c is the centroid of the planform anomaly, V is the total volume of sand placed, Q is the sand transport rate that will vary over the active length, Q_o is the ambient potential transport, and l_e is the effective length of the project which increases with time.

Similarly, the time rate of change of the planform variance was shown to be

$$\frac{\partial \sigma^2}{\partial t} = \frac{2}{V}\int_{-\infty}^{\infty} x'Q\,dx' \quad (4)$$

where $x' = x\text{-}x_c$. The linearized transport equation is given by

$$Q = Q_o + Q' = Q_o - (h_* + B)G\frac{\partial y}{\partial x} \quad (5)$$

in which Q_o is the ambient potential transport on an unperturbed shoreline, Q' is the transport associated with the nourishment project, and G is referred as the "longshore diffusivity" (Dean and Yoo, 1992). Substituting Eq. (5) into Eq. (4) gives

$$\frac{\partial \sigma^2}{\partial t} = 2G \tag{6}$$

i.e., the same as the case of nourishment on a beach composed of compatible sand.

However, in the case of a seawalled beach, the transport as given by Eq. (1) will not be valid near the ends of the project where all of the sand to be nourished is underwater and at the very ends is submerged to a depth, h_*, considered here to be the depth to the base level. In those locations, it is assumed for simplicity that the actual transport, Q_A, is related to the calculated transport, Q, by

$$Q_A = \begin{cases} Q\left(\frac{v}{v_T}\right)^n, & \frac{v}{v_T} < 1 \\ Q, & \frac{v}{v_T} \geq 1 \end{cases} \tag{7}$$

and Q_A is used in the continuity equation. In Eq. (7), v_T is defined as the threshold volume required to establish a profile over the entire depth and can be shown to be

$$v_T = 0.4\frac{h_*^{2.5}}{A^{1.5}}$$

for the case of an equilibrium profile given by $h=Ay^{2/3}$ (Bruun, 1954; Dean, 1977, 1991) and a horizontal bottom. For larger values of n, there is less transport near the ends. Also, in determining the effective shoreline orientation, β_s, for submerged profiles the effective shoreline displacement, y_e, is defined as

$$y_e = \frac{v - v_T}{h_* + B} \tag{9}$$

which is seen to be negative for $v < v_T$.

Although the transport reduction factor defined in Eq. (7) may be the most appropriate condition at the ends of the project, other boundary conditions may be possible. Another possible set of equations similar to Eqs. (7) and (9) can be expressed in terms of the ratio of the vertical active dimension rather than the ratio of the volume.

$$Q'_A = Q\left(\frac{h_* - h_w}{h_* + B}\right)^n \tag{10}$$

and

$$y_e = -\left(\frac{h_w}{A}\right)^{1.5} \tag{11}$$

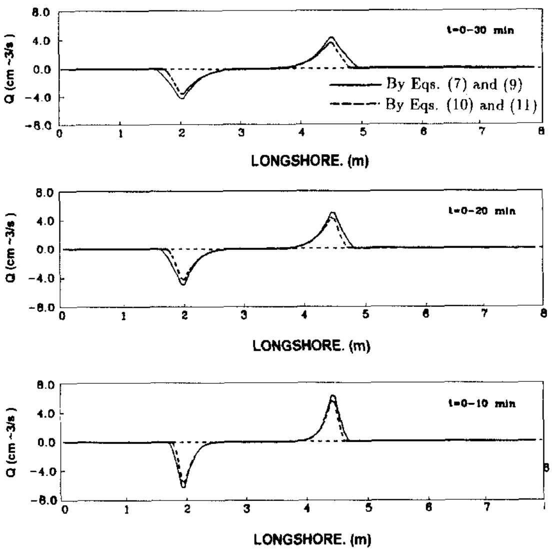

Fig. 2. Comparison of calculated transport distributions for an initially rectangular planform and normal wave incidence based on two different relationships.

in which h_w is the water depth at the seawall. For the case of an equilibrium beach profile and a horizon- tal bottom, the water depth at the seawall, h_w, can be shown to be

$$v = v_T - \frac{h_w^{1.5}}{A^{1.5}}(h_* - 0.6h_w) \tag{12}$$

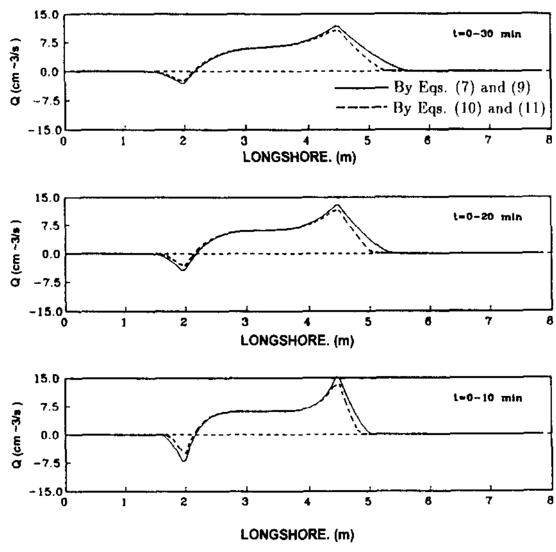

Fig. 3. Comparison of calculated transport distributions for an initially rectangular planform and oblique wave incidence based on two different relation ships.

in which v is the volume density at any time and v_T is the threshold volume density. This is a transcendental equation and must be solved by iteration. Note that this equation has two roots in general but only one root has physical significance.

