THREE-DIMENSIONAL TOPOGRAPHIC CHANGES ON THE FORESHORE ZONE OF SANDY BEACHES

BY

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I INTRODUCTION

1.1 Purpose of the study

Three-dimensional topographic surveys are repeatedly carried out, in order to obtain sufficient time-series data of beach change on an unbounded coast. As a result of these surveys, the sequential topographic changes observed in each storm cycle are classified into a few types by focussing special attention on (1) large cusps developed near the shoreline and (2) a bar and trough formed on the shallow water bottom.

The fluctuations or difference in the environmental variables, such as wave characteristics and grain size of beach material are considered to control the temporal or spatial change of foreshore zone topography. The occurrence conditions of individual type of topographic change are determined by taking account of the correlation between each type of topographic change and the environmental variables during each survey period. All types of topographic change are arranged on the basis of their occurrence conditions and a new three-dimensional beach model is constructed.

1.2 Previous studies

Coasts can be generally classified into two large groups. One is called a depositional coast which is covered with unconsolidated material, such as sand, shingle, cobbles, and the other is called a cliffed coast which is composed of bed rock. Based on the idea of Davis' geographical cycle, Johnson (1919) proposed the idea of marine cycle; that is, the process of shoreline development could be expressed in terms of the major stages of youth, maturity and old age, and individual shore form observed on any coast could be developed at the specific stage. Although he treated coastal landforms over a sufficient span of geologic time in his idea of marine cycle, he noted the shore forms which repeatedly appear or disappear on depositional coasts in a short term (Johnson, 1919, pp. 457-532). Such topographic change, commonly found in the foreshore zone, can be observed in a short period by the fluctuations of the characteristics of waves approaching the shore (Inman, 1950; Shepard, 1950; Vesper, 1961; Darling, 1964; Gorsline, 1966; Ball et al, 1967; Sonu and Van Beek, 1971; Fox and Davis, 1978).

Distinctive topographic features in the foreshore zone are (1) large cusps formed near the mean water line and (2) a few kinds of bar systems developed on the shallow water bottom. Both features form a rhythmic topography occurring in the nearshore zone (Hom-ma and Sonu, 1963).

Two kinds of typical rhythmic topography are illustrated in Figures 1 and 2. Early work on this subject was done by Johnson (1919) and Evans (1939). Their investigations put stress on the description of the configuration characteristics and qualitatively discussed the formative processes.

Later studies on the foreshore zone topography placed emphasis upon the measurement of some environmental variables such as waves, currents, wind, and attempted to understand the characteristics of topographic change on the basis of the measured data (King and Williams, 1949; Brunn, 1954; Mogi, 1959, 1960; Hom-ma and Sonu, 1963; Sonu and Russell, 1967). Mogi (1960) found that a systematic relation exists between large cusps and bar systems. Sonu and Russell (1967) emphasized that three-dimensional topographic survey should be made for the field study on unbounded coasts. Hom-ma and Sonu (1963) stated that the following two fundamental conditions are necessary for the formation of a crescentic bar system: (1) a beach must be located close to a supply source of beach sand and (2) the bottom must be sufficiently gentle in the shallow water zone.

On the other hand, researches on beach profile change were carried out by some investigators (Shepard, 1950;

Bascom, 1953; Darling, 1964 et al.). These investigation results indicate that the beach profile on a depositional coast shows a cyclic change, that is, during the period of small wave activity (ordinarily in summer or post-storm period) the berm advances seaward (Summer-type profile), while during the period of storm wave activity (usually in winter or storm period) the berm-forming sand is carried to the offshore zone and a beach profile with no berm occurs (Winter-type profile). Shepard (1963, pp. 178-181) pointed out that beach profiles change periodically in response to the periodic change of the characteristics of waves reaching the shore. He also stated that two kinds of periodic changes in wave characteristics are commonly found; one is a seasonal change (Seasonal cycle) and the other is a change associated with a storm (Storm cycle).

Since the early 1970's, investigations on the three-dimensional topographic changes in the foreshore zone have been conducted on the basis of the concept of beach cycle. Davis and Fox (1972) constructed a process-response model for displacement of the bars and changes in shoreline configuration. In their model, they attempted to give an explanation of topographic changes in a storm cycle by dividing the cycle into several stages.

The result of their field survey demonstrates, however, that two peaks corresponding to the pass of low pressure systems were found in the recorded time-series data of wave height, and each post-storm period was so short that a sequential topographic change during a storm cycle could not be fully completed. Sonu (1973) stated that crescentic bar systems could be found in many parts of the world and the crescentic bars formed between headlands are generated by a standing edge wave, whereas the bars formed on an unbounded coast are developed by sand-wave trains which result from instability of the surf zone bed perturbed by longshore currents and waves. He also developed a three-dimensional model on discontinuous bar system based on his own survey data. Applying the edge wave theory expanded by Eckart (1951) and Ursell (1952), Van Beek (1974) attempted to elucidate the mechanism of the rhythmic topography formation. After performing the field survey, he pointed out that rhythmic bars built up on the shallow water bottom had two superimposed sets of rhythms of different wave lengths and the formation of these bars was governed by two kinds of standing edge waves. Greenwood and Davidson-Arnott (1975) conducted a three-dimensional topographic survey and analysis of aerial photographs on the inner and the outer bar systems. They consequently described in detail the sequential topographic changes of these bar systems. The time intervals of their topographic survey were comparatively long, e.g., topographic surveys were carried out ten times during three months. Owens (1977) simultaneously studied on two coasts which have different types of wave climate. He found that, on a sheltered coast, seasonal variations in wave energy level result in topographic changes in a seasonal cycle, and, on an exposed coast, the variations of wave energy level associated with an individual storm result in topographic changes in a storm cycle.

Based on the daily wave records, aerial photographs and the results of beach survey, Short (1978a, 1978b, 1979) constructed a three-dimensional beach-stage model. This model consists of accretionary and erosional sequences; the former begins when wave height decreases following a storm period or a period of high swell and the latter begins just before the time when wave height increases following a long term of low swell. He stated that this model is applicable to all open coasts that are low to moderate bottom gradient and are composed of medium grained beaches. There exist, however, a few types of bar system (Sonu, 1969; Hayes, 1972; Davis and Fox, 1972; Davis et al., 1972; Davis and Fox, 1975; Owens, 1977) which Short's model does not include.

The 1970's researches on topographic changes in the foreshore zone may be briefly summarized in the following outline. Three-dimensional topographic surveys in the nearshore zone were conducted by some researchers and consequently several beach-stage models were proposed by them. All of these models except Short's, however, were not constructed on the basis of fully detailed data on topographic changes occurred in a storm or a seasonal cycle, and these models are incomplete. On the other hand, Short's model appropriately explains the three-dimensional topographic changes concerning crescentic bar system but the model can not explain all the topographic changes concerning other types of bar systems observed on open coasts in the world.

A review will be given on the previous experimental studies using a wave basin on topographic changes in the foreshore zone, especially bars and large cusps. Such experimental studies were generally carried out under controlled conditions by changing some variables such as beach gradient, grain size of beach material, wave height and period. It is possible that the results of these experimental studies enable us to evaluate the importance or the effect of each variable on topographic change in the nearshore zone of natural beaches. Horikawa and Sasaki (1968) conducted a laboratory experiment and observed the process of topographic change of the bar formed on the bottom of wave basin under the action of oblique waves. The result of their observation is summarized as follows. At first a continuous and straight bar was formed parallel to the shoreline. In the next place the bar was divided into a few parts and these bars were corresponding to each cusp formed near the shoreline. These bars eventually connected with the horn of each corresponding cusp. Komar (1971) carried out laboratory experiments by the use of two kinds of wave basins. He pointed out that nearshore cell circulation affects shoreline modifications and large cusps develop in the lee of the rip currents. Bowen and Inman (1971) theoretically suggested that standing edge waves provide a satisfactory explanation for the formation of crescentic bars. They performed laboratory experiments to ascertain the validity of their theoretical suggestions. Their experimental results illustrate that (1) the formation of crescentic bar system might be governed by drift velocities associated with the presence of standing edge waves and (2) the existence of standing edge waves whose periods were 30-60 seconds was necessary for the formation of such a bar system on long, straight natural beaches. Varying deep-water wave steepness, Tamai (1974, 1975) performed a laboratory experiment and observed bar systems developed in a wave basin. The result of his experiment shows that when the value of deep-water wave steepness was greater than 0.016, a crescentic bar system was always developed and large cusps were formed by the predominant water circulations occurring in a breaker zone. Sunamura, Mizuguchi and Ann (1977) conducted a laboratory experiment on rhythmic topography. In their experiment, wave period was kept constant and wave height was varied. The results indicate that low waves formed steps on the shallow water bottom and developed a rhythmic topography near the shoreline; on the other hand, high waves built up a few elongated bars and troughs on the shallow water bottom parallel to the shoreline and higher waves formed crescentic troughs on the shallow water bottom.

A series of previous field studies on nearshore zone topography has made clear that rhythmic landforms with a few kinds of bar systems can be observed on almost all depositional coasts. But if we closely examine these bar systems we would find that each bar system has its own configuration having temporal and/or local changes.

Laboratory experiments on rhythmic topography could show bar systems probably corresponding to a discontinuous or a crescentic bar system observed on natural beaches. The fundamental importance of wave steepness in building up these bar systems has also been confirmed in a laboratory environment. But the following items have been still veiled: (1) the effect of beach gradient, (2) wave incidence direction and (3) grain size of bottom material. Although a few models of topographic changes in the foreshore zone have been proposed, there are some differences among them. This suggests that these models do not contain sufficient generality. Incompleteness found in these models is due to lack of the ample time-series data of topographic changes during each storm cycle. A few researches have tried to explain the mechanism of the rhythmic topography formation on the basis of edge wave theory. The validity of such studies, especially for the case of unbounded coasts, should be checked using the data of edge waves actually measured.

II STUDY AREA

The Kashima Coast, Ibaraki Prefecture, Japan, is a nearly N-S oriented, 70-km long, Pacific coast which is bounded by the Tone River at the southern end and by Cape Oh'arai, a Cretaceous promontory, at the northern end. The study area is located in the northern part of this coast (Figure 3). A diluvial upland having a height of 40 to 45 m (Sakamoto, 1975, p. 1), called Kashima terrace, develops along the hinterland of the study area (Figure 4). At the seaward base of the terrace, sand dunes develop with some being protected by sand fences built after the World War II.

Underwater topography (Figure 4), which was drawn based on a hydrographic chart (Japan Maritime Safety Board, 1977), indicates that 10- and 20-m contour lines run nearly parallel each other to the coastline with the 20-m contour line slightly diverging near the northern end of this coast. The irregularity of 25-, 30-, and 40-m contour lines represents that a marine terrace, now located at a water depth of 25 to 50 m, was dissected by several valleys when the sea level rise halted during the Flandrian transgression (Mogi and Iwabuchi, 1961), although these contour lines were drawn by smoothing out the minor irregularity. This irregular topography would influence waves approaching the shore. Shallow-water bottom material in this area is fine to medium sand (Mogi and Iwabuchi, 1961).

In order to understand the seasonal characteristics of waves on the Kashima coast, mean annual occurrence frequencies of wave period and height were examined on the basis of the data of the daily measurement at Oh'arai harbor (Ministry of Transport, 1977) located 10 km north of the study area (Figure 4). A representative result is plotted on Figure 5, which shows that waves having a period of 6 to 10 sec dominate throughout the year, and waves more than 3 m in height occur only in summer (June-August) and autumn (September-November). This wave-height occurrence is almost always associated with the passage of a typhoon or a low pressure system.

Tides are mixed; spring range is 0.9 m and neap range is 0.3 m at Oh'arai located at the northern end of this coast (Japan Meteorological Agency, 1977).

Two sites, located with a distance of approximately 10 km in between, were selected in the study area; the one is Dainigorizawa and the other is Tamada (Figure 4). Figures 6 and 7 show nearshore topography at the Tamada and the Dainigorizawa sites, respectively; the underwater area deeper than a water depth of 3 to 4 m was surveyed using a depth recorder installed on a boat, the foreshore-backshore area was measured using a level, surveyor's rod, and tape, and the surf-zone, where the application of these two measuring techniques was not possible, was reconnoitered by the author equipped with a hydroscope and flippers. A continuous outer bar is markedly present at both sites, while an inner bar configuration is not so noticeable. Offshore distance from the shore to the outer bar is 190 to 220 m at the Dainigorizawa site and 150 to 170 m at the Tamada site, with the former having a slightly longer distance. A monotonous increase in water depth is seen in the offshore region from the outer bar at both sites (Figures 8 and 9). Figure 10 illustrates a generalized beach profile in the study area.

The beach material is well-sorted, fine to medium sand at both sites. The result of a sieve analysis of beach sand sampled in 1979 showed that the mean grain size was 0.20 mm at the Dainigorizawa site and 0.33 mm at the Tamada site. The mean sand sizes examined by Ijima et al. (1964) and Ministry of Transport (1972) were 0.20 mm and 0.19 mm at Dainigorizawa, respectively. Since the beach material size slightly varies in relation to time, a representative mean value was obtained by averaging these three data for each site; this results in 0.20 mm for the Dainigorizawa site and 0.27 mm for the Tamada site.

III METHODS

Reference stakes were installed at about 50-m intervals in a line nearly parallel to the coastline (Figures 11 and 12). The absolute altitude of each stakes was based on a benchmark on the Kashima terrace. Three-dimensional topographic measurements of the foreshore zone were conducted at low tide, based on these reference stakes. Beach profiles were surveyed on lines normal to the general shoreline trend, using a level, surveyor's rod, and tape. The survey was extended to the limit of wading. Figures 11 and 12 show the areas in which the beach survey areas were actually controlled by wave and tidal conditions. The surveys were repeatedly carried out every three or four days in order to obtain the time-series data of topographic change occurring in a storm cycle.

At each site, a visual observation station was set up on the seaward edge of the Kashima terrace. The observation included (1) offshore wave conditions including approximate height and period, and incidence direction, (2) characteristics of breaking waves, i.e., their types and angles, and (3) the foreshore topographic features. Photographs were also taken. Continuous wave data obtained at Kashima Port (Figure 4)(20 km south of the study area), are available. Wave measurement has been performed by the Ministry of Transport using an ultrasonic-type sensor installed at a water depth of 21 m.

IV DATA COLLECTION

4.1 Investigation results in the summer of 1978

4.1.1 Wave conditions

The wave data during the survey period is shown in Figure 13. Storm waves accompanying an abrupt increase in wave height occurred during the period from August 1st to 2nd. These waves were caused by the typhoon (7807) passed the offshore of the study area. Post-storm waves had significant heights of 0.4 to 0.7 m, occurring till August 16th. These low waves were swell whose wave incidence directions were E to ESE. A slight increase in wave height, observed during August 17th to 19th, was associated with the low pressure system developed at the eastern offshore area of Hokkaido which is located north of Honshu (Figure 3). During this period, northeasterly wind waves generated by this low pressure system superimposed in the study area on swell approaching from ESE direction. Around August 20th, a slight increase in wave height again occurred. This was caused by swell with incidence directions of E to ESE, which was propagated from the typhoon (7813) area located at the far southern offshore area of Honshu. Owing to the trouble of the wave recorder, there was a lack of data between August 23rd and 24th. No noticeable change in wave climate was visually observed during this period.

4.1.2 Topographic change at the Dainigorizawa site

Topographic surveys were conducted one time before the occurrence of storm waves and six times after that event (Figure 13). The results of topographic survey are shown in Figure 14. The lower part of this figure shows the alignment of the reference stakes which were shown by open circles with the stake number.

(a) July 30th, 1978

Figure 14-A shows the result of July 30th, when a swell-like forerunner of the typhoon-generated waves was observed in the study area. Before this topographic survey a calm weather condition had continued for at least 10 days. During this period a wide berm was formed. A berm crest was located near the 0.75-m contour line which is indicated by the dashed line, and the beach face was of nearly uniform gradient.

(b) August 1st to 4th, 1978

Photograph 1 shows the storm waves of August 1st. The waves approaching the shore broke far offshore from the location where the outer bar is usually found under a calm weather condition. Spilling-type breakers were observed, which are shown by the open arrow on this photograph. The heavy and light solid arrows show the breaking waves respectively under which outer bar is usually and inner bar is sometimes found during a calm weather condition. The swash limit was located at the base of the sand dune.

Although a rapid decrease in the height of the storm waves occurred on August 1st to 2nd (Figure 13), post-storm waves were still high on the following few days. This prevented the measurement of foreshore topography. The topographic survey was conducted on August 4th. The result is shown in Figure 14-B. A comparison between Figures 14-A and 14-B indicates that the shoreline receded 12 to 26 m. The storm waves carried the berm-forming sand offshore. At this stage, an inner bar was formed, which was elongate and parallel to the coastline. The wave break point was located at the seaward of this bar. The bar crest was located 1.1 to 1.2 m below MSL. The mean water line (denoted by the 0-m contour line in Figure 14) was almost straight.

(c) August 8th to 10th, 1978

Low waves dominated from August 4th to 8th (Figure 13). The beach topography surveyed on August 8th is shown in Figure 14-C. Comparing Figures 14-B with 14-C, we note that the inner bar migrated landward and was separated into three parts by rip channels (Figure 14-C). The rip channel spacing was 250 to 300 m. An observation showed that sea water in the surf zone was flowing out offshore to NE direction through these rip channels. The waves approaching the shore broke at the seaward of these bars. The mean water line became slightly wavy.

Photographs 2 and 3, taken respectively on August 8th and 10th, show waves breaking over the inner bar. The rip channels were located in the discontinuous parts of the breaker line, which are shown by the arrows on these photographs.

(d) August 12th, 1978

From August 8th to 12th, significant wave heights were almost constant with their values being between 0.4 and 0.7 m (Figure 13). Figure 14-D shows topography of August 12th. A topographic change from August 8th to 12th is characterized by further landward migration of the bars with the middle one being separated by a small rip channel into two parts (compare Figures 14-C with 14-D). The rip channel spacing became narrower and it was about 150 m. The trough developed in front of the reference stake No. 21 on August 8th (Figure 14-C) was buried at this stage. The wave break point was located at the seaward of these bars. The mean water line showed a wavy configuration with a wave length of about 300 m.

(e) August 17th, 1978

Figure 13 shows that the period between August 12th and 17th had nearly the same wave condition as the former period (August 8th to 12th). Topography of August 17th is plotted in Figure 14-E. The bars still migrated landward and welded onto the beach. The average migration speed of these bars was 4 to 5 m/day. The rip channels showed a northward alongshore movement; for instance, a rip channel formed in front of the reference stake No. 24 on August 12th (Figure 14-D) moved to the point in front of Stake No. 23 by this day (Figure 14-E). Waves broke about 65 m offshore from the shoreline. The mean water line became markedly sinuous and the wave length was 150 to 300 m.

(f) August 20th, 1978

During the period from August 17th to 20th, a slight increase in wave height was observed (Figure 13). Figure 14-F shows the survey result of August 20th. Two major rip channels moved alongshore toward the north, while a minor rip channel formed in front of Stake No. 20 on August 17th (Figure 14-E) was completely filled up by this stage (Figure 14-F). The wave break point was present about 60 m offshore from the shoreline. A well-developed berm crest was located between the 0.75- and 1.0-m contour lines. Large cusps were clearly formed, which are represented by the wavy mean water line on Figure 14-F. Comparing Figures 14-C with 14-F, we note that the horns of large cusps with a wave length of about 300 m moved toward the north. The approximate distance of this longshore movement was 120 m in 12 days; the average speed of the movement was about 10 m/day. The northward movement of two rip channels approximately kept pace with the movement of the cusp horns. The rip channel movement is illustrated in Figure 15.

Photograph 4, taken on August 20th, shows the wave condition and some topographic features. On this photograph a first breaker line is shown by the heavy solid arrow and a horn of large cusp is shown by the light solid arrow. The open arrow on the right of the horn denotes a dark colored water-surface under which a rip channel was formed. Photograph 5 almost covers the same area as Potograph 5; the horn of large cusps and the dark colored water-surface are shown by the light solid arrow and the open arrow, respectively; a berm crest composed of dry sand is shown by the heavy solid arrow.

(g) August 24th, 1978

From August 20th to 24th, wave height gradually decreased (Figure 13). Topography of August 24th is shown in Figure 14-G. A shallow water bottom was partly eroded; so that somewhat complicated topography appeared. This was caused by the slight increase in wave height occurred immediately after the topographic survey of August 20th (Figure 13). The wave break point was situated near the 1.25-m depth contour line.

A qualitative investigation on nearshore currents was performed near troughs and/or rip channels during the survey period. During this period longshore currents were flowing to N- to NE-directions. The currents were stronger when rip channels were formed (August 8th to 12th) in comparison to when rip channels were not formed (August 4th) or being buried (August 17th to 20th).

The summary of the topographic change at the Dainigorizawa site during the survey period is as follows. The beach having had a wide berm before the storm waves arrived was eroded during the storm period and the beach profile from backshore to foreshore became smooth with a small gradient. The post-storm waves caused the landward migration of the inner bar. During this migration the bar was divided into a few parts by rip channels. These rip channels were formed at approximate regular intervals. The divided bars migrated further landward and welded onto the beach to form a pronounced berm crest. In the latter half of the survey period, large cusps were formed and their horns moved toward the north.

4.1.3 Topographic change at the Tamada site

Topographic surveys were carried out one time before the arrival of storm waves caused by the typhoon (7807) and six times in the post-storm period (Figure 13). Figure 16 illustrates the result of the topographic surveys.

(a) July 29th, 1978

A swell-like forerunner of waves propagated from the typhoon area was observed in the study area. The beach topography surveyed on the 29th of July is shown in Figure 16-A. A berm crest was located slightly landward from the 0.75-m contour line. A wide berm was formed between the berm crest and the 1.50-m contour line. Waves broke 25 m offshore from the shoreline. The mean water line showed a wavy configuration without noticeable regularity.

(b) July 31st to August 3rd, 1978

Between July 31st and August 1st a distinct increase in wave height was observed, which resulted from the passage of the typhoon near the study area. The storm wave condition of August 1st is shown on Photograph 6. On this photograph the open and solid arrows indicate the spillingand plunging-type breakers, respectively. The latter was observed near the location where an outer bar was usually found under calm sea conditions.

Figure 16-B illustrates the topography of August 3rd. A comparison of Figures 16-A and 16-B shows that the shoreline receded 5 to 20 m and the wide berm disappeared. The beach extended from backshore to foreshore had a small gradient. An elongate and shallow trough developed parallel to the coastline in the zone between Stake Nos. 12 to 15. The waves approaching the shore broke about 55 m offshore from the shoreline. The mean water line was almost straight.

(c) August 7th, 1978

A gradual decrease in wave height occurred from August 3rd to 7th (Figure 13). The topography of August 3rd is illustrated in Figure 16-C. The elongate trough, developed in front of Stake Nos. 12 to 15 on August 3rd (Figure 16-B), was thoroughly buried by this day (Figure 16-C). Simultaneously the beach was accreted; the sand fill attained 0.40 m at the maximum depth in the area between the mean water line and the 1.00-m contour line. The wave break point was present about 40 m offshore from the shoreline.

(d) August 11th, 1978

Waves were approaching the study area with almost constant heights of 0.4 to 0.5 m during the period between August 7th and 11th (Figure 13). The beach topography was surveyed on August 11th. The result is shown in Figure 16-D. Beach cusps with wave lengths of 30 to 40 m were observed in the area between the 0.25- and 0.75-m contour lines. A sand fill with a maximum depth of 0.40 m took place again in the area between the mean water line and the 1.00-m contour line. A berm developed well in the vicinity of the 0.75-m contour line. The wave break point was present about 35 m offshore from the shoreline. The mean water line shows that large cusps with a wave length of 150 to 350 m were formed.

(e) August 16th, 1978

From August 11th to 16th waves approaching the study area were small, i.e., 0.4 to 0.7 m in height (Figure 13). The survey result of August 16th was given in Figure 16-E. Sand humps began to form in the area between the 0.50- and 1.00-m contour lines. The wave break point was located near the 1.75-m depth contour line.

(f) August 21st, 1978

A slight increase in wave height occurred two times during the period between August 16th and 21st (Figure 13). These minor events were associated with wind waves generated by the low pressure system and swell by the typhoon (7813). Figure 16-F shows the topography of August 21st. Well-developed humps, denoted by the closed-contour line of 1.0 m, were observed near a berm crest. The waves approaching the shore broke about 45 m offshore from the shoreline.

(g) August 23rd, 1978

Wave height gradually decreased from August 21st to 23rd (Figure 13). The beach topography of August 23rd is illustrated in Figure 16-G. Comparing Figure 16-F with 16-G, we note that marked sand accumulation occurred in the area between the mean water line and the 0.75-m contour line, while slight erosion took place at about 0.5 m below MSL. The wave break point was situated near the 1.75-m depth contour line.

The topographic change at the Tamada site during the survey period is summarized as follows. A wide berm developed during the pre-storm wave period. Then the storm wave activity cut back the berm to produce a beach profile with small gradient. After the storm an elongate and shallow trough was formed parallel to the coastline in the foreshore zone. After a while, however, the trough was completely filled up with sand. During a calm weather condition, a distinct sand fill occurred in the area between the mean water line and the 1.00-m contour line and eventually sand humps were formed. Throughout the survey period the sinuosity of the mean water line was obscure with a lack of noticeable regularity.

4.2 Investigation results in the summer of 1979

4.2.1 Wave conditions

Figure 17 illustrates the wave conditions during the survey period, i.e., from July 17th to August 9th. A baiu front activity caused storm waves occurring between July 18th and 19th. The significant wave height was about 4.0 m during this period. The storm waves decayed rapidly and wave height became 0.60 to 1.00 m. Such low amplitude waves continued till August 6th. These waves were swell, which was associated with some typhoons or tropical depressions moved the far southern offshore area of Honshu. Wave incidence directions were E to ESE. A lack of the wave data seen between July 27th and 30th (Figure 17) was due to a trouble of the wave recorder. During this period, any pronounced changes in wave condition were not visually observed.

4.2.2 Topographic change at the Dainigorizawa site

Topographic surveys were conducted seven times during the survey period. The first one was done immediately after the storm waves and the remaining six surveys were performed by August 5th under calm sea conditions (Figure 17). Figure 18 shows the result of these topographic surveys.

(a) July 19th to 20th, 1979

From July 18th to 19th the storm waves, closely related to the activity of the baiu front, were observed in the study site. Photograph 7 taken on July 19th shows the storm wave condition. On this photograph the open arrow shows waves broken far offshore from the location where an outer bar is usually found under a calm weather condition; this location is denoted by the heavy solid arrow. The light solid arrow indicates the location of an inner bar which is considered to be formed during the stormy weather.

The first topographic survey, carried out on July 20th, did not cover a deeper portion of the study site, because the post-storm waves were still high (Figure 17). The result is plotted in Figure 18-A. A smooth and gentle beach developed from foreshore to backshore. The mean water line was almost straight. The wave break point was present about 45 m offshore from the shoreline.

(b) July 24th, 1979

Between July 20th and 24th the storm waves gradually subsided and reduced to swell-dominant waves (Figure 17). The beach topography surveyed on July 24th is shown in Figure 18-B. Comparing Figure 18-A with 18-B, we find that a sand fill occurred in the area between the 0.25- and 0.75-m depth contour lines. A crescentic bar system (Figure 2) was observed in the foreshore zone. A shoal was present in front of Stake Nos. 23 to 24. Other two shoals were also found in front of Stake Nos. 15 and 30, respectively, both of which were located outside of the survey area (Figure 12). An arcked bar connected the shore by these shoals. On Figure 18-B the bar is not plotted because the troughs were so deep that the topographic survey could not extend to the bar area.

On Photographs 8 and 9 taken on July 24th the positions of shoals and a protruded bar arc are denoted by the open and solid arrows, respectively. The wave break points were located at the seaward of the bar.

(c) July 26th, 1979

The result of the topographic survey, conducted under calm sea conditions on the 26th of July (Figure 17), is shown in Figure 18-C. Two tongue-shaped protuberances formed at the landward side of the bar were located in front of Stake Nos. 17 to 18 and No. 20, respectively.

The 0.25- to 1.00-m depth contour lines showed the formation of a large cusp with the horn corresponding to the shoal. Three rip currents flowing northeast were visually observed in front of Stake Nos. 18 to 19, No. 21 and Nos. 25 to 26, respectively. These rip currents are denoted by the arrows in Figure 18-D. The waves approaching the shore broke at the seaward side of the bar.

(d) July 28th, 1979

Figure 18-D shows the beach topography of this day. A comparison between Figures 18-C and 18-D indicates that the bar migrated landward and the tongue-shaped protuberances advanced further landward burying the troughs. In response to this, the 0.50- to 1.50-m depth contour lines protruded seaward showing the formation of large cusps with a smaller wave length as compared to the July 26th cusp represented by the mean water line on Figure 18-D. The wave break point was situated at the seaward side of the bar.

(e) July 30th, 1979

Small waves were dominant from July 28th to 30th. Figure 18-E illustrates the beach topography surveyed on July 30th when it was neap tide. The small tidal range made it difficult to survey a deeper area, so that the bar is not shown on this figure. A reconnaissance confirmed, however, that the bar actually existed beyond the troughs and had some tongue-shaped protuberances. The mean water line showed a wavy configuration. The wave break points were present at the seaward of the bar.

(f) August 3rd, 1979

During the period from July 30th to August 3rd the waves approaching the study area were small in height (Figure 17). Figure 18-F shows the survey result of August 3rd. The bar slightly migrated landward and the troughs were being buried by sand. The mean water line became markedly sinuous and the wave length of the sinuosity was about 200 m. The waves broke at the seaward of the bar.

(g) August 5th, 1979

Between August 3rd and 5th a slight increase in wave height was observed (Figure 17), which was associated with a low pressure system crossing the northern part of Honshu from west to east. The beach topography surveyed on August 5th is plotted on Figure 18-G. Comparing Figures 18-F with 18-G, we note that the troughs were widened and partially filled up with sand. The wavy configuration of the mean water line showed that large cusps with wave lengths of 150 to 250 m were being developed. The wave break point was at the seaward of the bar.

