

## CHAPTER 176

## Field Observation and Numerical Simulation of Beach and Dune Scarps

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### ABSTRACT

Beach and dune scarps are prominent erosional features and probably interfere with post-storm beach profile recovery because of wave reflection on the scarp face during high tide and reduced swash height. As examples, beach and dune scarps, created by typhoon waves on the Pacific Coast and on the East China Sea Coast in Kagoshima Prefecture, were investigated. The highest scarp elevation on these coasts were found to be approximately to 7 m on the Pacific Coast and 10 m on the East China Sea Coast. Following the field observation, a numerical study was conducted to study the generation of scarps.

### INTRODUCTION

A sandy beach and dune will be vulnerable to storm waves and storm surge when a severe storm approaches to a coastal zone. These high waves will change cross-shore profile significantly and cause shoreline recession. Following beach and dune erosion by a storm, a beach profile recovery process will take place under the incidence of ordinary waves. This process probably correspond to a ordinary profile suggested by Johnson (1949). Regarding cross-shore profile recovery, it is mentioned by Kriebel (1986) that "Time scales of beach profile recovery are highly variable. It is generally known that recovery processes occur on much slower time scales than erosion. As observed by Meyer (1936); " the time required for the bar to move shoreward under normal conditions is four to six times as long as to form the bar during storm conditions." Recovery typically occurs over time scales of several days to several months. In some extreme cases, recovery may take on the order of several

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years due to the infrequent onshore motion of sand in deeper water. On the other hand, observations immediately after the peak of a storm indicate that a large portion of the eroded volume may recover within one to two days, seemingly accelerated by elevated water levels and fairly energetic but constructive wave conditions." The study at Ocean City, Maryland by Randall and Kraus (1993) also suggested that large amount of profile recovery occurred during the last part of storm condition.

The recovery process depends on the wave condition during and after the storm, as well as on the post-storm beach profile such as scarps and longshore bar features, because the cross-shore profile interacts with a wave transformation and effects the resulting cross-shore sediment transport rate. Beach and dune scarps are significant erosional features and probably retard post-storm recovery by ordinary waves, because some of the low steepness waves with constructive force under the normal circumstance have undermined a foot of scarp and reflected by a vertical scarp face during high tide. As an example, the dune scarp was caused by the Typhoon 9119 in Kashiwabara beach, Kagoshima in 1991. The height of dune scarp was nearly 7 m according to the Minami Nippon Daily Newspaper. Once these scarp features are generated by storm waves, potential risk for properties behind the dune/beach will increase, because there is either only a narrow beach or no beach at all to dissipate incident wave energy and to resist destructive forces of successive storms. Since the average annual wave height along Japan Coast has increased in the last decades and the sediment supply from river is decreasing due to the structures placed in river, again it seems that the rate of beach profile recovery might be slower compared to the last decades. Therefore, from an engineering point of view, it is important to collect the data of erosional features and antecedent recovery process for the purpose of improving shore-protection and coastal management. It is also recognized that dunes have several functions, such as (i) serving as soft structures against storm surge and severe wave attack including tsunami waves, (ii) filtering effect of wind blown sand and salt by the coastal forest on and behind the dune, (iii) sediment source to the foreshore and longshore bar in a severe storm condition, (iv) a habitat and nesting area for sea animals and vegetation, (v) a setback area for the sea-level rise as well as storm surge, and (vi) a recreational area for local residents and tourists, etc. Therefore, proper dune management is very important.

Regarding numerical studies of dune erosion, there are several numerical methods, from two dimensional to quasi-three dimensional, to predict the dune erosion quantitatively. (Vellinga (1983, 1986), Kriebel and Dean (1984, 1985), Stieve and Battjes (1984), Sargent and Birkemeier (1985), Larson and Kraus (1989, 1990), Kriebel (1990), Wang and Miao (1992), Steetzel (1993), etc.) However, there is very little knowledge of physical processes on the beach and dune erosion and resulting scarps under a severe storm condition. (For instance, Kana (1977), Vellinga (1986), and Fisher (1986)). It is necessary to obtain enough physical knowledge on dune erosion process, however it is almost impossible to obtain a data set of beach and dune profile evolution just before and during the storm activity in the natural condition. Therefore, field surveys are usually carried out between and after storms.

