Compaction effect on beach stabilization

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Abstract
A Laboratory study, on beach stabilization by using artificial compaction control, has been conducted. Erosional and accretional waves were applied to un-compacted, moderately compacted, and densely compacted sandy beaches. Changes in beach profile and cross-shore distribution of compaction were measured, then the net cross-shore sediment transport, the shoreline change, the average size of ripples, and the volumetric change were calculated. The results generally show that the higher the compaction, the lesser the net offshore sediment transport and erosion volume. On the other hand, the effect on the decrease of accretion volume was relatively small. This paper also presents a methodology to estimate a cross-shore distribution of local porosity based on the measured local compaction.

Introduction

In nature, a sandy beach gets eroded due to storm waves and accreted due to calm swell waves. This seasonal profile change can be characterized by incident wave steepness, sediment diameter, and beach slope. In addition to these parameters, the compaction of a sandy beach and dune is an important mechanism of coastal processes to protect human beings (Nishi et al., 1999) and is also significant for coastal environments such as turtle nests as shown in Fig. 1 (see, Steinitz, et. al., 1998 and Davis, et. al.1999). A sandy beach becomes compacted while it erodes, whereas the beachface becomes softer and more porous while it is accreting.

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(a) Swell waves caused by a typhoon

(b) Beach erosion and dune scarp.

(c) Protection of a residential area

(d) Beach nourishment.

(e) Loggerhead turtle nesting.

(f) The hatchling from a sandy beach.

Fig. 1. Coastal features which might be affected by the compaction.

A compacted beach is preferable from viewpoints of driving and walking. However, the compactness as well as the porosity of the beach significantly affect the ecosystem inside the sandy beach. Previous research by Nishi et al. (1999)

suggests a possible method to decrease erosion volume and shoreline recession by compacting a sandy beach. Although this technique is still an idealized one, it is more environmental-friendly compared to other methods such as the utilization of hard structures for beach stabilization. Therefore, studies on compaction effects on the profile change, cross-shore sediment transport, change in shoreline, and the volume of erosion and accretion are carried out by using the initially uniform slope beach with different compactions.

In the laboratory study, an artificial compaction control has been applied. Erosional and accretional waves with regular wave height and period were applied to un-compacted, moderately compacted, and densely compacted sandy beaches. Changes in beach profile and cross-shore distribution of compaction were measured, then the net cross-shore sediment transport, the shoreline change, and the volumetric change were calculated. In general, the results show that the higher the compaction, the lesser the net offshore sediment transport and erosion volume. On the other hand, the effect on the decrease of accretion volume was relatively small. A method is proposed to estimate the cross-shore distribution of local porosity based on the measured local compaction.

Experimental set-up

To study the compaction effect on beach stabilization, well-sorted sand with 0.2mm mean diameter and 2.6g/cm^3 density was used to set sandy beaches with 1/10 initial slope in a wave flume as show in Fig. 2.

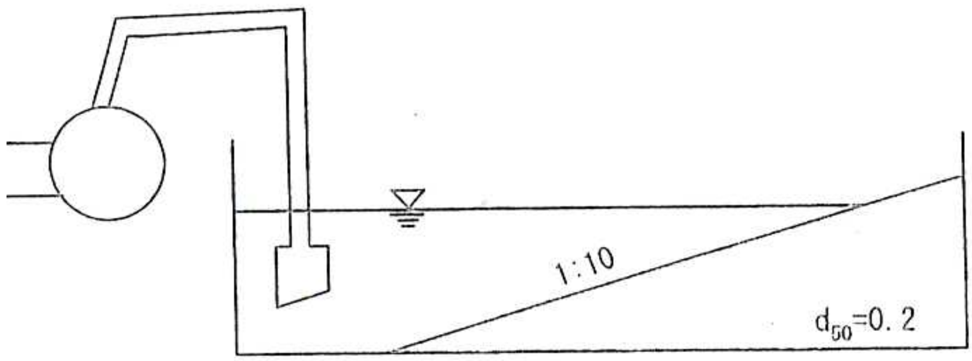

Fig. 2. Experimental set-up.

