B−10.4 Deformation of Barrier Islands due to Sea Level Rise and Barrier Preservation (Final Report)

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Abstract

(1) CSIRO(1992) estimated that the sea level rise would be 15 − 90cm in 2070. Since sea level seems to rise faster than expected, sea level rise rate was estimated to become 0.15 − 0.75 cm/year in 2010 and 0.18 − 1.01 cm/year in 2070.

(2) It was found that the distribution of barriers are global. Because the barrier has a lagoon, which is precious environment and is utilized for navigation etc., it can be said that the barrier is one of the characteristic landforms that should be conserved.

(3) A hydraulic experiment on 1/100 seabed slope showed following; Under the condition of fluctuating water level and wave height, several large−scale bars may be formed due to sectional coastal process. The large−scale bar closest to shore may become a barrier with a lagoon if the water level settle abruptly.

(4) A hydraulic experiment focusing on the deformation of barrier showed that the barrier moves toward the land as the water level rises.

(5) It was suggested for the countermeasure against extinction of barrier due to the sea level rise that widening barrier by beach nourishment is effective. In case that a coastal structure cuts the littoral drift, sand bypassing is also effective. Furthermore, these countermeasures should be appreciated because they use built−in beach stabilizing mechanism of nature.

Key Words sea level rise, barrier, lagoon, barrier formation process, countermeasure.

Ⅰ. Introduction

The temperature of the lower atmosphere has increased by 1.5 to 4.5 ° C as the concentrations of greenhouse gases such as carbon dioxide increase, triggering the thermal expansion of salt water and the melting of mountain glaciers and polar ice sheets, and eventually resulting in sea level rise. This is the mechanism of sea level rise caused by global warming. To evaluate the effects of sea level rise on coastal areas, we must be able to predict how global warming will progress in the future. The role that Japan should play as an advanced country in the Asian region is to take a leadership role in studying associated effects and policies in the east Asian region.

A barrier island is a flat sedimentary landform found in coastal areas. Being a serene sea area, a lagoon inside a barrier is an important, biodiverse coastal feature that is utilized for marine transportation and living aquatic resources. Since relative sea level fluctuations are assumed to affect the barrier formation in both of these formation processes, existing barriers are considered to be vulnerable to sea level rise caused by global warming, a problem that has recently attracted global attention.

Therefore, it is necessary to identify the deformation mechanism of barriers and design methods to preserve them. After a literature review on the global distribution and formation processes of barriers and lagoons.

Ⅱ. Scenarios of Sea Level Rise

In 1990, two years after its inception, the Intergovernmental Panel on Climate Change (IPCC) presented several scenarios of sea level rise in which global warming continues in the future. The "business as usual" scenario is the one most often used to evaluate the influences of sea level rise. "Business as usual" assumes that the present state continues as is without any effective restrictions on greenhouse gas emissions. According to this scenario, sea level had been estimated to rise by 21 - 27 cm by 2070 as shown in Figure 1.

Since 1990, however, the model has been revised. CSIRO(1992), for example, estimated that sea level will rise by 15 - 90 cm by 2070, which was corrected on the basis of IPCC (1990). On the other hand, since sea level has been rising faster than predicted, it is now expected to rise by 0.15 - 0.75 cm/year by 2010 and 0.18 - 1.01 cm/year by 2070.

Ⅲ. Review of Barrier Literature

First, the authors conducted a literature review of research papers such as "Barrier Islands" (Schwartz, 1973), "Barrier Islands" (Leatherman, 1979), and "Barrier Islands Handbook" (Leatherman, 1982).

Figure 2 shows a distribution map. Barriers are few in number along the

Pacific coast: Alaska and California and the west coast of North America; the west coast of South America; and the east coast of Japan on the other side of the Pacific. On the other hand, barriers are numerous along the Atlantic coast, i.e., from Washington, D.C. to Florida on the east coast of North America, all on the east coast of South America. On the west coast of Africa on the opposite side of the Atlantic, barriers are distributed sporadically of South Africa. Accordingly, barriers are more common along the Atlantic coasts than along the Pacific coasts.

In addition, barriers are numerously distributed along the coasts of the Mediterranean Sea and the North Sea, while some barriers are seen along the coast of the Indian Ocean, the south coast of Australia, and the north coast of Alaska. These distribution patterns suggest that barriers are not peculiar to the tropics, but are a major coastal landform that is found around the world.

Figures 3, 4 and 5 show the schematic diagrams of three typical theories of barrier formation processes. The first theory holds that a spit formed at a headland develops along the coast; then, it is disjoined when it attains a certain length, by which a tidal inlet is formed, which in turn forms a barrier island (Figure 3). The second theory holds that a sand dune formed on land turns into a barrier island due to a relative rise in sea level (Figure 4). The third theory holds that a bar formed under the sea level emerges onto the surface due to a relative lowering of the sea level, and becomes a barrier island (Figure 5).

Since various conditions surrounding the barriers around the world differ depending on each marine area, and their formation processes vary accordingly, it is unlikely that only one of these three theories is true. Thus, it is important to clarify barrier formation processes by conducting validation experiments and in-situ investigations.