For an idealized rectangular initial planform, the comparison between two different transport reduction factors is presented in Figs. 2 and 3 for normal and oblique wave incidence, respectively at times 10, 20, and 30 minutes. It can be seen that the differences between the two transport relationships are quite small. Thus, the first transport reduction factor at the ends of the project will be used for the calculations and analysis.

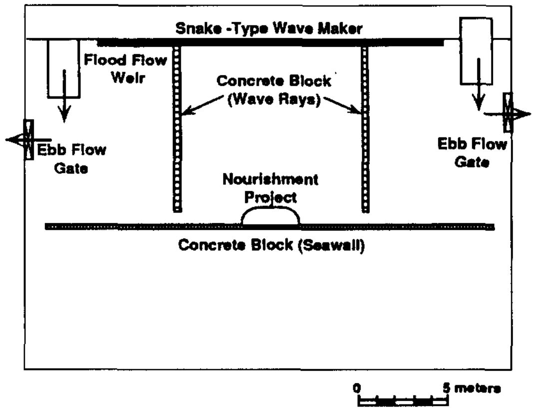

Fig. 4. Wave basin arrangement. wave rays shown for normal wave incidence.

3. EXPERIMENTAL STUDY

A series of experiments was conducted to investigate the characteristics of beach nourishment projects in the presence of a seawall. Six different conditions of nourishment characteristics were studied and a repeatability test (the "*b*" tests in Table 1) was conducted for each case. Experimental conditions included both sandy and seawalled shorelines and normal and oblique wave incidence. The effects of sediment size were also investigated for a seawalled coast.

Fig. 4 presents the wave basin arrangement. The wave basin characteristics are 20 m in width, 15 m in length with 88 paddles of a "snake" type wavemaker. The wavemaker is capable of generating periodic waves and wave height and wave direction can be varied by changing the paddle stroke and phasing the adjacent paddles, respectively. The water depth at the wavemaker was 55 cm. Two different sediment sizes (0.2 mm and 0.5 mm in median size) were used in this experiment. See Table 1 for the detailed experimental conditions.

The tests commenced with an initial nourished planform of approximately 2.4 m length, 0.2 m width at mean water level (MWL) and 0.2 m water depth and constructed of reasonably uniform size sand. The ends of the planforms were tapered back to the seawall. Prior to establishing the initial planform and profiles, the sand was completely submerged to minimize possible additional compaction during testing. Once the initial plan-

Table 1. Experimental conditions.

Experiment	Shoreline	Sediment Size	Wave Obliquity*	Wave Height	Figure
1.a	Seawall	0.2 mm	0°	3.5 cm	5
1.b		0.2 mm	0°	3.5 cm	-
2.a	Seawall	0.2 mm	30°	3.5 cm	6
2.b		0.2 mm	30°	3.5 cm	-
3.a	Seawall	0.5 mm	0°	3.5 cm	7
3.b		0.5 mm	0°	3.5 cm	-
4.a	Seawall	0.5 mm	30°	3.5 cm	8
4.b		0.5 mm	30°	3.5 cm	-
5.a	Sand	0.2 mm	0°	3.5 cm	9
5.b		0.2 mm	0°	3.5 cm	-
6.a	Sand	0.2 mm	30°	3.5 cm	10
6.b		0.2 mm	30°	3.5 cm	-

*Referenced to wavemaker location where depth = 55 cm.

form and profiles were constructed and documented, the desired wave conditions were established. In addition, wave guides composed of concrete blocks were established to mimic incoming wave rays, thereby minimizing "basin effects".

For each test, 40 profiles were monitored at equal spacings of 0.2 m. The profiles were measured by a point gage lowered from a frame with an estimated accuracy of 1.0 mm. Each run was monitored for 105 minutes for the seawalled coast and 150 minutes for the sand coast, respectively. During each run, the profiles were measured 4 times including the initial and final times. Water depths were maintained constant for all tests. The desired wave conditions were obtained by adjusting the wavemaker stroke and phase. From time to time, the wave height was measured at various locations to ensure that wave heights were relatively uniform in the wave basin.

In the following description of the model tests, due to space limitations, the graphical results to planform evolution will be presented only for Experiments 1, 2, 4 and 6.

3.1 Experiment 1

For simplicity, only one experimental result will be presented here for each case. The overall results for the repeatability test will be presented later in tabular form. Fig. 5 presents the contours defined by linear interpolation between the adjacent profiles for normal wave incidence. The figure includes results for the initial planform and 15, 45 and 105 minutes. The general characteristics of each planform relative to the initial are that for the first 45 minutes both the longshore spreading and offshore transport are important but at later times most of the sand is transported seaward and only small amounts of longshore transport occur. Although the planform spreading patterns are not perfectly symmetric, inspection of each planform indicates that the centroid of the planforms remained nearly fixed. Note that during the period between 45 minutes and 105 minutes most of the sand becomes submerged with only a minor amount remaining above mean water level. Although not presented here for the repeatability test for this case, except for minor differences, the planform evolutions from both tests are quite similar.