(h) August 9th, 1979

Waves during the period between August 6th and 9th were not recorded (Figure 17). According to the result of visual observations, however, waves approaching the shore were small and no pronounced changes in wave activity occurred. During this period, the bar migrated landward filling the troughs with sand and eventually welded onto the beach. Consequently a step was formed near the wave break point and shallow rip channels were left on the foreshore bottom. Some photographs were taken on August 9th (Photographs 10, 11, 12 and 13). On Photograph 10, the heavy and light solid arrows show the breaking waves under which the outer bar and the step were found, respectively. The bottom topography landward of the breaker line denoted by the light solid arrow was almost flat. The dark colored water-surface denoted by the open arrow suggests a shallow rip channel flowing to the northeastwards. Photograph 11 taken toward the northeast covers nearly the same area as Photograph 10. The same dark colored water-surface is indicated by the open arrow and a horn of the large cusp is denoted by the heavy solid arrow. Photograph 12 taken looking the north-northeast shows the beach topography of this area. The light solid arrow on Photograph 12 indicates a berm crest. The heavy solid and open arrows individually illustrate the same horn and water-surface as shown on Photograph 11. This photograph shows that the large cusp fully developed. On Photograph 13, the open and solid arrows indicate the dark colored water-surface and the berm crest, respectively.

During the survey period large cusps with the horn corresponding to each shoal were first formed (Figure 18-C) and cusps with the horn corresponding to each tongue-shaped protuberance were secondly formed (Figure 18-D). In this paper the former will be called "primary large cusp" and the latter will be named "secondary large cusp".

The summary of the topographic change at the Dainigorizawa site during the survey period is as follows. A crescentic bar system (Figure 2) developed at this site immediately after the storm period. During a small-wave activity, the bar connected the shore by shoals leaving a trough in between, and migrated landward to form some tongue-shaped protuberances at the landward side of this bar. Afterward the landward bar migration temporarily halted. The trough, however, was rapidly buried. Eventually the bar welded onto the beach leaving a shallow rip channel in the foreshore zone. A primary and secondary large cusps were formed near the mean water line. The horn of the former corresponded to each shoal and that of the latter to each tongue-shaped protuberance.

The crescentic bar system investigated by King and Williams is formed by the waves coming from two predominant directions more or less at right angles to each other (King and Williams, 1949). Our survey results demonstrate, however, that such a bar system is developed by the waves from unidirection.

4.2.3 Topographic change at the Tamada site

Topographic surveys were carried out only two times during the survey period. Visual observations were done several times and simultaneously some photographs were taken at the visual observation station. These investigation results are shown in Figure 19 and Photographs 14 and 15.

(a) July 29th, 1979

After the storm period between July 18th and 19th small-wave activity continued 10 days up to this day (Figure 17). Photograph 14, taken on July 29th, shows the wave condition and some topographic features. On this photograph two rip currents are denoted by the arrows. Visual observations showed that the bars separated by the rip currents with a spacing of about 300 m partially connected with the beach.

(b) August 1st, 1979

The beach topography surveyed on August 1st is shown in Figure 19-A. Though the topographic survey could not cover all the study site, the existance of a rip channel in front of Stake Nos. 13 to 14 was confirmed by wading. The wave break point was about 45 m offshore from the shoreline.

(c) August 3rd, 1979

The topographic survey was conducted on August 3rd when small waves dominated (Figure 17). The result is plotted in Figure 19-B. A comparison between Figures 19-A and 19-B indicates that the rip channel formed in front of Stake Nos. 13 to 14 on August 1st was completely plugged up with sand by this day. Another rip channel, located between Stake Nos. 18 and 20, still existed. The waves approaching the shore broke about 35 m offshore from the shoreline.

(d) August 9th, 1979

From August 3rd to 9th small waves were dominant (Figure 17). Some topographic features and waves are shown in Photograph 15. This photograph indicates that a wide berm developed well in the backshore zone, while the shallow water bottom of the foreshore zone was smooth. This smooth features were due to the filling of the trough.

Though the topographic change occurred at the Tamada site during the 9 days immediately after the storm period is unknown, the subsequent topographic change observed during the survey period is summarized as follows. The foreshore zone topography on the 10th day after the storm event was that the bars formed on the shallow water bottom were separated by rip channels whose spacing was about 300 m. Each bar partially connected with the beach. Then the bars migrated landward and welded onto the beach. Shallow rip channels were left on the shallow water bottom. They were shortly filled up with sand and a well developed berm was formed in the backshore zone.

V RESULTS AND DISCUSSION

5.1 Factors affecting beach changes

On a sandy beach two characteristic beach profiles are generated by the change in the properties of waves reaching the shore. The one formed by smaller swell waves is characterized by a well developed berm in the backshore and a smooth bottom with no bars in the nearshore zone. The other developed by storm waves is illustrated by a smooth subaerial beach with no berm and the presence of nearshore bars.

Johnson (1949) found that such beach profiles could be classified by the parameter of deep-water wave steepness. In his wave channel experiments, he found that when the deep-water wave steepness is greater than 0.03 an offshore bar is always formed, while when the steepness is less than 0.025 an offshore bar is never formed. Since then it has been considered that the value of deep-water wave steepness is closely related to the onshore-offshore sediment transport.

Recently wave tank experiments have been conducted taking the effect of grain size of beach material into consideration (e.g. Iwagaki and Noda, 1963; Nayak, 1971; Sunamura and Horikawa, 1974; Hattori and Kawamata 1980). Sunamura (1980) also examined the grain size effect using field data. These studies indicate that the grain size of beach material is another important factor for beach changes.

Considering that the breaker height has a close relation to the size of bar-trough system formed on the foreshore zone, Davis and Fox (1972), Owens and Frobel (1977) and Short (1979) monitored the breaker height characteristics in the field. Based on the field survey, Short (1979) related the breaker height to beach stages in his beach model.

As stated in the chapter IV, different types of topographic change were observed during different survey periods or at different study sites. The occurrence of these phenomena seems to be controlled by the three factors: (1) Deep-water wave steepness (H_o/L_o), (2) Mean grain size of beach sediment (d_{50}) and (3) Breaker height (H_b). These three variables are examined in the present study.

5.1.1 Deep-water wave steepness

The computation of deep-water wave steepness (H_o/L_o) was based on the wave data obtained using the wave gage at a water depth of 21 m (Figures 13 and 17). Deep-water wave height (H_o) was obtained by use of Equation (1):

$$K_s = \frac{H}{H_o} = \left[\frac{2\cosh^2 kh}{\sinh 2kh + 2kh}\right]^{\frac{1}{2}} \qquad (1)$$

where h is still-water depth, k is wave number and K_s is shoaling coefficient. Deep-water wave length (L_o) was given by

$$L_o = \frac{gT^2}{2\pi} \qquad (2)$$

where g is the gravitational acceleration. The results are shown in Figures 20 and 21. These figures denote that the maximum wave steepness during the storms is 0.0313 in 1978 and 0.0509 in 1979. The average steepness during the calm sea conditions in 1979 is slightly greater than that in 1978.

5.1.2 Grain size of beach sediment

As described in the chapter II, the mean sand size (d_{50}) is 0.20 mm for the Dainigorizawa and 0.27 mm for the Tamada sites. The beach material at the Tamada site is slightly coarser than that at the Dainigorizawa site.

5.1.3 Breaker height

Waves approaching the shore are affected by the topography of shallow water bottom. Wave refraction diagrams were constructed using a hydrographic chart published by Japan Maritime Safety Board (1977). The prevailing wave direction was determined by the graphical method of oblique terrestrial photographs (Shino, 1976, pp. 214-217) using the 35-mm slides and 8-mm cinefilms taken during the survey periods. Figure 22 shows that irregularity of the 25- to 40-m submarine contour lines causes wave convergence at the Dainigorizawa site and divergence at the Tamada site; this suggests that a difference in wave height near the break point should occur between at the two sites.

Breaker height (H_b) was computed using Komar and Gaughan's (1973) relation. The computation procedure was as follows:

[1] From the wave refraction diagrams, refraction coefficients (K_r) for both study sites were obtained using

$$K_r = \sqrt{\frac{b_o}{b_1}} \qquad (3)$$

where b_o and b_1 are the spacing between two orthogonals on the refraction diagram in deep and shallow water, respectively.

[2] Shoaling coefficient at the 5-m water depth $(K_s)_{5m}$

was calculated using Equation (1).

[3] Assuming that waves with the same deep-water characteristics approach to both study sites, wave height at the 5-m water depth at each site (H_{5m}) was obtained using

$$H_{5m} = (K_s)_{5m} \cdot (K_r)_{5m} \cdot H_o \tag{4}$$

where $(K_r)_{5m}$ is the refraction coefficient at the 5-m water depth.

[4] Using the value of H_{5m}, deep-water wave height was recalculated from Equation (1). The wave height thus obtained is imaginary and is denoted by H_o'. This was done because Komar and Gaughan's relation does not contain the effect of wave refraction.

[5] Using the following equation (Komar and Gaughan, 1973), the breaker height was calculated for both sites.

$$\frac{H_b}{H_o'} = \frac{0.563}{(H_o'/L_o)^{0.2}} \tag{5}$$

The computed breaker height is plotted in Figures 23 and 24. Breaker heights measured using a surveyor's rod and hand level are also plotted in Figure 24. These measured values do not quantitatively accord with computed values but qualitatively do. These two figures illustrate that even if the deep-water wave height is of the same value in the offshore area the breaker height at the Dainigorizawa site is greater than that at the Tamada site, due to the wave refraction effect.

5.2 Temporal changes of mean water line

It is well known that the position of mean water line recedes landward under stormy conditions, while it gradually advances seaward under calm sea conditions. Figures 25, 26 and 27 show the temporal change of the mean water line. On these figures the open circle and the vertical line indicate the average and the range of the data scatter, respectively. Since no topographic surveys were carried out at the Dainigorizawa site just before the storm event in the summer of 1979, the result of July 3rd surveyed on only two traverses of the reference stakes Nos. 25 and 26 is plotted for reference in Figure 27. Weather maps during the period between July 3rd and the storm wave arrival (July 18th) denote that calm sea conditions continued: the position of the mean water line would probably change as shown by the dashed line (Figure 27).

Figure 25 indicates that the mean water line at the Tamada site retreated landward during the storm period and afterward it advanced rapidly to attain the pre-storm position by August 11th. In contrast to this, the Dainigorizawa site shows that the mean water line did not reach the pre-storm position by August 24th in 1978 (Figure 26) and August 5th in 1979 (Figure 27). This means that the beach did not recover the pre-storm position within the survey periods. The data scatter in Figure 27 becomes larger during the latter half of the survey period; this suggests that the mean water line became very sinuous. Actually, large cusps developed well near the mean water line during this post-storm period.

Comparing Figures 20 with 25, we find that the mean water line at the Tamada site receded landward during the period of large deep-water wave steepness under the storm conditions, while the line advanced seaward during the period of small deep-water wave steepness under the calm sea conditions. Similar phenomena are also noticeable by comparisons between Figures 20 with 26 and between Figures 21 with 27.

A comparison of the temporal change of mean water line (Figure 25) and the time-series data of breaker height (Figure 23) indicates that the breaker height has also a similar influence upon the shifting of the mean water line to the deep-water wave steepness. From Figures 23 and 26, it is found that the greater the value of breaker height during the storm period was, the larger the recession of mean water line occurred; moreover, the larger the recession distance of mean water line occurred, the longer the time required for the return to the pre-storm position of the line became. The change of the mean water line observed at the Dainigorizawa site in the summer of 1979 (Figure 27) was examined in connection with the time-series change in breaker height (Figure 24). This examination led to that the breaker height greatly affected the temporal change of mean water line in the similar way to that in the summer of 1978. However, no quantitative discussion concerning the temporal change of mean water line can be done because there is no survey data about the position of mean water line just before the storm event.

Using the data of mean sand size described in 5.1.2, a comparison between Figures 25 and 26 shows that the mean water line at the Dainigorizawa site composed of finer sediment was more largely retreated landward during the period of storm wave activity than that at the Tamada site composed of coarser sediment.

5.3 Bar migration and related topographic changes

A bar-trough system is a distinctive feature found in the foreshore zone on sandy coasts. The beach profiles which were first surveyed in the post-storm period are plotted in Figure 28. This figure indicates that the water depth at the trough obviously differs with one another, and the trough on 26th of July, 1979 at the Dainigorizawa site is the deepest of the three. Comparing this figure with the data of breaker height (Figures 23 and 24), we find that the trough depth increased in proportion to the breaker height during each storm event.

Let us examine the landward migration of the bar using the beach profile data (Figures 29, 30 and 31). A common phenomenon denoted by these figures is that the bar formed during the storm period gradually migrated landward and welded onto the beach to form a berm under the post-storm period. The troughs shown in these figures were gradually filled up with sand while the bars migrated landward. The 1978 trough formed at the Tamada site (Figure 29) was most quickly buried of the three. A comparison of Figures 23 with 29 or 30 shows that as the water depth at the trough developed by the breaking waves during the storm period increased, the time required for the trough burial also increased.

It is commonly observed on unbounded coasts that as a bar migrates landward, the sea water in the surf zone begins to flow along the shore and the resultant topography in the foreshore zone indicates pronounced longshore variations. Such three-dimensional currents and topography (rhythmic topography) were schematically illustrated in Sonu's (1973) model. He also proposed that the mechanism of the rhythmic topography formation was attributed to instability of the loose surf zone bed perturbed by longshore currents (Sonu, 1969). Short (1979) expressed in his beach-stage model that the three-dimensional topography constructed on the foreshore zone bottom (crescentic bar system) is developed in the accretionary sequence and it is built up by edge waves generated in the foreshore zone. However, these views has not yet been fully accepted. Then the effect of bar migration on the formation of the current system and the resultant topography is examined.

Based on the radiation stress concept, Longuet-Higgins and Stewart (1964) theoretically showed that the change in the mean sea level should occur in the nearshore region of a plane beach. This phenomenon, known as wave "set-up" or "set-down", was thereafter confirmed experimentally (Bowen et al., 1968) and was observed in the field (Sonu, 1972; Hotta and Mizuguchi, 1978).

When waves approaching the shore break over a bar, a certain volume of sea water is brought into the surf zone. Although part of the seawater returns to the offshore flowing over the bar, it is clear that the bar prevents to some extent such a return flow and brings about the rise of the mean water level in addition to the wave "set-up" caused by radiation stress in the surf zone. Moreover in the case of that the water depth above a bar is large (Figure 31), the seawater in the surf zone returns easily to the offshore; while when the water depth is small (Figure 30), it is very difficult for the seawater to go back to the offshore.

To examine this phenomenon, a wave-tank experiment was carried out using a mortar-made fixed bar (Appendix A). The result of the experiment clearly indicates that the smaller the water depth above the bar crest becomes, the higher the mean water level in the surf zone rises (Figure A-13).

It is expected on the actual coast that the water depth above the bar crest becomes small as the bar migrates landward and consequently a distinct rise of the sea level in the surf zone should occurr with the seawater having much potential energy. When a return flow toward the offshore zone excavates furrows across the bar to form rip channels, the sea water in the surf zone begins to flow alongshore as a rip feeder current and then three-dimensional current system is established. The current system generates a pronounced longshore variation of foreshore topography.

5.4 Three-dimensional beach model

The topographic changes observed at the two study sites can be divided into three types, i.e., Type A (July-Aug. 1978, Tamada), Type B (July-Aug. 1978 and 1979, Tamada and Dainigorizawa) and Type C (July-Aug. 1979, Dainigorizawa); their sequential topographic changes during a storm cycle are illustrated in Figures 32, 33 and 34. These schematic diagrams are based on the assumption that waves reach at angles to the shoreline and the storm cycle consists of four or five stages. The characteristics of three types of topographic changes are summarized as follows.

Type A (Figure 32 and Table 1): As a storm subsides, a shallow and elongate trough is formed in the foreshore zone parallel to the coastline (Stage 2). Thereafter the trough is rapidly filled up with sand. A berm grows while calm sea conditions continue (Stage 3). Eventually sand humps are formed on the seaward portion of the berm (Stage 4). During the post-storm period, no pronounced development of large cusps occurs.

Type B (Figure 33 and Table 1): With decreasing wave heights following a storm, a continuous and elongate bar-trough system is formed in the foreshore zone parallel to the coastline (Stage 2). During time of low waves the bar gradually migrates landward and is divided into a few parts by rip channels (Stage 3). Thereafter these bars migrate further landward and eventually weld onto the beach to form a berm (Stages 4 and 5). During the latter half of the period of low energy conditions, large cusps with regular wave length are formed near the mean water line.

Type C (Figure 34 and Table 1): During decreasing wave height in a post-storm period, a bar forms connecting adjacent shoals developed in the foreshore zone (Stage 2). Afterward the bar migrates landward and troughs are gradually buried under calm weather conditions, and primary and secondary large cusps are formed near the mean water line (Stages 3 and 4). The bar shifts further landward and finally welds onto the beach to form a berm. Shallow rip channels are left on the foreshore zone bottom (Stage 5).

The characteristic foreshore change observed at the Tamada site in the summer of 1979 strongly suggests that this change is probably equivalent to Type B: foreshore topography shown on Photograph 14 corresponds to Stage 4 and the topography in Figures 19-A and 19-B is similar to

Stage 5. The data of preliminary field survey (Appendix B) indicate that the topographic change observed at the Dainigorizawa site in April 1978 is equal to Type B. The accretionary sequence in Short's model almost coincides with Type C of the present classification.

To determine the occurrence condition of the topographic changes, a new parameter was introduced. This is $\overline{H_b}/d_{50}$, in which the bar means the time-average in each storm period. Figure 35 shows the relationship between $\overline{H_b}/d_{50}$ and $\overline{H_o/L_o}$ with the last being the time-average of deep-water wave steepness in each storm period. In computing these parameters, the values described in 5.1.2 were used for d_{50}, and 24-hour average values of the data before and after the climax of storm waves were adopted for $\overline{H_o/L_o}$ and $\overline{H_b}$. On Figure 35 the data points showing Types A and C are respectively plotted in the lower left and the upper right, while Type B data points are fallen in the sandwiched area between the two dashed lines. Some previous field data of Sonu (1969) and Owens and Frobel (1977) (Table 2) are also plotted in Figure 35.

Three types of topographic change based on the above discussion are put in order and a three-dimensional topographic model for the foreshore zone on a sandy beach is constructed (Figure 36). In this model the determination for what type of topographic change will occur is made during Stage (1), and as illustrated in Figure 35 the occurrence of the type of topographic change is determined by the parameters, $\overline{H_o/L_o}$ and $\overline{H_b}/d_{50}$.

VI SUMMARY AND CONCLUSIONS

Topographic changes in the foreshore zone on sandy beaches are closely associated with the properties of waves approaching the shore and the grain size of beach material. In this study, two study sites were chosen on the Kashima Coast, Ibaraki Prefecture, Japan. One is Dainigorizawa and the other is Tamada. The mean sand size of beach material at the Dainigorizawa site is slightly smaller than that at the Tamada site. Topographic surveys were repeatedly carried out to elucidate the characteristics of topographic changes in the foreshore zone at both study sites during each storm cycle. On the basis of the survey result, temporal changes in the foreshore zone topography were examined using the wave data and the sand size data.

In the first place, temporal changes of mean water line were examined in connection with the deep-water wave steepness, the breaker height and the grain size of beach material. The results show that when the deep-water wave steepness under storm conditions was large, the mean water line retreated landward, while when the wave steepness under calm sea conditions was small, the mean water line gradually advanced seaward. It is also noted that the larger breaker height during a storm event brought about the larger recession of the mean water line and it needed more time for the mean water line to recover the pre-storm position. In contrast, the difference in grain size of beach material conversely affected the shifting of the mean water line; that is, the smaller the grain size of beach material was, the larger the recession of the mean water line occurred.

In the next place, the processes of bar migration during each survey period were investigated. The investigation results show that the bar formed during a storm period gradually migrates landward and welds onto a beach to form a berm under the post-storm period. It is also found that when the breaker height during the storm event was large, the trough became deeper and the time required for the trough burial became longer in proportion to the water depth at the trough.

Such bar migrations have an important effect on the topographic changes occurring in the foreshore zone. As a bar migrates landward, the water depth above the bar becomes small and the bar prevents to some degree the sea water in the surf zone from flowing out to the offshore. Consequently the bar hindering such a return flow brings about the distinct rise of the mean water level in the surf zone. A similar rise of the mean water level caused by radiation stress, known as wave "set-up", also occurs simultaneously in the same area. To make sure of these two effects, a wave tank experiment was carried out using a mortar-made fixed bar and the result clearly showed that the smaller the water depth above the bar becomes, the higher the mean water level in the surf zone rises. The sea water having much potential energy in the surf zone, returning to the offshore, would probably excavate furrows across the bar to form rip channels. At this stage, the current system in the surf zone becomes three-dimensional, giving rise to the pronounced longshore variation of foreshore zone topography.

Topographic changes observed at two study sites were classified into three types, which were schematically illustrated in Figures 32, 33 and 34. The characteristics of the three types are described as follows:

Type A : After a storm event a shallow and elongate trough is found in the foreshore zone parallel to the shoreline. The trough is quickly filled up with sand during the interval of small wave activity. A berm develops well and sand humps are formed on the seaward portion of the berm. No pronounced development of large cusps and bars is observed.

Type B : After a storm event a continuous and elongate bar-trough system is found in the foreshore zone parallel to the coastline. The bar begins a landward movement under calm sea conditions. Rip channels separate the bar into a few parts. Finally each separated bar welds onto the beach to form a berm. Large cusps with a regular wave length develop near the mean water line during the latter half of a storm cycle.

Type C : During a storm wave decay period a crescentic bar system develops. The bar begins a landward migration, and primary and secondary large cusps are formed in the vicinity of the mean water line while calm sea conditions continue. Thereafter the bar migrates further landward and welds onto the beach. A well developed berm is constructed in the backshore zone.

The repeated topographic survey revealed the different types of topographic change were present in different survey periods or study sites. This means that the occurrence of each type of topographic change is largely dependent on (1) wave characteristics during each storm period and (2) beach sediment size of the study area. The time-average value of the breaker height in each storm event divided by the mean size of beach material at a study site ($\overline{H_b}/d_{50}$) and the time-average value of the deep-water wave steepness in each storm period ($\overline{H_o/L_o}$) are adopted in order to determine the occurrence condition of topographic changes of the three types. Finally, three types of topographic change were put in order and a three-dimensional beach model in the foreshore zone on sandy beaches was constructed (Figure 36).

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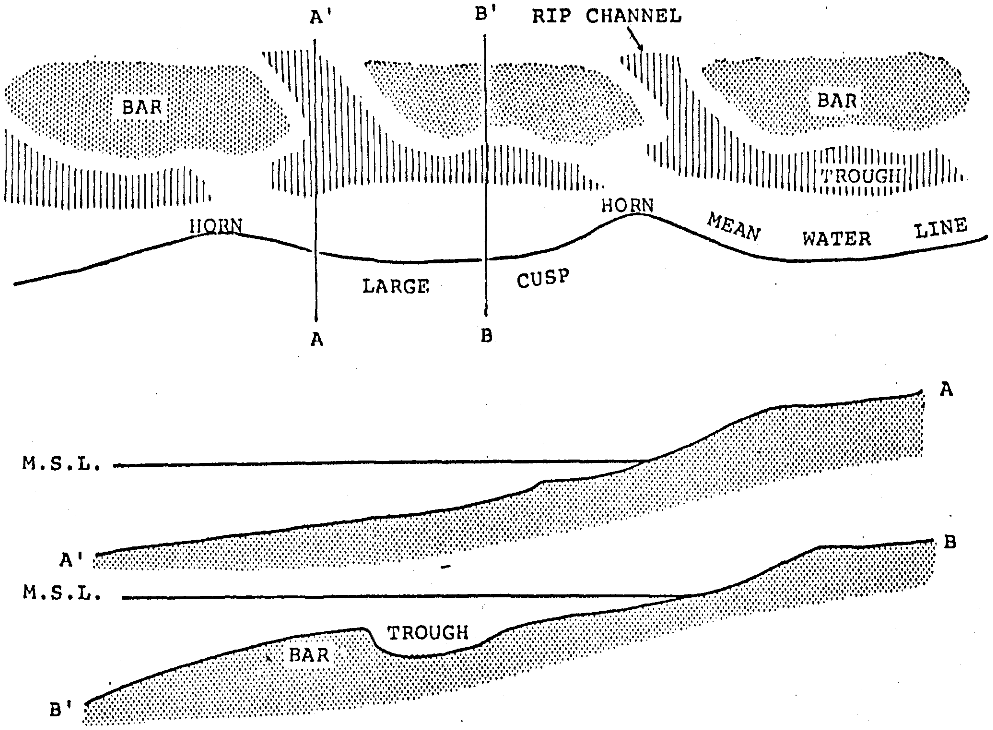


Fig. 1 Discontinuous bar system.

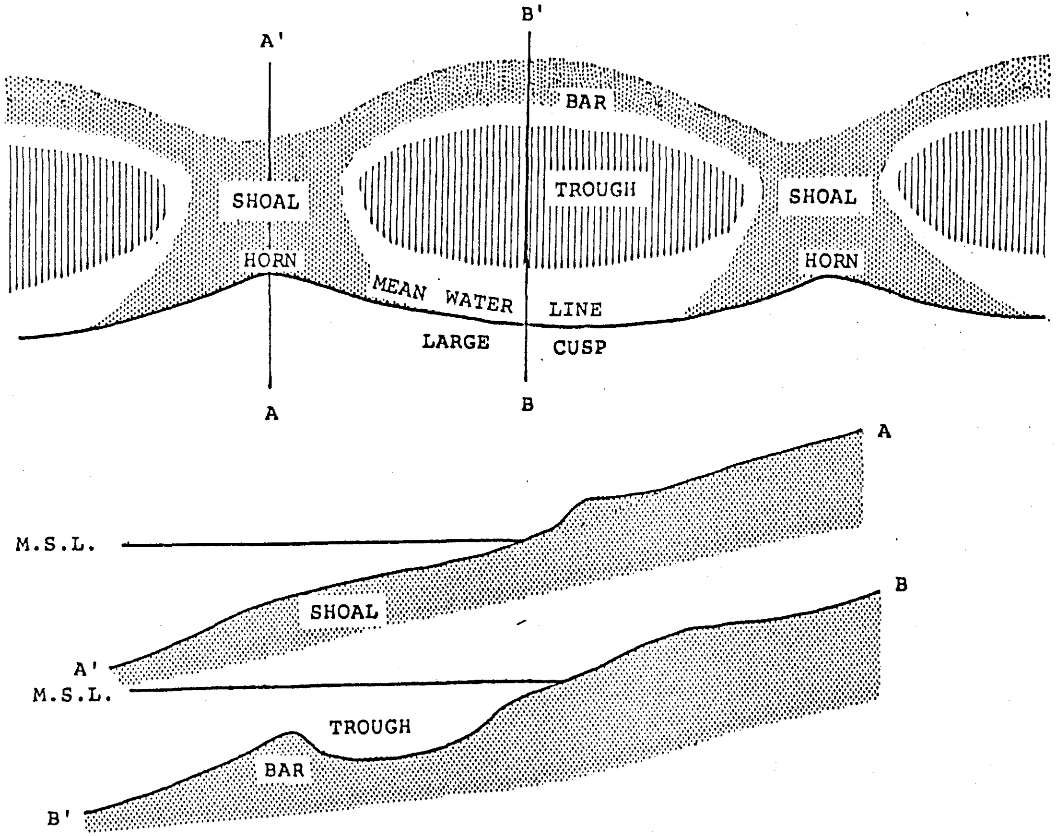


Fig. 2 Crescentic bar system.