Ⅳ. Two-dimensional Model Experiment on Barrier Formation Processes

Given that clarification of barrier formation processes is required as mentioned above, a two-dimensional model experiment was conducted to study the barrier formation processes when inshore-offshore sediment movement plays the main role. On the basis of the third theory (Figure 5) of barrier formation process, it was tested whether or not a barrier could be formed by two-dimensional deformation of a coast with a gentle gradient by varying water levels and wave heights.

For the experiment, a model beach with a sea floor gradient of 1/100 was made by using sand with a median diameter of d50 = 0.3 mm, which was placed inside a 0.6 m-wide, 1.5 m-high and 150 m-long two-dimensional water channel (Figure 6). Four test cases were established by combining four different water levels and three different wave heights.

Figure 7 shows the topographical changes when the water level was fixed at

$Z = 0$ cm and the period at $T = 1.76$s, while the wave height was varied with time (Case 1). During $t = 0-8$ hr when waves with a small height of around 5 cm were set in motion, there were no major geomorphological changes except for some sand ripples. During $t = 8-16$ hr when the wave height was raised to 10 cm, a bar was formed near $Y = 18$ m. At $t = 16-24$ hr when the wave height was further raised to 15 cm, the seaward side of the bar was eroded, and the sediments that came off the bar accumulated on the shoreward side of the bar.

Thereby, the bar widened slightly and shifted toward the land. Here, the height of the bar top was $Z \quad -5$ cm, and the bar did not emerge above the water surface. When 10 cm-high waves were set in motion during $t = 24-32$ hr, partial clapotis appeared because of the bar formed up to $t = 24$ hr, and a new large-scale bar with a height of about 20 cmand an inter-trough distance of about 7 m was formed on the seaward side of the initial bar, sharing the same starting point. Finally, when 5 cm-high waves were set in motion for 8 hours ($t = 32-40$ hr), almost no changes occurred. Consequently, three bars were formed in total.

Figure 8 shows a two-dimensional deformation when the wave height was fixed at about 10 cm and the period at $T = 1.76$s, while the water levels were changed with time (Case 2). During $t = 0-8$ hr when the water level was set low at $Z = -5-0$ cm, erosion occurred at $Y = 24-27$m, sedimentation occurred at $Y = 22-24$ m and $Y = 27-30$ m, and a bar was formed at $Y = 23$ m. During $t = 8-16$ hr when the water level was set at $Z = 5-10$ cm, the area near $Y = 20$ m of the bar was eroded and the sediment that came off accumulated thinly on the shoreward side of the bar.

Then, during $t = 16-24$ hr when the water level was lowered to $Z = 0$ cm, another bar was formed near $Y = 16$ m. The top of this bar developed to a height of $Z \quad -5$ cm. Furthermore, when the water level was lowered to $Z = -5$ cm, the bar was eroded ($t = 28$ hr). Then, the water level was raised abruptly from $Z = -5$ cm to $Z = 10$ cm to create waves, by which another new bar was formed near $Y = 9$ m ($t = 36$ hr).

Consequently, a total of four bars were formed with tops near $Y = 9$, 16, 22, and 29 m, respectively, and their sizes were larger the farther they were from the coast. In addition, the height of the bar top at $Y = 9$ m at $t = 48$ hr was $Z = 2$ cm; this bar may become a barrier with a lagoon to be formed at $Y = 1-8$ m, should the water level drop abruptly from $Z = 10$ cm to $Z = 0$ cm, provided there are no waves acting upon it.

Figure 9 shows the topographical changes when both wave heights and water levels are changed with time (Case 3). During $t = 0-32$ hr when both the water level and the wave height were gradually lowered, a bar was formed near $Y = 17$ m, which was eroded on both the shoreward and seaward sides. In addition, two more bars with a small relative height were formed near $Y = 23$ and 29 m, respectively. During t =32–48 hr when both the water level and the wave height were raised gradually, three bars developed at Y = 17, 23, and 29 m, respectively.

Consequently, three large–scale bars with bar tops near Y = 17, 23, and 29 m, respectively, were formed. The bar sizes in Case 3 were larger than those in Case 1 (Figure 7) in which three bars were also formed. In addition, the bar size at Y = 16 m was larger than that in Figures 7 and 8, and its height at the top was Z = 0 cm. This bar is presumed to become a barrier with a lagoon to be formed at Y = 0–15 m, should the water level drop abruptly from Z = 10 cm to Z=0 cm, provided there are no waves acting upon it.

Figure 10 shows the topographical changes when the period is fixed at T = 1.46s and the wave height at Ho=10 cm, while the water level is changed from Z = 5 to Z = −5 cm (Case 4). The range of wave and water level fluctuations was made smaller than that in Cases 1, 2 and 3. During t = 0–24 hr when the water level was gradually lowered, a small bar with a top near Y = 15.21 m was formed.

During t = 24–40 hr when the water level was gradually raised, three bars with tops near Y = 13, 18, and 22 m, respectively, were formed. In comparison with Cases 1, 2, and 3, both the size of these bars and the distance between each bar was small. The small bar size may have been attributable to small wave conditions, and the distance between the bars may have been dependent upon the period.