The sand in the wave flume was taken outside the wave flume to naturally dry under the sun for one day just after each experimental run. Then the sand was carried into the flume again to set-up a sandy beach with a certain compaction. Thus, a net volume of sand inside the wave flume is kept the same during all the experimental runs. The compaction of sandy beach was adjusted by a concrete-vibrator. The vibrator was applied for 30 minutes to cases 2 and 5, and for 50 minutes to cases 3 and 6. Cases 1 and 4 correspond to un-compacted conditions. In this paper, cases 2 and 5 correspond to moderately compacted conditions. Cases 3 and 6 correspond to densely compacted conditions. The regular waves which are shown in Table 1 were acted on each individual sandy beaches for two hours. The initial beach profiles with different compaction of cases 4, 5, and 6 are shown in Fig. 3.

It can be seen that the average beach surface elevations are lowered by beach compacting. Beach profiles and cross-shore distributions of compaction were measured as shown in Fig. 4 before and after each wave action.

Case	Wave height	Period
Case 1	9.8 cm	1.1 sec
Case 2	9.8 cm	1.1 sec
Case 3	11.1 cm	1.1 sec
Case 4	4.5 cm	2.0 sec
Case 5	3.8 cm	2.0 sec
Case 6	4.7 cm	2.0 sec

Table 1. Experimental wave conditions.

Beach profiles were measured by a point-gauge. Therefore, the resolution of measurement can be achieved the order of the size of a sediment particle. It means that the accuracy of profile measurement can be less than 0.2mm in this study. The profiles were carefully measured to satisfy the conservation of sand volume inside the wave flume as much as possible. Thus, the changes in profile and resulted sediment transport rate are considered as reasonably accurate. It was noted that the volume of sand inside the wave flume was conserved, thus the decrease in porosity of a compacted beach is recognized by visual observation of the lowering of average beach slope.

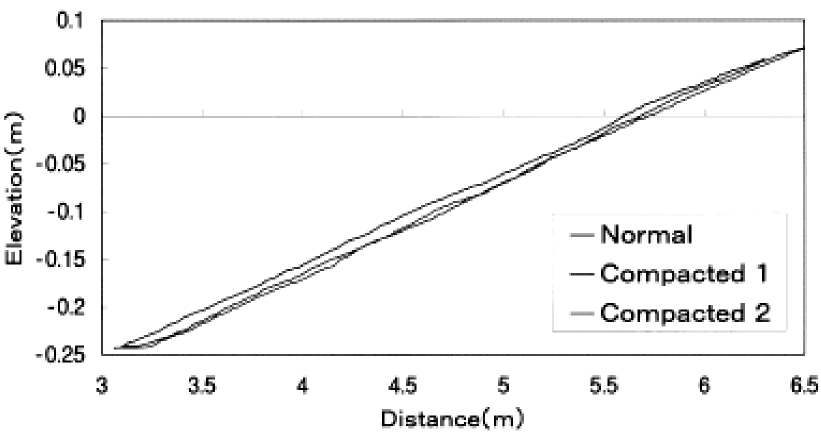

Fig. 3. Initial beach profiles with different level of compaction.

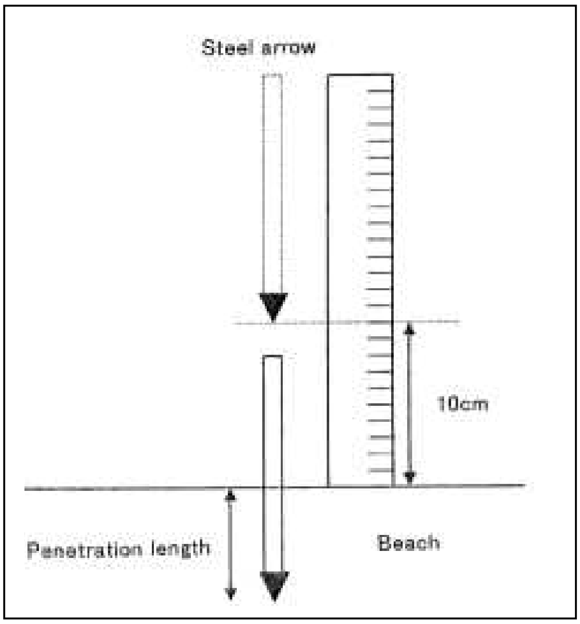

Fig. 4. Measuring techniques of compaction.