Strictly speaking, the beach profile after the storm contains an information of beach profile recovery, since the waves may have high constructive force in the last part of storm period according to several beach profile predictors, for instance Kraus et al. (1991).

In the current study, field observations were conducted to study the geomorphological features of dune and beach scarps, and generation of scarp by storm waves. Based on these field observations, a numerical study has been carried out to simulate the scarps.

## FIELD OBSERVATION OF SCARPS

The coast line of Kagoshima Prefecture, which exceeds 2200 kms, suffered extensive damage by two of the biggest typhoons in this century, one in 1991 and the other in 1993. Due to these recent and successive severe typhoons, beach and dune scarps have been generated along the Fukiage coast which extends about 30 km south to north on the East China Sea, and along the Shibushi coast which extends about 8.2 km on the Pacific Coast in Kagoshima. The locations of these two coasts are shown in Fig. 1.

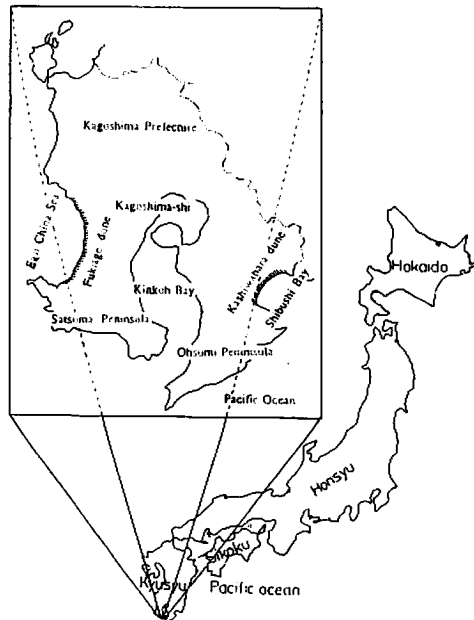


Fig. 1. Locations of study areas

### Cross-shore processes

The maximum height of dune scarp at Fukiage Beach was nearly 10 m, and an initial stage of dune scarping is shown in Fig 2. It can be seen that the dune has a steep seaward slope, and has a vertical face at the foot of the dune which was truncated by waves. Other field surveys have been carried out at Kashiwabara Beach on the Pacific Ocean Coast. Since dune scarp, beach nourishment, and beach scarp after the nourishment have alternatively appeared in this study area, the physical processes in this coast are probably particularly attractive from coastal engineering view point. Therefore, scarps in this area are mainly discussed in this paper. General characteristic of this coast are shown by a series of photographs, and then the longshore distribution of scarps will be discussed based on the field data.

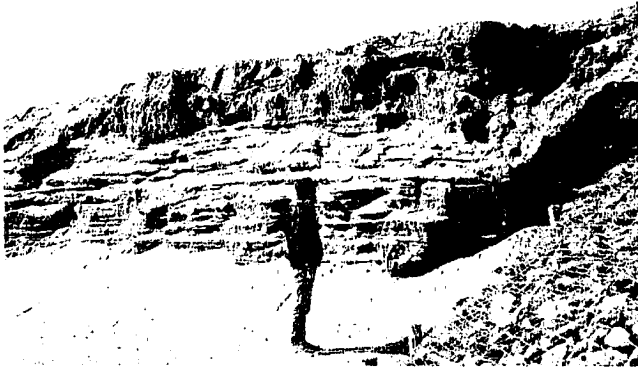
Dune scarps at Kashiwabara Beach caused by Typhoon 9119 is shown in Fig 3. The photograph was taken one year after the Typhoon 9119, thus the foot of the dune is partially filled by onshore sediment transport. The height of dune scarp just after the Typhoon was about 7m according to the local newspaper (Minami Nippon Daily News), and the height of scarp shown in Fig. 3 was about 5 m. Because the shoreline and the crest of the dune regressed further landward, there was little foreshore remaining to dissipate wave energy. As a result, part of the coastal forest on and behind the dune was damaged by the collapse of dune and by the wind-blown salt. To protect the coastal forest and properties, a beach nourishment project was carried out in the beginning of 1993. The nourishment project area shown in Fig. 4 extends 2 km to cover the highly eroded beach. A few months after the beach nourishment project, storm waves caused by one of the biggest typhoons in this century, Typhoon 9313, for which the lowest pressure was 914 hp(mb), affected the project area, and produced beach scarps which extended along the whole nourished beach. Beach scarps in the central area of the project is shown in Fig. 5. In contrast to the nourished beach, there was little beach scarp at the neighboring natural beach. This difference probably arose from the fact that the nourished nearshore beach profiles was much steeper than the natural or equilibrium beach profile. The field survey showed that the maximum height of beach scarp was close to 3m where the shoreline retreated significantly landward. In addition, it was noted that the most severe damage was located in the same area as that of the heaviest dune scarp area produced by preceding Typhoon 9119 which caused a maximum of 7 m dune scarp.