A comparison of Cases 1, 2, 3 and 4 reveals that a bar, once formed, will develop into a large–scale bar when the water level increases. This is a reproduction of the processes at Stages 1 and 2 in Figure 5. However, since the large–scale bar never became part of the land when waves were acting upon it, the processes of Stages 2 to 4 could not be reproduced. Thus, a hypothesis of an abrupt, relative lowering of the sea level is required to explain the phenomenon that a large–scale bar emerges and becomes connected to the land.

Ⅴ. Existing Research on the Effects of Sea Level Rise on Barriers

Being a low–elevation landform, a barrier is vulnerable to the effects of sea level rise, which can be explained in terms of coastal engineering, respectively, as follows:

From the viewpoint of coastal engineering, a coast where a barrier with a lagoon exists is subject to deformation due to sea level rise. According to Dean and Maurmeyer (1983), the topographical changes in a lagoon occur up to the water depth h' as illustrated in Figure 11, and the recession of the shoreline is given by the following equation:

$$R = S(L + W + L') / (h - h') \dots\dots\dots\dots (1)$$

where W is the barrier width; L', the width of the sediment movement belt in the tidal flat; and h', the critical water depth of sand transport in the lagoon. However, Dean's law is based on the hypothesis that the sea level increases at a slow pace and that the cross section of the beach changes to maintain geometrical equilibrium.

In addition, since the barrier is displaced toward the main land, the recession of the shoreline is greater than that of general beaches. Furthermore, the bar may be completely submerged when sand transport toward the coast is not sufficient to compensate the sea level rise. Since, in this case, the cross section of the beach is totally different from a conventional cross section, a shoreline recession which is much greater than that in Dean's law may occur. Therefore, equation (1), which was derived on the hypothesis of an equilibrium cross section, must be validated by experiments before applying it to actual situations.

Ⅵ. Experiment on the Barrier Deformation Processes Caused by Sea Level Rise

An experiment was conducted using a model beach with a sea floor gradient of 1/100 formed by using bottom sediments with a median diameter of d50 = 0.3 mm which was placed inside a 0.6m-wide, 1.5m-high, and 150m-long two-dimensional water channel (Figure 12). The study, conducted in fiscal 1993 (Tanaka, et al., 1994), has already proved that large-scale multistage bars form under the sea when waves are set in motion while changing water levels with time.

This time, the formation of such large-scale multistage bars was reproduced, and the large-scale bar closest to the shore when the water level was lowered was considered the initial topography. Then, the processes of its deformation were studied by varying the water-level rise. The wave conditions were set constant, i.e., Ho' = 10 cm and T = 1.79s, and no sediment was supplied to represent the lack of sediment supply from the seaward direction.

Figure 13 shows the barrier deformation processes when the water level was raised by 2.5 cm at 8-hour intervals (Case 1). The area of sedimentation at Y = 17 m at t = 48 hr when the water level was set at Z = −10 cm was regarded as a barrier, and the closed water area at Y = 15 −10 m on the coastal side of the barrier as a lagoon. Here, the height of the barrier top was about 10 cm (Z=0 cm) from the water surface, and the barrier width was about 2.2 m.

First, waves were set in motion for 8 hours at a water level of Z = −10 cm (t = 56 hr). Neither the barrier at Y = 17 m nor the lagoon on its shoreward side showed any significant topographical changes; thus, the barrier was stable under this water level condition. However, the large-scale bar near Y = 23 m was eroded, and the sand that came off accumulated on its seaward side, making the sea floor flat.

Next, waves were set in motion for 8 hours and the water level was raised by 2.5 cm to $Z = -7.5$ cm ($t = 64$ hr). The barrier became slightly narrower, since the seaward side of the barrier, which was stable at $t = 56$ hr, was eroded, but its shoreward side did not exhibit any changes. After setting waves in motion for 8 hours at a water level of $Z = -5.0$ cm ($t = 72$ hr), the barrier top was slightly augmented. After another 8 hours of same at a water level of $Z = -2.5$ cm ($t = 80$ hr), the barrier showed almost no changes. Consequently, the barrier showed no major changes during $t = 64$ hr - 80 hr, since the topographical deformation on the seaward side was greater than that at $Y =$ 20 m.

At $t = 88$ hr after the water level was raised to $Z = 0$cm to reach the barrier top, sand accumulated on the barrier top and the barrier moved shoreward. Furthermore, at $t = 96$ hr after the water level was raised by another 2.5 cm, the barrier height increased to Z 5 cm, and continued moving shoreward. Between $t = 48$ hr and $t = 96$ hr, the barrier height increased from Z 0 cm to Z 10 cm but its width decreased from 2.2 m to 0.8 m as the water level increased.

Figure 14 shows the barrier deformation processes when the water level was raised by 5.0 cm at 8–hour intervals (Case 2). The topography at $t = 48$ hr was roughly the same as in Case 1. After setting waves in motion for 8 hours at a water level of $Z = -10$ cm ($t = 56$ hr), the seaward side of the barrier was slightly eroded. As with Case 1, the large–scale bar near $Y = 23$ m was eroded and became flat.