Experimental results

The influence of beach compaction on profile change, the cross-shore distribution of local compaction, the net cross-shore sediment transport rate, and the volume change behind a still water shoreline of initial beaches are described one by one below:

Profile change: Fig. 5 shows beach profiles generated by erosional waves. The relative heights of longshore bar are getting shorter as the initial beach gets more compacted. It is clearly seen that, the harder the compaction of sandy beaches, the narrower the width of surf-zone. In other words, the offshore migration speed of the longshore bar on compacted beach is slower than that of un-compacted beach. The position of a longshore bar on a compacted beach tends to be located closer to the shoreline. The change in shoreline position between an initial profile and final profile is also smaller if the compaction of initial beach is higher.

In contrast, the sizes of berm of un-compacted sandy beaches and compacted beaches are identical as seen in Fig. 6. The change in shoreline positions in each accretional run is also similar even though the degrees of compaction of three sandy beaches are different. The decrease in berm height of normal sandy beach is in the order of ten percent, thus it can be said that the negative effect by compacting a beach on the accretion process is small. In general, the amount of sediment movement for erosion and accretion processes decreases as the sandy beach compactions increase.

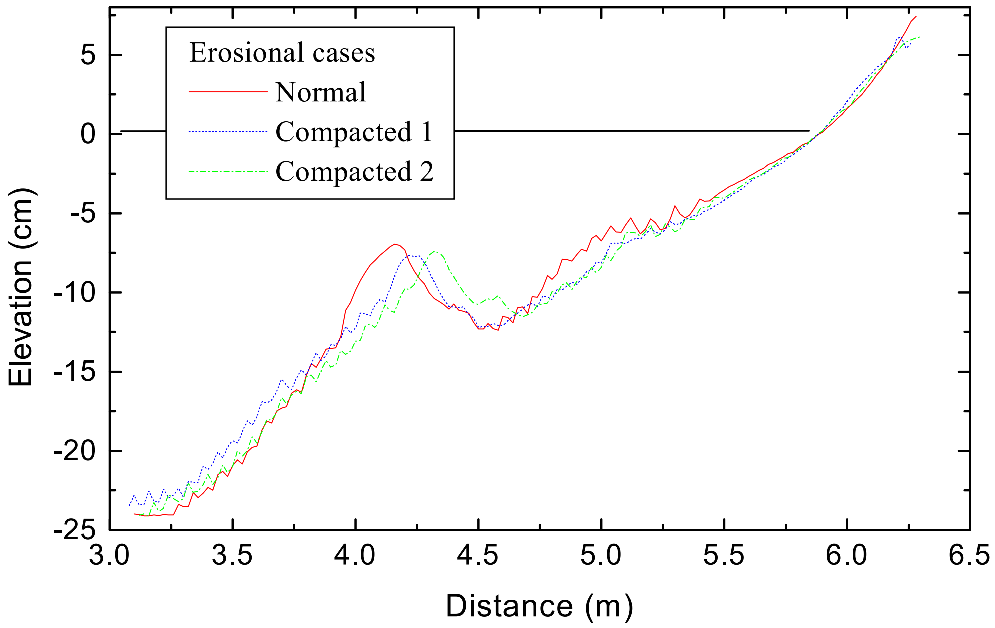

Fig. 5 Erosional profiles with different degrees of compaction.

