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AN IMPROVED SHORT-TERM SWASH ZONE BEACH PROFILE CHANGE MODEL FOCUSING ON BERM FORMATION AND EROSION

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ABSTRACT: A short-term swash zone beach profile change model focusing on berm formation and erosion proposed by Suzuki and Kuriyama (2010) was improved. The model was developed using a 2.5-year data set of beach profiles and offshore waves observed at the Hasaki coast, Ibaraki, Japan, facing the Pacific Ocean. The distributions of cross-shore sediment transport rate for berm formation and erosion were determined using the curve slopes at the inflection points. The curve slopes for berm formation and erosion were estimated by using the wave energy flux, and the product of the wave height of long-period wave and berm height, respectively. The investigation area was set from the maximum wave run-up position to the shoreline position at the mean tide level. The both models were applied to the calculation of the beach profile change for three months, which results were compared with observed data. It is found that the present model well predicts not only the shoreline change, but also the beach profile change, including the berm formation and erosion. The correlation coefficient (R) of shoreline position at the high tide level between the numerical results and observed data is 0.70, which is 0.37 higher than the previous model. Also, the averaged correlation coefficient of shoreline positions at five different ground elevations is R = 0.73.

Keywords: Berm, swash zone, beach profile change, modeling, field data, hasaki coast.

INTRODUCTION

In the swash zone, sediments are transported by wave run-up and run-down, and the beach profile is changed by the imbalance of its onshore and offshore sediment transport rates. Owing to these sediment transport rates, berms are commonly formed between a mean sea level and a maximum wave run-up level.

The sediment transport rates in the swash zone have been studied by a number of researchers (e.g., Katoh and Yanagishima, 1993; Puleo et al., 2000). Suzuki et al. (2007) investigated the characteristics of the distributions of the cross-shore sediment transport rates for berm formation and erosion.

Also, numerical models for the swash zone have been proposed (e.g., Larson et al., 2004; Vousdoukas et al., 2011) Suzuki and Kuriyama (2008) proposed models of the spatial distributions of the cross-shore sediment transport rates for berm formation and erosion using the offshore wave energy flux and the berm height. By using these spatial distributions, they proposed a swash zone beach profile change model, including berm formation and erosion (Suzuki and Kuriyama 2010). The calculated results were compared with the observed beach profile data and showed that the tendency of the beach profile changes and shoreline movement are similar in a qualitative sense. However, there is still room for improving the model.

The objectives of this study are thus to re-examine the model of Suzuki and Kuriyama (2010) and develop an enhanced model for short-term swash zone beach profile change focusing on berm formation and berm erosion. Also, the calculated results are compared with the observed field data and the results of the model of Suzuki and Kuriyama (2010).

DATA DESCRIPTION

Beach profile data were obtained from August 1987 to January 1990 at Hazaki Oceanographical Research Station (HORS), a research facility on the Hasaki coast of Japan (Fig. 1). HORS has a 427-m-long pier located perpendicular to the shore. The cross-shore distance along the pier is defined relative to the reference point of HORS, and the seaward direction is set as being positive.

Beach profiles along the pier were measured at 5 m intervals every weekday. The data of weekends and holidays were interpolated using weekday’s data. All through the year, the median sediment diameter is 0.18 mm and almost uniform along the pier (Katoh et al. 1990). The high, mean and low water levels based on the datum level (D.L.) at Hasaki coast (Tokyo Peil -0.687 m) are 1.25 m, 0.65 m, and -0.20 m, respectively.

Fig. 2 shows the mean beach profile and its standard deviation in the surf zone, the foreshore and the backshore. The seaward position at the intersection of

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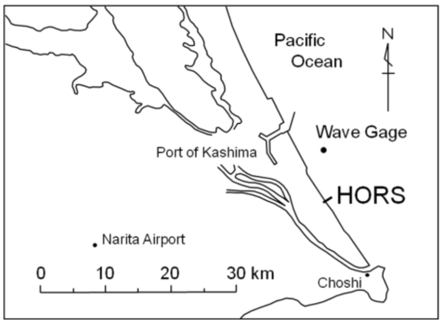

Fig. 1 Location of Hazaki Oceanographical Research Station (HORS).