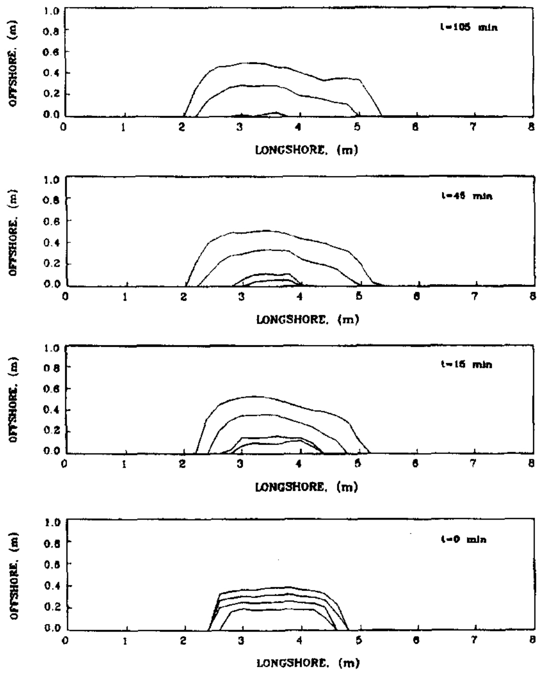

Fig. 5. Experiment 1. Contours showing planform evolution for a seawalled shoreline. normal wave incidence. contours shown include +8 cm, +4 cm, 0, and -4 cm relatived to still water level. sediment size = 0.2 mm.

3.2 Experiment 2

With the exception of wave obliquity, conditions of this experiment are identical to those of Experiment 1. Again, two experiments with the same wave conditions were conducted. The planform evolution for one of the two tests is presented in Fig. 6 for times of 0, 15, 45, and 105 minutes. Some difficulties were experienced in establishing uniform wave conditions along the nourishment planform. This may be the cause of some of the irregular planform features which are particularly evident at 105 minutes. In spite of this irregularity, it is clear that the overall planform translated downdrift with time. Although the initial planform was very similar to that of Experiment 1, most of the sand was transported downdrift due to the wave obiliquity and the offshore transport of sand is relatively small. It is interesting to note that the slope near the updrift end is somewhat greater that near the downdrift end.

3.3 Experiment 3

The objective of this experiment is to investigate the

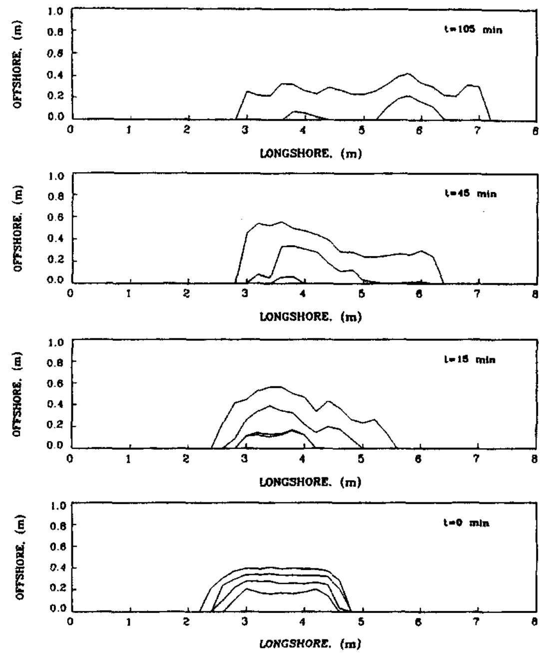

Fig. 6. Experiment 2. Contours showing planform evolution for a seawalled shoreline. oblique wave incidence (30°). contours shown include +8 cm, +4 cm, 0, and -4 cm relative of still water level. sediment size = 0.2 mm.

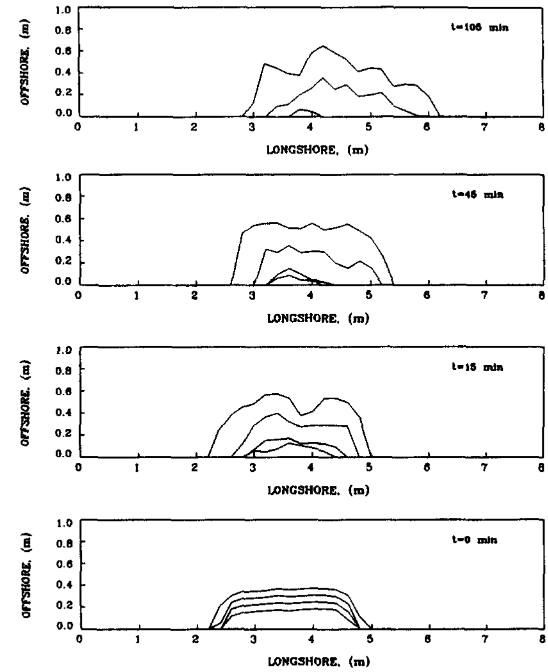

Fig. 7. Experiment 4. Contours showing planform evolution for a seawalled shoreline. oblique wave incidence (30°). contours shown include +8 cm, +4 cm, 0, and -4 cm relative of still water level. sediment size = 0.5 mm.

effect of sediment size for nourishment along a seawalled coast. Wave conditions were the same as Experiment 1 with the 0.2 mm sediment replaced by coarser material (0.5 mm). The general characteristics of planform evolution for the repeatability test were in fairly good agreement with the initial test. The planform shapes of the nourishment were similar to those of Experiment 1 where finer sediment was used; however, somewhat smaller changes due to less transport of the coarser sand was evident.