After another 8 hours of wave motion but with the water level raised by another 5.0 cm to $Z = -5.0$ cm ($t = 64$ hr), the seaward side of the barrier was slightly eroded, and the sand that came off accumulated on the barrier top, increasing the barrier height, but generally unaffecting the barrier width. At $t = 72$ hr, after the water level was raised to $Z = 0$ cm to reach the barrier top, sand accumulated on the barrier top augmenting the barrier height to Z 5 cm, and the barrier was displaced shoreward and became narrower.

The barrier deformation processes when the water level was increased from $Z = -10$ cm to $Z = 0$ cm were the same as Case 1 in which the barrier height increased and the barrier width decreased, although the water–level rise per stage of Case 2 was greater than that of Case 1.

At $t = 80$ hr, after the water level was raised to $Z = 5.0$ cm to reach the barrier top, waves got over the barrier and came into the lagoon (overwash), by which the barrier top was eroded and finally destroyed. Then, after the water level was raised by $Z = 10$ cm, the shoreward side of the barrier became flat, and a small bar was formed near $Y = 3$ m. No overwash occurred in Case 1, since there was relatively little water–level rise per stage.

Accordingly, the barrier increased in height as the water level increased, and was displaced toward the land. On the other hand, since the water-level rise was great in Case 2, the barrier was destroyed due to overwash.

Figure 15 shows the barrier deformation processes when the water level was increased by 10.0 cm at 8-hour intervals (Case 3). Although the basic features were generally the same, the topography at t = 48 hr was slightly different from that in Cases 1 and 2, i.e., the barrier was wide, the barrier top was rounded, and the bar on the seaward side was high. After setting waves in motion for 8 hours at a water level of Z = −10 cm (t = 56 hr), the barrier remained almost unchanged, and the large-scale bar near Y = 23m was eroded and became flat as with Cases 1 and 2.

After having set waves in motion for 8 hours by raising the water level abruptly by 10.0 cm to reach the barrier top (t = 64 hr), the seaward side of the barrier was eroded and the sand that came off accumulated on the barrier top. The barrier height thereby increased to Z=7.5 cm, but the barrier width decreased from 2.5 m to 1.5 m. Since the barrier itself was the sediment source in this case, it developed while moving toward the land. At t = 96 hr, after the water level was increased to Z = 10.0 cm, which was higher than Z 7.5 cm at the barrier top, the barrier top was eroded and eventually destroyed.

Since the wave conditions were kept constant in the experiment, there were almost no topographical changes on the shoreward side of the barrier when the water level was controlled so that the waves did not get over the barrier. As for the geomorphological changes obtained by the experiment, the barrier merely moved toward the land as the water level increased.

On the other hand, Dean's law assumes that sedimentation occurs on the shoreward side of the barrier as the barrier moves toward the land with the increase in water level. This is because Dean's law considers the strength of waves as it is affected by gradual increase in water level. Thus, this is a matter requiring further study through experimentation.

Ⅵ. Conclusion

(1) CSIRO(1992) estimated that the sea level rise would be 15 − 90cm in 2070. Since sea level seems to rise faster than expected, sea level rise rate was estimated to become 0.15 − 0.75 cm/year in 2010 and 0.18 − 1.01 cm/year in 2070.

(2) It was found that the distribution of barriers are global. Because the barrier has a lagoon, which is precious environment and is utilized for navigation etc., it can be said that the barrier is one of the characteristic landforms that should be conserved.

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bars may be formed due to sectional coastal process. The large-scale bar closest to shore may become a barrier with a lagoon if the water level settle abruptly.

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References

CSIRO, Climate Change Scenarios for South and Southwest Asia, Division of Atmospheric Research, Australia, 1992.

Dean, R.C. and E.M. Maurmeyer, Models for Beach Profile Response, Handbook of Coastal Processes and Erosion, CRC Press, Ed. Boca Raton, Fla., 1983, pp. 151-166.

IPCC, Strategies for Adaptation to Sea Level Rise, Ministry of Transport and Public Works, the Netherlands, 1990.

Leatherman, S.P., Barrier Islands, Academic Press, New York, 1979, p. 324.

Leatherman, S.P., Barrier Islands Handbook, Maryland, 1982, p. 109.

Schwartz, M.L., Barrier Islands, Dowden, Huthinson & Ross, Inc., Pennsylvania, 1973, p. 451.