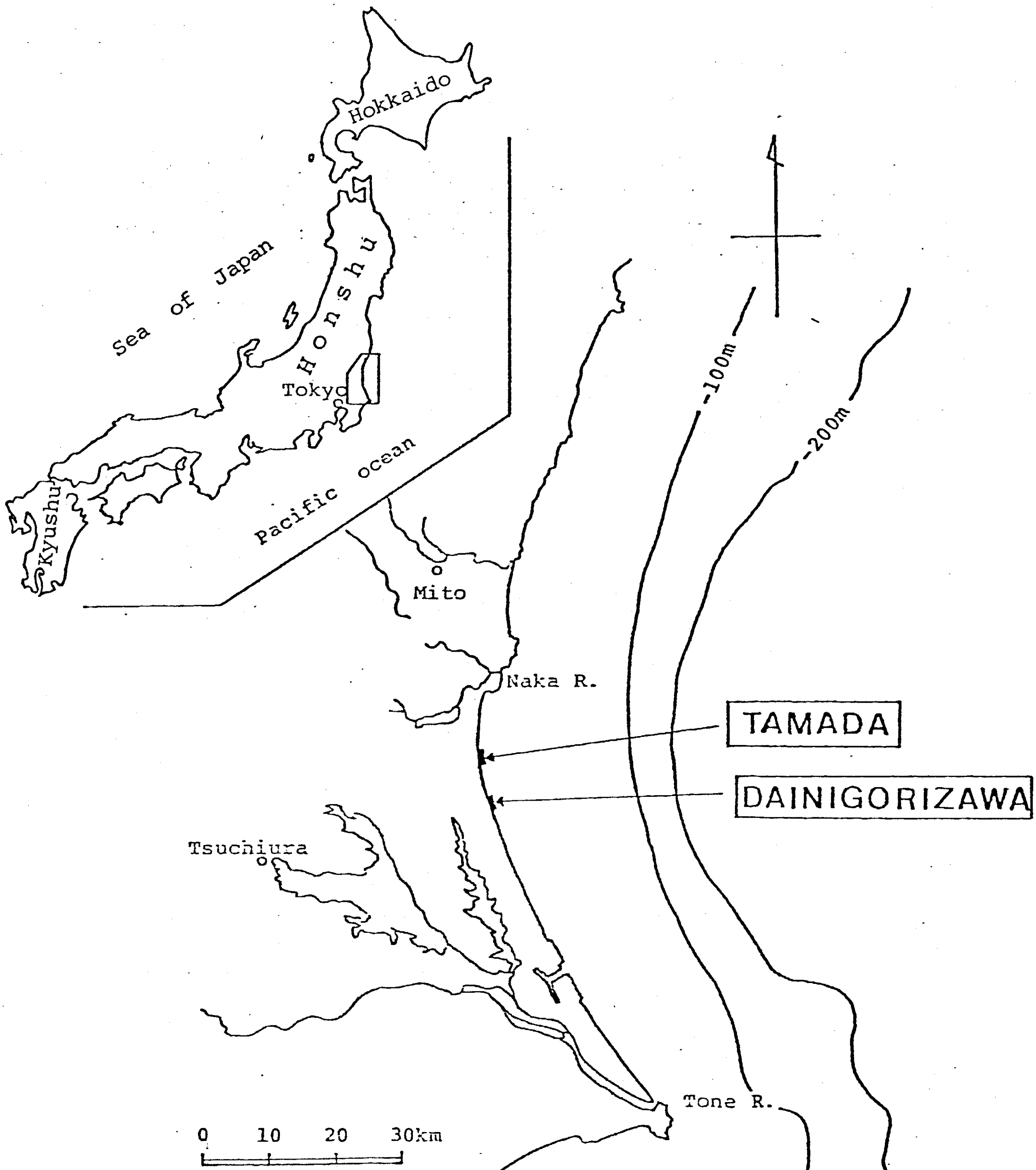
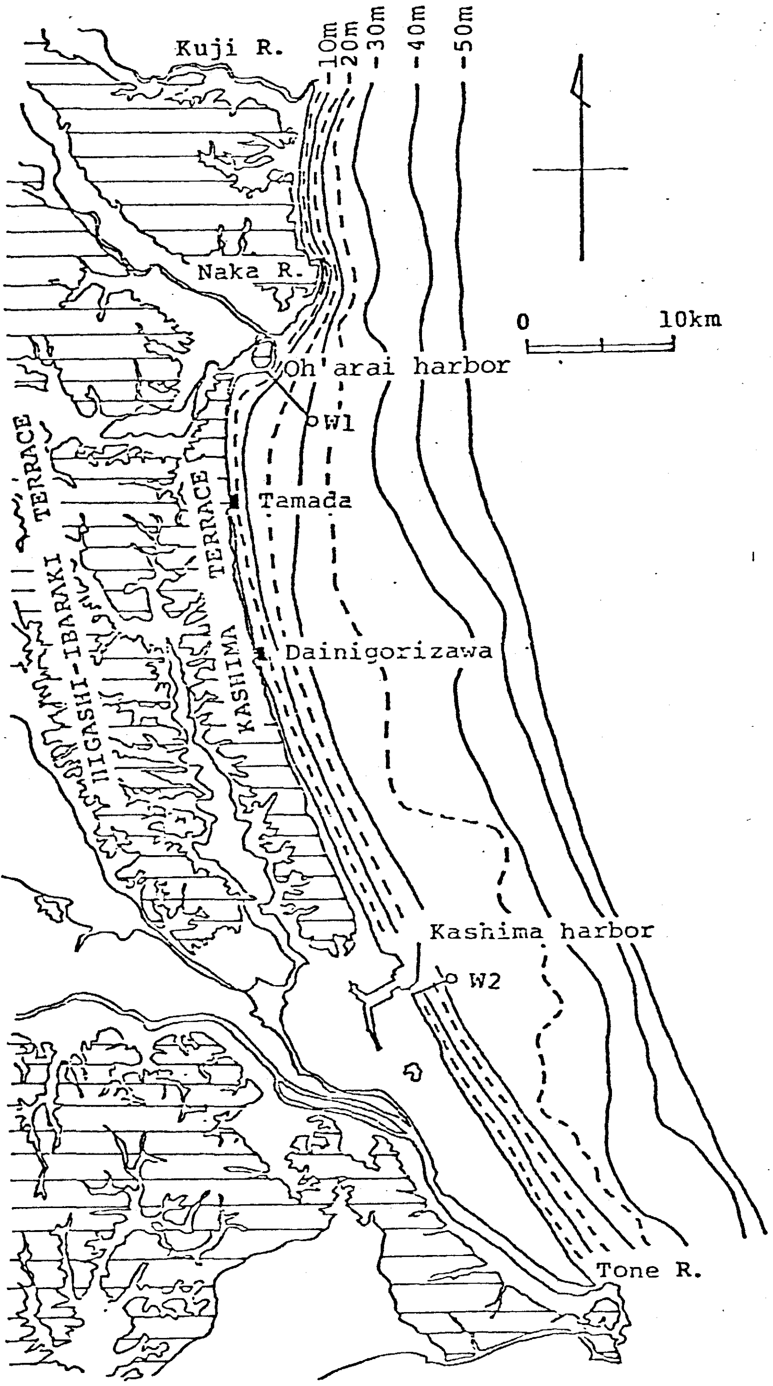


Fig. 3 Study area.



W1: The position of wave gage (Oh'arai)
W2: The position of wave gage (Kashima)

Fig. 4 Study sites and their surrounding topography.

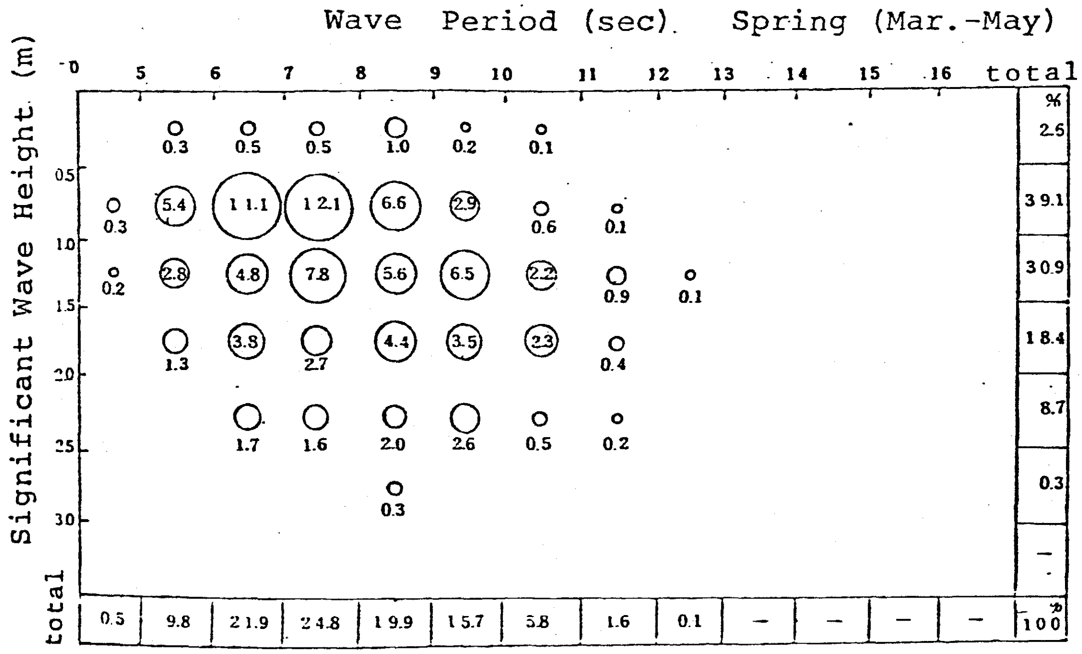


Fig. 5-A Occurrence frequency of wave period and wave height. [After Ministry of Transport (1977)]

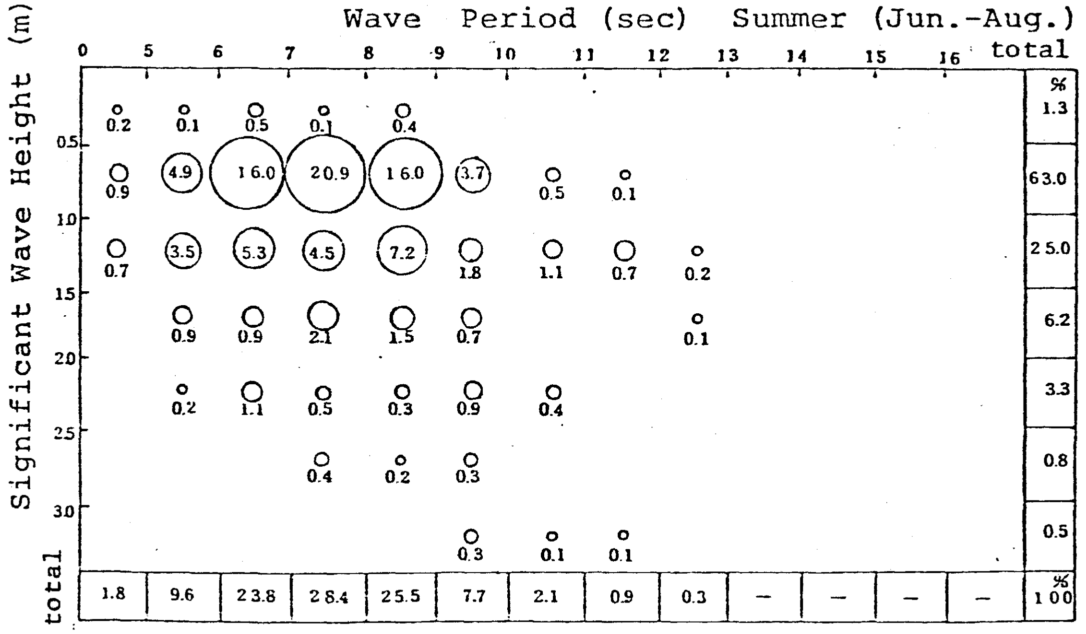


Fig. 5 -B Occurrence frequency of wave period and wave height. [After Ministry of Transport (1977)]

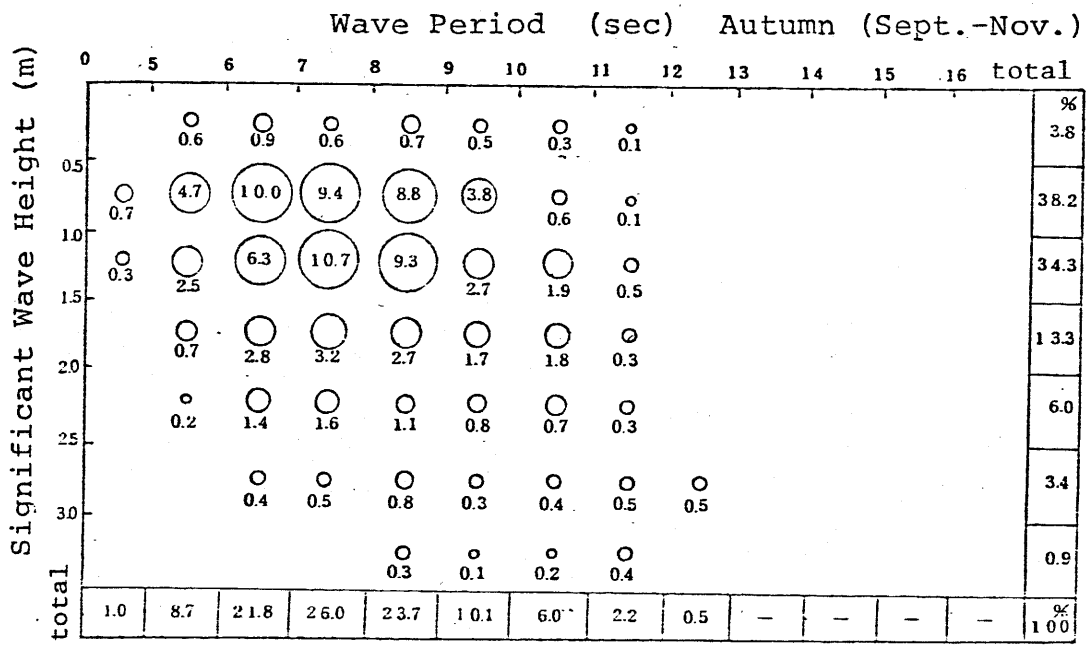


Fig. 5 —C Occurrence frequency of wave period and wave height.
[After Ministry of Transport (1977)]

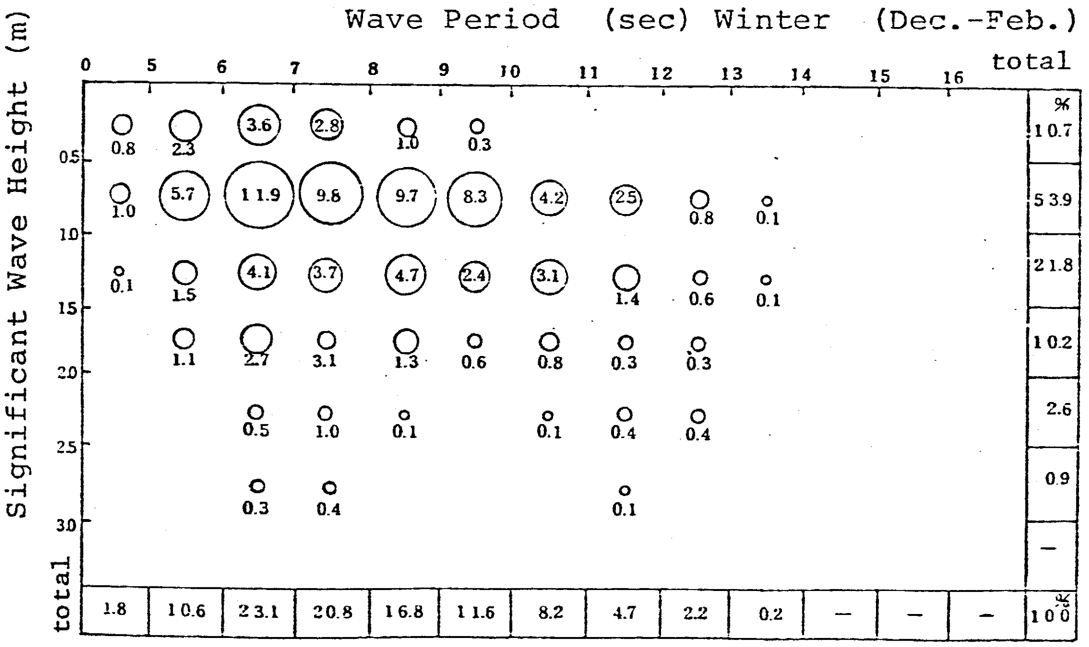


Fig. 5 —D Occurrence frequency of wave period and wave height.
[After Ministry of Transport (1977)]

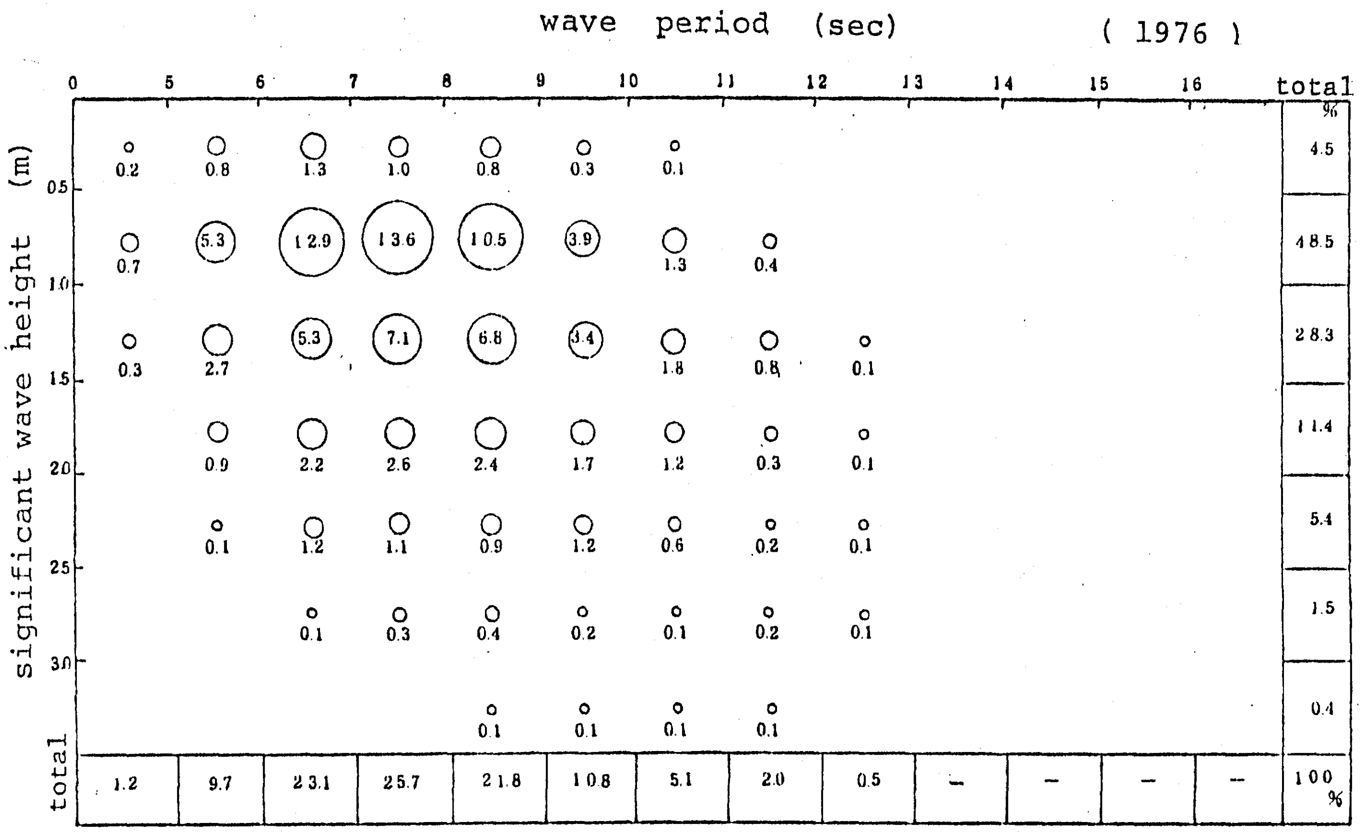


Fig. 5 -E Occurrence frequency of wave period and wave height.
[After Ministry of Transport (1977)]

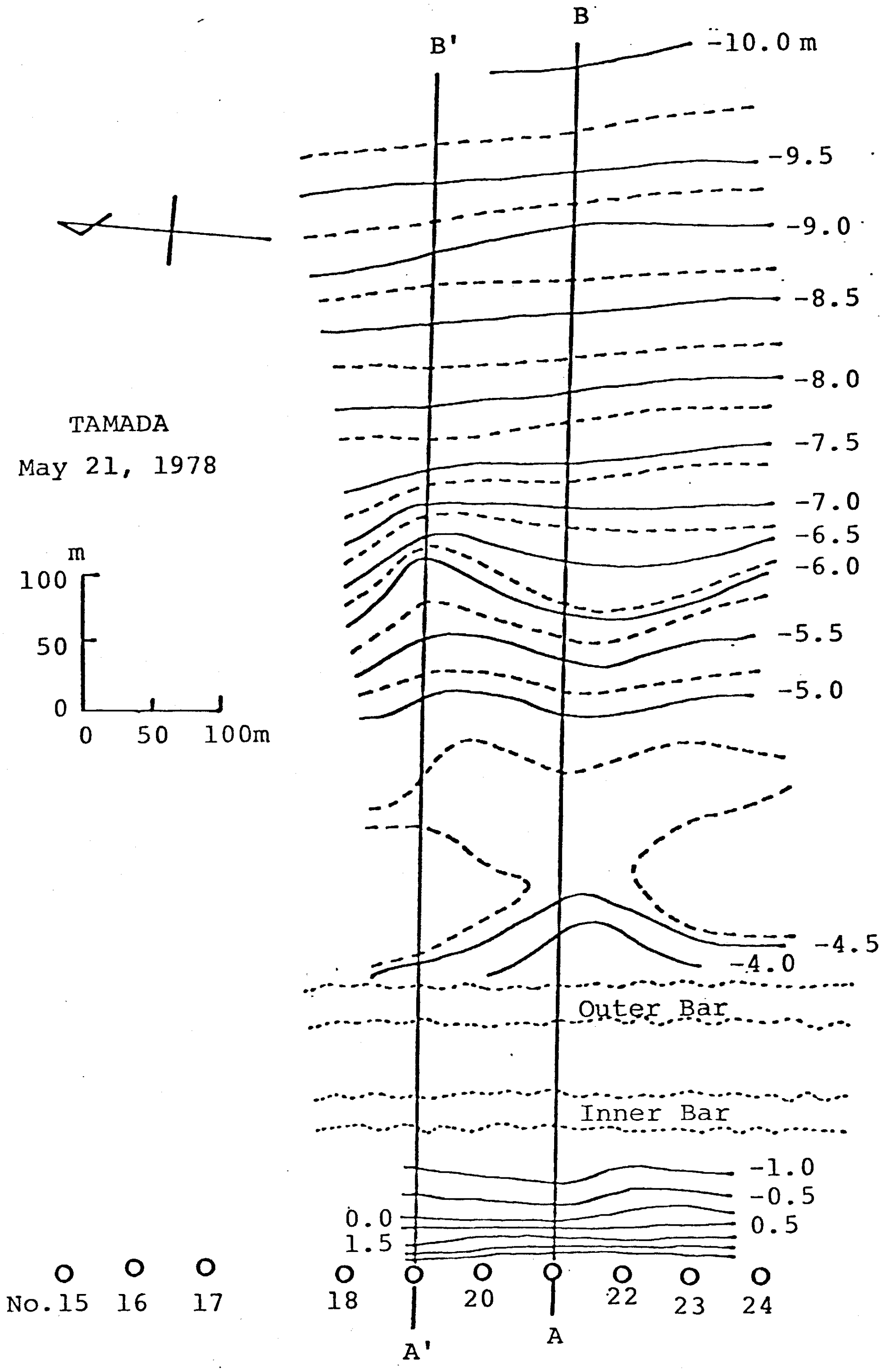


Figure 6 Nearshore topography at the Tamada site.

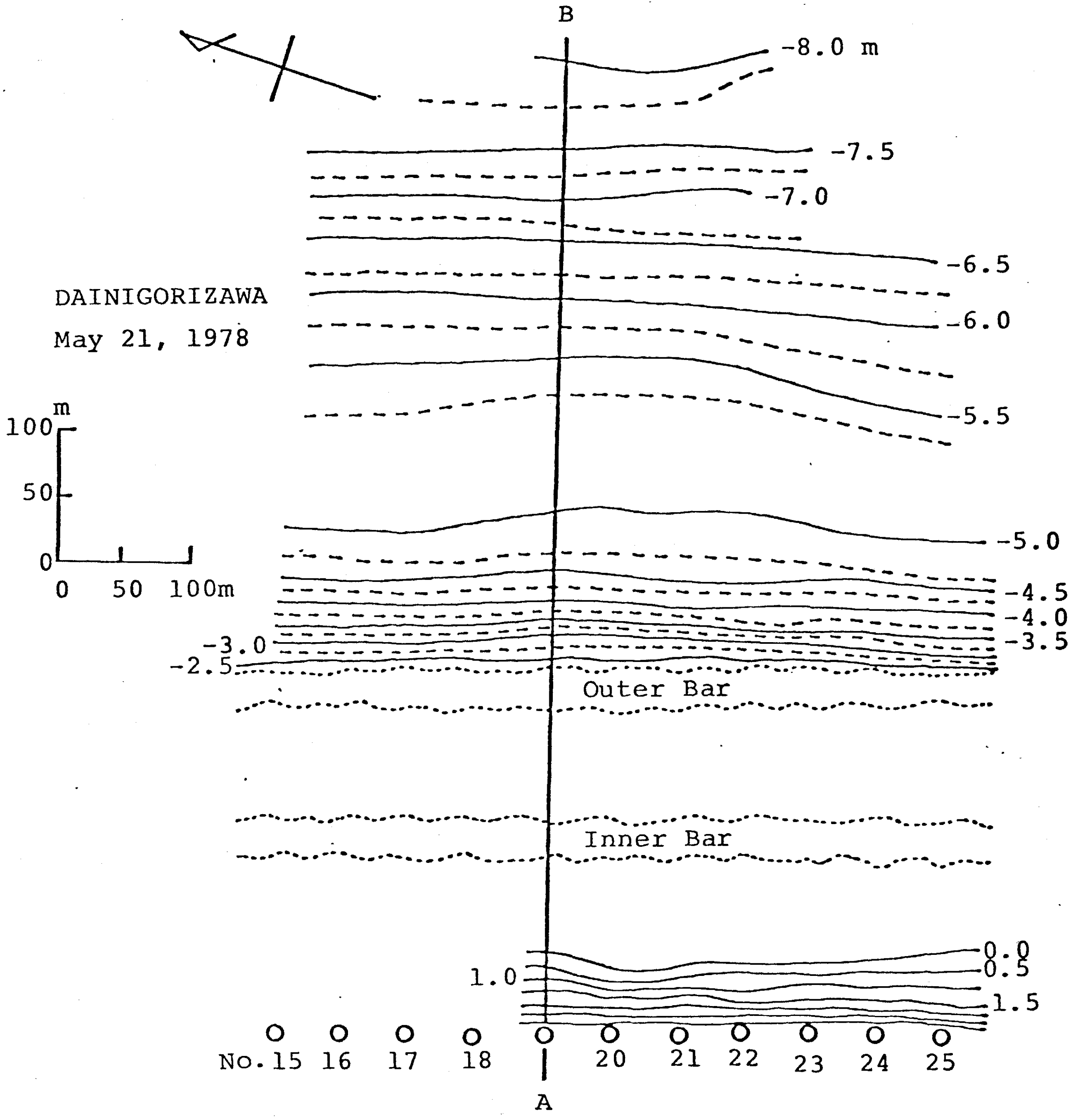


Figure 7 Nearshore topography at the Dainigorizawa site.

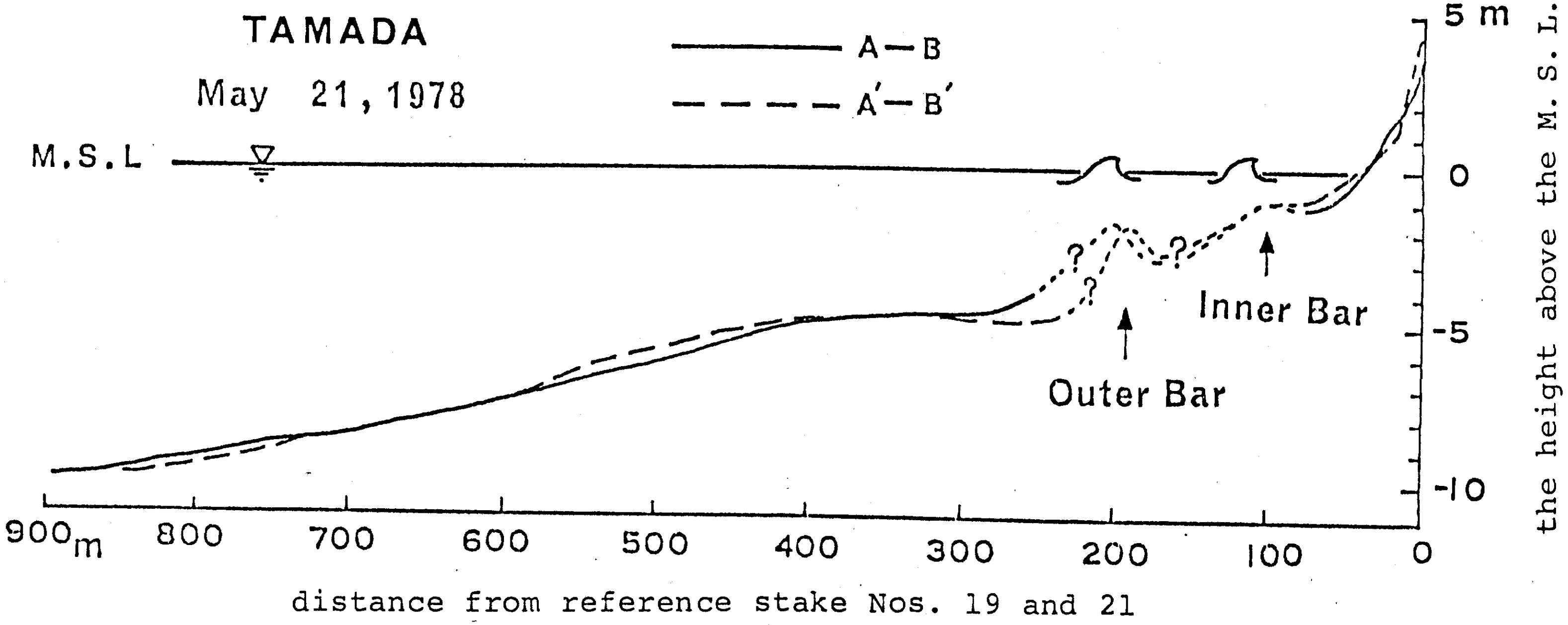


Fig. 8 Beach profile at the Tamada site

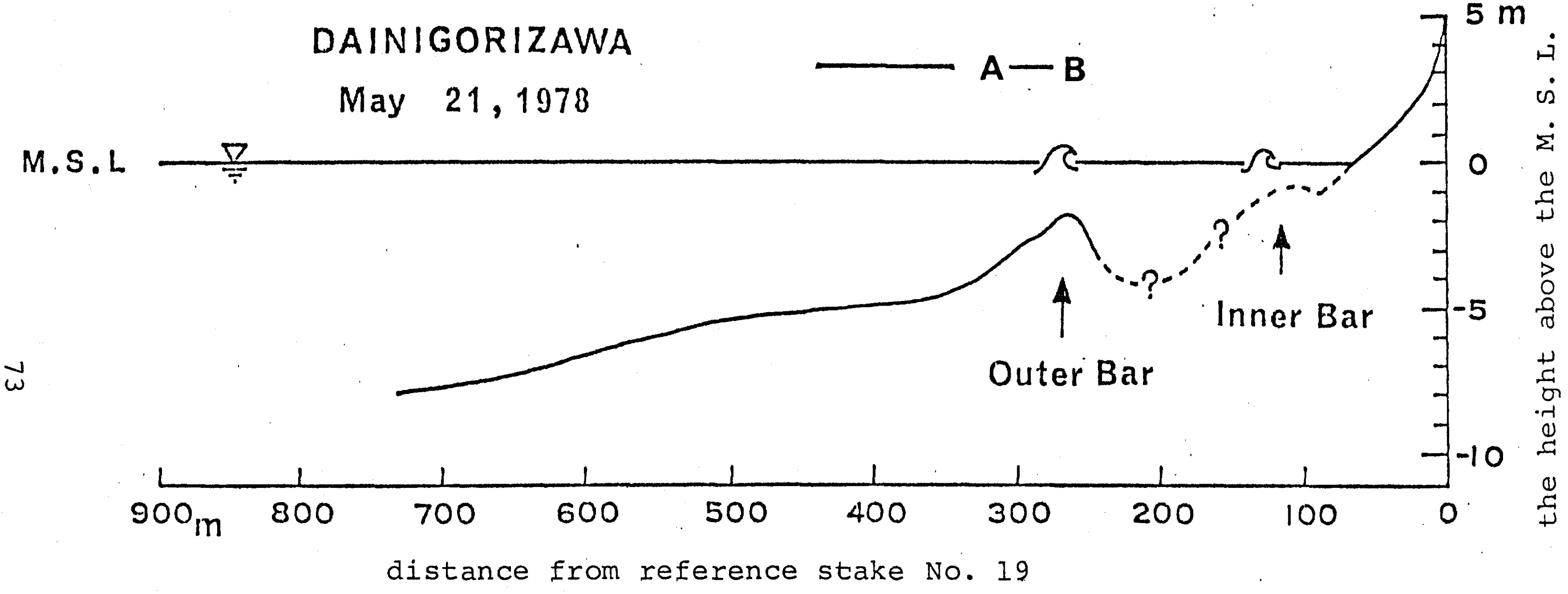


Fig. 9 Beach profile at the Dainigorizawa site.