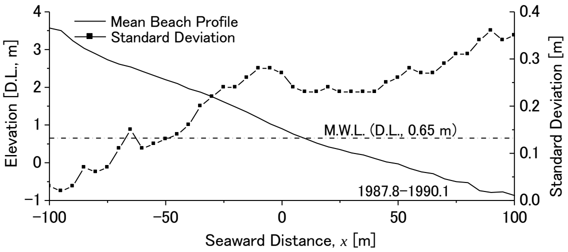

Fig. 2 Mean beach profile and its standard deviation.

the mean beach profile with the mean water level is x = 9.5 m, and beach slope around the shoreline position is about 1/40. The relatively high values of the standard deviation around x = -15 m are due to berm formation and erosion.

An Ultra Sonic Wave gauge (USW) sensor was mounted at a water depth of 23.4 m offshore the port of Kashima (see Fig. 1). The offshore waves were measured for 20 minutes every 2 hours by the USW. During the investigation period, the averaged offshore significant wave height and period were 1.65 m (varied from 0.37 m to 6.49 m) and 8.51 s (varied from 4.88 s to 17.2 s), respectively. The offshore wave energy flux (E_f) is calculated from the offshore wave height and the group velocity, and is positive for the landward direction. (Suzuki and Kuriyama, 2010)

The shoreline position varies depending on beach topography, tide and wave set-up near the shoreline. Katoh and Yanagishima (1993) proposed an equation for estimating the wave run-up level R_E, which had been empirically derived from field observation data obtained at HORS:

$$R_E = \bar{\eta}_0 + 0.96H_L + 0.31 \text{ [D.L., m]} \qquad (1)$$

where $\bar{\eta}_0$ is the mean sea level and H_L is the height of the infragravity waves at the shoreline. The second and third terms on the right hand side of the equation are considered to be presenting the run-up heights caused by the effect of infragravity waves and incident wind waves, respectively.

RE-EXAMINATION OF CROSS-SHORE SEDIMENT TRANSPORT RATE MODEL

In this study, we firstly re-examine the cross-shore sediment transport rate model proposed by Suzuki and Kuriyama (2010) and develop an enhanced model of the cross-shore sediment transport rate of foreshore beach profile change. Secondly, we apply these models to reproducing three months observed data for validation of the models.

Cross-shore sediment transport rate

The spatial distributions of cross-shore sediment transport rate for berm formation and erosion were estimated to be the same as Suzuki et al. (2007). The sediment transport volume of each cross-shore section is estimated from beach profile changes on the basis of a mass conservation equation:

$$\left[Q(i,t) - Q(i-1,t)\right] = \gamma\left[z(i,t) - z(i,t-1)\right]\Delta x/\Delta t \qquad (2)$$

where Q is the cross-shore component of sediment transport rate per unit length in the alongshore direction, i is the number of the point where the cross-shore sediment transport rate is defined, t is the time, Δx is the spacing interval in the cross-shore direction, γ is the volume of sediment in a unit volume of the bed (= 0.7, Nielsen, 1992), and z is the elevation.

The sediment transport rate for each position from the foot of the foredune, x = -115 m, to the offshore boundary is estimated. The estimation of the cross-shore sediment transport rate is based on the assumption that the beach profile changes were induced by the cross-shore gradient of the cross-shore sediment transport, and the alongshore gradient of longshore sediment transport rate is negligible due to the alongshore uniformity of the topography around HORS (Kuriyama, 1991). The positive and negative values indicate the landward and the seaward sediment transport rates, respectively.
The investigation area is set to include the areas of berm formation and erosion. The onshore boundary is defined at the maximum wave run-up position, and the offshore boundary is defined at the shoreline position of the mean tide level (D.L., 0.65 m). The onshore boundary position is set at the cross point of the beach profile and the wave run-up level which is calculated by Eq. (1). The offshore and onshore boundary positions varied due to wave conditions and beach profile changes. Therefore, the cross-shore positions are normalized using the distance between the boundaries, X. Namely, the onshore boundary is set as x/X = 0.0 and the offshore boundary is set as x/X = 1.0.