To reduce further beach and dune erosion by an antecedent typhoon, it is necessary to accurately estimate the beach and dune profile before and after the typhoon. Then, the behavior of the dune and beach profile under the action of another storm can be predicted. Unfortunately, in the present case, beach profile data before the typhoon was not available to the authors and the field data were collected only after the generation of dune and beach scarps.

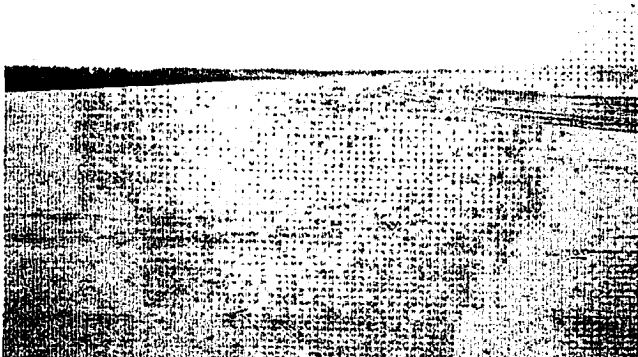
Field observations showed that swells with low steepness during high tide easily reach to the foot of scarp and undermine the vertical scarp face, while a low steepness swell has the constructive force in general. Following the undermining, the



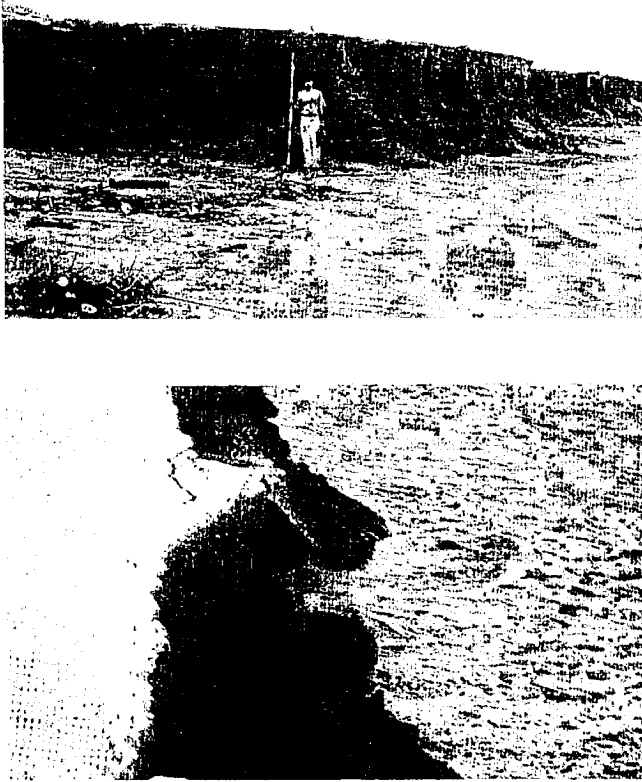
**Fig. 2. Small dune scarp at Fukiage Beach**