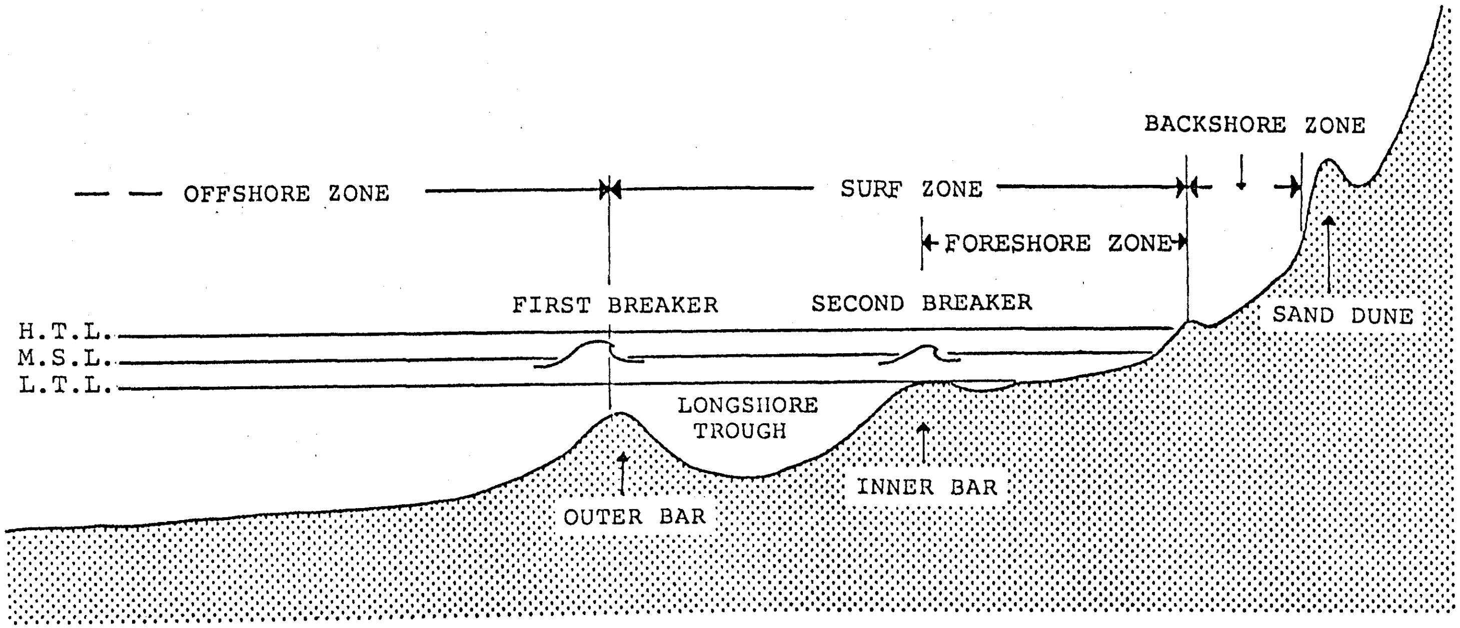


Fig. 10 Generalized beach profile in the study area.

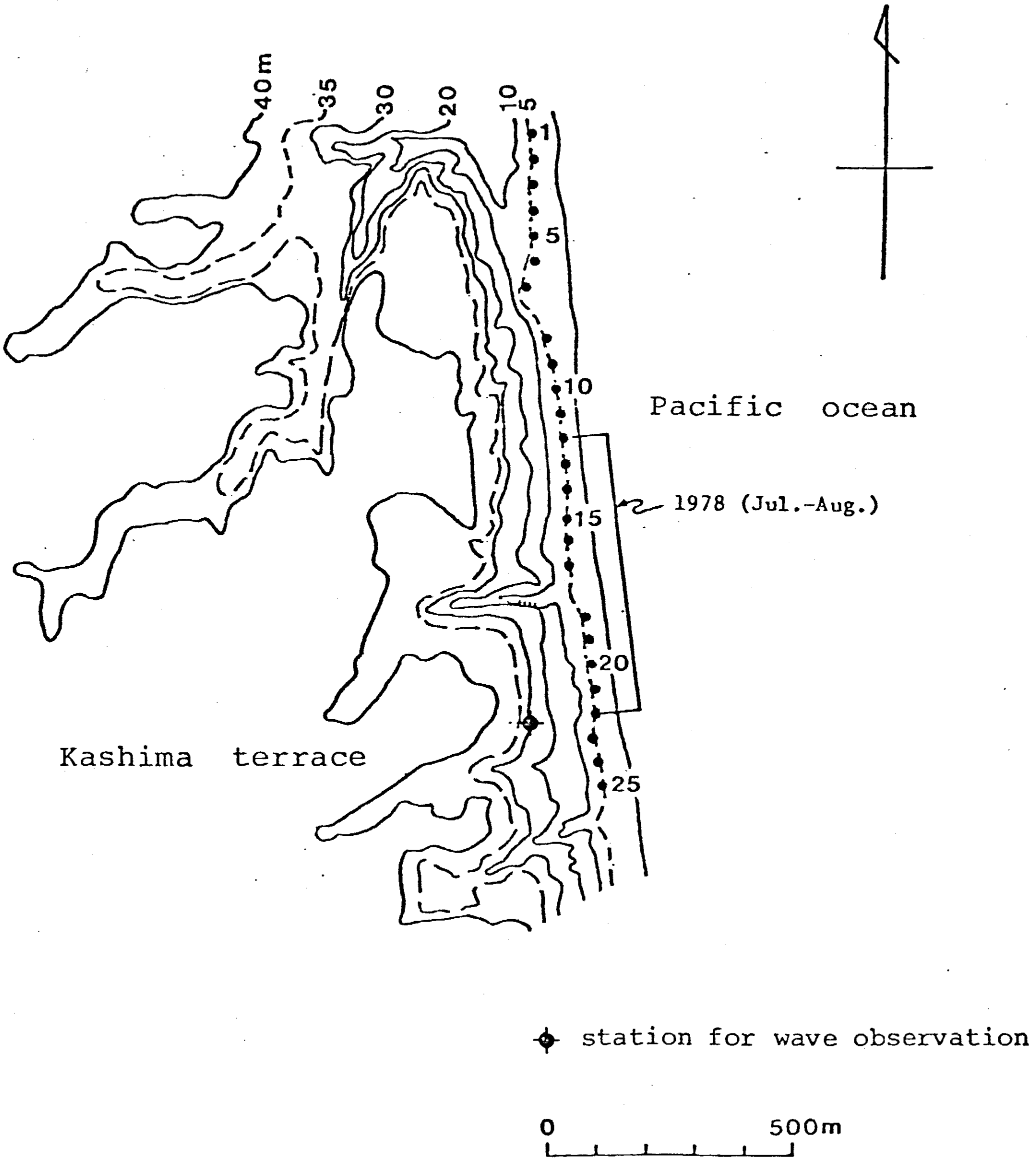


Fig. 11 The arrangement of reference stakes in the Tamada site.

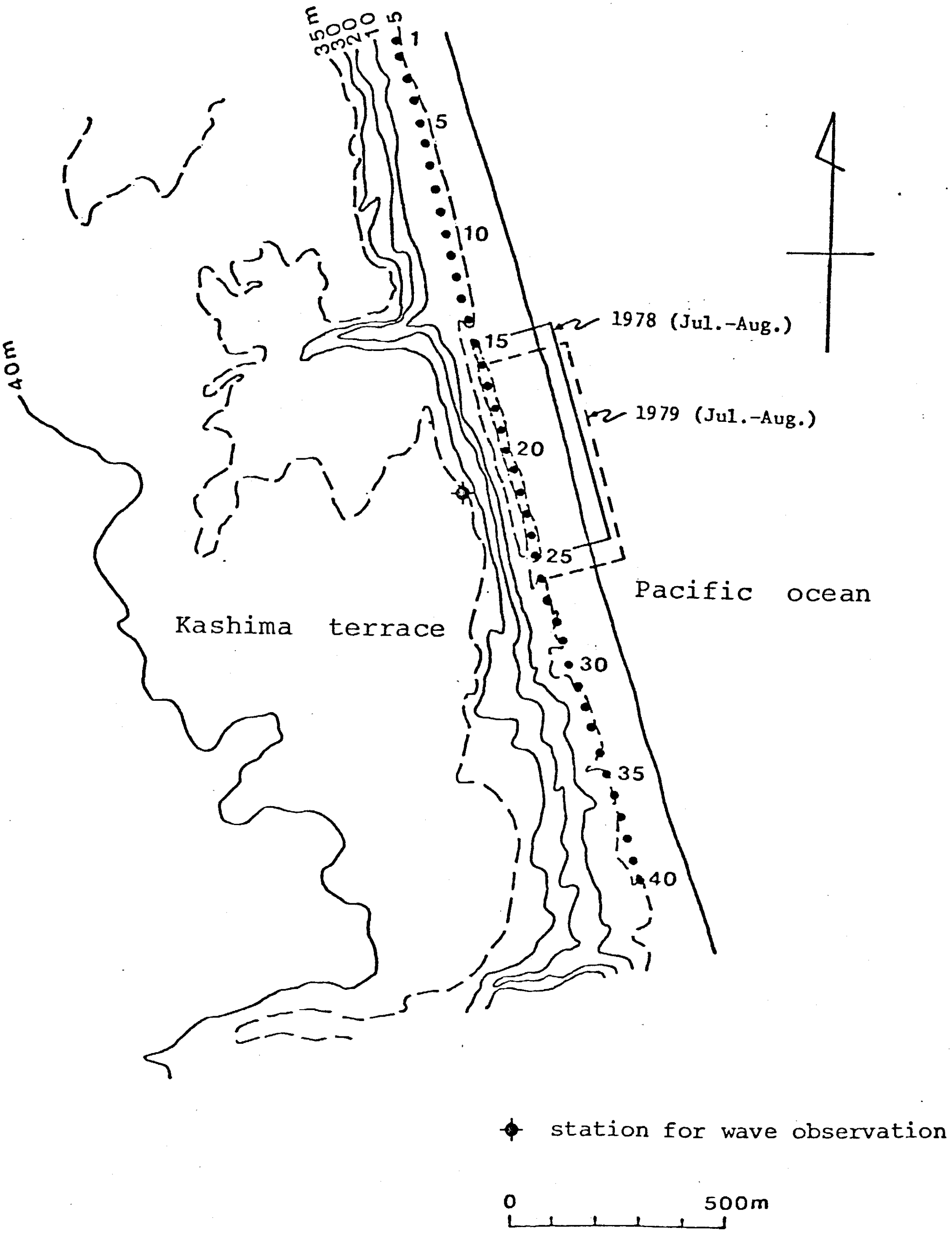
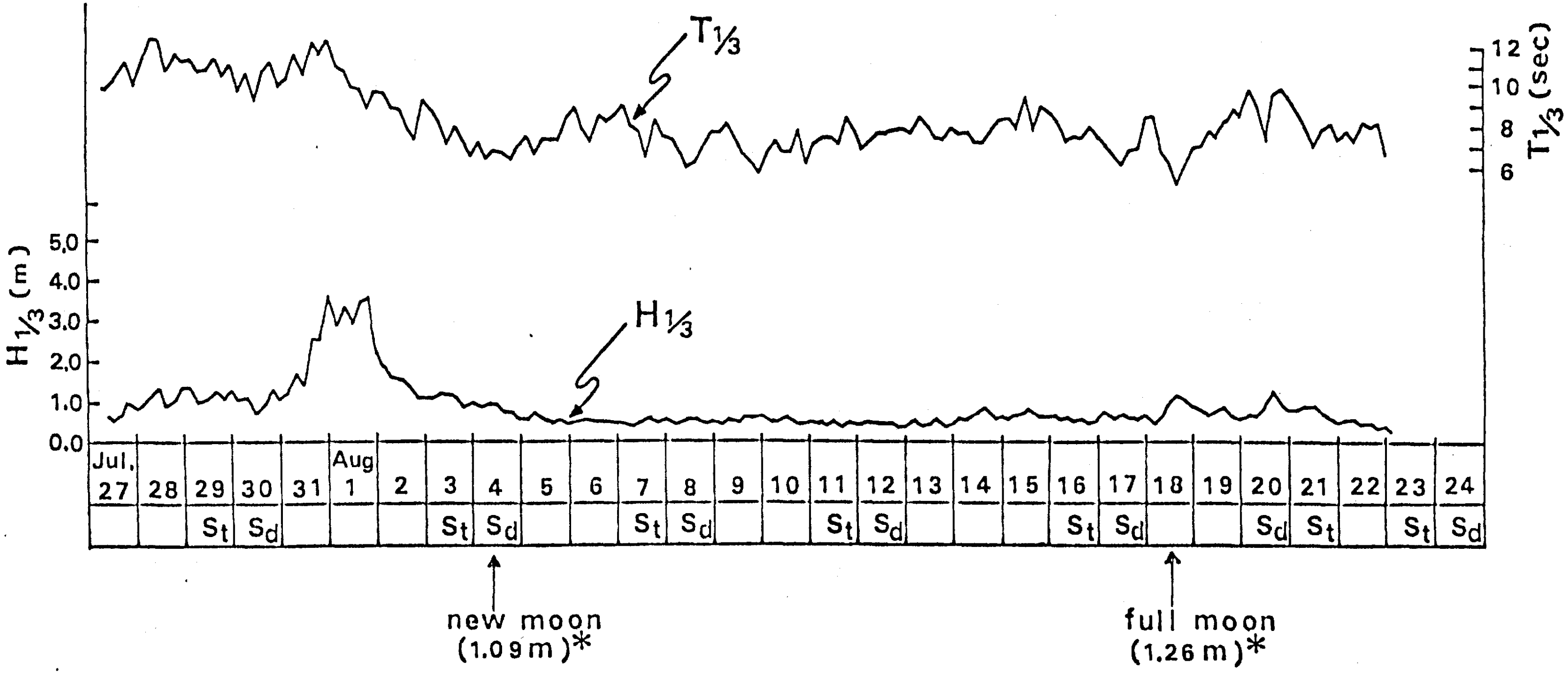


Fig. 12 The arrangement of reference stakes in the Dainigorizawa site.

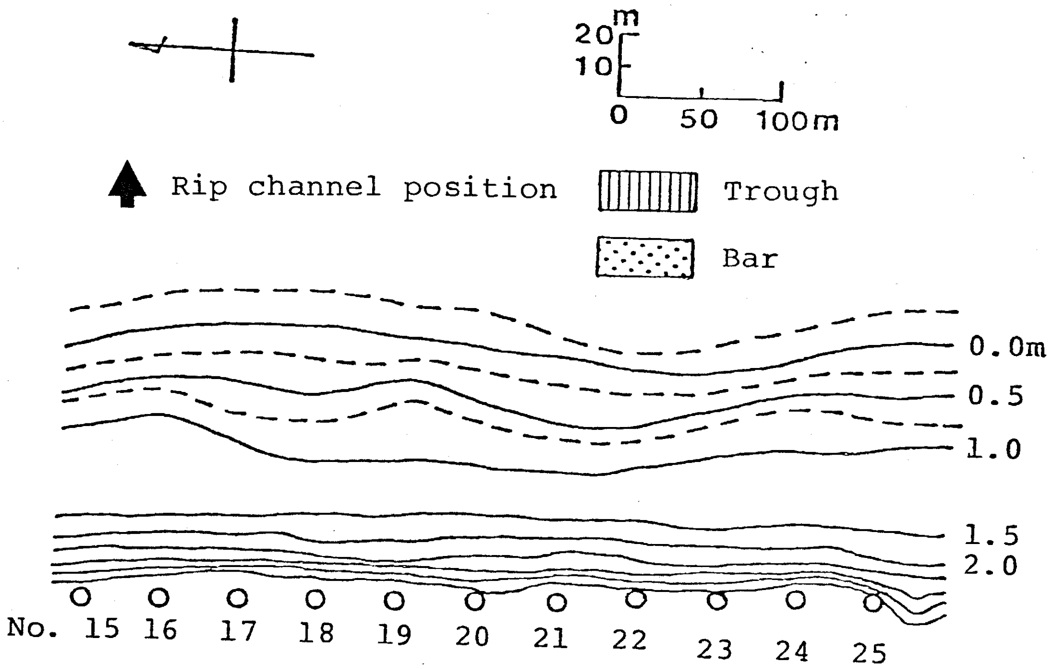


S_d : Survey in Dainigorizawa

S_t : Survey in Tamada

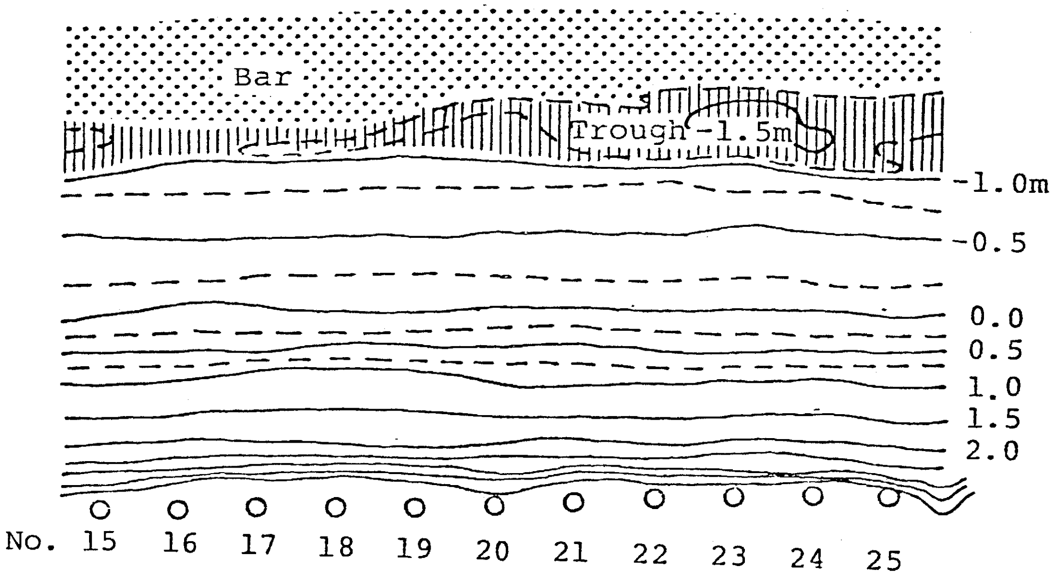
* : Tidal range

Fig. 13 Wave conditions during the summer survey of 1978.
(by the Construction Work Office of Kashima Port)



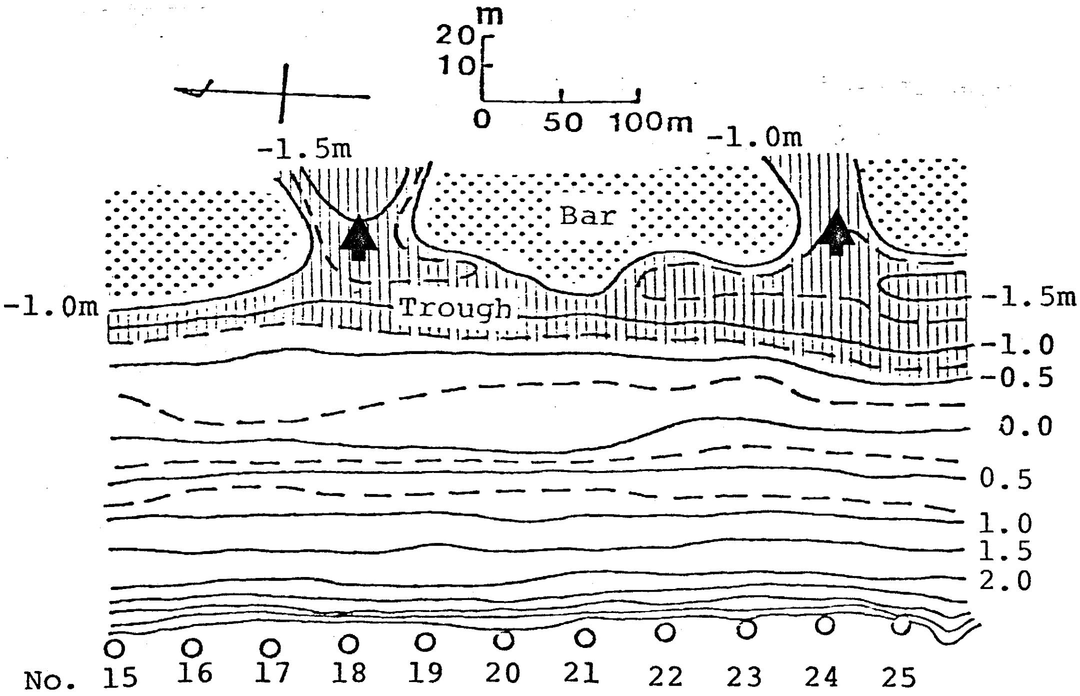
Jul. 30, 1978 (10:35-12:50)

Fig. 14-A Foreshore zone topography (Dainigorizawa).



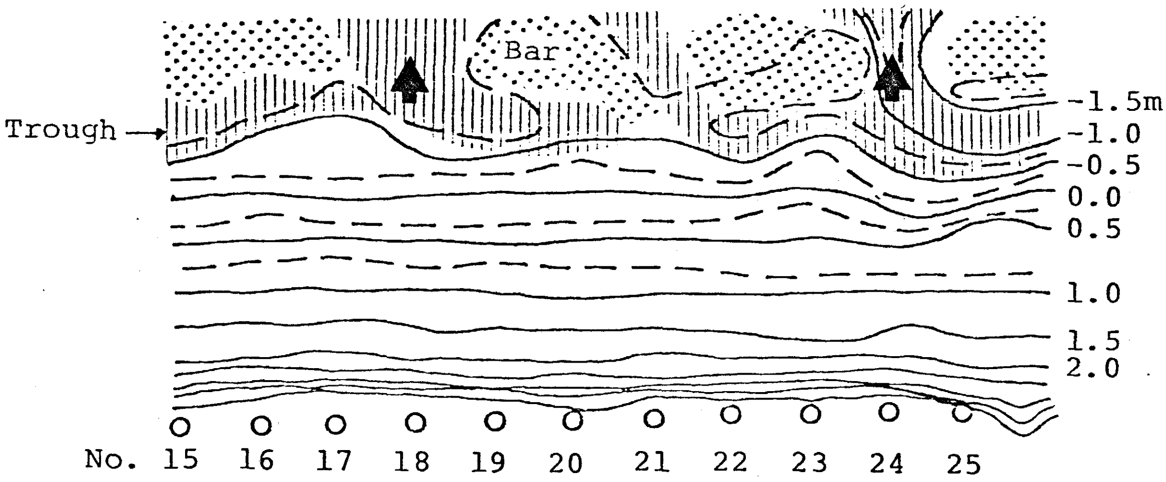
Aug. 4, 1978 (9:40-12:55)

Fig. 14-B Foreshore zone topography (Dainigorizawa).



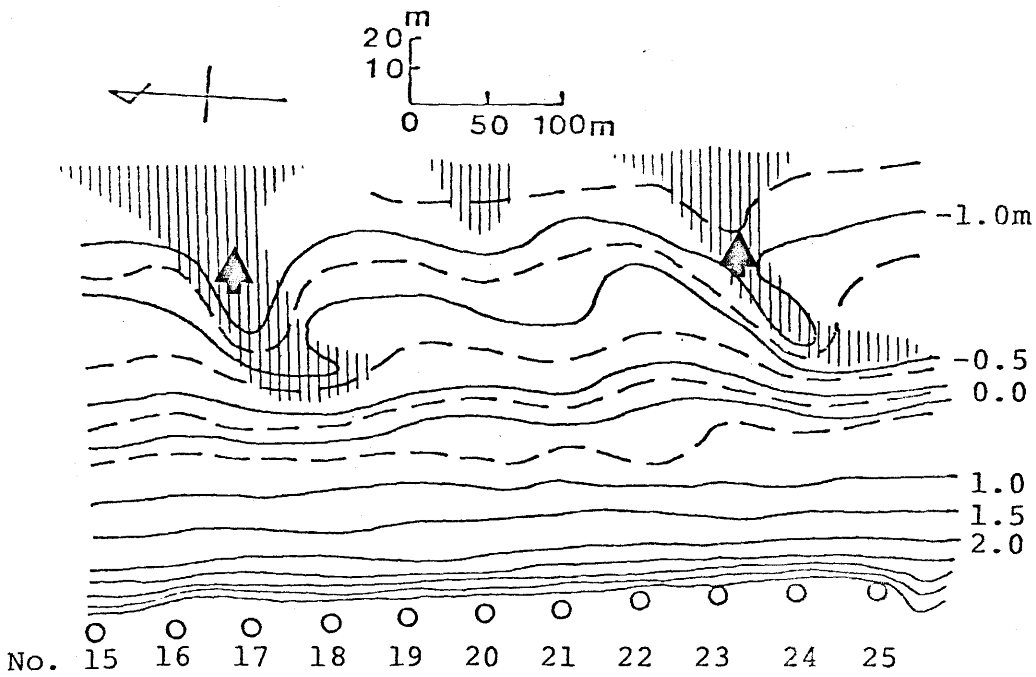
Aug. 8, 1978 (10:30-13:05)

Fig. 14-C Foreshore zone topography (Dainigorizawa).



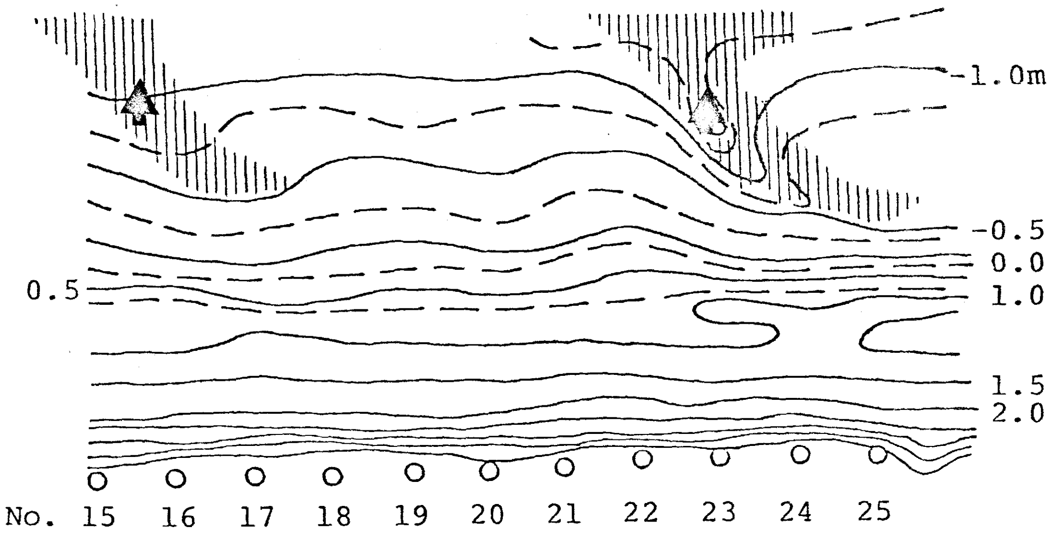
Aug. 12, 1978 (13:30-15:45)

Fig. 14-D Foreshore zone topography (Dainigorizawa).



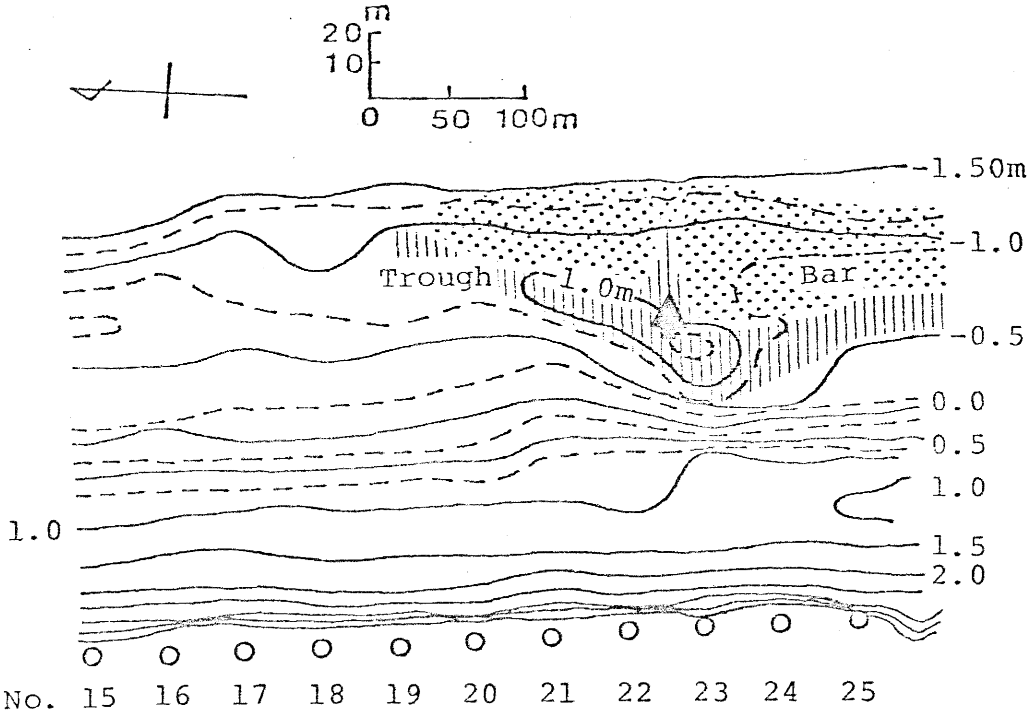
Aug. 17, 1978 (8:40-11:00)

Fig. 14-E Foreshore zone topography (Dainigorizawa).



Aug. 20, 1978

Fig. 14-F Foreshore zone topography (Dainigorizawa).



Aug. 24, 1978 (13:00-15:20)
Fig. 14-G Foreshore zone topography (Dainigorizawa).