The spatial distributions of the averaged sediment transport rate for berm formation and erosion are shown

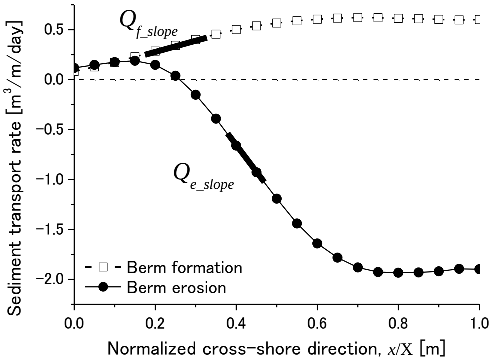

Fig. 3 Distribution of averaged cross-shore sediment transport rates for berm formation and erosion.

in Fig. 3. For the berm formation case, the landward sediment transport rate gradually increases from x/X = 0.0 to around x/X = 0.7 and takes a steady value at the seaward of x/X = 0.7. On the other hand, during the berm erosion, the sediment accumulation occurs from x/X = 0.0 to 0.15. At x/X = 0.26, the sediment transport rate changes the direction to the seaward and decreases until around x/X = 0.7. From around x/X = 0.7, the rate takes almost constant value.

Cross-shore sediment transport rate model of Suzuki and Kuriyama (2010)

Here, brief introduction of the cross-shore sediment transport rate model of Suzuki and Kuriyama (2010) is described. The spatial distribution of sediment transport rate for berm formation from x/X = 0.0 to x/X = 0.7 was formulated using a quadratic curve (see Fig. 3). The curve starts from the origin (x/X = 0.0, Q = 0.0) and increases until the rate at x/X = 0.7, which is determined by the offshore energy flux. The rates from x/X = 0.7 to 1.0 are assumed to be constant with the rate at x/X = 0.7.

The spatial distribution of the sediment transport rate for berm erosion from x/X = 0.0 to x/X = 1.0 was modeled by a cubic curve which starts from the origin (x/X = 0.0, Q = 0.0), goes through the rate at x/X = 0.15 and ends at the rate at x/X = 0.7 (see Fig. 3). The rates at x/X = 0.15 and x/X = 0.7 are determined by the berm height. The rates from x/X = 0.7 to 1.0 are assumed to be constant taking the value at x/X = 0.7. The details can be found in Suzuki and Kuriyama (2008).

Re-examination of the cross-shore sediment transport rate model

Once the distribution curve is set as a cubic function, the shape of the curve is unambiguously fixed if the position of an extreme value and the slope of the inflection point are determined. This method is used to model the distribution curves of sediment transport rate for berm formation and erosion.

For the berm formation case, the spatial distribution of the cross-shore sediment transport rate between x/X = 0.0 and x/X = 0.7 where the values of sediment transport rate gradually increases was modeled by a cubic curve instead of the quadratic function. The curve was determined so that it passes through the origin (x/X = 0.0, Q = 0.0), having the curve slope of the inflection point at x/X = 0.25 and taking the local minimum at x/X = 0.7. The distribution of the rate between x/X = 0.7 and 1.0 was assumed to be uniform, taking the value at x/X = 0.7.

Berms are formed at foreshore when the bed sediment transport is dominant compared with the suspended sediment transport, and the resultant onshore sediment transport becomes dominant. The relation between the curve slope of the distribution of sediment transport rate at the inflection point and the wave energy flux is shown in Fig. 4. A weak correlation can be seen in the figure (correlation coefficient, R = 0.32) given by:

$$Q_{f\_slope} = 6.76 \times 10^{-7} E_f + 1.63 \tag{3}$$

where Q_{f_slope} is the curve slope of the distribution of the sediment transport rate at the inflection point. Though the correlation is not very high, we try to use Eq. (3) as the spatial distribution curve of the sediment transport rate for berm formation.

For the berm erosion case, though the sediment transport rate was modeled by a cubic curve again, the curve was determined between x/X = 0.0 and x/X = 0.75 so that it passes through the origin (x/X = 0.0, Q = 0.0), having the curve slope of the inflection point at x/X = 0.45 and taking the minimum value at x/X = 0.75. The rates from x/X = 0.75 to 1.0 are assumed to be constant taking the value at x/X = 0.75.