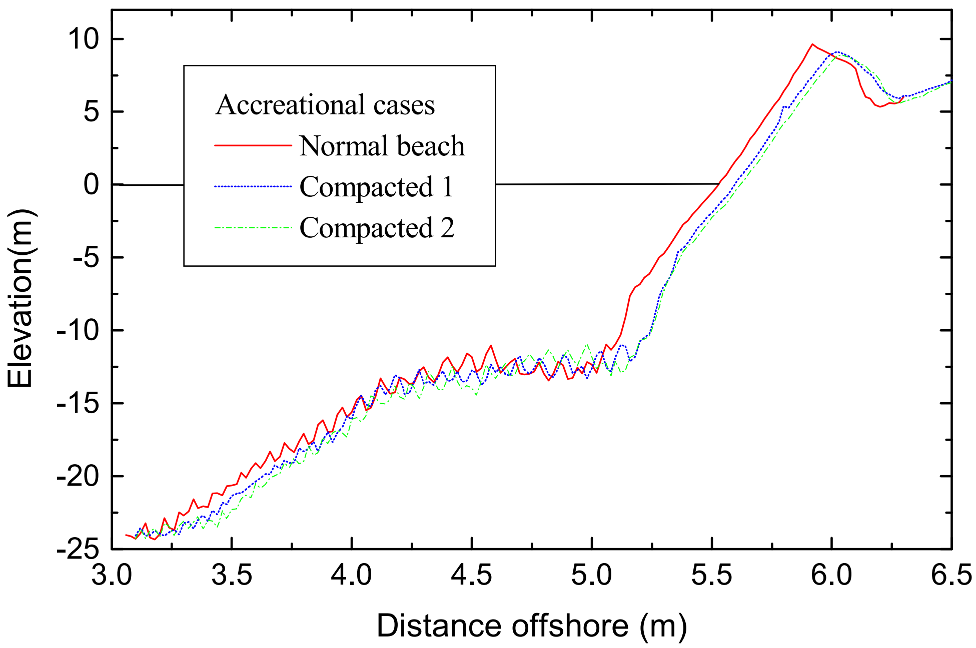

Fig. 6 Accreational profiles with different compaction.

Cross-shore distribution of the compaction:

Compaction is an important parameter to describe the hardness of the sandy beach and it possibly affects the stabilization and utilization of a beach. Therefore, local compaction of initial and final profiles were measured at every 4cm cross-shore direction by a penetration test with a steel arrow as shown in Fig. 4. Cross-shore distributions of compaction over erosion and accretion profiles are shown in Figs. 7 and 8, respectively. The ordinate showing compaction, corresponds to the penetration length of an arrow into the sandy beach. The average compactions, which correspond to the average penetration length, are 2.78, 1.99, 1.89, 2.40, 1.81, and 1.84cm for the cases 1 through 6, respectively. It is apparent that the shorter the average penetration length, the harder the beach. Thus, the small number on the ordinate correspond a higher compaction.

It is seen that the spatial variance of local compaction over initially compacted beaches were relatively large compared to that of initially un-compacted beach. In addition, local compaction scattering of final beaches are more apparent. In general, areas of longshore bars and seaward slope of berms tend to be more compacted than other areas. It is possible that the compaction around the bar might be the highest in natural coastal process. It is recognized that a longshore bar is hard and a berm is softer than longshore bar in natural condition. The difference of compaction of the berm in natural and laboratory condition is probably due to the composition of beach material. The berm in nature is usually composed of coarser material than other parts of the beach and thus becomes more porous and softer, whereas the berm in the experiment is composed of uniform fine sand and is not so porous. In general, the compaction at the longshore bar can be used as a criterion for maximum compaction of artificial and natural beaches.