**Fig. 3. Dune scarp by Typhoon 9119 at Kashiwabara Beach, 1992  
(Photograph taken one year after the typhoon)**



**Fig. 4. Beach nourishment at Kashiwabara Beach in 1993.**



**Fig. 6. Moment of collapsing (the sand blocks are falling)**

vertical layer of sand above the scoured foot loses support and collapses around the foot of scarp, and is deposited at the foot with an angle of repose. Fig. 6 shows the moment of collapsing of a scarped face. The block of sand which is in motion can be seen in the middle of the figure. The sand deposited at the foot of the scarp is transported offshore by successive waves and probably supplies sand to enhance the generation of longshore bar. This cross-shore process repeats itself at the end of wave attack during high water level. Thus, beach scarp plays a role as a moving boundary for the wave and moving sediment source for which a sand layer with a certain thickness is cut from the scarp face at distinct moments in time. It is also expected that the cross-shore sediment transport rate has a peak at the position of scarp during the collapse of the scarp face. This kind of process was also noted by Vellinga (1986) that "The first series of waves reaching the dune front causes erosion and a consequent lowering of the beach just in front of the dunes. After a number of waves the foot of the dune is eroded to such an extent that the dune front becomes unstable. Then, a slice of sand of between 0.2 and 2.0 m thick

(depending on the height and form of the dune) slides down, forming a pile of sand at the foot of the dune. This volume of sand is then gradually eroded by the waves. After some 50 to 100 waves, the pile of sand is cleared away and a new dune front instability occurs. In course of time it takes longer and longer before the pile of sand is removed. The rate of dune erosion decreases with time."

### LONGSHORE PROCESSES

In contrast to the ordinary dune erosion which is two dimensional, scarp on this beach shows a longshore curved distribution. To see a planform, the beach width, defined as a length from the vegetation line to the crest of the scarp, is shown in Fig. 7. In addition, the height of beach scarp is shown in Fig. 8. There is a T-

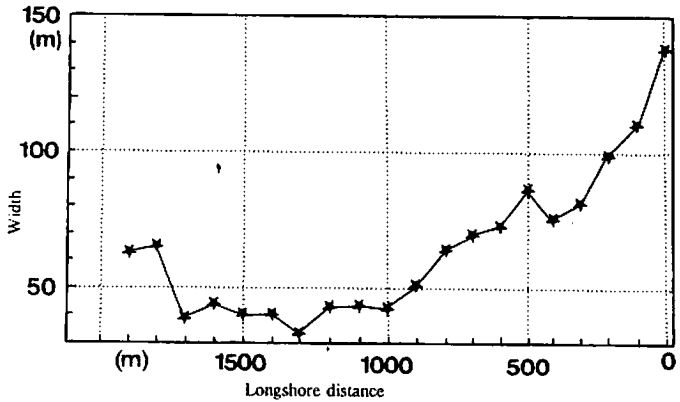


Fig. 7. Width of the beach at Kashiwabara Beach

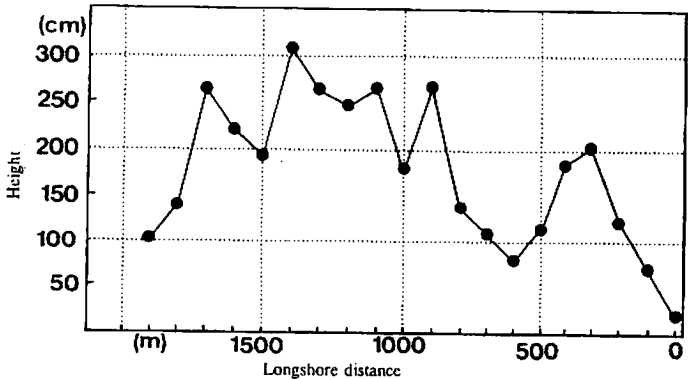


Fig. 8. Height of the beach scarp

shaped groin at the south end ( $x=0$  m) for which the longshore sediment transport further south is blocked at this boundary. It is seen that the beach is wider around the groin ( $x=0$ m), gradually decreasing in width to the north, and reaches a minimum width of 35 m at the location of  $x=1300$  m. Because of the narrow width of the beach in this area, waves break just near the dune and occasionally strong winds scatter the blown salt around the coastal forest. As a result, the coastal forest at this location has been damaged and many pine trees have withered. Also, the height of beach scarp was a maximum of 3 m around the area where the beach was the narrowest, and it was smallest at both the north and the south sides of the nourishment project area. It is noted that the position of the highest beach scarp caused by Typhoon 9313 was consistent with the position of the highest dune scarp caused by the Typhoon 9119.