The relation between the berm erosion and waves was investigated by Katoh and Yanagishima (1992). They reported that the significant extreme force for the berm erosion was considered to be highly related to the wave height of long-period waves. Furthermore, Suzuki and Kuriyama (2008) suggested that the correlation can

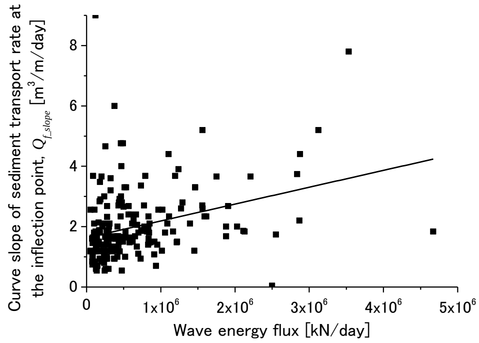

Fig. 4 Relation between the curve slope at the inflection point and the offshore wave energy flux.

be seen between the berm height and the cross-shore sediment transport rate.

The relation between the curve slope of the distribution of sediment transport rate at the inflection point and the product of the wave height of long-period wave, H_L, and the berm height, B_h, is shown in Fig. 5. From the figure, a negative relationship can be seen with the correlation coefficient, R, of -0.80:

$$Q_{e\_slope} = 31.8\left(H_L \times B_h\right)^2 - 51.4\left(H_L \times B_h\right) - 1.95 \qquad (4)$$

where Q_{e_slope} is the curve slope of the distribution of the sediment transport rate at the inflection point. Thus, we decided to adopt Eq. (4) for the estimation of the sediment transport rate under the berm erosion condition.

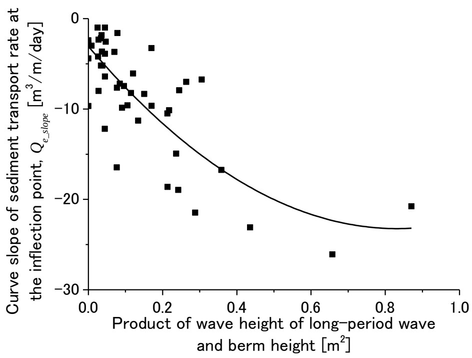

Fig. 5 Relation between the curve slope at the inflection point and the product of wave height of long-period wave and berm height.

Threshold for berm formation and erosion

Katoh and Yanagishima (1992) suggested that the berm erosion occurs when enhanced wave run-up passes through the berm crest. Thus, the threshold between the berm formation and the berm erosion was determined by the berm crest elevation and the maximum wave run-up elevation. The relations between the berm crest elevation and the wave run-up elevation for berm formation cases and erosion cases are considered, and a threshold line between the two cases is defined by a discriminant analysis. The details can be found in Suzuki and Kuriyama (2008).

RESULTS AND DISCUSSION ON CALCULATION OF SHORT-TERM BEACH PROFILE CHANGE IN SWASH ZONE

The model calculation for estimating the cross-shore distribution of the cross-shore sediment transport rate on the foreshore consists of two steps. The first step is to determine whether a berm is formed or eroded on the basis of the wave run-up elevation. The second step is to estimate the cross-shore sediment transport rate using two different sub-models; one is for berm formation and the other is for erosion.

The model was applied to the calculation of a three-month (from May 1, 1988 to July 31, 1988) foreshore beach profile change, and the results were compared with the observed data and calculated results of Suzuki and Kuriyama (2010). The beach profile on May 1, 1988 was set as the initial beach profile. Fig. 6 shows a time series of observed significant wave height and significant wave period during the investigated period. During these three months, the mean significant wave height and period were 1.34 m and 7.36 s, respectively.

Comparison of computed and measured mean beach profiles is shown in Fig. 7 along with the standard deviation. From the observed data (solid line and solid-circle line), the values of standard deviation rapidly increase from x = -60 m and they become approximately 0.14 m at the seaward of x = -30 m.

From the calculated results of the present model (bold solid line and solid-square line), the mean beach profiles from x = -70 m to -45 m show better fits compared to those of the previous model. Regarding the standard deviation, the values from x = -35 m to -20 m are highly improved, and the values from x = -60 m to -15 m are also in good agreement with the observed data. However, the values of the area offshore of x = -10 m rapidly decrease. This is because the sediment transport rates of berm formation and erosion were assumed to take constant values near the offshore boundary (see Fig.