3.4 Experiment 4

This experiment is the counterpart of Experiment 2 but coarser sediment was used. This test was also conducted with the same wave conditions as Experiment 3 but with oblique waves. Fig. 7 presents the planform evolutions at 0, 15, 45, and 105 minutes. Inspection of Fig. 7 shows that the overall planform tends to migrate downdrift with time but at a slower speed than Experiment 2 in which finer sediment was used.

There are some irregularities in the planform features, especially at 105 minutes. This may be due to the nonuniform wave height distribution along the planform. Nevertheless the general characteristics of the planform evolution are quite different than for the normal wave incidence case and the spreading rate is reduced compared to Experiment 2 with the finer grain size. Note that the +8 cm contour has completely disappeared and only a minor part of the 0 cm contour is present at 105 minutes. Although a clear trend is not evident, it can be seen that the two tests yield quite similar behavior in terms of migrational features of the planforms, the major difference being the slower evolution of the nourishment with coarser sand.

3.5 Experiment 5

This experiment was conducted for the purpose of investigating the nourishment planform evolution on a compatible sandy coast under normally incident waves. The sandy beach was formed with the same material as the nourishment sand to ensure hydrodynamic compatibility of the native and nourishment materials. To commence with a near natural beach slope, the initial beach was allowed to equilibrate under wave action for approximately one-half hour before nourishment placement. Wave conditions were the same as in the previous four tests in order to provide comparable results.

The behavior of the planform evolution was found to be quite different from than for the seawalled beach case. Nourishment material was spread out effectively due to the gradient of longshore sediment transport and the width of the dry beach decreased with time. Note that the highest contour remained intact for the full test period.

3.6 Experiment 6

With the exception of oblique waves, conditions of this experiment are the same as for Experiment 5. Fig. 8 presents the planform evolution for times of 0, 30, 90 and 150 minutes. As for a seawalled beach with wave obliquity, some difficulties were experienced in establishing uniform wave height along the nourishment planform, which may be the cause of some of the irregular planform features. Another difficulty was encountered in maintaining a constant sediment supply from the updrift beach. Under oblique wave action, the updrift sediment supply should be maintained as near as possible to the potential transport rate in order to not disturb the original beach. Sand collected from the downdrift side was supplied manually to the updrift side in order to maintain approximately appropriate conditions.

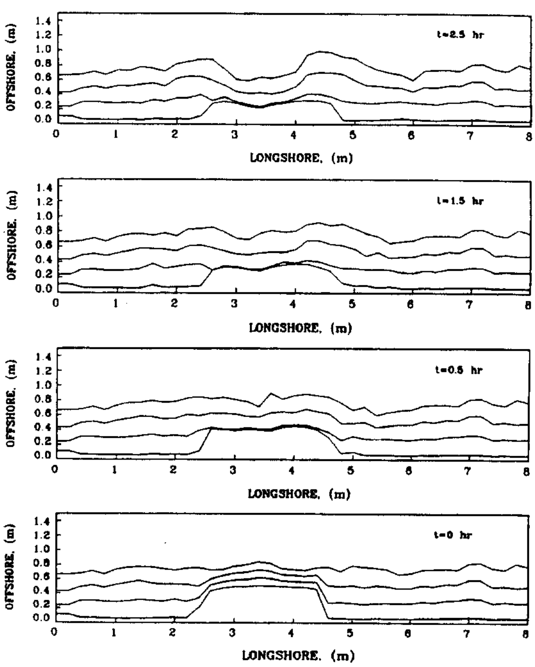

Fig. 8. Experiment 6. Contours showing planform evolution for a sandy shoreline. oblique wave incidence (30°). contours shown include +9 cm, +5 cm, +1 cm, and -3 cm relative of still water level. sediment size = 0.2 mm.

There are some interesting features in planform evolu tion shown in Fig. 8. The most significant result relative to the seawalled coast case is that the planform, as expected, remained nearly fixed without migration even under oblique wave attack. Thus the planform evolution in this experiment may exhibit some similarity with that of Experiment 5 where waves propagate normal to the shoreline.

4. ANALYSIS AND DISCUSSION

Data described in the previous section are analyzed and compared to the analytical model results. The primary objective of the analysis is, through correlation of calculated and measured project evolution, or equivalently average transport rate, to develop the relationship between the transport coefficient, K, and the transport reduction characteristics at the ends of the project defined as Eqs. (7) and (10). The relative importance between the exponent, n, and the longshore transport coefficient, K, can be calculated by defining the error surface

$$\varepsilon^2(K, n) = \frac{\Sigma(Q_m - Q_p)^2}{\Sigma(Q_m)} \tag{13}$$

in which Q_m and Q_p are the measured and predicted average transport rate, respectively, Q_m is determined from the measured volume change utilizing the continuity equation given by Eq. (2), and the summation in Eq. (13) encompasses results for all three intersurvey periods.