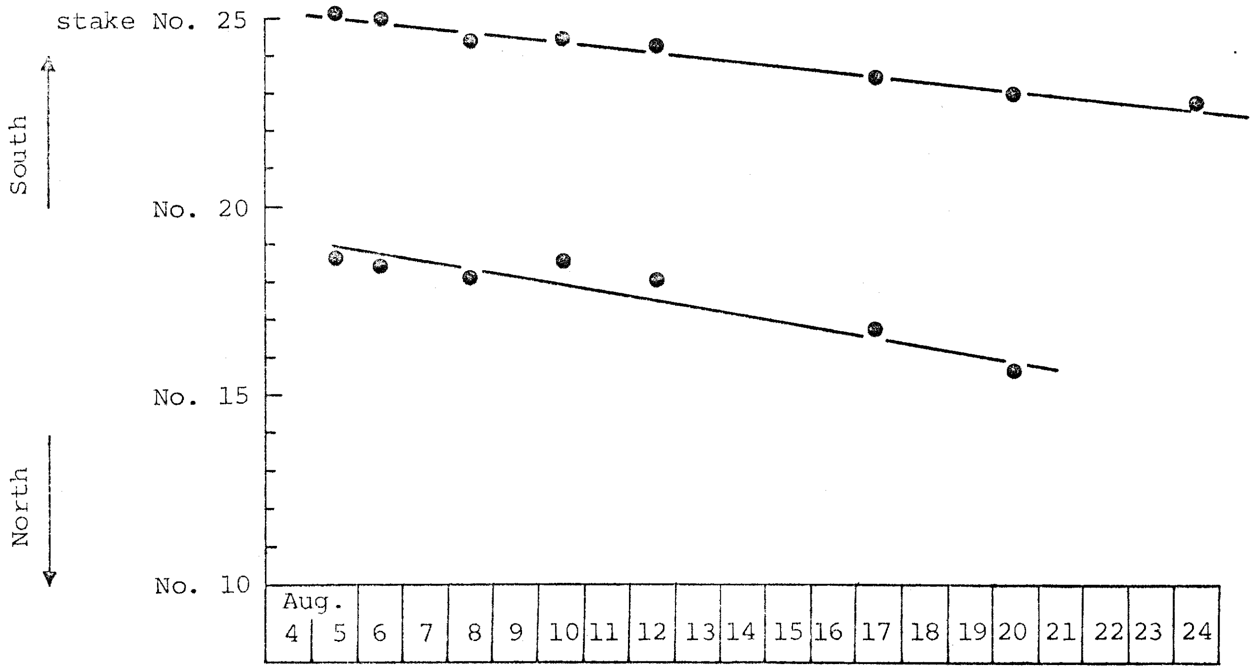
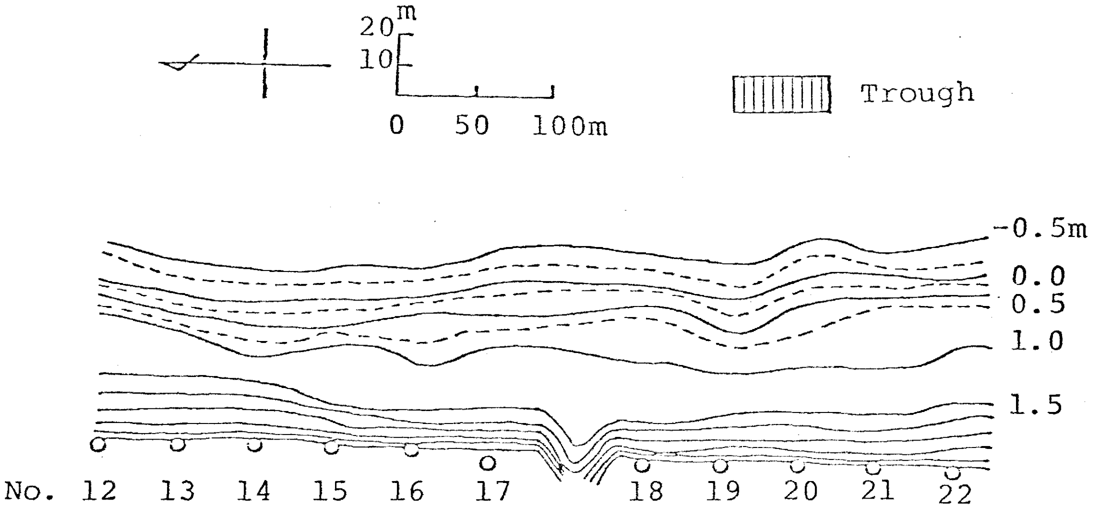
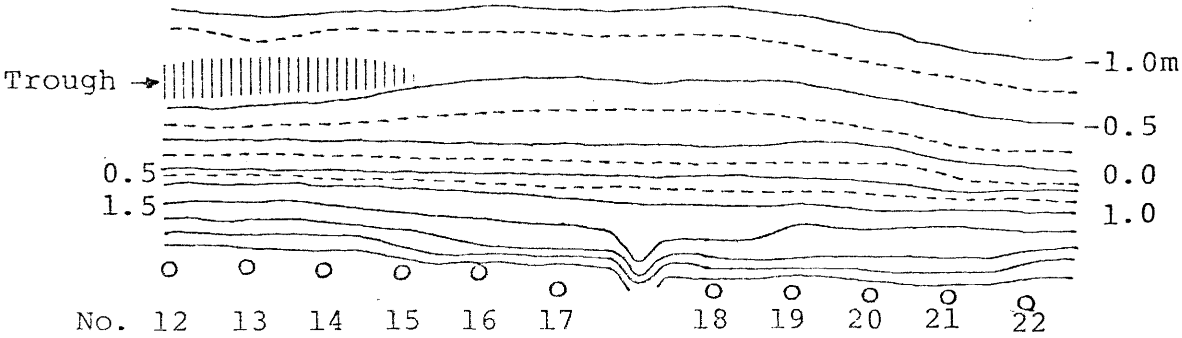


Fig. 15 Rip channel position (denoted by the solid arrows on Figures 14-C - 14-G.) and its longshore movement (Dainigorizawa, 1978).



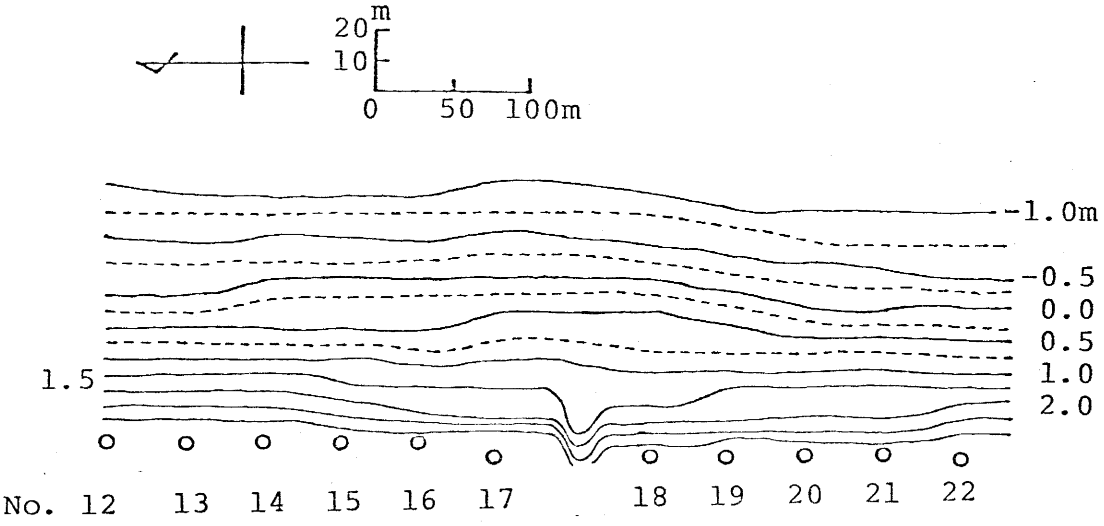
Jul. 29, 1978 (9:45-11:35)

Fig. 16-A Foreshore zone topography (Tamada).



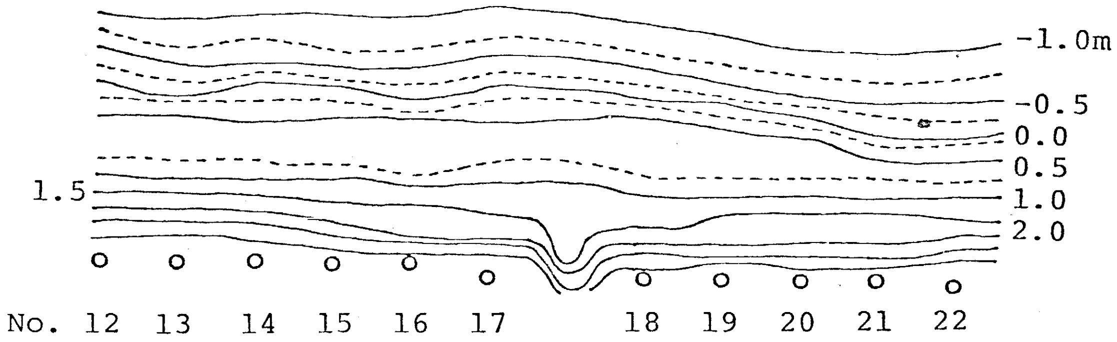
Aug. 3, 1978 (9:20-12:00)

Fig. 16-B Foreshore zone topography (Tamada).



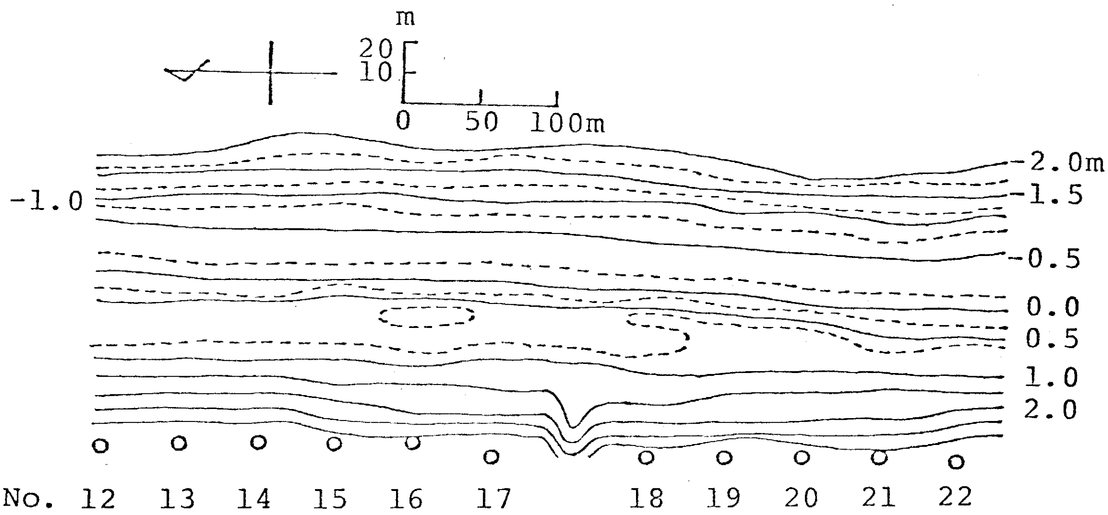
Aug. 7, 1978 (9:08-11:00)

Fig. 16-C Foreshore zone topography (Tamada).



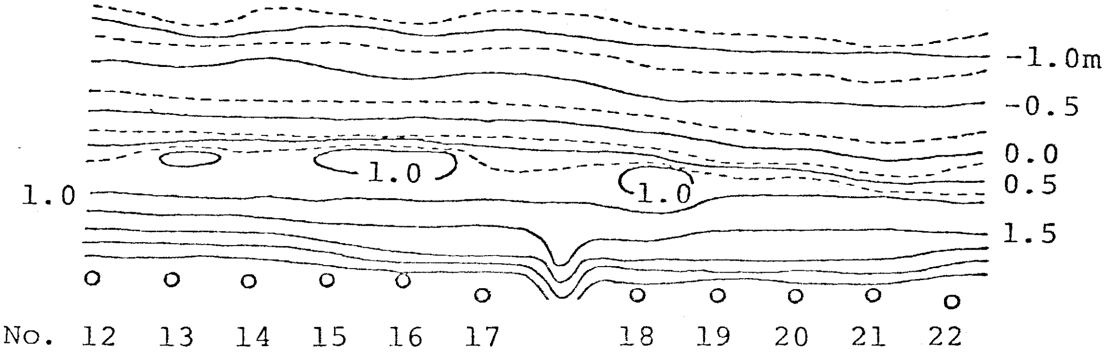
Aug. 11, 1978 (12:35-14:30)

Fig. 16-D Foreshore zone topography (Tamada).



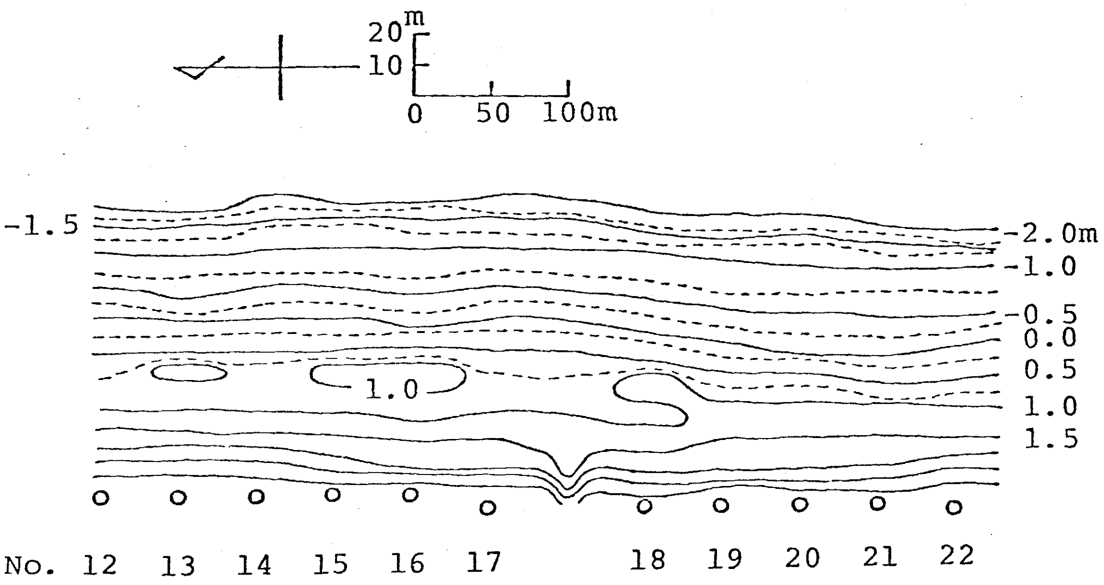
Aug. 16, 1978 (8:15-10:07)

Fig. 16-E Foreshore zone topography (Tamada).



Aug. 21, 1978 (10:05-11:52)

Fig. 16-F Foreshore zone topography (Tamada).



Aug. 23, 1978 (11:15-14:10)

Fig. 16-G Foreshore zone topography (Tamada).

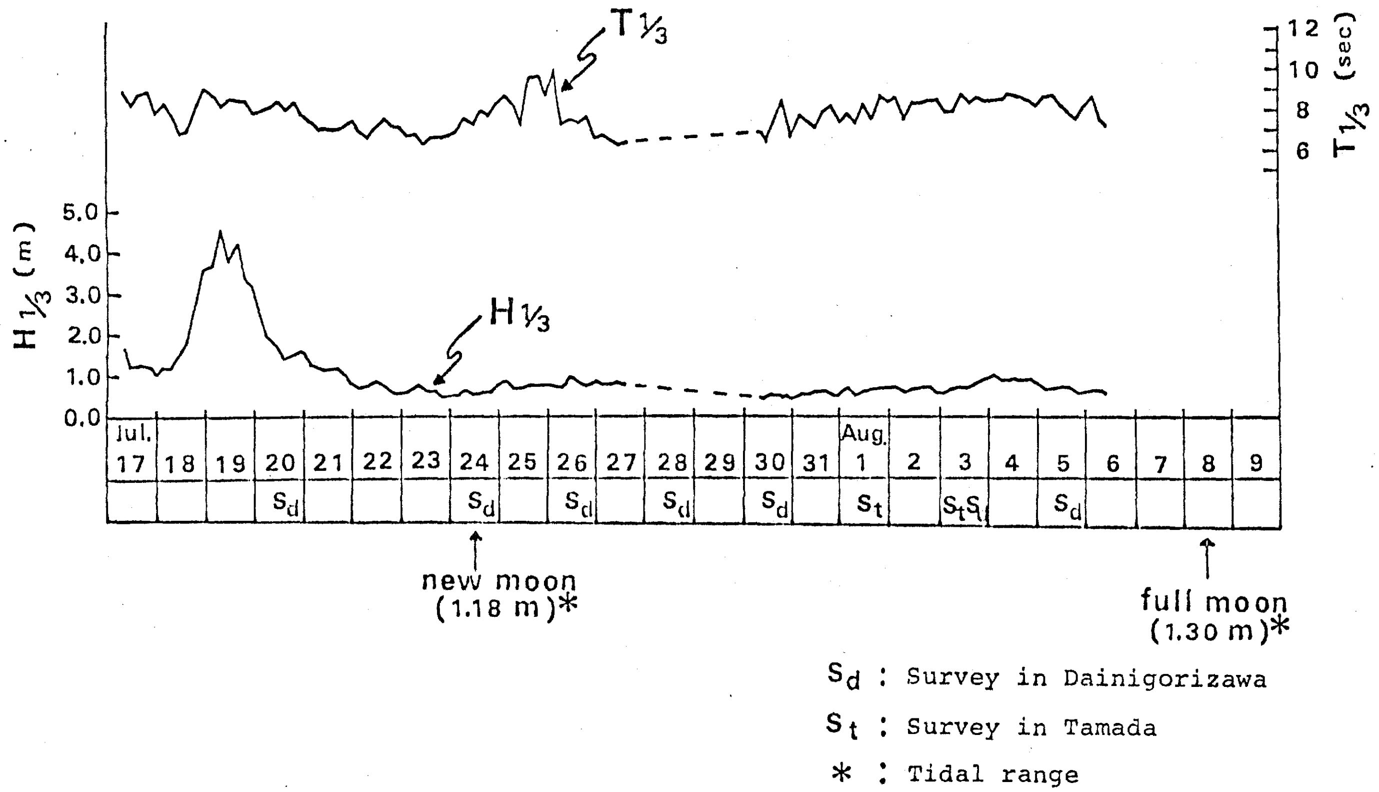
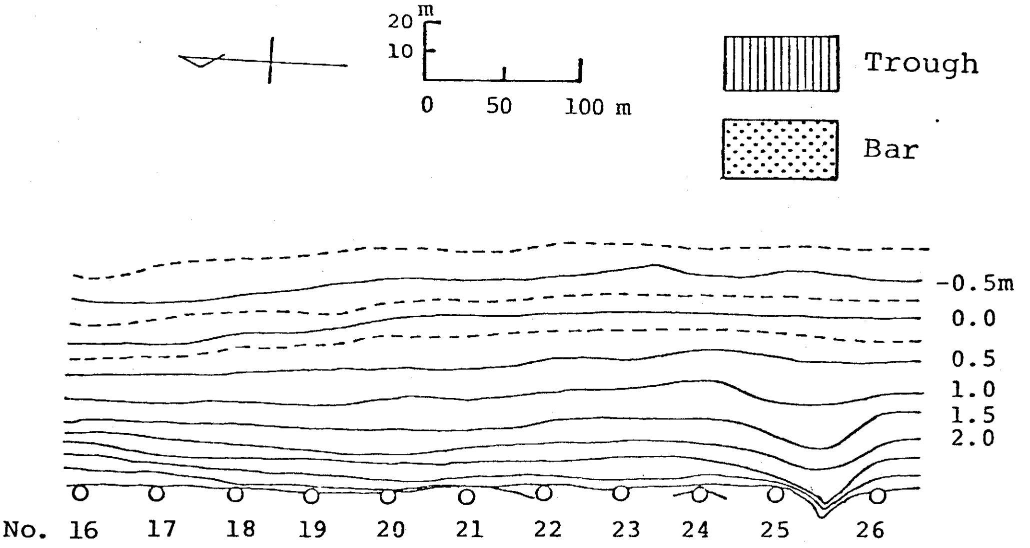
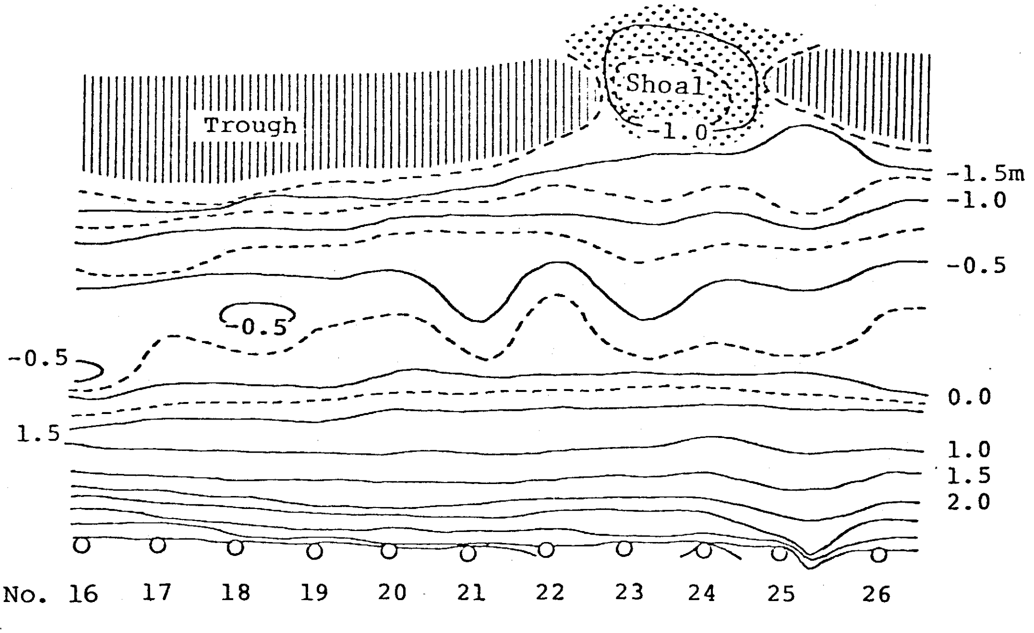


Fig. 17 Wave conditions during the summer survey of 1979.
(by the Construction Work Office of Kashima Port)



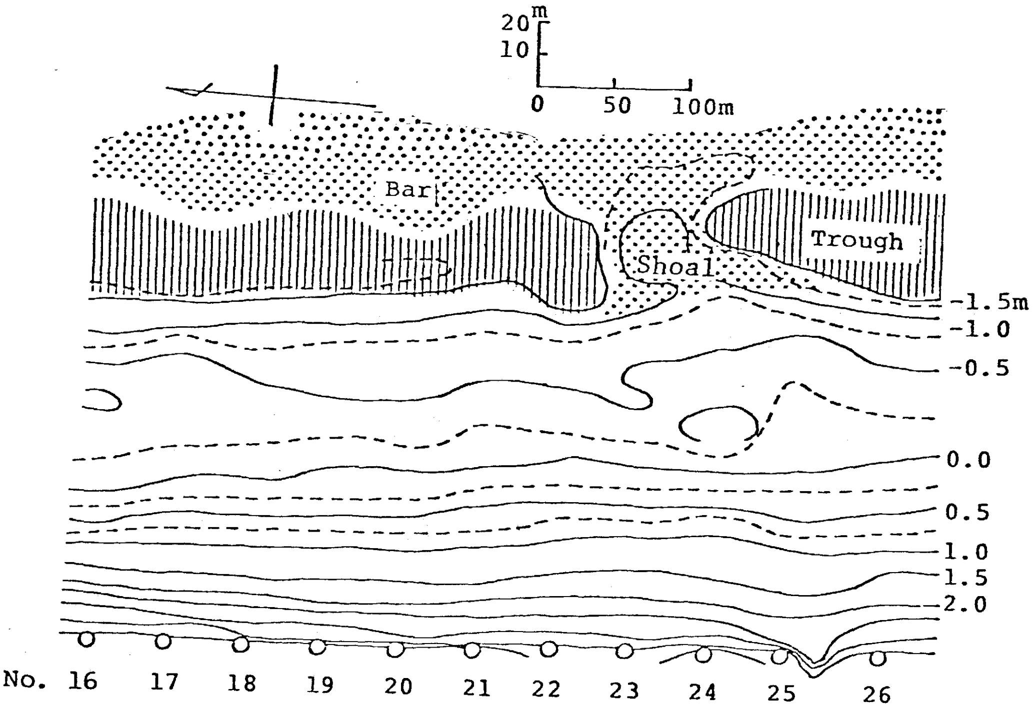
Jul. 20, 1979 (8:40-10:40)

Fig. 18-A Foreshore zone topography (Dainigorizawa).



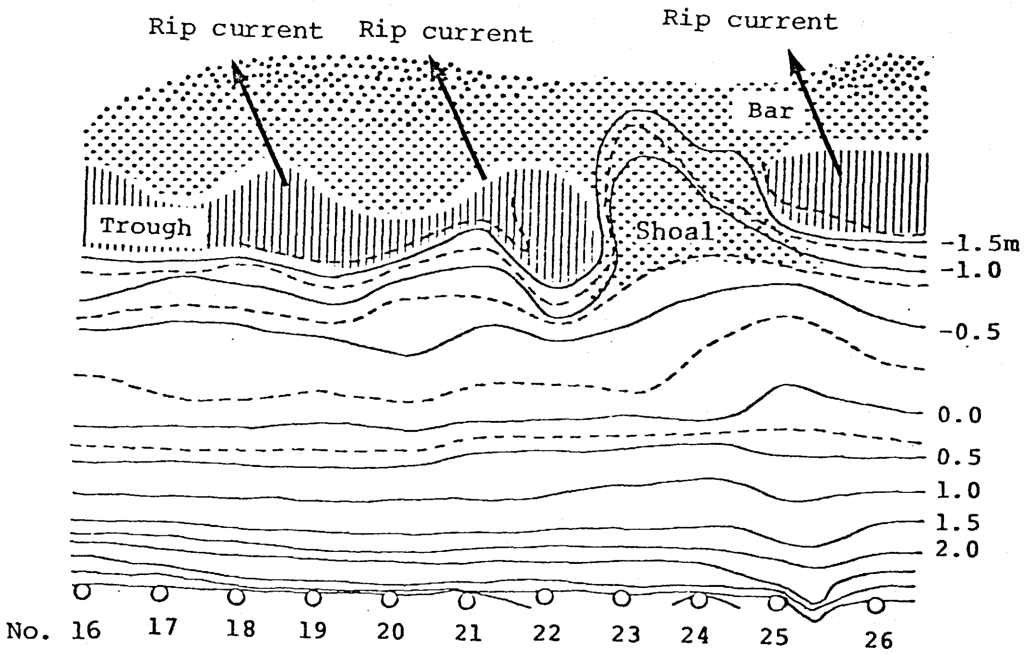
Jul. 24, 1979 (9:05-11:45)

Fig. 18-B Foreshore zone topography (Dainigorizawa).



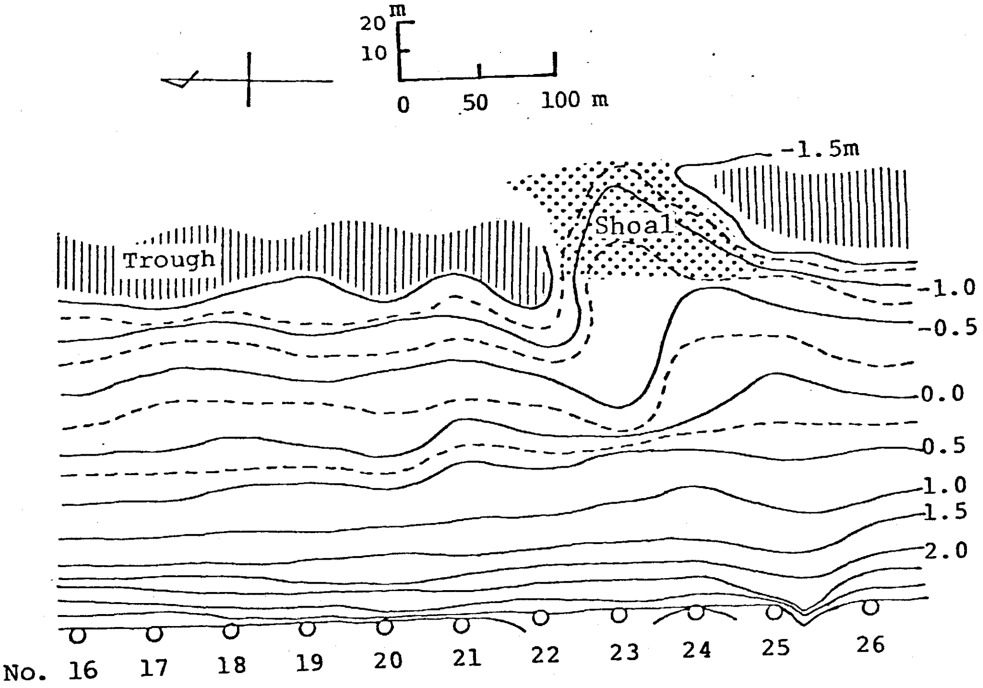
Jul. 26, 1979 (9:15-11:35)

Fig. 18-C Foreshore zone topography (Dainigorizawa).



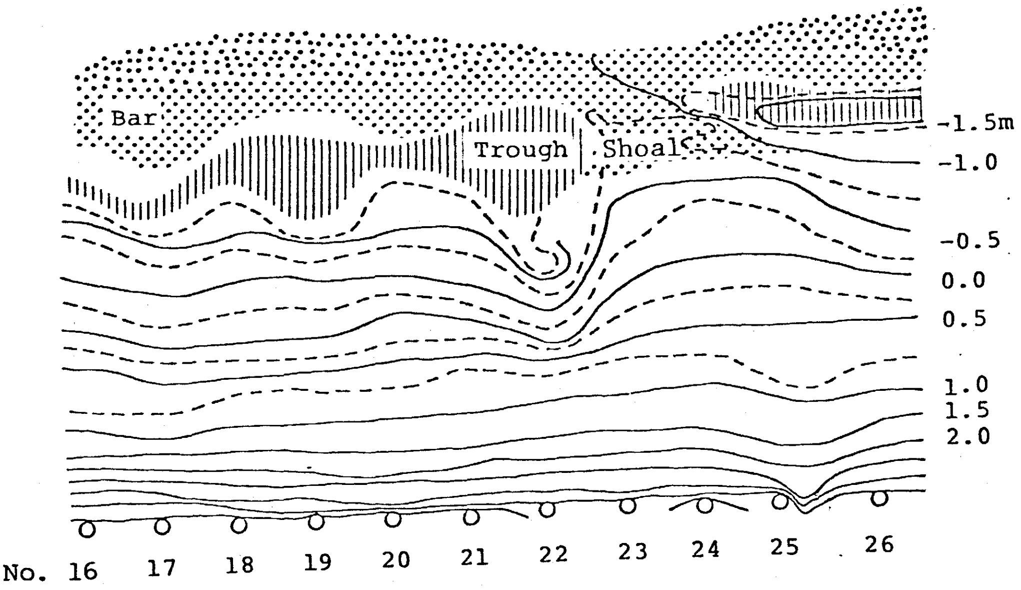
Jul. 28, 1979 (11:35-13:35)

Fig. 18-D Foreshore zone topography (Dainigorizawa).