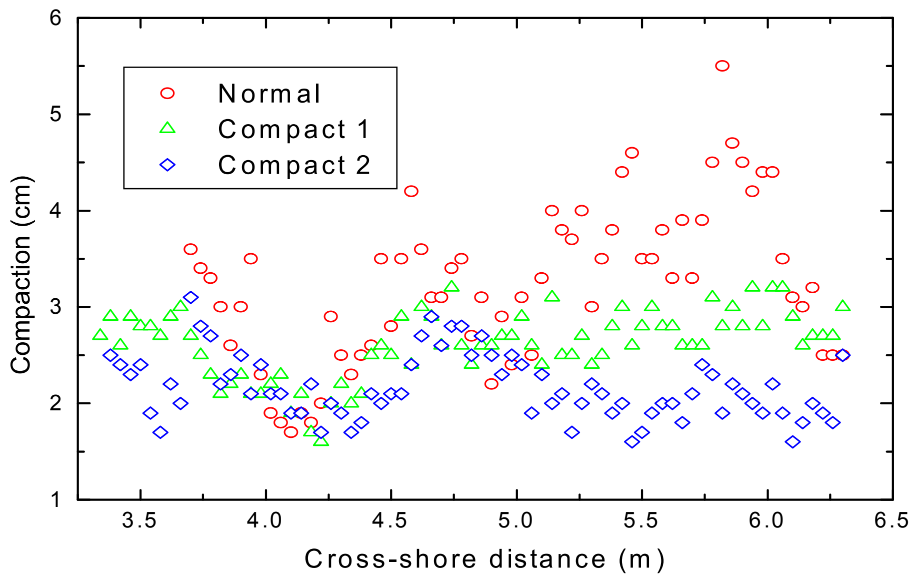

Fig. 7. Compaction distribution over bar profiles.

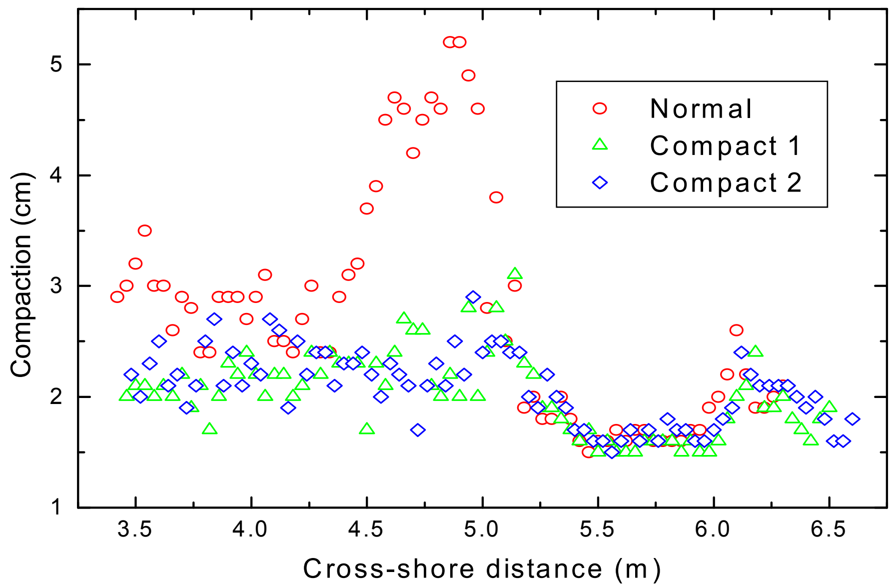

Fig. 8. Compaction distribution over berm profiles.

Estimation of porosity distribution by a measured local compaction: Local compaction of a beach can be a function of the local porosity of the beach. In addition, the porosity distribution, $\lambda(x)$, should be considered in the continuity equation to estimate an accurate net cross-shore sediment transport rate as shown in eq. (1).

$$q(x) = \int_0^x \frac{1}{1-\lambda(x)} \frac{\partial h}{\partial t} dx \qquad (1)$$

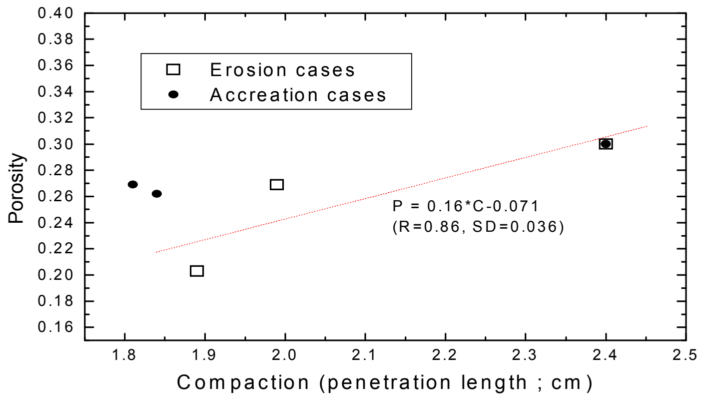

Fig. 9 A relationship between average compaction and mean porosity.