Tanaka, S., Da Ping Zhang, and K. Yamamoto, An Experimental Study on the Deformation of a Coast with Gentle Gradient under the Conditions of Changing Wave Heights and Sea Levels, Proc. Coastal Engineering, 1994, pp. 381-385. (In Japanese)

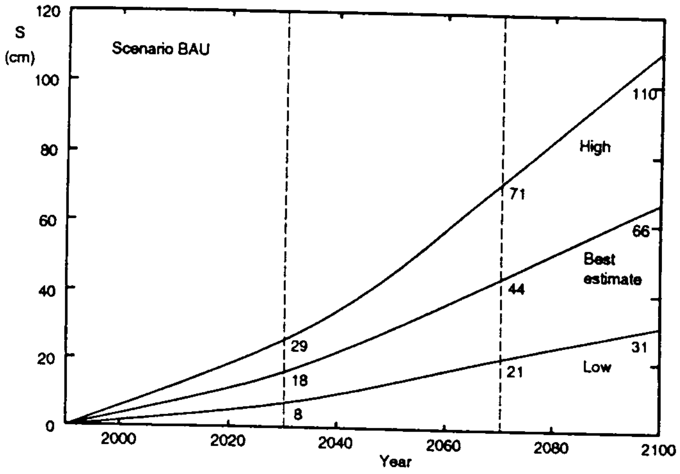
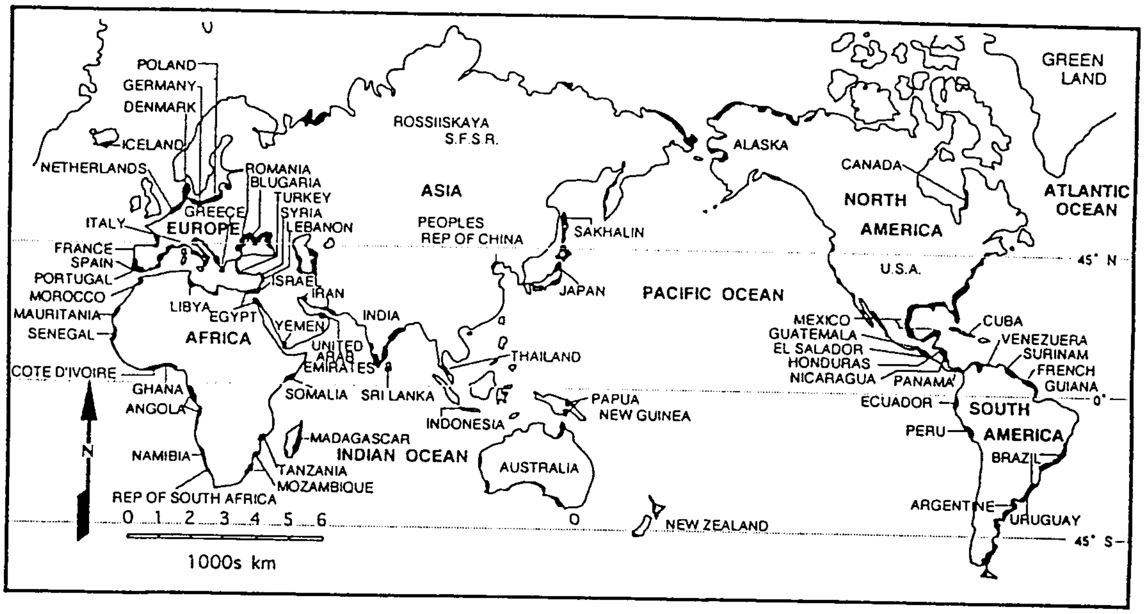


Figure 1



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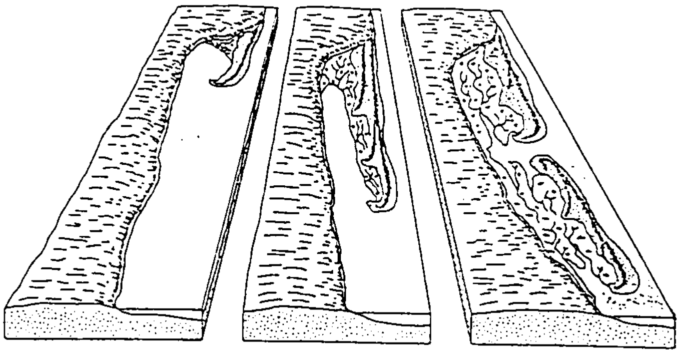

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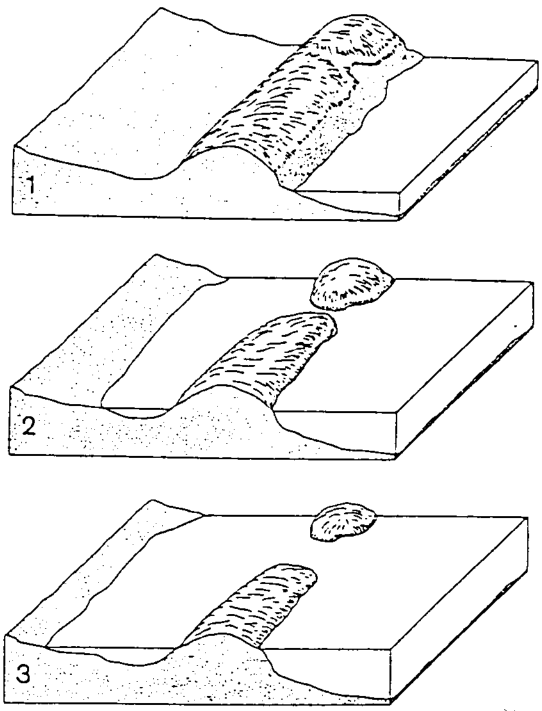