For the volume change calculations, the measured volumes at each time are not necessarily conserved although residuals are quite small (less than 3%). These residuals were distributed evenly over the monitored domain to adjust the total measured volume to always be the same as the calculations.

In the following, detailed graphical results will only be presented for Experiments 1, 2, 4 and 6.

4.1 Experiment 1

Again only one result will be presented here for the corresponding planform evolutions. This experiment is for the normal wave incidence and finer grain size. As shown in Fig. 5, the planform evolution remained almost symmetric and spreading rate is relatively small. Although the planform evolutions at each time are not perfectly symmetric, the even component of the volume per unit length can be extracted and the corresponding average transport rate can be compared to the model result which is symmetric.

Fig. 9 shows the calculated error surface. There is a minimum error value near $K=0.15$ and $n=3.0$ for the first test. Although not presented here, there are no closed contours for the repeatability test such that the exponent, n could be greater than 4 such that there is very small transport when the volume is less than the threshold volume. It can be shown that the data are well defined for the longshore transport coefficient, K, but poorly conditioned for determination of the exponent, n, for both cases. Nevertheless, it may be argued that an appropriate value of the longshore transport coefficient, K, and the exponent, n, would be near 0.15 and 3.0, respectively for this particular case. It is noted that the errors increase rapidly with increase in the longshore transport coefficient.

Fig. 10 presents the measured and predicted average transport rates associated with the best-fit K, n values described above. The model overpredicts slightly but the difference is relatively small. Note that the distribution of the longshore transport is antisymmetric due to even component of the initial planform.

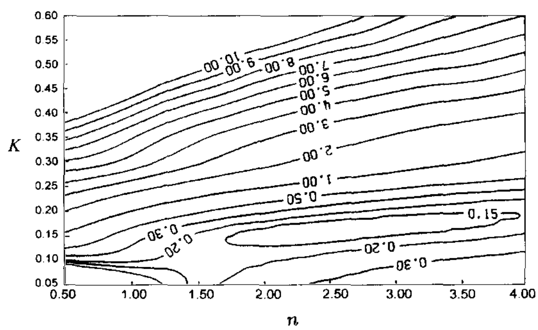

Fig. 9. Error surface for normal wave incidence for experiment 1, sand size = 0.2 mm.

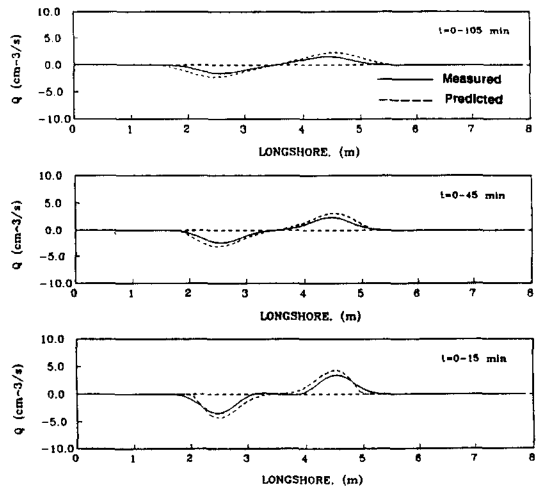

Fig. 10. Comparison of the measured and predicted Transport rates for normal wave incidence for experiment 1. parameters for calculated results: $K=0.15$, n = 3.0.

4.2 Experiment 2

The purpose of this experiment was to investigate the planform evolution under the action of oblique waves using the same sand grain size as Experiment 1. As shown in Fig. 6, the planform evolutions were remarkably different from Experiment 1 with normal wave propagation to the shoreline. The most notable differences are the planform migration and different spreading rates with time.

Although not shown here, the error surfaces for the first experiment had a minimum near $K=0.32$ and $n=1.6$ while there are several local contour minima were evident for the repeatability test.

As in Experiment 1, the minima were well defined for the longshore transport coefficient, K, but poorly conditioned for determination of the exponent, n. The appropriate values of the longshore transport coefficient, K, and the exponent, n, are approximately 0.3 and 2.0, respectively for this experiment. Compared to the normal wave incidence case, it is somewhat surprising that the transport coefficient, K increases but the exponent, n decreases although the same sediment was used. This may be interpreted, at least in part, as a result of the strong influence of transport near the project ends.

Fig. 11 presents the measured and predicted average

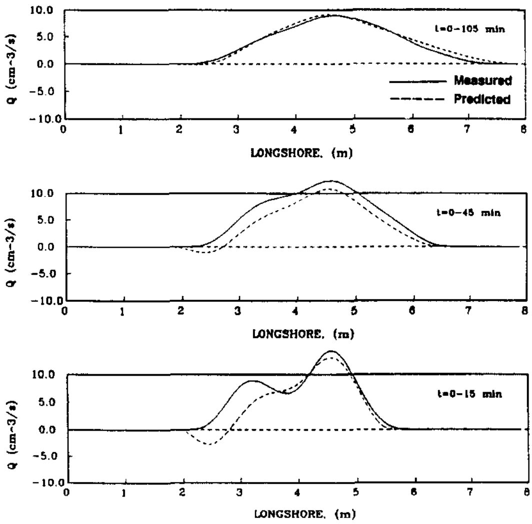

Fig. 11. Comparison of the measured and predicted Transport rates for oblique wave incidence for experiment 2. parameters for calculated results: $K = 0.32$, n = 1.5.