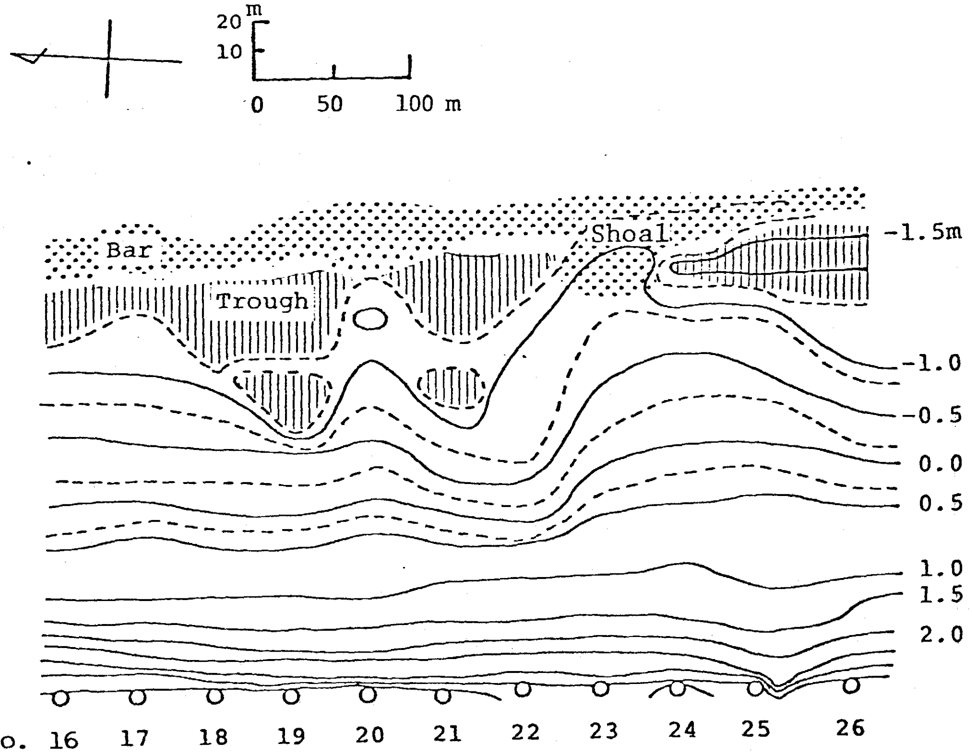
Jul. 30, 1979 (12:20-14:25)

Fig. 18-E Foreshore zone topography (Dainigorizawa).



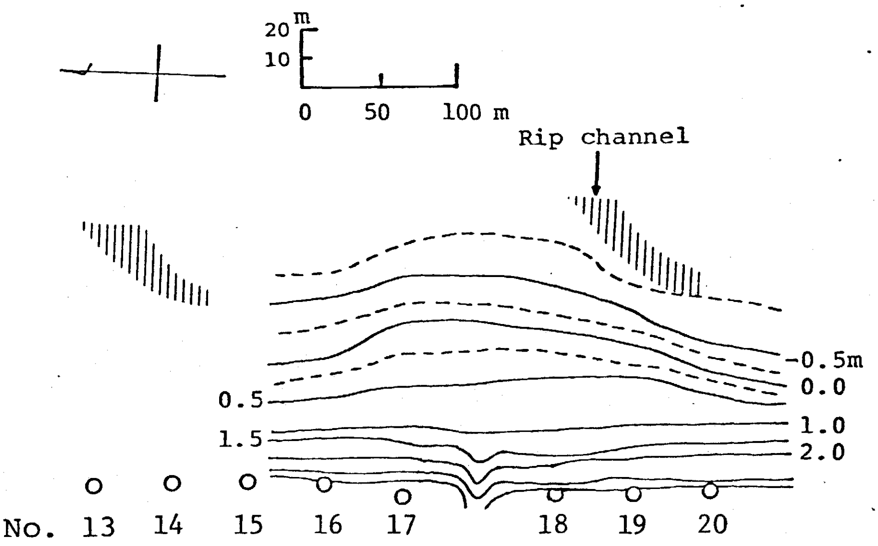
Aug. 3, 1979 (5:35-7:30)

Fig. 18-F Foreshore zone topography (Dainigorizawa).



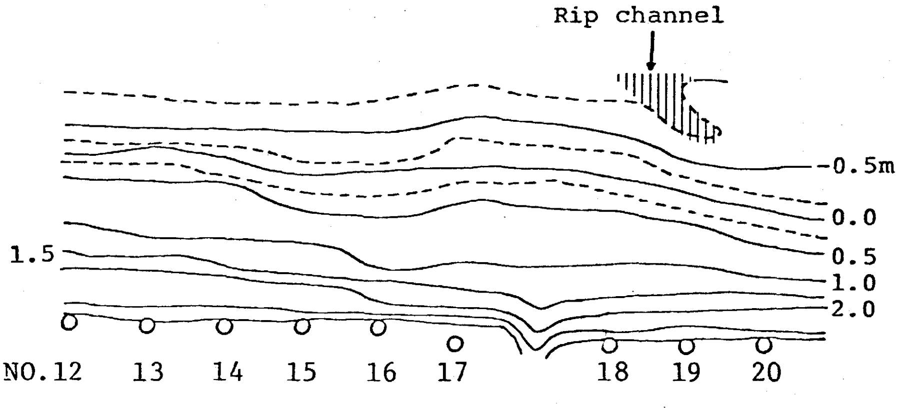
Aug. 5, 1979 (6:20-8:40)

Fig. 18-G Foreshore zone topography (Dainigorizawa).



Aug. 1, 1979 (12:33-13:20)

Fig. 19-A Foreshore zone topography (Tamada).



Aug. 3, 1979 (15:50-16:45)

Fig. 19-B Foreshore zone topography (Tamada).

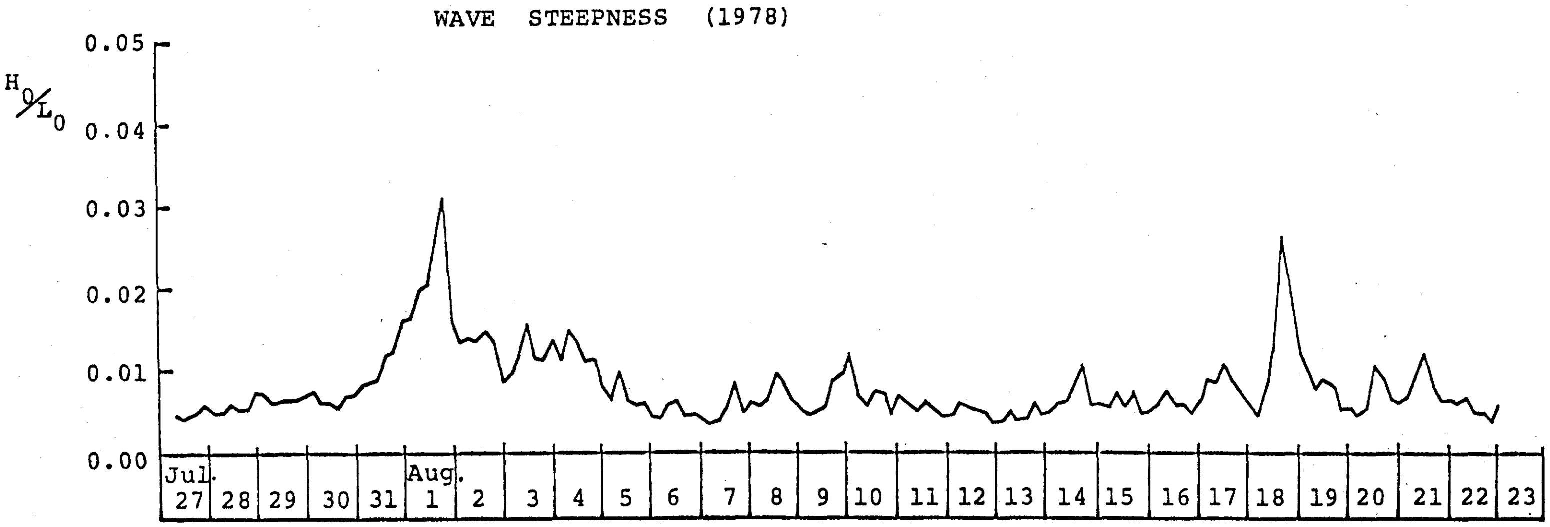


Fig. 20 Changes in wave steepness of deep-water waves during the summer survey of 1978.

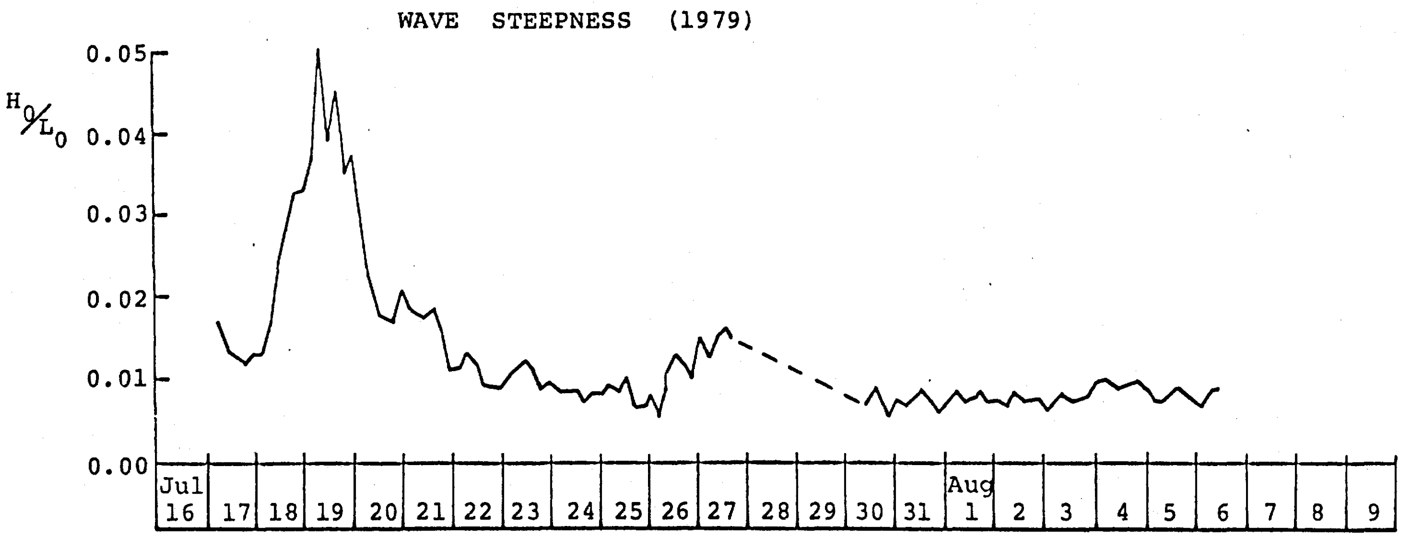


Fig. 21 Changes in wave steepness of deep-water waves during the summer survey of 1979.

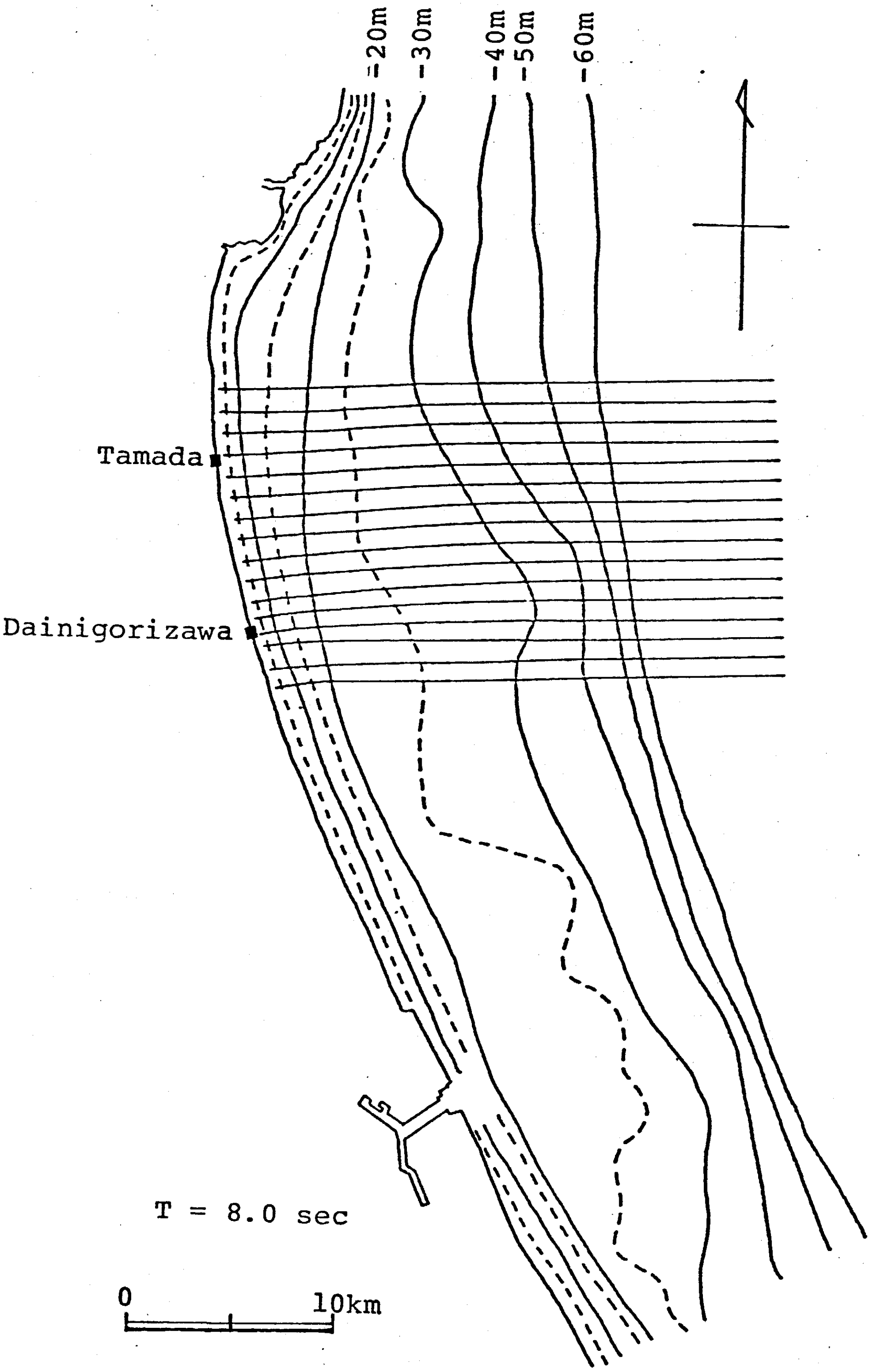


Fig. 22-A Wave refraction diagram.

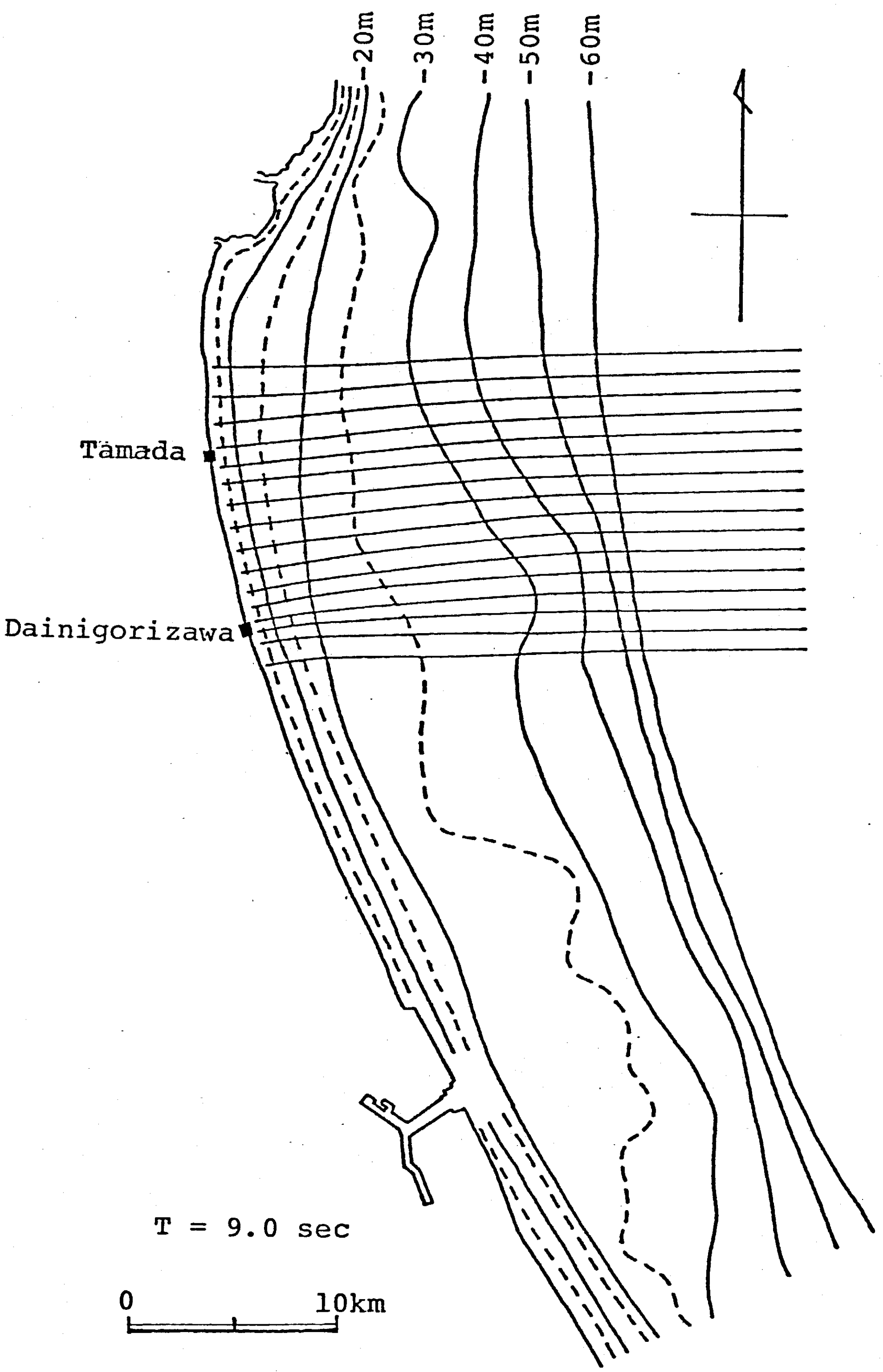


Fig. 22-B Wave refraction diagram.

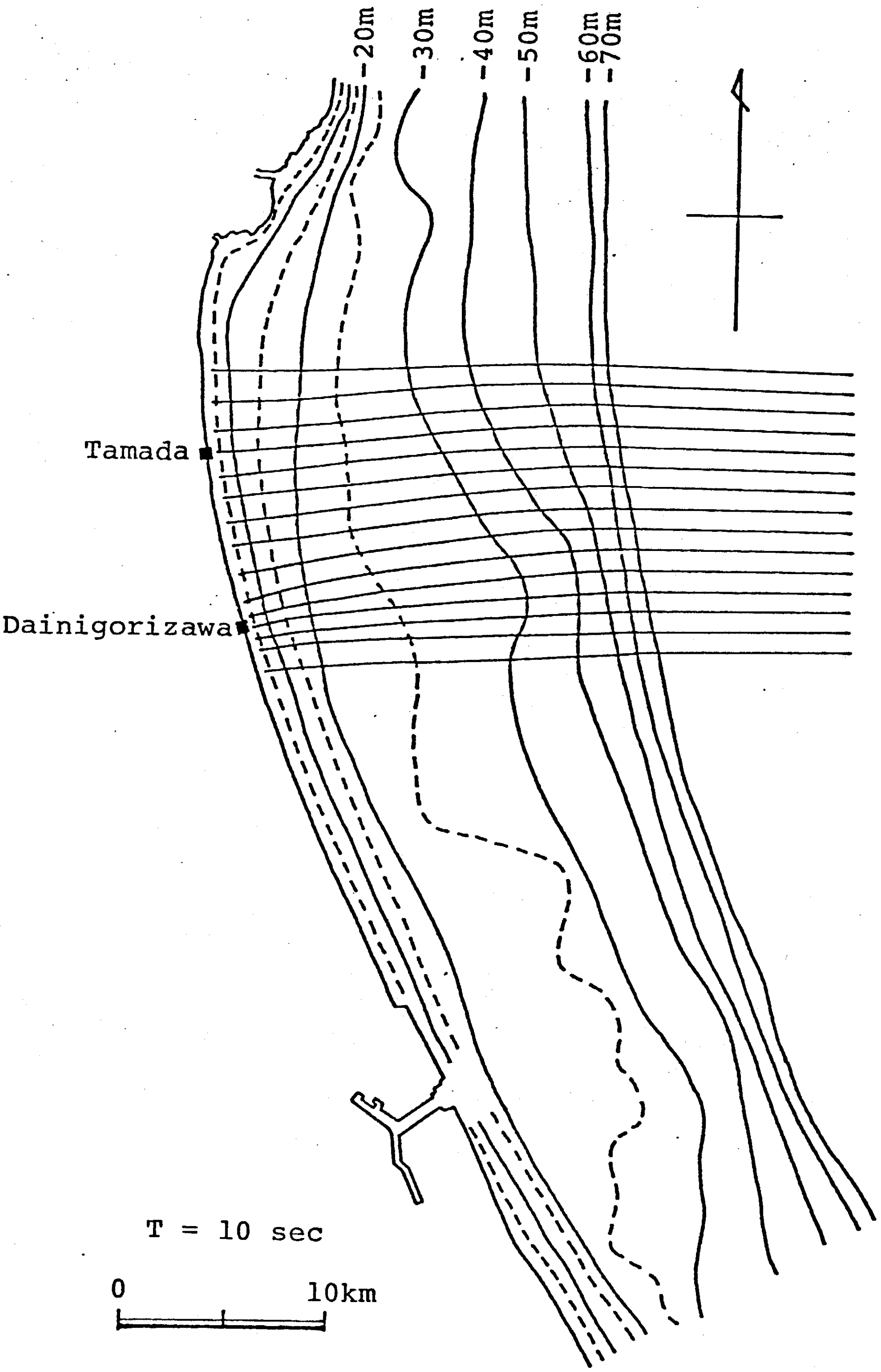


Fig. 22-C Wave refraction diagram.

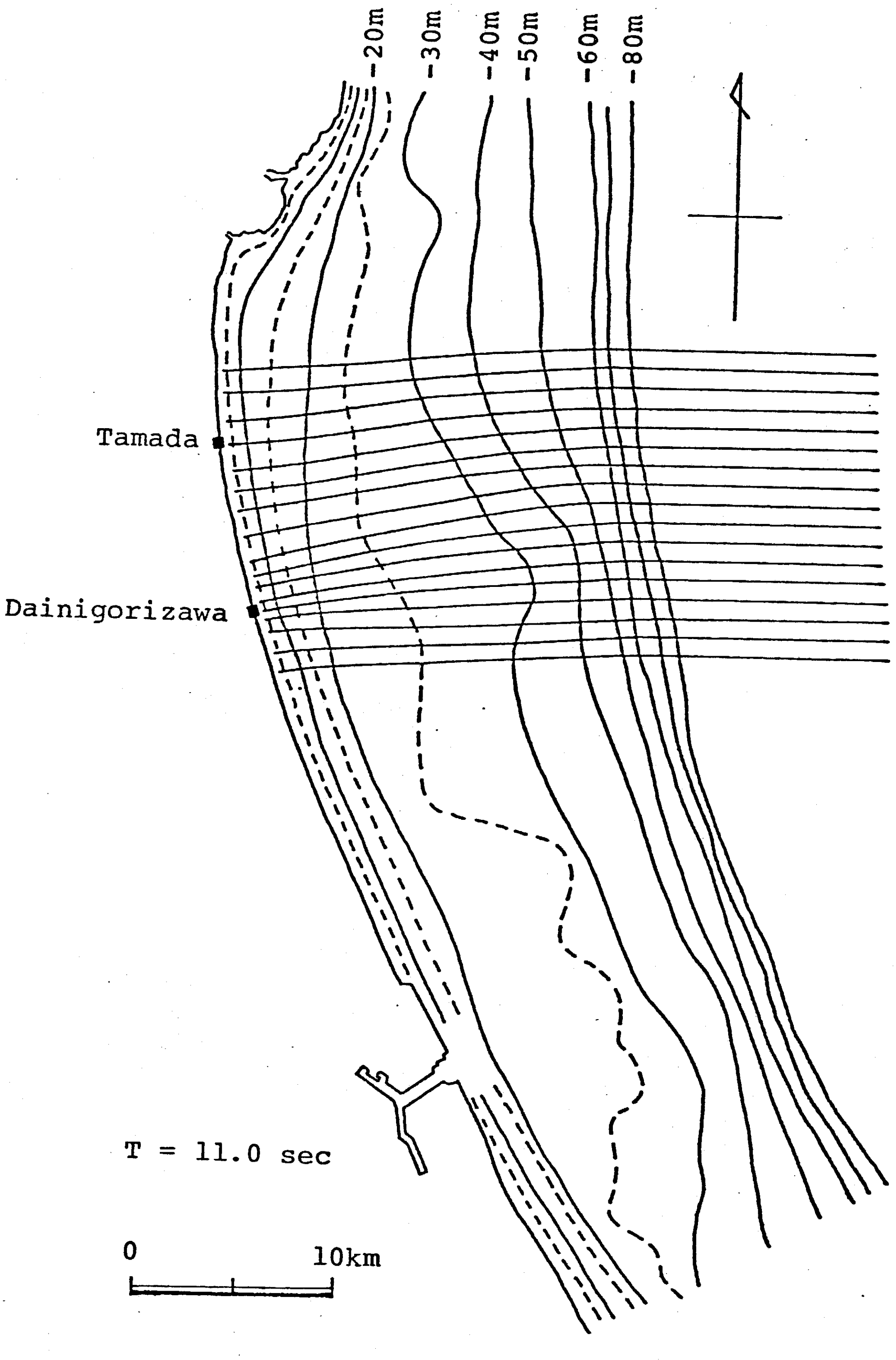


Fig. 22-D Wave refraction diagram.

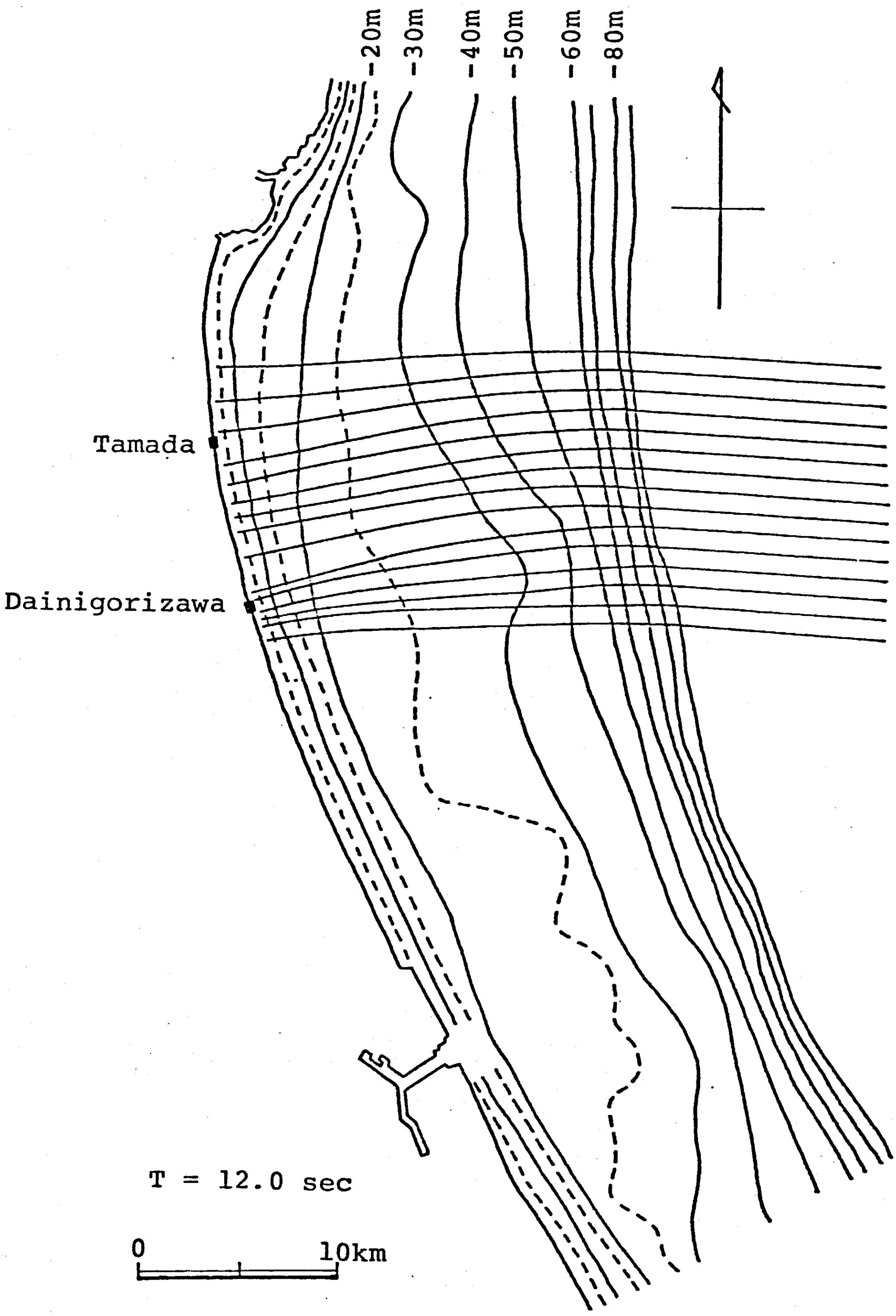


Fig. 22-E Wave refraction diagram.