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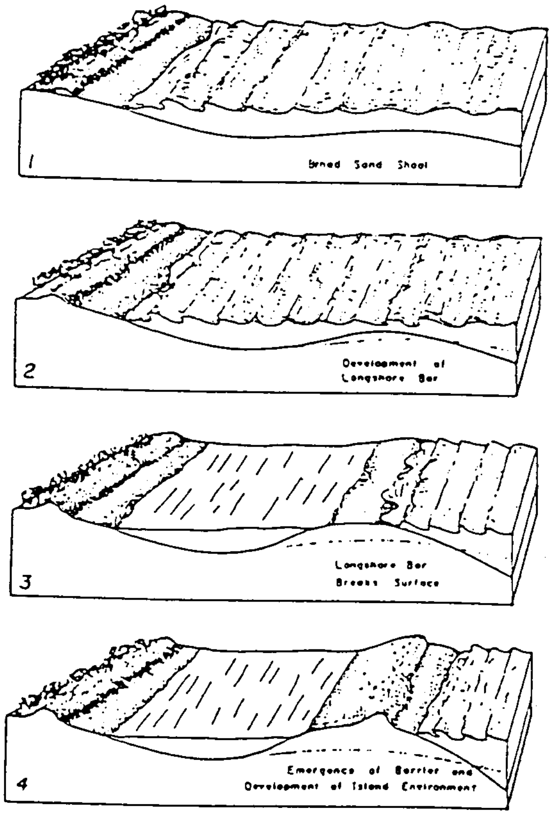

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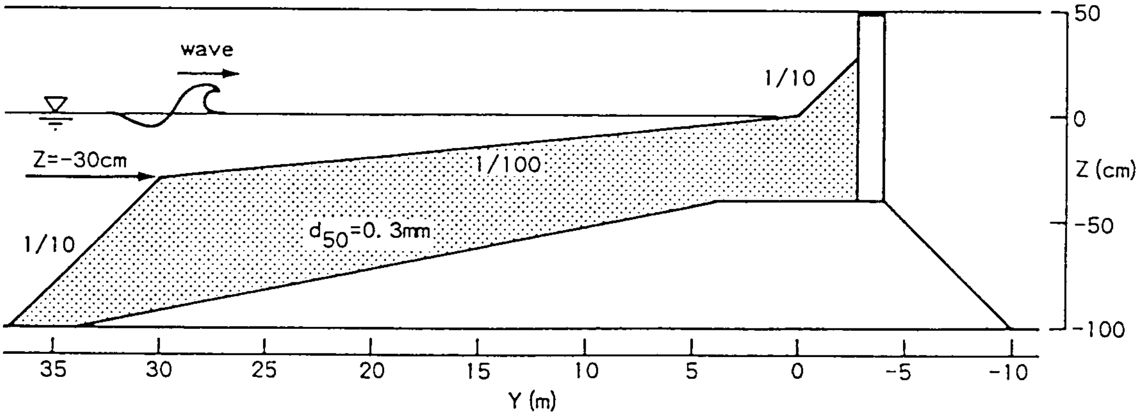

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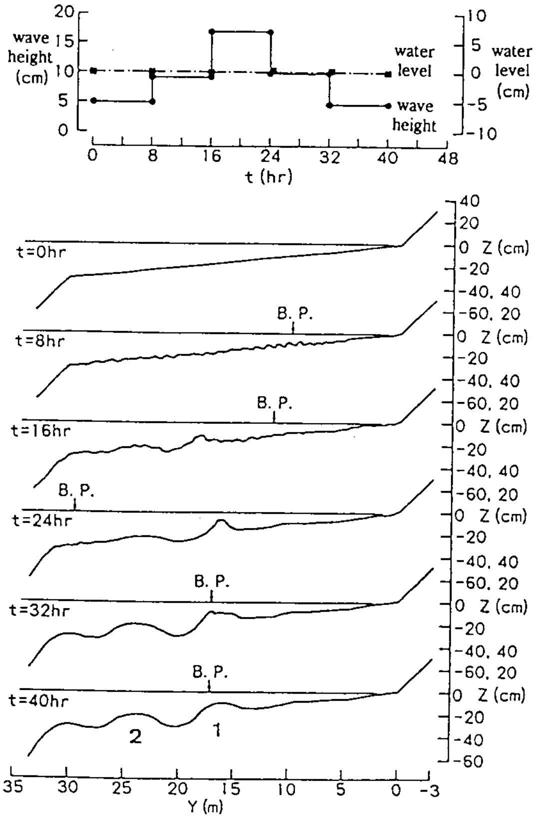