Therefore, the mean compaction of a beach which is measured in this experiment was correlated to the mean porosity of sandy beaches as shown in Fig. 9. The average porosity of an un-compacted beach was assumed to be 0.3 first, and the porosity of other compacted beaches were estimated by comparing the sum of measured elevation data of each sandy beach, because the net sand volume for each individual beach was conserved for all runs. The solid line in the Fig. 9 shows a linear regression as:

$$\lambda = 0.16 \cdot C - 0.071 \tag{2}$$

in which λ is the average porosity and C is the average compaction. This empirical equation is applied to estimate the local porosity by using local compaction as shown in Fig. 10 for which the eq. (2) is extended as:

$$\lambda(x) = 0.16 \cdot C(x) - 0.071 \tag{3}$$

where, x is the cross-shore distance.

In natural conditions, the porosity of sandy beaches hardly exceeds 0.45 and is rarely smaller than 0.1. As seen in the figure, most of the estimated porosity fall into this range. Therefore, the upper and lower limit of local porosity, to estimate the net cross-shore sediment transport rate, should be adjusted to 0.45 and 0.1 respectively, if the estimated porosity exceeds these limits.

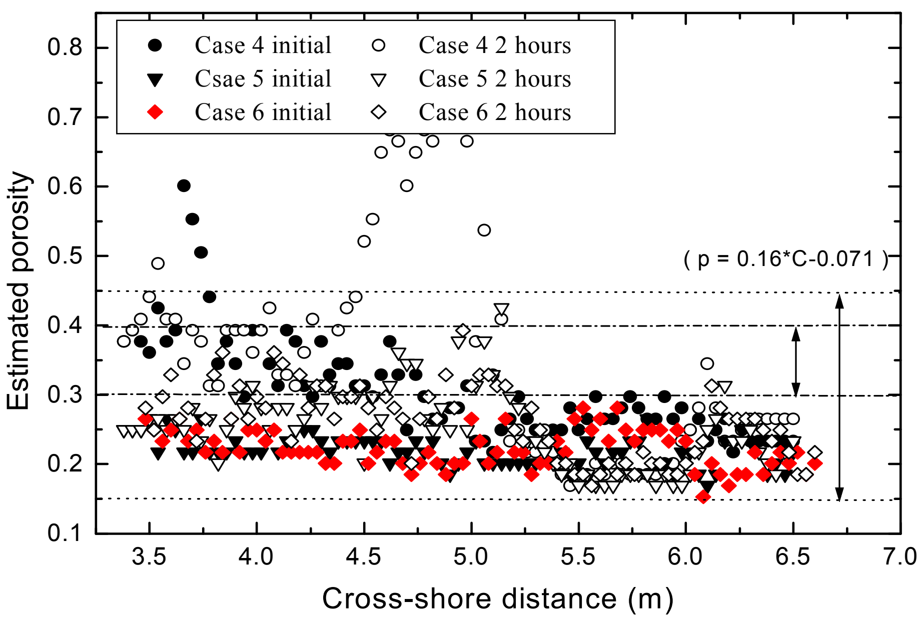

Fig. 10. Cross-shore distribution of estimated porosity.

Net cross-shore sediment transport rate: Net cross-shore sediment transport rate is usually estimated by applying the conservation equation under a laboratory condition using the relation:

$$q = \frac{1}{1-\lambda}\int_0^x \frac{\partial h}{\partial t}dx \qquad (4)$$

where, λ is the average porosity and is to be kept constant or is to be neglected. As previously mentioned, local porosity $\lambda(x)$ over a beach profile changes in space as well as in time. If $\lambda_1(x)$ and $\lambda_2(x)$ are the local porosities over an initial and a final profile, and $L_{mix}(x)$ is a vertical mixing length of bed material at the location of x, the cross-shore sediment transport rate can be estimated as:

$$q(x) = \int_0^x \frac{[(1-\lambda_1(x))h_1(x) - (1-\lambda_2(x))L_{mix}(x) - (1-\lambda_2(x))(h_2(x) - L_{mix}(x))]}{dt}dx \qquad (5)$$