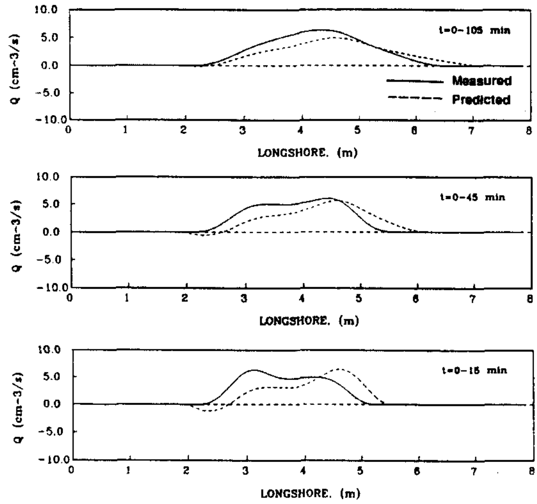

Fig. 12. Comparison of the measured and predicted Transport rates for oblique wave incidence for experiment 4. parameters for calculated results: $K = 0.14$, n = 1.5.

transport rates associated with the minimum error K and n values. It can be seen that at earlier times the predicted transport rate is slightly less than the measured but at later times both values yield good agreement. Note that at times 0-15 minutes and 0-45 minutes, the model predicts negative transport at the downdrift side which did not occur in the measured results.

4.3 Experiment 3

In this experiment, the effects of larger sediment size (0.5 mm) were investigated and compared to Experiment 1 in which finer sediment (0.2 mm) was used. A smaller rate of spreading was found relative to Experiment 1 resulting in a smaller longshore transport coefficient, K. Although the error surfaces for this case are not presented here, it was found that the error was relatively insensitivity to the exponent, n, however, the best fit K values for both the initial and repeatability tests were found to be approximately 0.02, which is one-sixth to one-seventh the values for the finer sediment.

4.4 Experiment 4

With the exception of wave obliquity, the conditions were the same as in Experiment 3. As shown in Fig. 12, the spreading rates due to the planform anomaly were reduced significantly due to the increase in sand size. The agreement between the measured and predicted average transport is not as good as for Experiment 2 (Fig. 11) where finer sediment was used. The best K values for both tests (original and repeatability) were approximately 0.14, which is seven times greater than for Experiment 3 (for normal incidence) and about the same as the Experiment 1 where finer sediment was used and the wave propagated normal to the shoreline.

4.5 Experiment 5

This experiment investigated the planform evolution of nourishment on a compatible sandy coast under normal wave incidence. Measured and predicted volume changes were used as a basis for comparison for the sandy beach experiments, due to the lack of a transport boundary conditions required in applying the continuity equation. The predicted volume changes were calculated by the best fit K value. Since there is no transport reduction at the ends of the project, the error can be defined by a single variable, K, instead of two independent variables, K and n.

Fig. 13 shows the error variation with K. Although the error minimum is not well defined, the best fit K values for the first and second tests were found to be 0.57 and 0.62, respectively. The predicted volume change patterns were found to agree fairly well with the measured over the entire region, with much better agree-

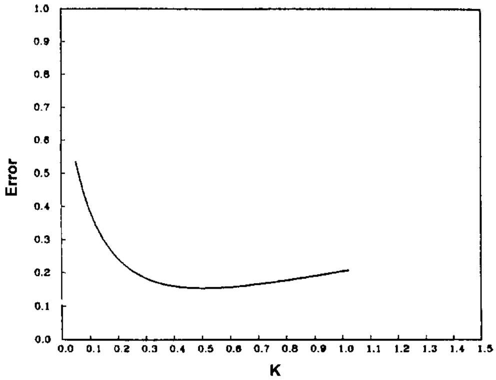

Fig. 13. Variation of normalized mean square error with K, for normal wave incidence for experiment 5, sand size = 0.2 mm.

ment for the later times compared with earlier times.

4.6 Experiment 6

The primary objective of this experiment was to inv estigate the behavior of planform evolution under oblique wave incidence for nourishment on a sandy shoreline. The best fit K values were 0.38 and 0.30 for the first and second test, respectively, however, the variation of error with K is not presented due to space limitation. The measured and predicted volume changes are presented in Fig. 14.

As mentioned earlier, some difficulties were encountered in maintaining a constant sediment supply from the updrift. This may be responsible for a considerable error compared to the normal wave incidence case. The agreement for this test is not as good as for Experiment 5.

However, the general trend of the volume change pattern is nearly identical to the case of normal wave incidence. Thus as supported by theory, wave direction does not appear to be important for the nourishment projects on a sandy beach composed of compatible sand.