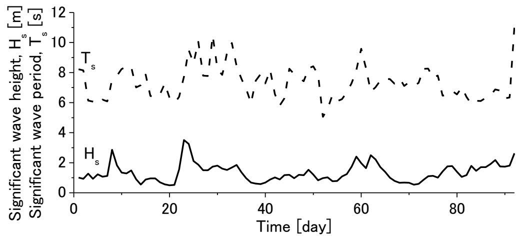

Fig. 6 Time series of observed significant wave height and significant wave period from May 1 to July 31, 1988.

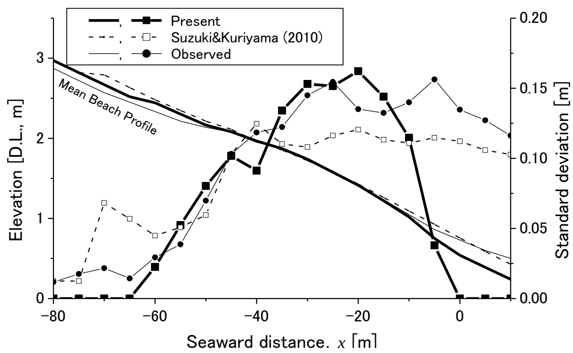

Fig. 7 Comparison of computed and observed mean beach profiles with the standard deviation.

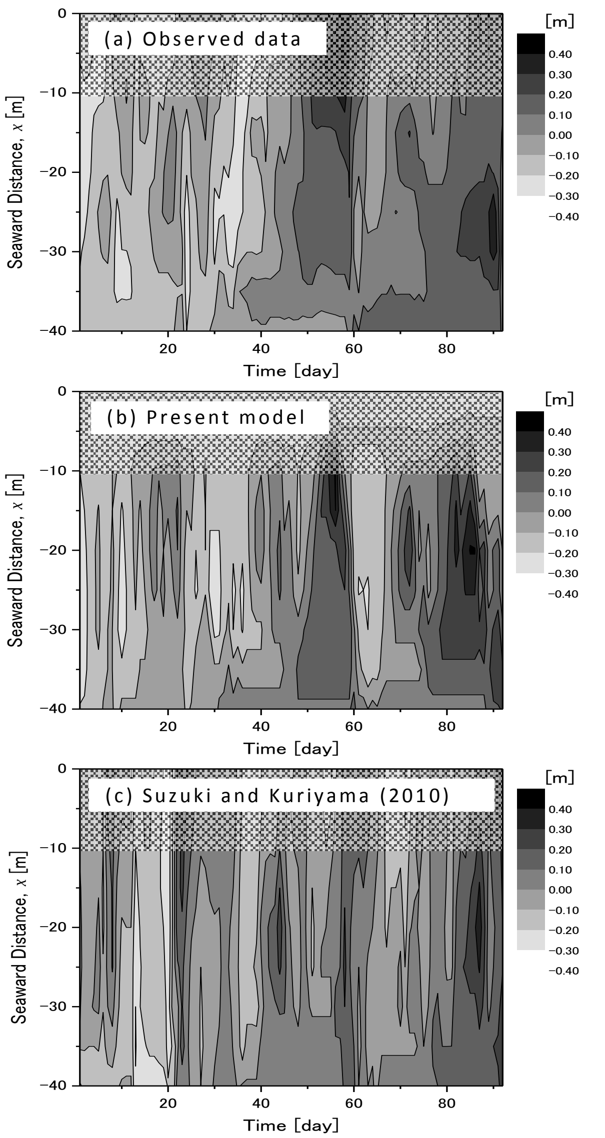

Fig. 8 Time series of the deviation of beach profiles from the mean beach profile: (a) Observed data, (b) Present model, and (c) Suzuki and Kuriyama (2010).

3). Therefore, the present model application is considered to be valid in the region from x = -10 m to the onshore end.

Comparison of a time series of observed and computed deviation of beach profiles from the mean beach profile is shown in Fig. 8; (a) observed, (b) computed using the present model, and (c) computed using the model of Suzuki and Kuriyama (2010). Since the offshore area more than x = -10 m is out of the consideration, the area was hatched.