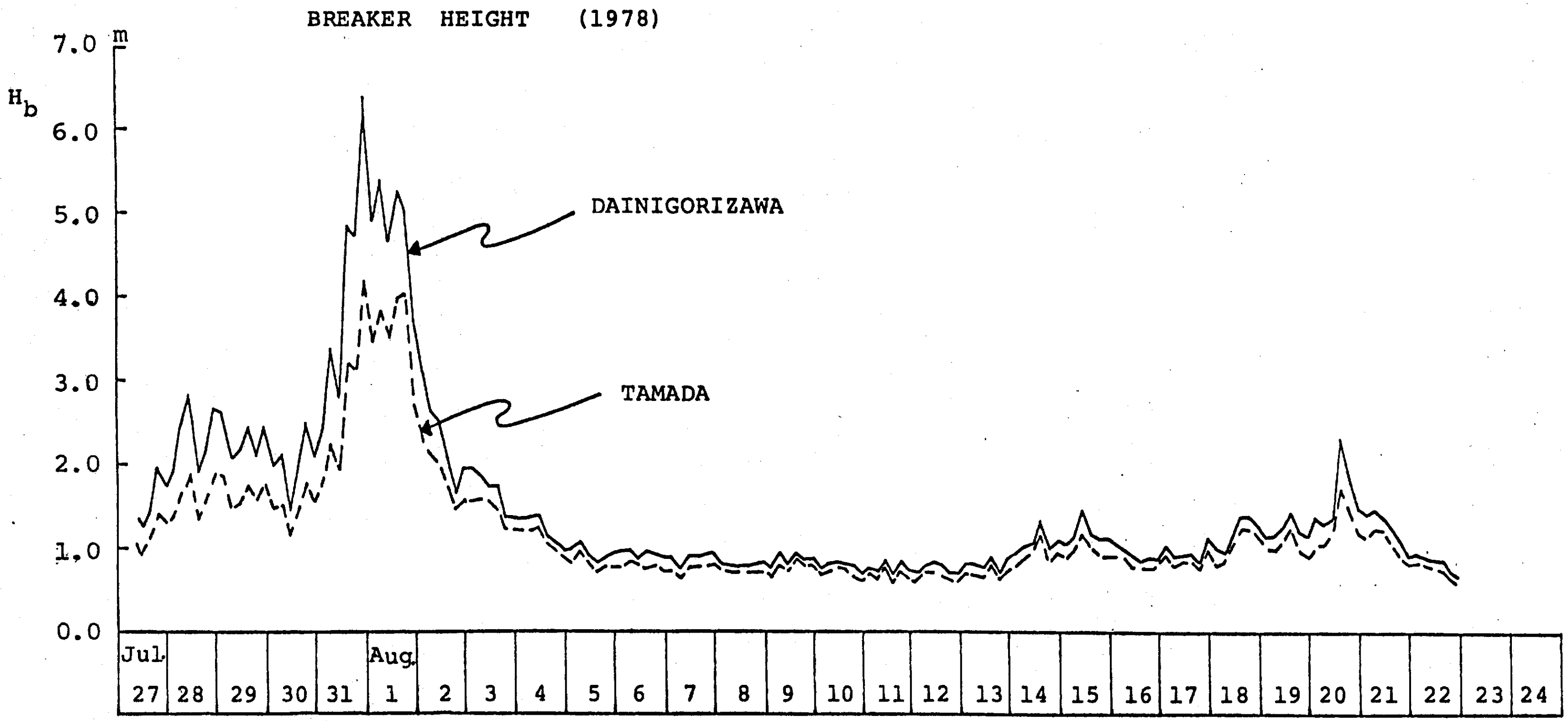


Fig. 23 Estimated breaker height on both study sites during the summer survey of 1978.

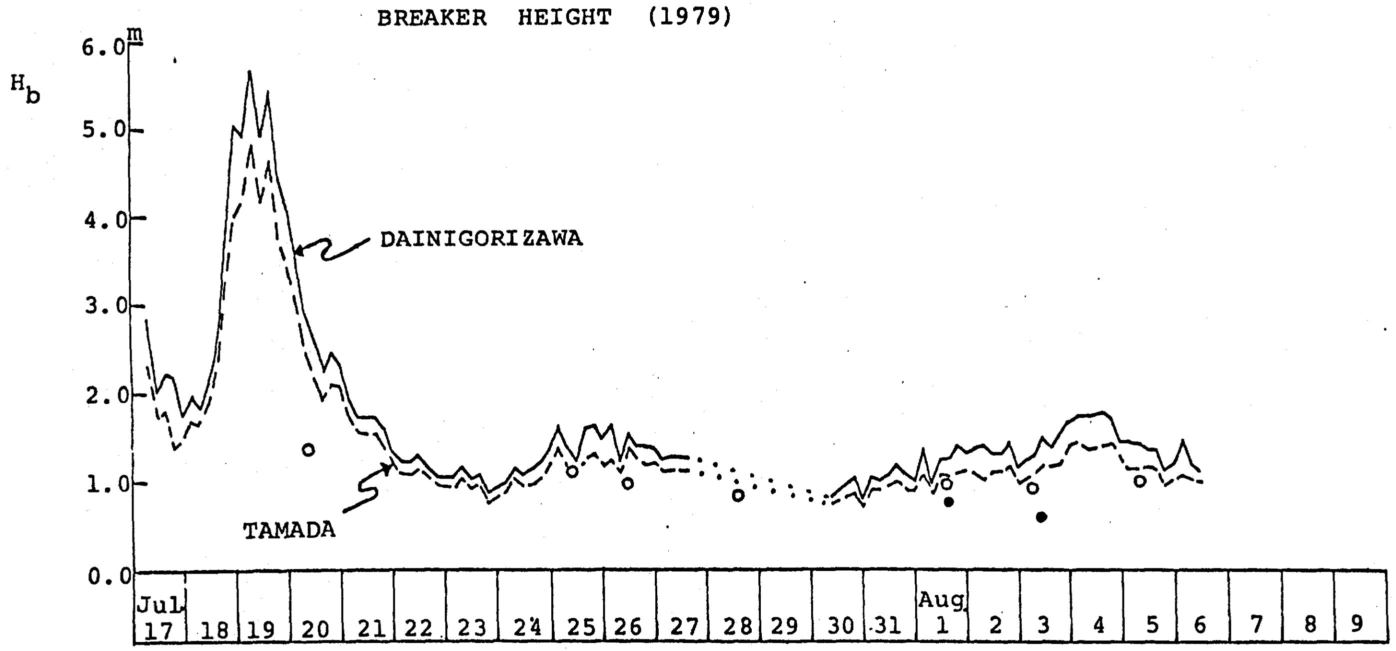


Fig. 24 Estimated breaker height on both study sites during the summer survey of 1979. (solid and open circles denote measured breaker height at the Tamada and Dainigorizawa sites, respectively).

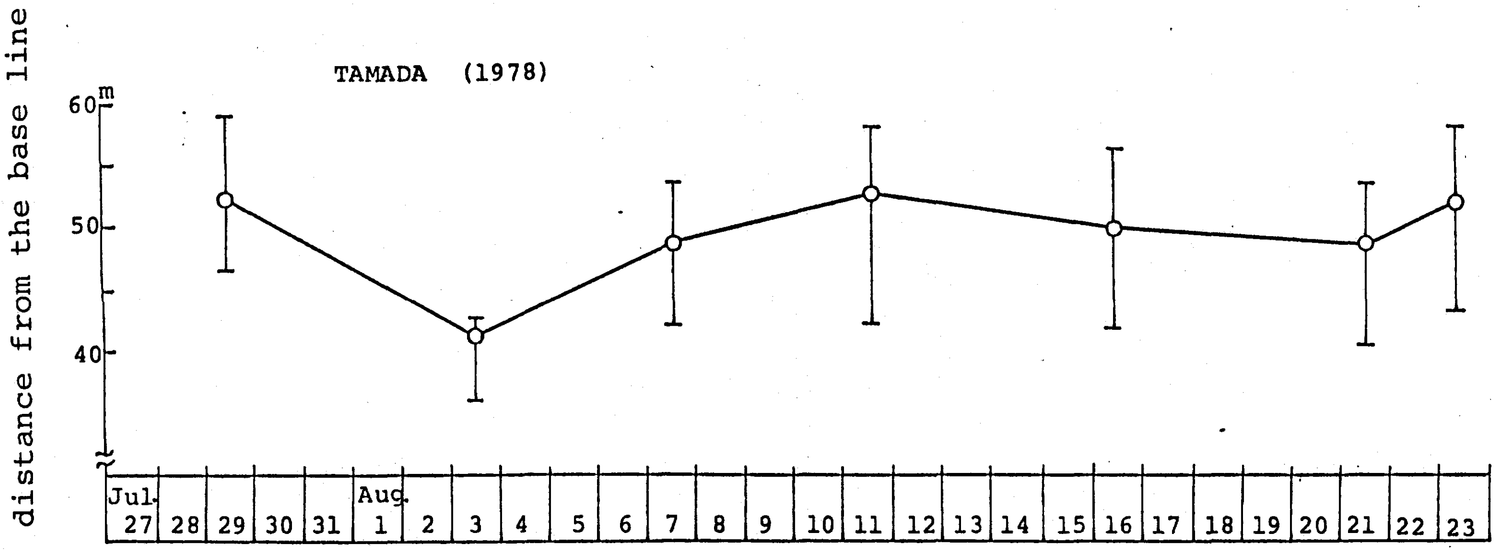


Fig. 25 Changes in the position of the mean water line (Tamada, 1978).

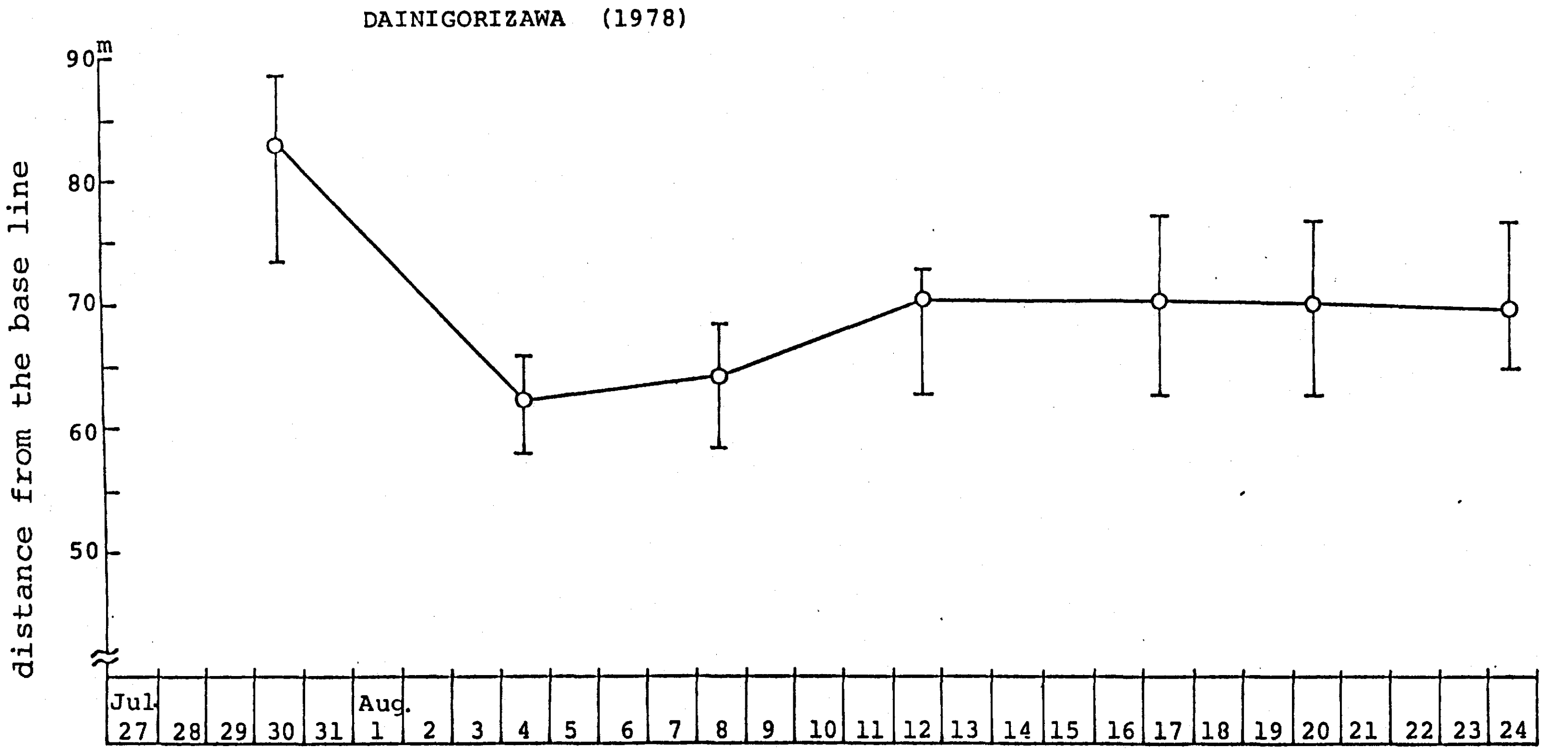


Fig. 26 Changes in the position of the mean water line (Dainigorizawa, 1978).

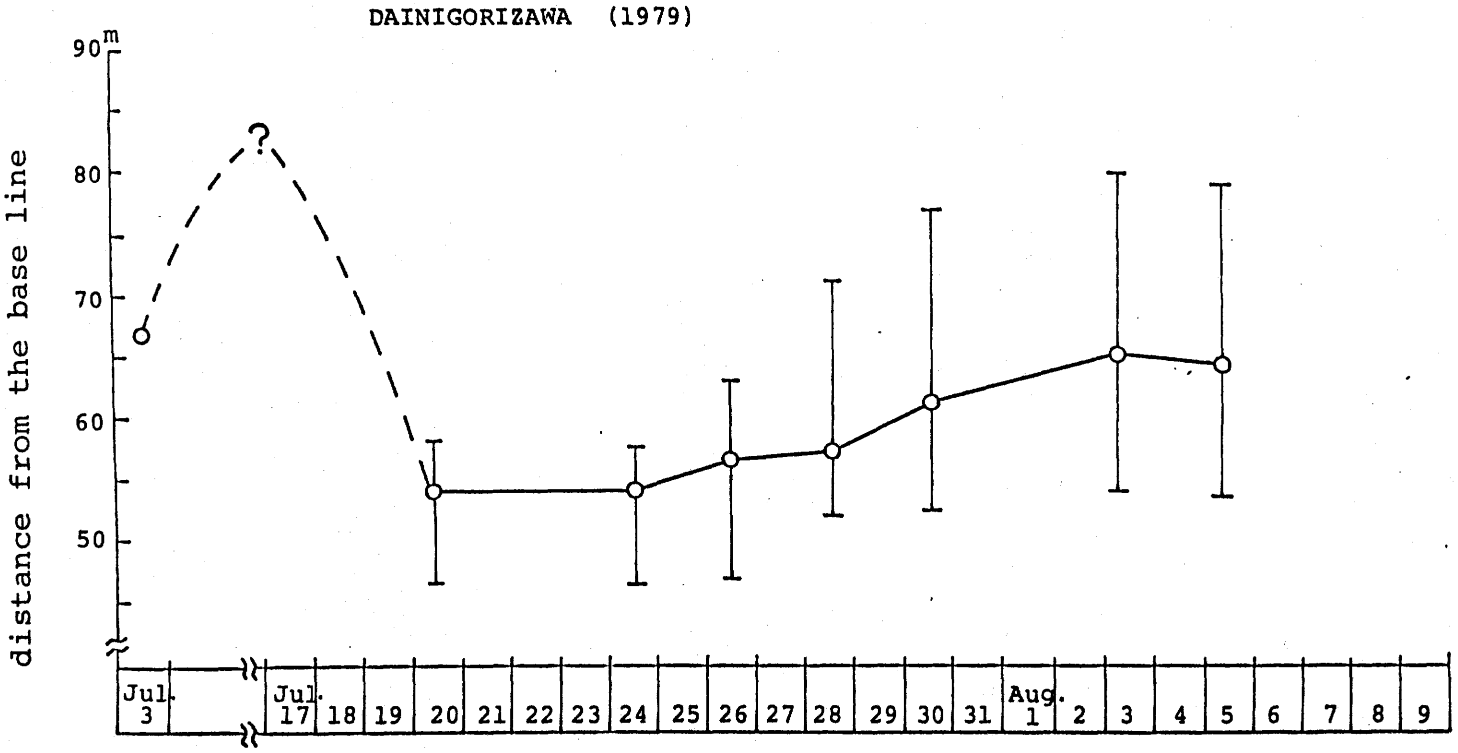


Fig. 27 Changes in the position of the mean water line (Dainigorizawa, 1979).

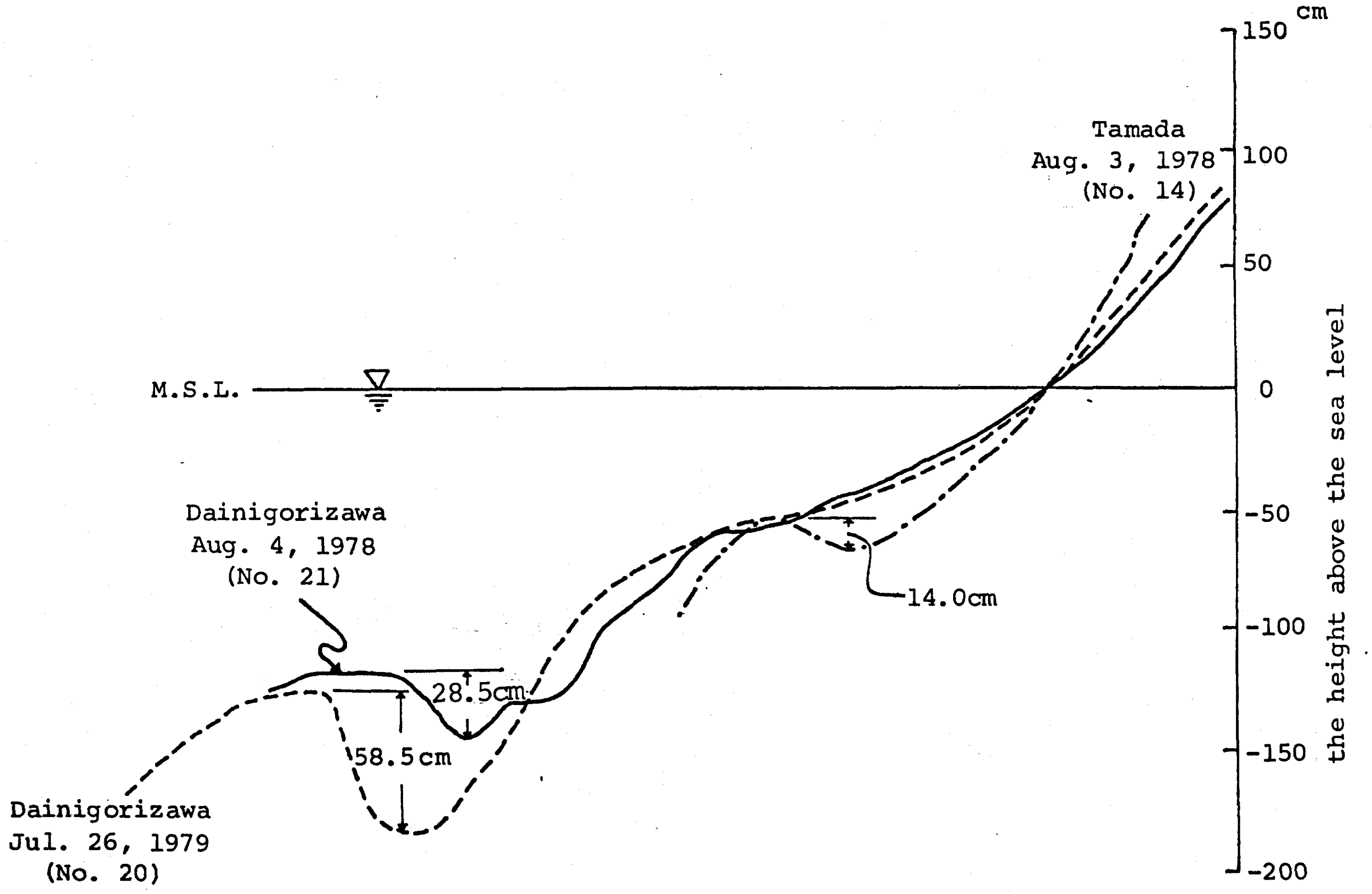


Fig. 28 A comparison on the scale of bars and troughs appeared immediately after the storms.

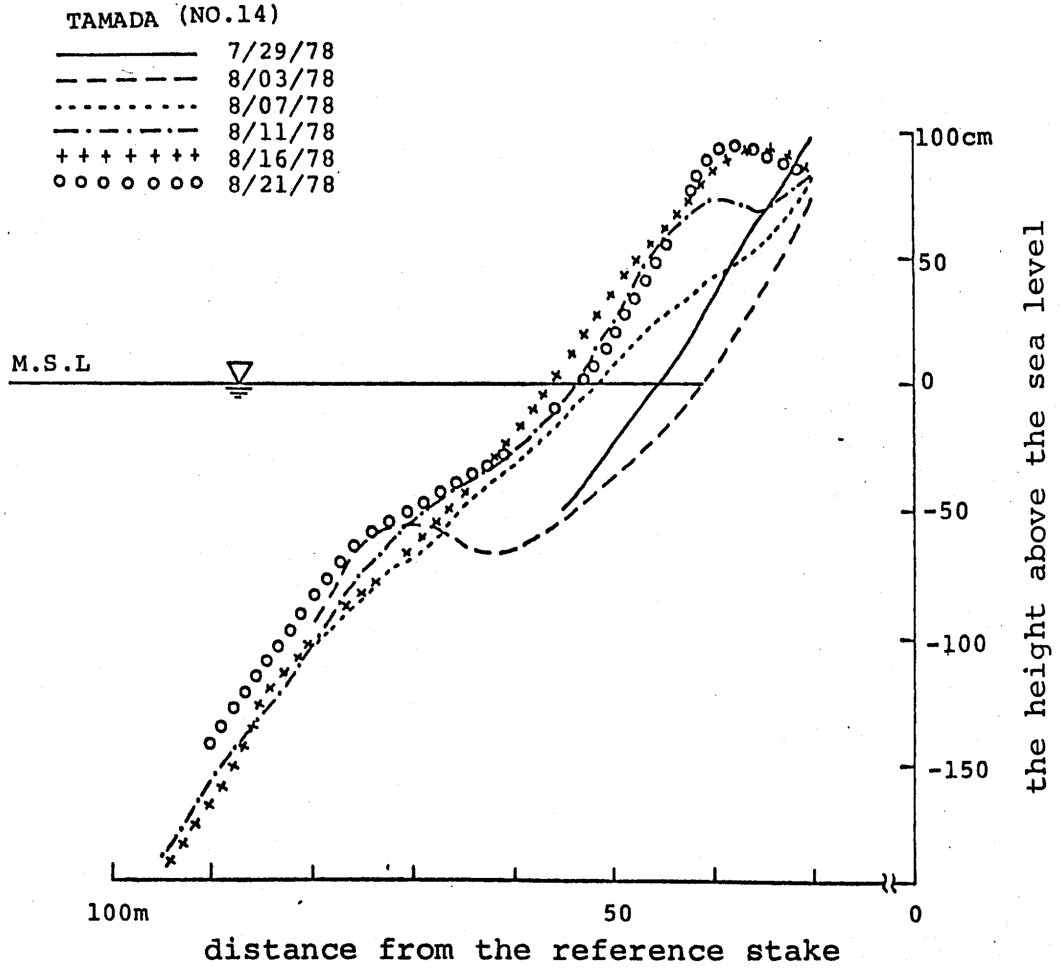


Fig. 29 Changes in beach profile on the traverse No. 14 (Tamada, 1978).

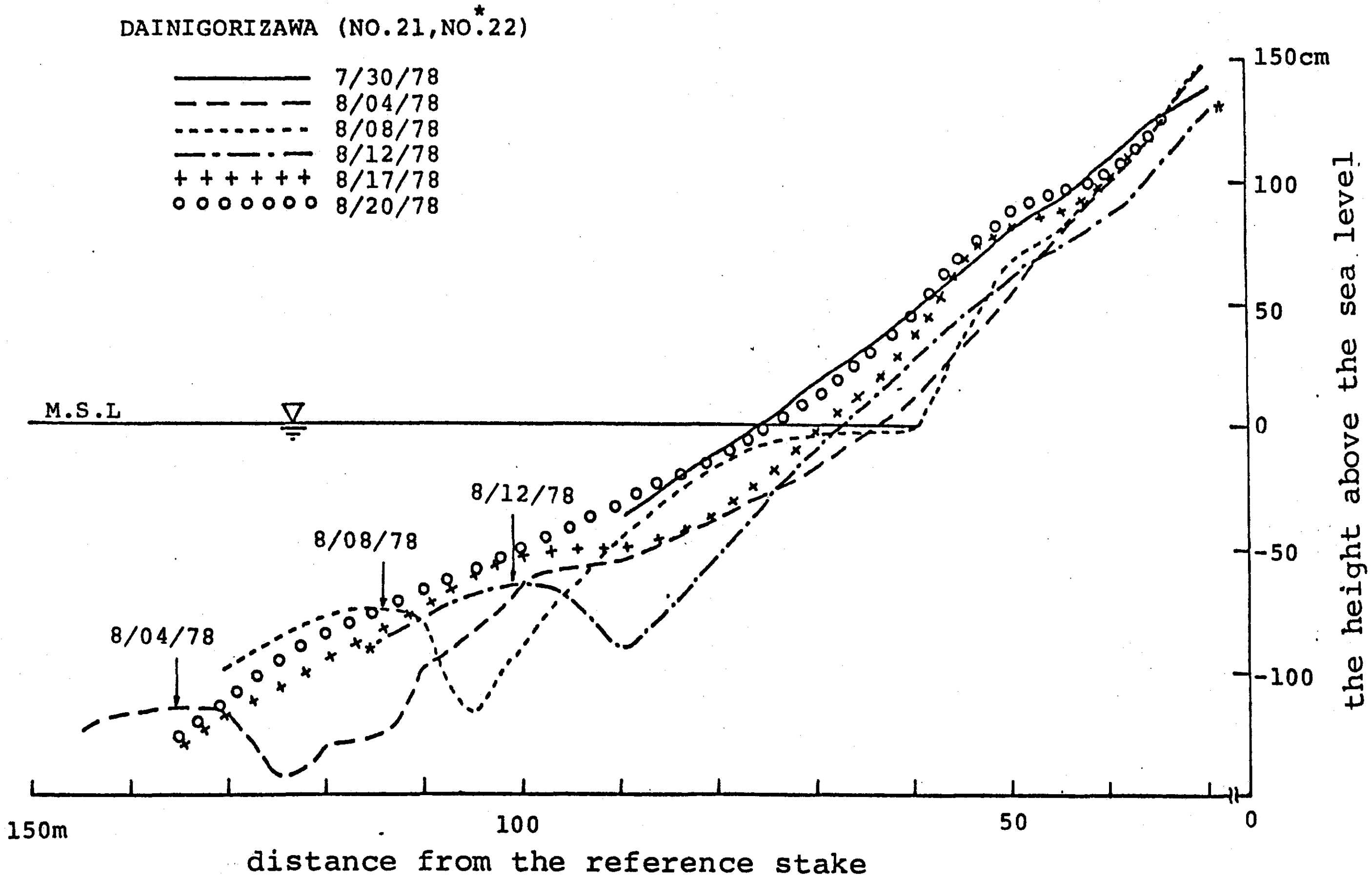


Fig. 30 Changes in beach profile on the traverse Nos. 21 or 22 (Dainigorizawa, 1978).

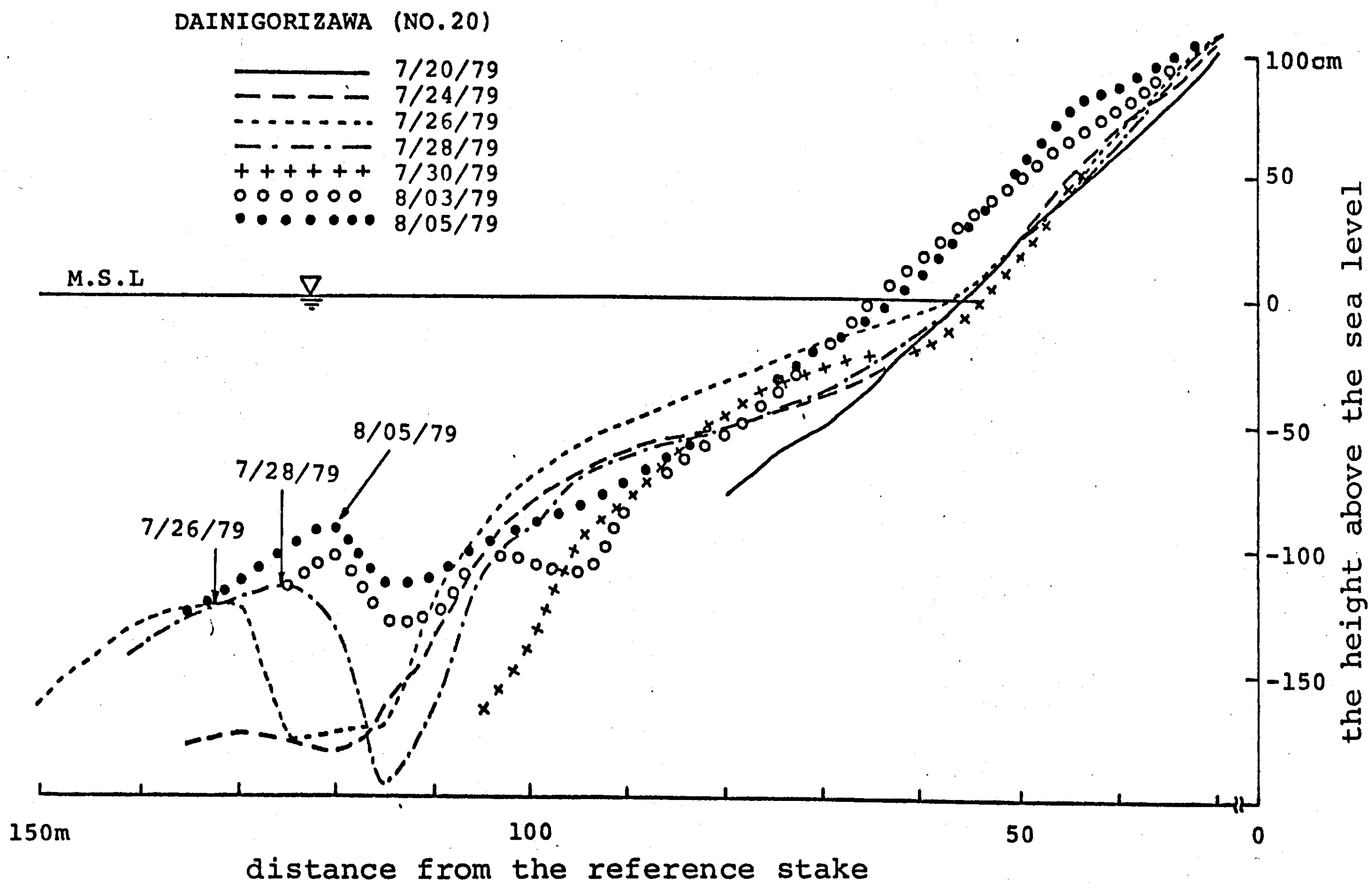


Fig. 31 Changes in beach profile on the traverse No. 20
(Dainigorizawa, 1979).