## NUMERICAL TESTS

Based on the knowledge gained with the above field surveys, a numerical study was conducted to examine the cause of erosion and the generation of dune and beach scarps. Regarding numerical modeling of dune erosion, Vellinga (1983,1986), Kriebel and Dean (1984, 1985), Kriebel (1990) and other researchers have proposed two-dimensional cross-shore models. Here the SBEACH model (Larson and Kraus, 1989, 1990) has been applied to simulate dune and beach scarps. Because waves on a natural beach are random and their wave height distribution in offshore region might be expressed by the Rayleigh distribution, a simple model for the beach profile evolution due to random waves is also applied to simulate the dune erosion. Due to space limitation, the SBEACH model is only briefly reviewed.

### *SBEACH model*

The main structure of this model is composed of three sub-programs, (1) wave transformation, (2) cross-shore sediment transport, and (3) profile change calculated from conservation equation for bed material as the same in the other two-dimensional models. This model can be classified as semi-open model which uses an equilibrium beach profile concept. In contrast to the equilibrium concept which was originally developed by Dean (1977), Moore (1982) and Kriebel and Dean (1984), the SBEACH model simulates the generation of bar-trough features, avalanching, and some beach profile recovery. The wave transformation calculation is based on the model proposed by Dally (1984) and Dally et al. (1985 a,b) which is shown by Eq.(1).

$$\frac{\partial}{\partial x} (F \cdot \cos \theta) + \frac{\partial}{\partial y} (F \cdot \cos \theta) = \frac{\kappa}{d} (F - F_g) \quad (1)$$

where,  $F$  is the energy flux of progressive wave,  $\theta$  is the incident wave angle,  $x, y$  are coordinates normal and parallel to the coast respectively,  $\kappa$  is an empirical decay coefficient, and  $d$  is the total water depth which is the sum of still-water depth  $h$  and the mean water level  $\eta$ . In the present study, the wave angle is restricted to normal



incidence, so that the  $y$  component is negligible.  $F_s$  is the energy flux of a stable wave. The mean water level  $\eta$  is computed as follows;

$$\frac{\partial S_{xx}}{\partial x} = -\rho g d \frac{\partial \eta}{\partial x} \quad (2)$$

where,  $S_{xx}$  is the radiation stress,  $\rho$  is the density of the water, and  $g$  is the acceleration due to the gravity.

The cross-shore sediment transport rate in the surf zone is a type of energy dissipation model for which the transport rate is proportional to the difference between the actual wave dissipation per unit water volume,  $D$ , and the energy flux in equilibrium condition,  $D_{eq}$ . The local slope term is also added to the transport rate to account for the slope effect as shown :

$$q = K(D - D_{eq} + \frac{\epsilon}{K} \frac{\partial h}{\partial x}) \quad (3)$$

where,  $q$  is the net cross-shore sediment transport rate,  $K$  is an empirical coefficient for the sediment transport, and  $\epsilon$  is an empirical coefficient,  $h$  is a still water depth. To compute the depth change (profile change) in a time increment  $\Delta t$ , conservation equation for bed material is used as;

$$\frac{\partial h}{\partial t} = \frac{\partial q}{\partial x} \quad (4)$$

## NUMERICAL RESULTS

Because the natural beach with mild foreshore slope showed less damage compared to the nourishment area in Kashiwabara beach, the effect of beach slope on the generation of scarps was studied, first. Regular waves were applied for a plane beach with 1/10, 1/15, 1/20 uniform slope, respectively. Numerical results of the beach profile evolution and resulted scarps are shown in the Fig. 9 for regular waves with height 2.3 m and period 6.0 sec. It is seen that the shoreline was retreated as the wave duration increased, and sediment which was eroded around the shoreline was transported offshore to generate a longshore bar. The resulting scarped face migrated shoreward, while the shoreline retreated. It is clearly seen that the steeper is the initial beach profile, the higher is the resulting beach scarp. It appears that the numerical predictions agrees qualitatively with the field data.