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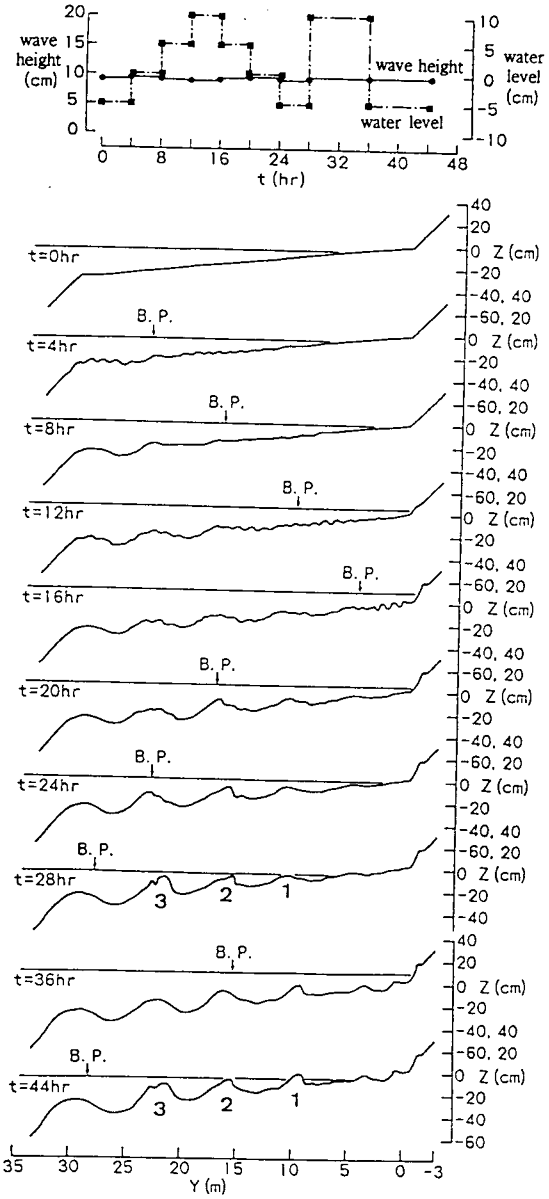

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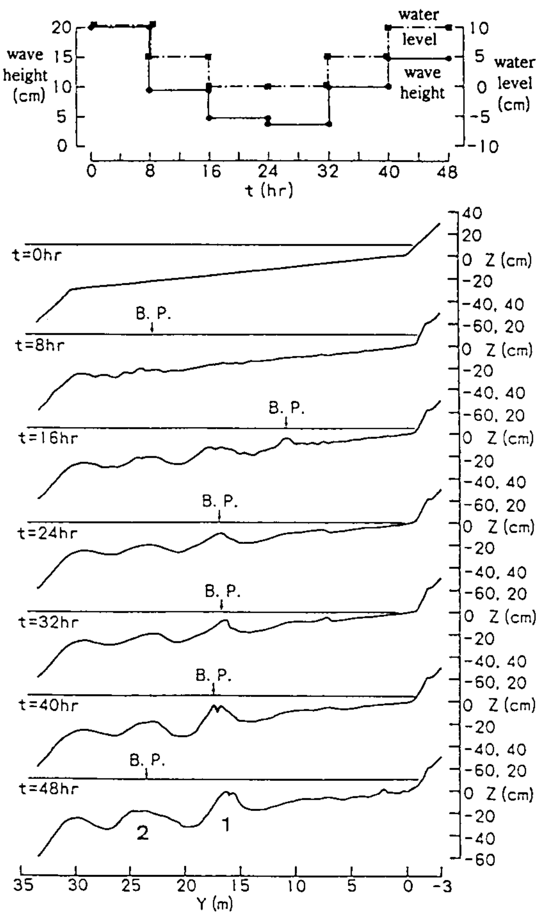

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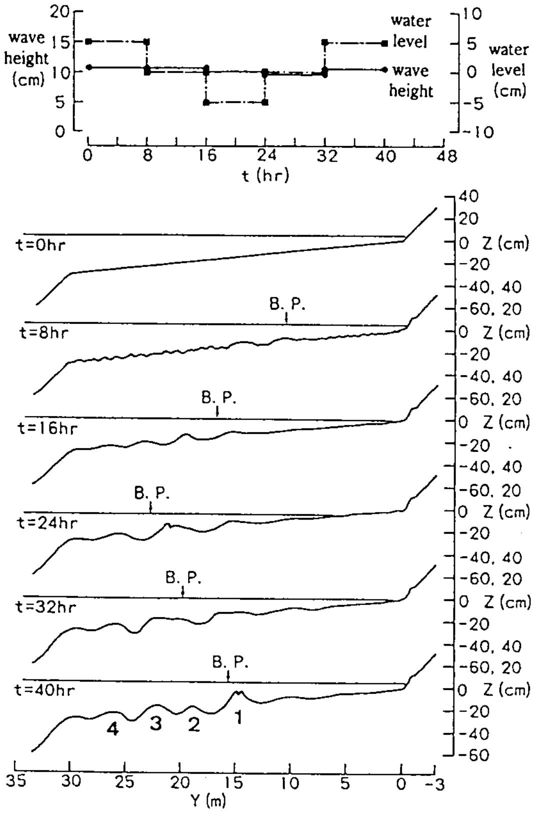
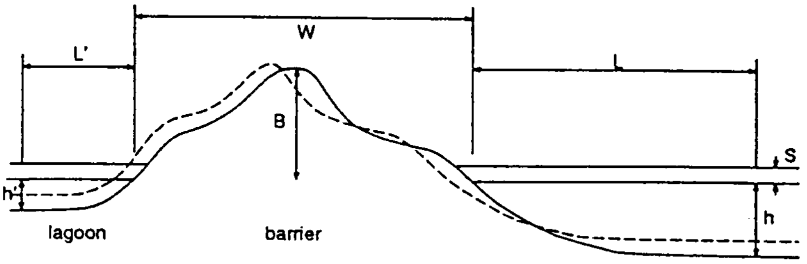