However, the vertical mixing length $L_{mix}(x)$ is still uncertain, thus it is assumed to be the same for the initial and final profiles for each run. Therefore, the eq. 5 can be reduced to eq. 6 as follows;

$$q(x) = \int_0^x (1 - \frac{\lambda_1(x) + \lambda_2(x)}{2})\frac{\partial h}{\partial t}dx \qquad (6)$$

Since the porosity distribution in space and in time is usually not measured and is different for estimation, an alternative method to apply the average porosity of initial and final beaches can be used to assess the net cross-shore sediment transport rate as shown by eq. 7;

$$q(x) = \frac{1}{(1-\frac{\lambda_1+\lambda_2}{2})}\int_0^x \frac{\partial h}{\partial t}dx \qquad (7)$$

where the λ_1 is assumed to be 0.3 for un-compacted beach and λ_2 is derived based on the sum of profile elevation change such as;

$$\lambda_2 = \frac{V_2(1-\lambda_1)V_1}{V_2} = 1-(1-\lambda_1)\frac{V_1}{V_2} = 1-(1-\lambda_1)\frac{\sum_{i=1}^{N} h_{1i}}{\sum_{i=1}^{N} h_{2i}} \qquad (8)$$

where, the Σh_{1i} and Σh_{2i} are the sum of local elevations measured every 2cm and correspond to the sand volume with a certain porosity inside the wave flume. In fact, the net sand volume is kept to be constant for all runs. The final beaches for each run can be classified as compacted, stable, loosen as shown in eq. (9)

$$\frac{\lambda_1}{\lambda_2} > 1 \cdots\cdots\cdots Compacted$$
$$\frac{\lambda_1}{\lambda_2} = 1 \cdots\cdots\cdots Const \qquad (9)$$
$$\frac{\lambda_1}{\lambda_2} < 1 \cdots\cdots\cdots Loosen$$

The net cross-shore sediment transport rate of each run is shown in Fig. 11 in which the average porosity is used. It is apparent that whether it is erosion or accretion, the harder the sandy beach, the smaller the maximum net transport rate. In addition, the peaks of each cross-shore sediment transport distribution tend to appear more onshore as the initial beaches are more compacted. Therefore, it is shown that the enhancement of compaction decreases the volume of sediment transport offshore.

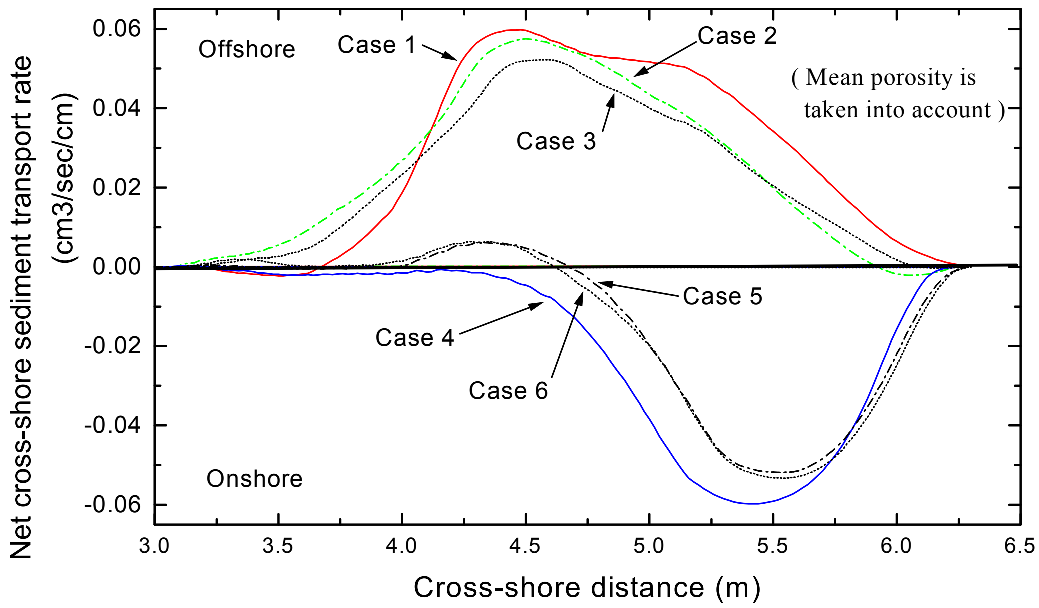

Fig. 11. Net cross-shore sediment transport rate estimated with average porosity.