Second, a composite dune-beach profile was used to generate dune scarp under a steady storm surge condition. It meant that the storm surge level did not vary in time. A 1-m and 2-m steady storm surge was added to the still water level.

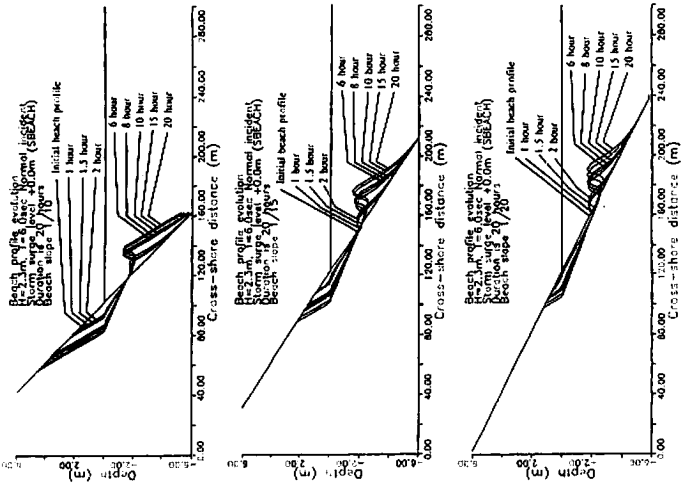


Fig. 9. Calculated beach profile evolution on beaches of different slope

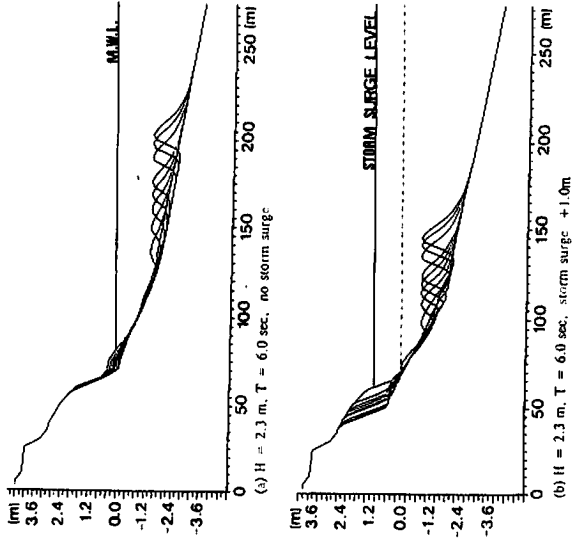


Fig. 10. Dune erosion during storm surge

Numerical results for the case of no increase in water level, and 1-m increase in water level during the storm are shown in Fig. 10. It is seen that longshore bars were generated by waves and migrated offshore with the passage of time. Corresponding to the migration of longshore bars, the sediment around the shoreline was transported offshore and then the dune erosion started. The resulting dune scarp became higher, while the cross-sectional area of dune erosion widened with time. In addition, it is clear that the larger the increase in water level due to storm surge, the higher the dune scarp for these cases. This is interpreted that the slope of the dune face is usually steep compared to the foreshore slope, so the slope where the stormy waves act probably is steeper during a high increase in water level. Therefore, the dune profile is eroded much more and as a result higher dune scarp appears.

Since the dune material is usually finer than the beach material, it is more easily carried away by the storm waves. However, the effect of different grain sizes between beach and dune is not taken into account in the present study. Vegetation also functions to strengthen a dune face, but its role is not taken into account in the present study.

As shown in Fig. 7 and Fig. 8, the beach scarp in this study area exhibits a longshore curved shape in terms of height and width. This curvature was perhaps caused by a negative gradient of longshore sediment transport. However, there was little shoreline progress along the coast even at the T-shaped groin just after the Typhoon 9113, though storm waves caused a significant beach erosion at the central area of nourished beach. It is expected that if the longshore sediment process mainly governs the topography change at this area, the area beside the groin should prograde or a part of the beach should widen, but there is little evidence to show such shoreline changes in this study area. Therefore, it is believed as a first step of the research that the longshore curved beach scarp was probably caused by an incident wave field which has a longshore uneven wave height, caused by an artificial island in front of the study area and dredging hole in the offshore region, and is mainly manifested in the cross-shore sediment transport. It is noted that this assumption need to be verified by a bathymetry data covering the area from the dune to beyond the depth of closure for considering the sand budget and a direction of sediment movement. However, such data were not available for this study.