Figure 10



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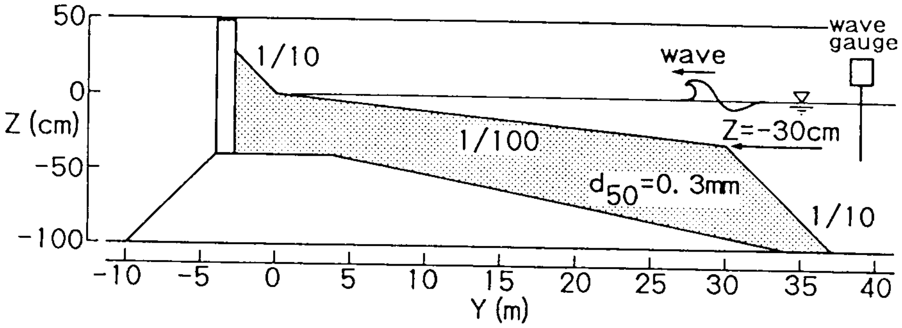

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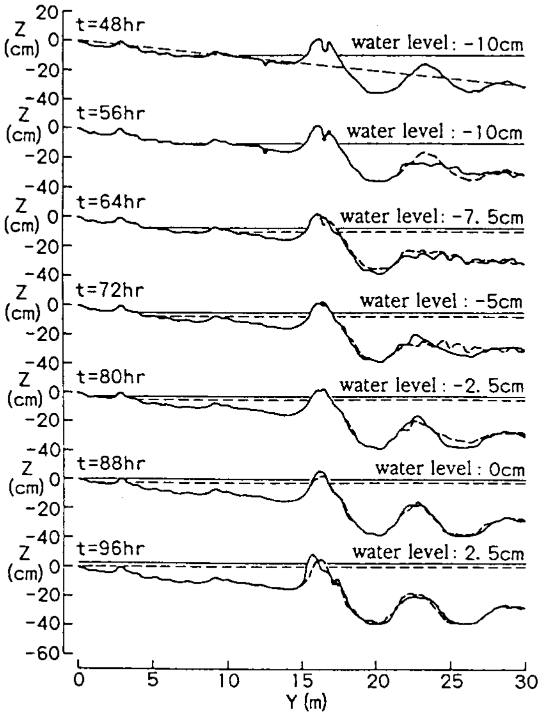

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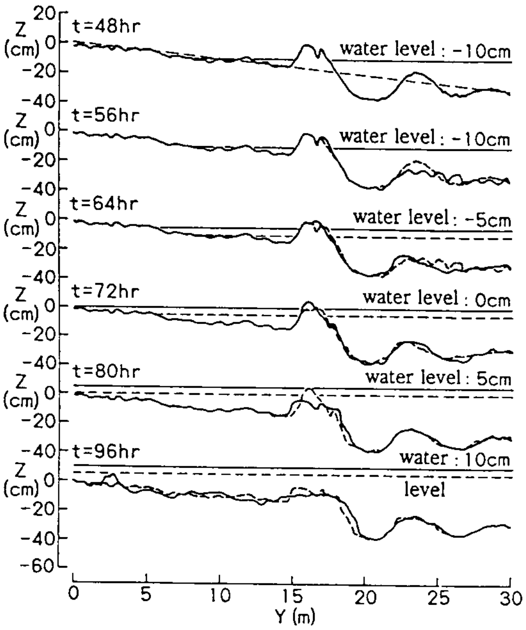

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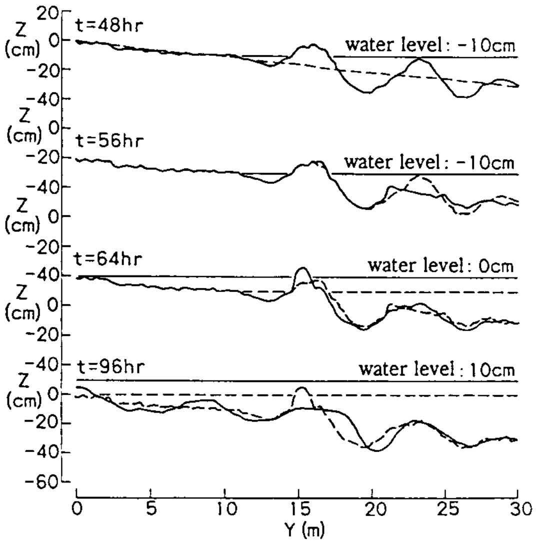

Figure 15