Change in accretion and erosion volume behind the initial shoreline: Change in sand volume per unit longshore width behind the initial shoreline was calculated for accretional and erosional conditions as shown in Fig. 12.

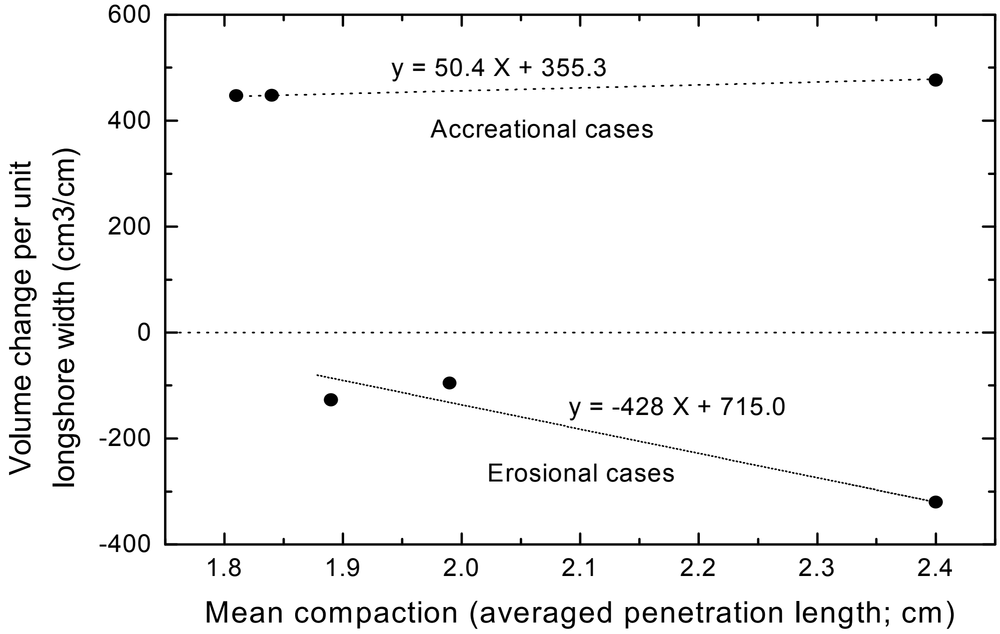

Fig. 12. Change in sand volume behind the initial shoreline.

The upper and lower parts of this figure correspond to accretion and erosion cases, respectively. The general trends are shown by broken line for accretion and solid line for erosion, respectively. These linear regression can be expressed by;

$$y = 50.4X + 355.3 \tag{10}$$

$$y = -428X + 715.0 \tag{11}$$

where, X is the averaged compaction (average penetration length of arrow) for each run, and y is the volume change (including porosity) per unit longshore width. It is shown that the change in erosion volume of case 3 (densely compacted) is nearly one-third of the erosion volume of case 1 (un-compacted beach), whereas the accretion volume of case 6 (densely compacted) is only 6% less than that of the normal sandy beach. Therefore, the compaction techniques enhance the shore protection potential as well as the beach stabilization, while showing a little negative impact on accretion process.

Conclusion

Compaction effect on the beach stabilization had been conducted in laboratory condition. The major conclusions are as follows:

1. The surf-zone width becomes narrower and the position of the longshore bar

tends to be closer to the shoreline if the compaction of sandy beach is enhanced artificially.

2. It is shown that the net-onshore and offshore sediment transport rates due to accretional and erosional waves are decreased by enhancing the compaction of the sandy beach.
3. The erosion volume behind an shoreline of initial profile becomes one-third of that of normal sandy beach when the beach is densely compacted. On the other hand, accretional volume behind the shoreline becomes only 6 % less than that of the normal sandy beach in this study.
4. Compaction at a longshore bar can be applied as a criterion for the maximum (optimal) compaction for stabilizing a sandy beach.

Even though further field experiments are necessary, this study shows that compaction enhancement can be a promising beach stabilization method.

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