The uneven longshore wave height distribution was calculated by eq. (5)

$$H(y) = H_1 + H_2 \sin^2\left(\frac{2\pi}{400}y\right) \quad (5)$$

where,  $H(y)$  is the wave height at shoreline position  $y$ .  $H_1$  was set to be 1.0 m, and  $H_2$  was set to be 3.0 m. Based on this wave height distribution, beach profile evolution and scarp were computed at 50 m spatial intervals alongshore. Fig. 11 shows a numerical result for this case. In accordance with the field data, the

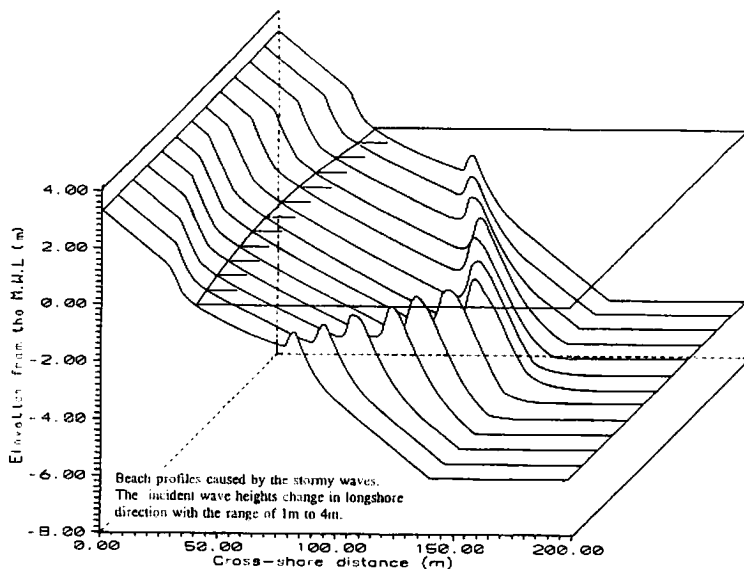


Fig. 11. Longshore curved scarping calculated by numerical model

numerical result shows a longshore curved scarp as well as curved longshore bar. The height of the beach scarp in the central region is the highest corresponding to the height of incident wave height. The crest line of the scarp also shows a curved longshore distribution.

## CONCLUDING DISCUSSION

The general characteristics of the dune and beach scarps at the Fukiage beach and the Kashiwabara Beach, Kagoshima, were investigated in field surveys. Dune scarp caused by the Typhoon 9119 and beach scarp by the Typhoon 9313 show similar longshore curved distribution. It was observed that once a vertical scarp face was generated, the waves directly attacked the scarp face during high water and undermined the foot of the scarp. As a result, blocks of sand collapsed, deposited at the foot of the scarp and was transported offshore by successive waves. This is a straight-forward process and agreed well with a set of physical model data by Detté et al. (1992). In addition, there was little evidence to show that the negative gradient of longshore sediment transport dominated the scarp generation in this study area. It was also shown by a numerical study that the steeper is the beach face the higher is the resulting scarp.

The sediment budget in the study area should be confirmed in the future. It is expected that the direct measurement of scarp generation and the recovery process at the foot of scarp are required for further investigations. The estimation of the sand movement in the offshore region and depth of closure due to extreme typhoons is

also necessary, because it could be a source of onshore sediment transport during the beach profile recovery. Although it is not discussed in this paper, there is a man-made island of 192ha area and also a dredging area near the study site which strongly affect local wave fields and result in the change of planform of the beach. Before the Typhoon 9119, the planform of the beach was significantly changed by a construction of the man-made island and was narrowed especially around the area where dune and beach scarp had been generated by severe storm waves. Thus, a further study of the wave field affected by islands can help the proper coastal management at this area.

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