Computed results of the present model are more consistent with the observation than those of the previous model in terms of the beach profile change related to berm erosion observed from the 50-day to 60-day and berm formation from the 70-day. The present model is thus highly improved compared to the previous

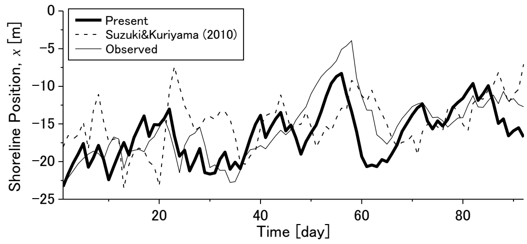

Fig. 9 Comparison of shoreline positions of the high tide level.

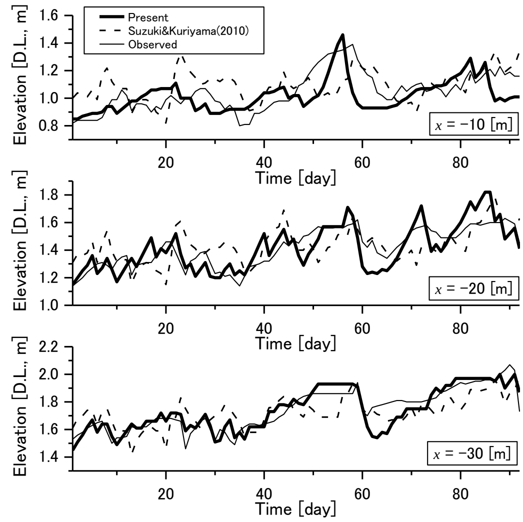

Fig. 10 Comparison of observed and simulated time series distributions of the ground elevation level at the cross-shore locations of x = -10 m (top), -20 m (middle) and -30 m (bottom).

model. However, the simulated cross-shore location of the berm formation area from the 50-day to 60-day is slightly landward compared to that of the observed data. This discrepancy may be attributed to the error of the estimated locations of the onshore and offshore boundaries.

Fig. 9 shows temporal distributions of shoreline positions of the high tide level (D.L., 1.25 m). Although the calculated results are underestimated from the 50-day to 70-day, the trend of the overall shoreline movement is basically similar to that of the observation. The reproducibility of the oscillatory movement is improved in the present model for the most of the period. The correlation coefficient between the observed data and the calculated results of the previous model and the present model are 0.33 and 0.70, respectively.

Temporal distributions of the ground elevation level at the cross-shore locations of x = -10 m, -20 m and -30 m are shown in Fig. 10. From the figure of the ground elevation level at x = -10 m, the oscillatory movement of the present model from the 45-day to 65-day is less than that of the previous model, which is more consistent with the observation. It can thus be said that the present model can well reproduce not only the shoreline change but also the beach profile change.

Fig. 11 shows the correlation coefficients between observation and computation of the ground elevation levels at each cross-shore location for the present model and the previous model. Although both the correlation coefficients decrease toward the offshore direction, the value of the present model is higher than that of the previous model at every location, whose averaged values for the present and the previous models are 0.73 and 0.45, respectively.

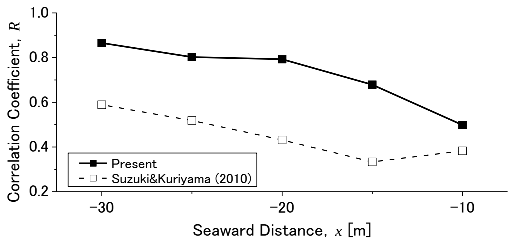

Fig. 11 Correlation coefficients between observed data and calculated results of ground elevation at each cross-shore location

CONCLUSIONS

The short-term swash zone beach profile change model developed by Suzuki and Kuriyama (2010) focusing on berm formation and erosion was enhanced. The sediment transport rate models for berm formation and erosion were re-examined, and an improved model was proposed. This model was applied to reproducing observed three months beach profile change. The model was evaluated comparing the results with the observed and computed results using the previous model.

Conclusions obtained in the present study are as follows: (1) A short-term swash zone beach profile change model focusing on berm formation and erosion was re-examined. The sediment transport rates for berm formation and erosion are modeled by using the wave energy flux and the product of the wave height of long-period wave and berm height, respectively. (2) During the three months calculation, the present model can well predict the trend of the beach profile changes of berm formation and erosion, and the observed repeatability was improved compared to the previous model. The correlation coefficients of the shoreline position of the high water level and the ground elevation level increased from 0.33 and 0.45 to 0.70 and 0.73, respectively.

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