4.7 Behavior of Planform Centroid and Variance

The variations with time of the nourishment volume center of gravity were determined from each test and plotted in Fig. 15 and 16 for a seawalled and sandy beach, respectively. Fig. 15 also presents the theoretical results based on the measurement of the average length of the nourishment project using the best fit K and n values. In Fig. 15, the two solid lines represent the

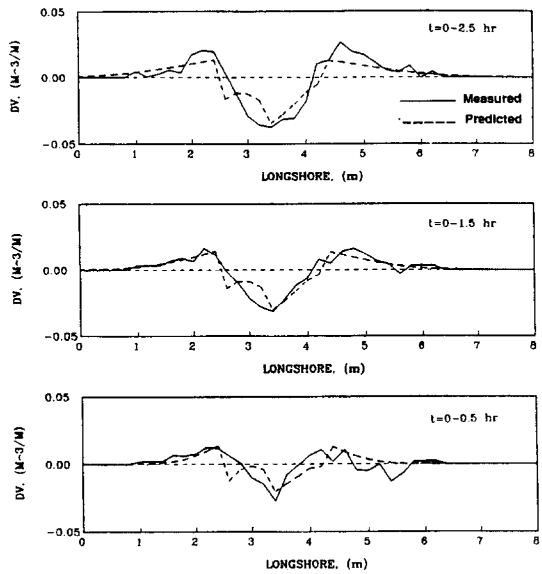

Fig. 14. Comparison of the measured and predicted volume changes for oblique wave incidence for experiment 6, parameter calculated results: $K = 0.38$.

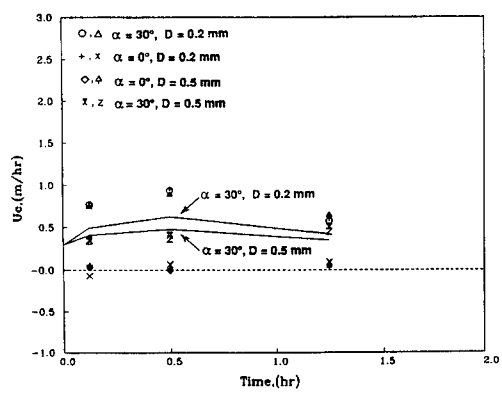

Fig. 15. Translational speed of center of gravity for a seawalled shoreline.

theoretical results for the fine (0.2 mm) and the coarse (0.5 mm) sand with oblique wave incidence.

As expected, the migrational speed of the centroid of the finer sand is greater than that of the coarser sand. Although there are some variations, the agreement between the measured and predicted values is reasonably good. Note that as shown in Fig. 16 the migrational speed for normal wave incidence and the sandy shoreline case are essentially zero.

Figs. 17 and 18 present the normalized variance along a seawalled and a sandy shoreline, respectively. The

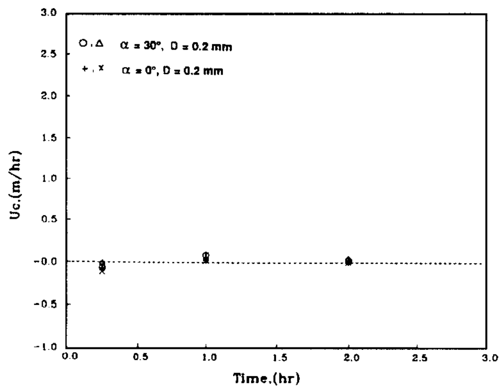

Fig. 16. Translational speed of center of gravity for a sandy shoreline.

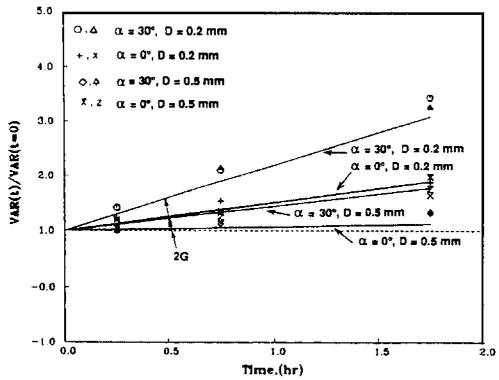

Fig. 17. Variation of valumetric varianced as a function of time for a seawalled shoreline.

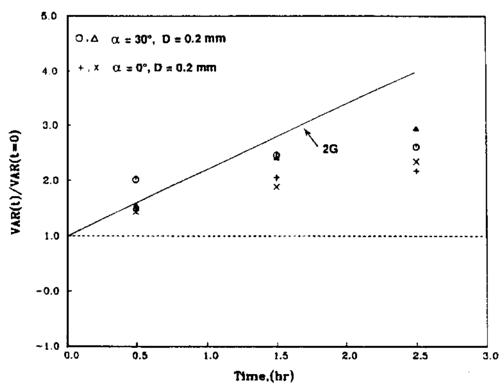

Fig. 18. Variation of valumetric varianced as a function of time for a sandy shoreline.

four solid lines in Fig. 17 represent 2G values based upon the best fit K values determined previously for a seawalled shoreline and one solid line in Fig. 18 represents 2G value for a sandy shoreline. For a seawalled shoreline, the predicted variance is in good agreement with the data, while for a sandy shoreline the rate of predicted variance is somewhat larger than the measured data, possibly due to difficulties in maintaining an appropriate supply of "feed" sand.

It is noted that the rate of variance increases for a seawalled shoreline with oblique wave incidence differs by approximately a factor of three for the case of normal wave incidence. The reason for this appears to be that with oblique wave incidence, sediment is transported readily along the "full profile" section of the beach and deposited on the downdrift side of the nourishment project. However, sediment is not removed (eroded) as readily from the updrift side due to the relative transport reduction for partially submerged profiles.

5. SUMMARY AND CONCLUSION

The best fit K and n values are summarized in Table 2. As expected, the behavior of beach nourishment fronting a seawall is significantly different from that on a beach composed of compatible sand. On a beach composed of compatible sand, the centroid of the planform anomaly remains nearly fixed for both normal and oblique wave incidence while on a seawalled beach, the centoid of the planform anomaly migrates downdrift under oblique wave incidence. For oblique waves and a seawalled shoreline, the centroid migrational speed increased slightly initially and then remained nearly constant. The rate of variance for a seawalled shoreline increases with oblique wave incidence.

Table 2. Summary of experimental results.

Experiment	Shoreline	Sediment Size	Wave Obliquity	K	n
1.a	Seawall	0.2 mm	0°	0.15	3.0
1.b		0.2 mm	0°	0.12	3.0
2.a	Seawall	0.2 mm	30°	0.32	1.5
2.b		0.2 mm	30°	0.35	1.8
3.a	Seawall	0.5 mm	0°	0.02	3.0
3.b		0.5 mm	0°	0.02	3.0
4.a	Seawall	0.5 mm	30°	0.15	1.5
4.b		0.5 mm	30°	0.14	1.5
5.a	Sand`	0.2 mm	0°	0.57	–
5.b		0.2 mm	0°	0.62	–
6.a	Sand	0.2 mm	30°	0.38	–
6.b		0.2 mm	30°	0.30	–

For waves incident at a 30° angle (deep water), the rate of increase is approximately a factor of three greater than the case of normal wave incidence.

Although not clear, the longshore transport coefficient, K, found for a sandy shoreline is greater for normal than oblique wave incidence ($K=0.6$ for normal wave incidence and $K=0.34$ for oblique wave incidence) whereas for a seawalled shoreline it is smaller for normal than oblique wave incidence ($K=0.15$ for normal wave incidence and $K=0.32$ for oblique wave incidence) for the same sediment size (0.2 mm). However, for the coarser sediment (0.5 mm) K value was found to be very small for normal wave incidence ($K=0.02$) but much larger for oblique wave incidence ($K=0.15$).

Although the exponent, n, in the transport reduction factor was not defined well, the best values were found to be approximately 3.0 for normal wave incidence and 1.5 for oblique wave incidence for both sediment sizes. With some variations, comparisons between the predicted and the measured transport rates for the all cases tested showed good general agreement.

It should be noted that the experimental scale employed here may introduce scale effects. To validate the model performance and to compare the numerical results with actual field phenomena, large scale physical model tests should be conducted. It is also suggested that the effects of both monochromatic and random wave results be evaluated in future experiments.

REFERENCES

Bruun, P., 1954. Coast erosion and the development of beach profiles, *Tech. Memor. No. 44*, Beach Erosion Board, CERC, U.S. Army Corps of Engineers, Waterway Experiment Station, Vicksburg, Mississippi.

Davison, A.T., Nicholls, R.J. and Leatherman, S.P., 1992. Beach nourishment as a coastal management tool: An annotated bibliography on developments associated with the artificial nourishment of beaches, *J. Coastal Res.*, **8**(4), pp. 985-1022.

Dean, R.G., 1977. Equilibrium beach profiles: U.S. Atlantic and Gulf coasts, *Ocean Engrg. Rep. No. 12,* Department of Civil Engineering, University of Delaware, Newark.

Dean, R.G., 1991. Equilibrium beach profiles: Characteristics and applications, *J. Coastal Res.*, **7**(1), pp. 53-84.

Dean, R.G. and Yoo, C.H., 1992. Beach nourishment performance predictions, *J. Waterway, Port, Coastal and Ocean Engrg.*, **118**(6), pp. 567-586.

Dean, R.G. and Yoo, C.H., 1994. Beach nourishment in presence of seawall, *J. Waterway, Port, Coastal and Ocean Engrg.*, **120**(3), pp. 302-316.

Hanson, H. and Kraus, N.C., 1989. Genesis: Generalized model for simulating shoreline change; Report 1, Technical Reference, *Tech. Rep. CERC-89-19*, U.S. Army Corps of Engineers, Waterway Experiment Station, Coastal Engineering Research Center, Vicksburg, Mississippi.

Larson, M., Hanson, H. and Kraus, N.C., 1987. Analytical solutions of the one-line model of shoreline change, *Tech. Rep. CERC-87-15*, U.S. Army Corps of Engineers, Waterway Experiment Station, Coastal Engineering Research Center, Vicksburg, Mississippi.

Verhagen, H.J., 1992. Method for artificial beach nourishment, *Proc. 23rd Coastal Engrg. Conf.*, ASCE, pp. 2474-2485.

Received January 21, 1999
Accerted May 31, 1999