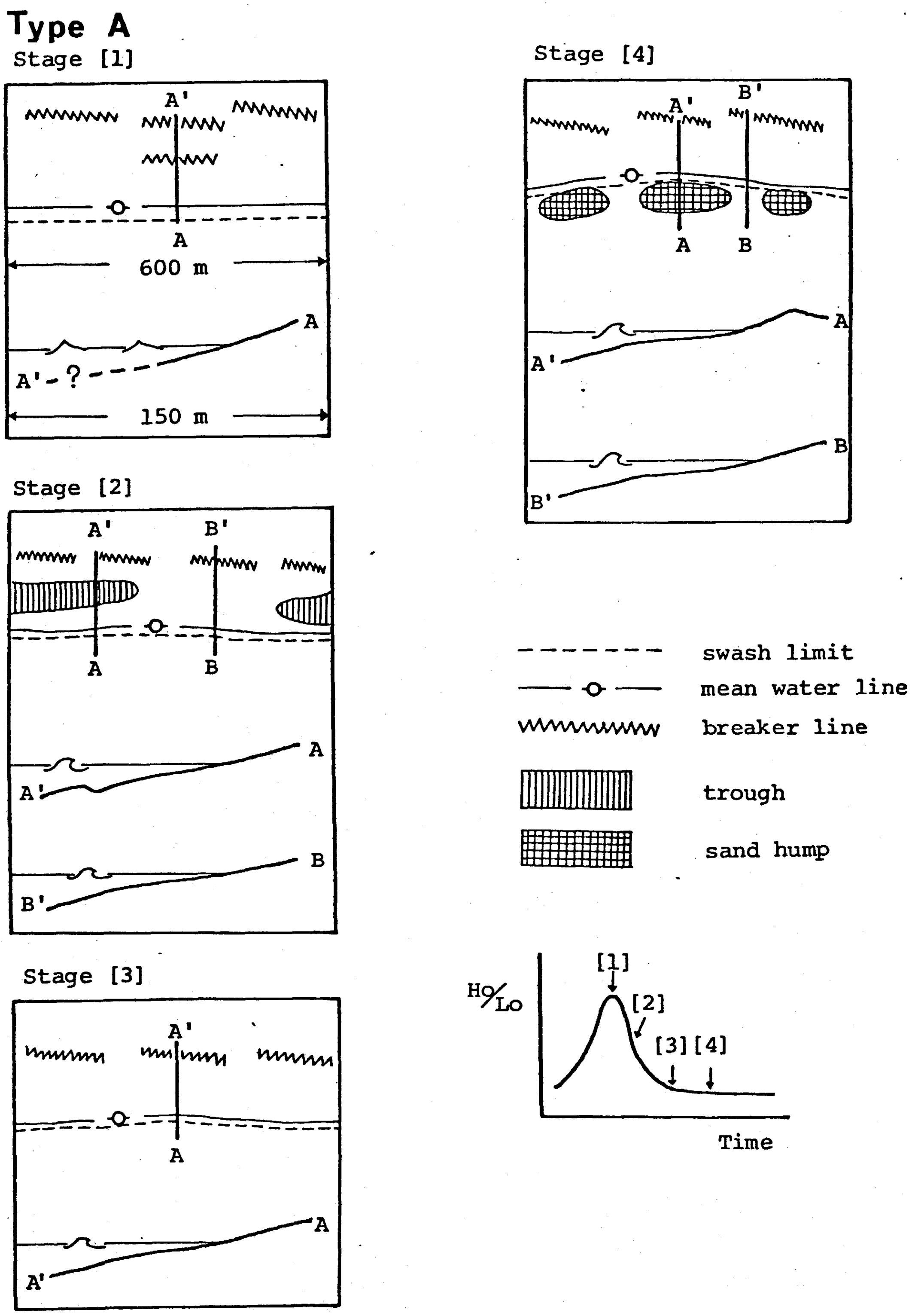


Fig. 32 Topographic change of type A.

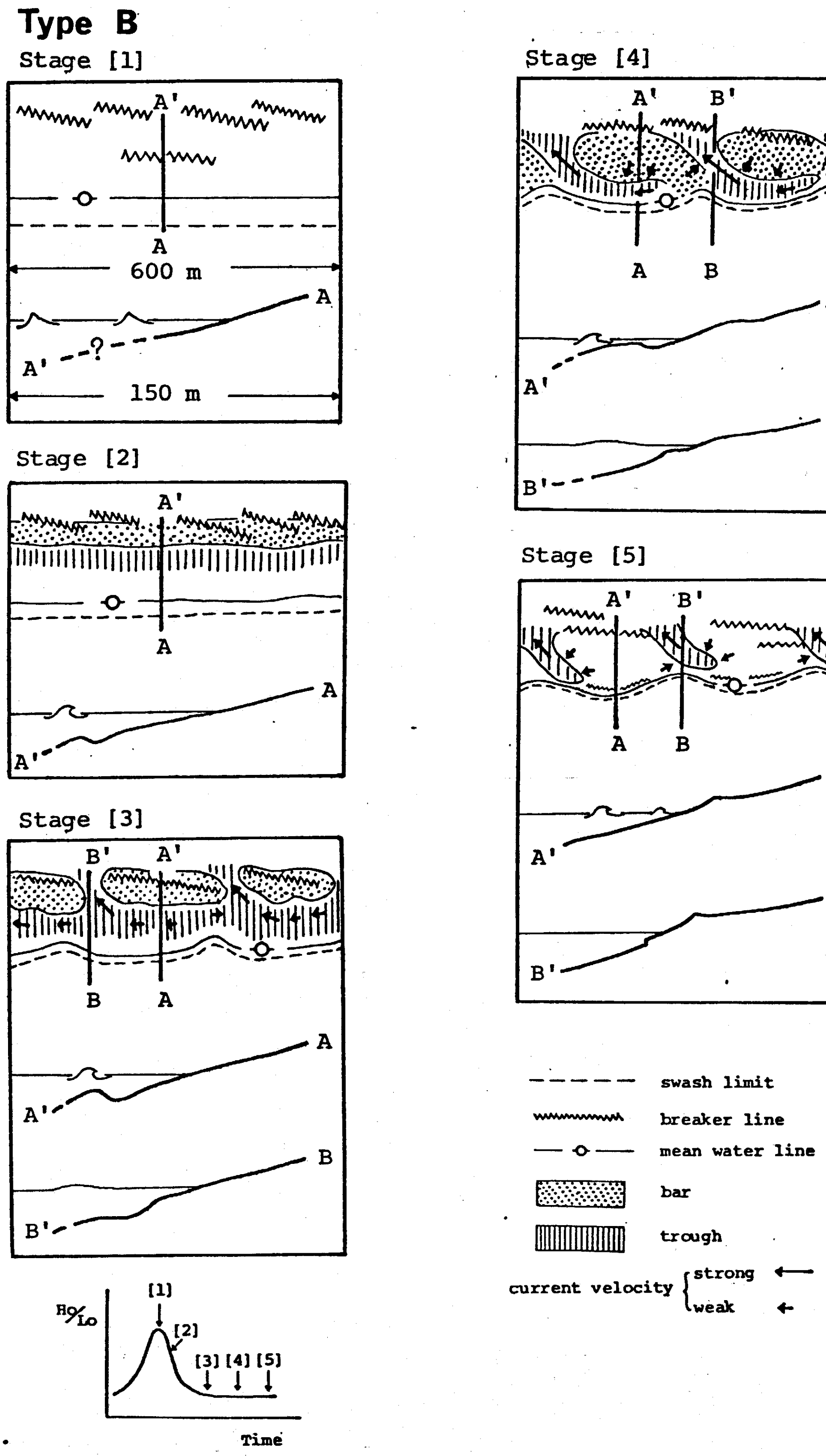


Fig. 33 Topographic change of type B.

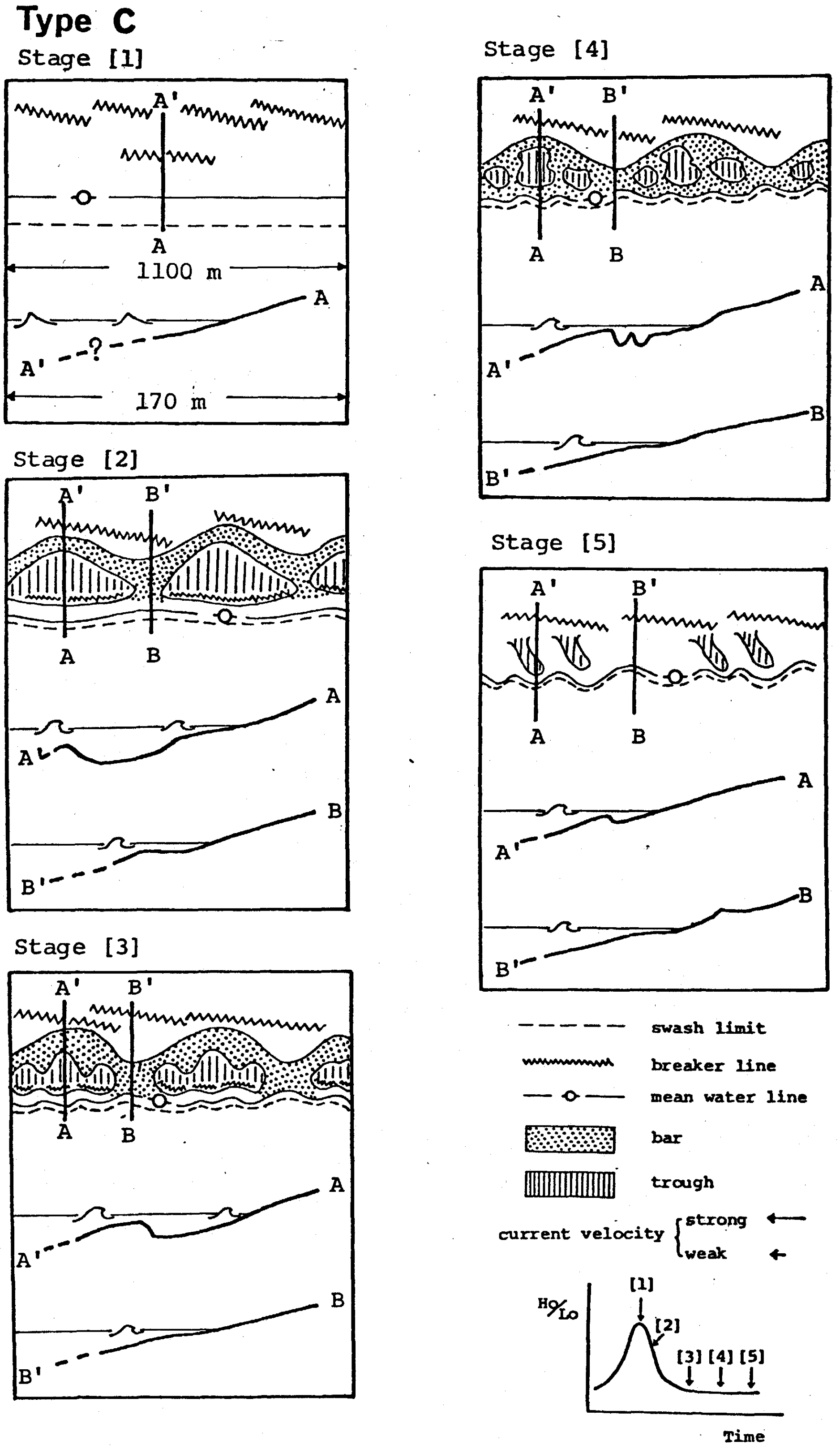


Fig. 34 Topographic change of type C.

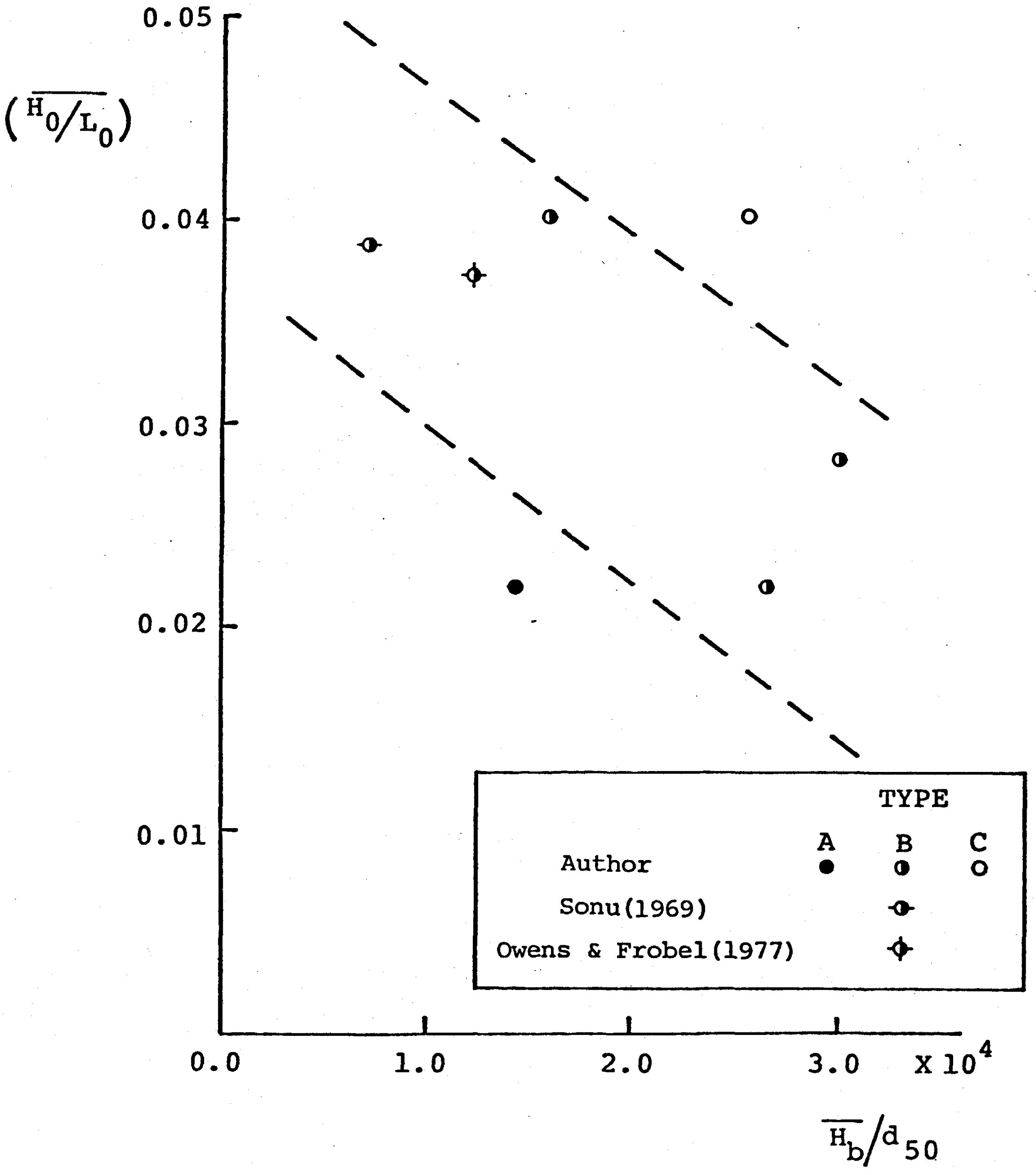


Fig. 35 Demarcation of three types of topographic change.

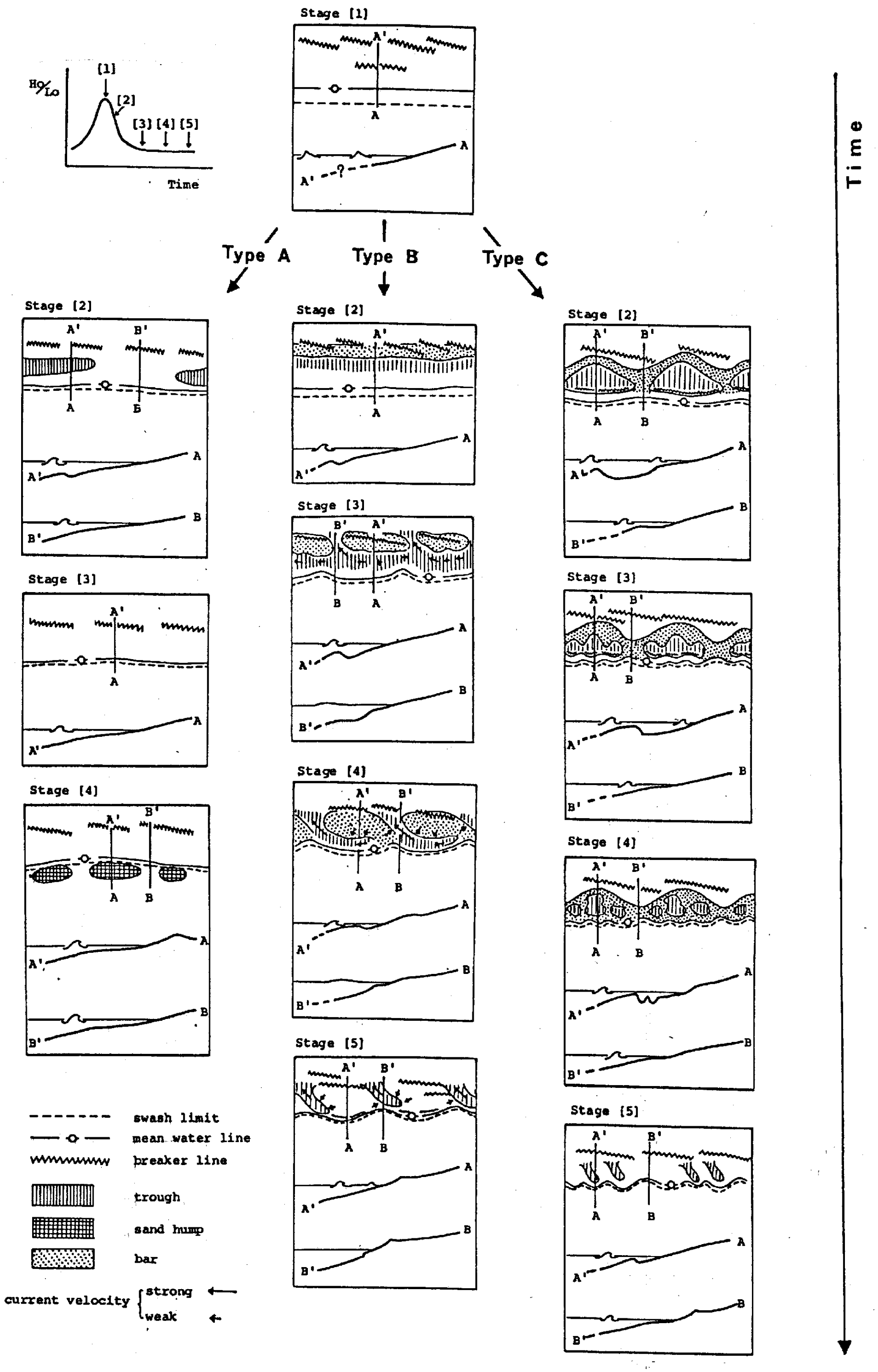


Fig. 36 Three-dimensional beach model.

Table 1 Three types of topographic change and their characteristics.

	Main topographic changes observed in the foreshore zone during a storm cycle	Large cusp formation	Names of bar system used by other researchers
Type A (Figure 32)	After a storm wave period, elongate and discontinuous bars and shallow troughs appear parallel to the coastline (Stage 2). These troughs are filled up with sand in a few days (Stage 3). During the last stage some sand humps are formed on the seaward part of a berm (Stage 4).	Large cusps with a lack of regularity are occasionally formed.	
Type B (Figure 33)	After a storm wave period, a continuous bar and trough appear parallel to the coastline (Stage 2). Then, the bar migrates landward and is divided by rip channels at regular intervals (Stage 3). The discontinuous parts of the breaker line correspond to each position of these rip channels (Photographs 2 and 3). Eventually the bar welds onto the beach to form a pronounced berm crest (Stage 5).	Large cusps with a noticeable regularity are always formed. Their wave length almost accords with the intervening space of two adjacent rip channels. When the waves arrive at angles to the shoreline the horns of large cusps move longshore direction.	Bar type sand wave Sonu (1969) Ridge and runnel system Davis and Fox (1972) Hayes (1972) Owens and Frobel (1977)
Type C (Figure 34)	After a storm wave period, a continuous and arcked bar appear parallel to the coastline (Stage 2). The breaking waves on this bar showing an arcked shape are often observed (Photographs 8 and 9). The bar migrates landward and tongue-shaped protuberances are formed at the landward side of the bar (Stage 3). The bar finally welds onto the beach to form a berm crest (Stage 5).	"Primary large cusps" with the horn corresponding to each shoal are first formed and "Secondary large cusps" with the horn corresponding to each tongue-shaped protuberance are secondly formed.	Cusp type sand wave Sonu (1969) Crescentic bar system King and Williams (1949) Short (1978a, 1978b, 1979)

Table 2 Results of calculation for each type of topographic change.

	Study area	Period of survey	d_{50} (mm)	$\overline{H_0/L_0}$	$\overline{H_b}/d_{50}$	Type
Author	Tamada	July-August 1978	0.27	0.0219	1.42×10^4	A
	Dainigorizawa	April 1978	0.20	0.0281	2.98	B
	Dainigorizawa	July-August 1978	0.20	0.0219	2.64	B
	Tamada	July-August 1979	0.27	0.0400	1.58	B
	Dainigorizawa	July-August 1979	0.20	0.0400	2.53	C
Sonu (1969)	Outer Banks beach at Nags Head, North Calorina	February 26-March 2 1964	0.25	0.0381	0.78	B
Owens & Frobel (1977)	East coast of the Magdalen islands, Quebec	November 12-30 1974	0.29	0.0373	1.21	B

PHOTOGRAPHS

Photograph

Photograph

14 Wave condition and some topographic features in the foreshore zone (Tamada, 1979). 1440 hours, Jul. 29

15 Wave condition and some topographic features in the foreshore zone (Tamada, 1979). 1000 hours, Aug. 9

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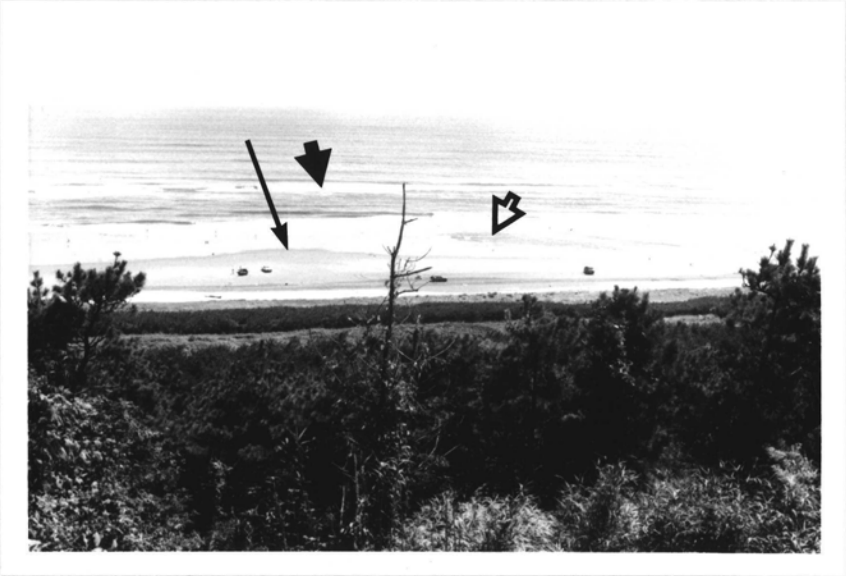

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APPENDIX A

WAVE TANK EXPERIMENT ON THE CHANGE OF MEAN WATER LEVEL

INTRODUCTION

In a surf zone a complicated flow pattern is established by a combination of (1) the to-and-fro water motion produced by waves and (2) wave-induced currents. Since Longuet-Higgins and Stewart (1964) presented the concept of the radiation stress in water waves, multiple studies on a nearshore current system or a rise of the mean sea level in the surf zone have made a rapid progress. The experiment on wave "set-up" and "set-down" caused by the radiation stress were conducted by Bowen, Inman and Simmons (1968) using a wave tank with a uniform beach slope. The result shows that the theory based on the radiation stress concept predicts well the wave "set-down" in the offshore area beyond the breaker zone and the wave "set-up" inside the surf zone although the theoretical values of the wave "set-down" near the wave break point are somewhat greater than the experimental ones. The field measurement on wave "set-up" was carried out and wave properties were simultaneously measured by Hotta and Mizuguchi (1978) on the Ajigaura Coast in Ibaraki Prefecture, Japan.

The wave "set-up" must occur in the surf zone of the study area. As stated in 5.3 a bar migration during the post-storm wave period was a characteristic event observed at the study sites. When the bar migrates landward beyond a certain point, a distinct rise of the mean sea level would occur in the surf zone due to (1) the preventive effect of the bar on the return flow plus (2) the radiation stress effect in the surf zone. Such a sea level rise in the surf zone would have an important effect on the nearshore current system and the resultant topographic changes in the fereshore zone. It has not been fully understood, however, how the mean sea level rises when a bar is present in the surf zone. Mizuguchi, Tsujioka and Horikawa (1978) made a wave tank experiment and presented a model which estimates a distribution of wave height within a surf zone. At the same time they examined a change of the mean water level when a bar is formed on the shallow water bottom but they did not quantitatively discuss on this point. Therefore, an experiment was done to examine the change of the mean water level when a bar is present on the shallow water bottom.

EXPERIMENTAL EQUIPMENT AND METHOD

A laboratory experiment was conducted using a wave tank at the Environmental Research Center of the University of Tsukuba (Figure A-1, Photographs A-1 and A-2). The wave tank was 16 m long, 0.5 m wide and 0.75 m deep. A beach was made of a smooth plywood with an 1:20 slope and thiry holes 3 mm in diameter each were drilled in the center of the plywood at 10-cm intervals in a line. As shown in Figure A-1 each hole was connected by a vinyl tube to the water gage in order to measure the elevation of the mean water level. The model bar used in this experiment is made of fat clay and is schematically illustrated in Figure A-2. A series of measurements of the characteristics of (1) breakers, (2) broken waves and (3) swashes were made (Figure A-3). Three cases of the experiments were conducted: a bar was absent (CASE A), a bar was present (CASE B) and a bar was present but the water depth above the bar was smaller than CASE B (CASE C)(Table A-1).

RESULT AND DISCUSSION

All the experimental results are shown in Table A-2 and the typical ones are plotted in Figures A-4 to A-12. These figures show that a rise of the mean water level always occurs in the surf zone whether or not a bar exists on the shallow water bottom. A comparison between the experimental results of CASE A and CASE B indicates that there is no significant difference in the rise of the mean water level (Figures A-4 to A-9). The experimental results of CASE C demonstrate, however, that the rise of the mean water level is pronounced in the surf zone (Figures A-10 to A-12).

When waves break, most of the water mass forming breaking waves rushes in the surf zone. The water mass is approximately proportional to the breaker height. Figure A-13 shows the relation between the breaker height (H_b) and the average value of mean water level rise ($\overline{\zeta^*}$) which was obtained by averaging the elevation of the mean water level inside the surf zone. This figure indicates that the experimental results of CASE A and CASE B are denoted by the solid line as a general trend. On the other hand, the results of CASE C have a tendency as shown by the broken line with the gradient being much larger than that of the solid line.

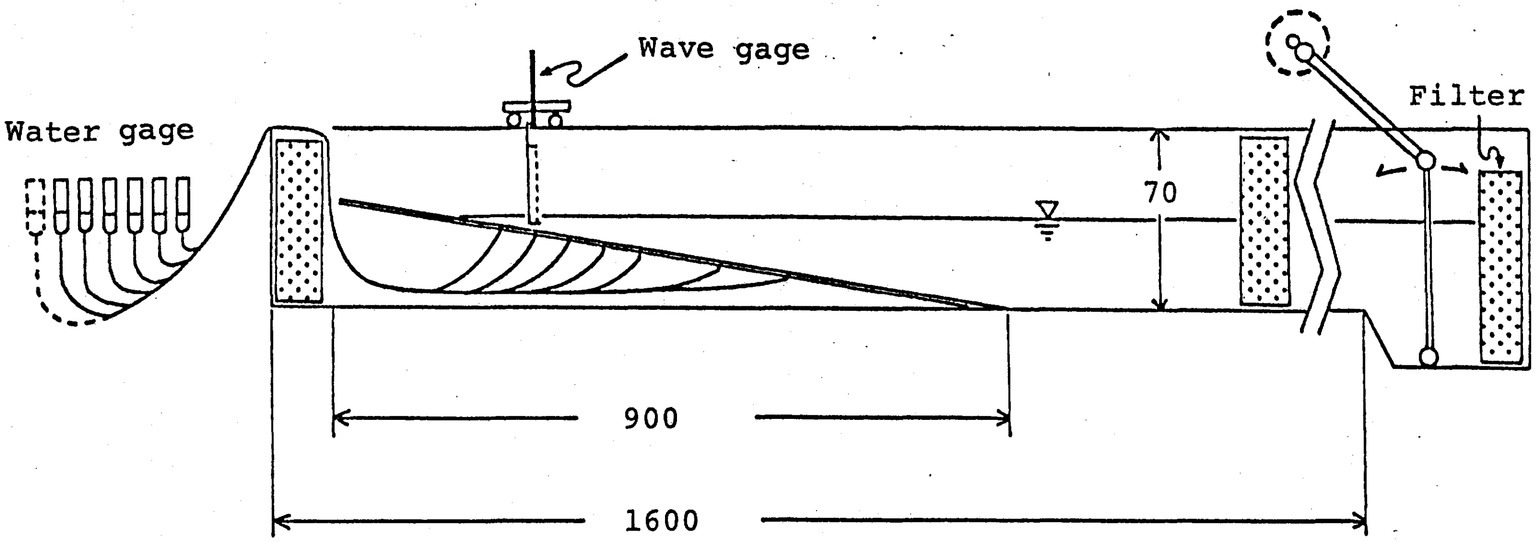


Fig. A-1 Experimental equipment (Unit: cm).

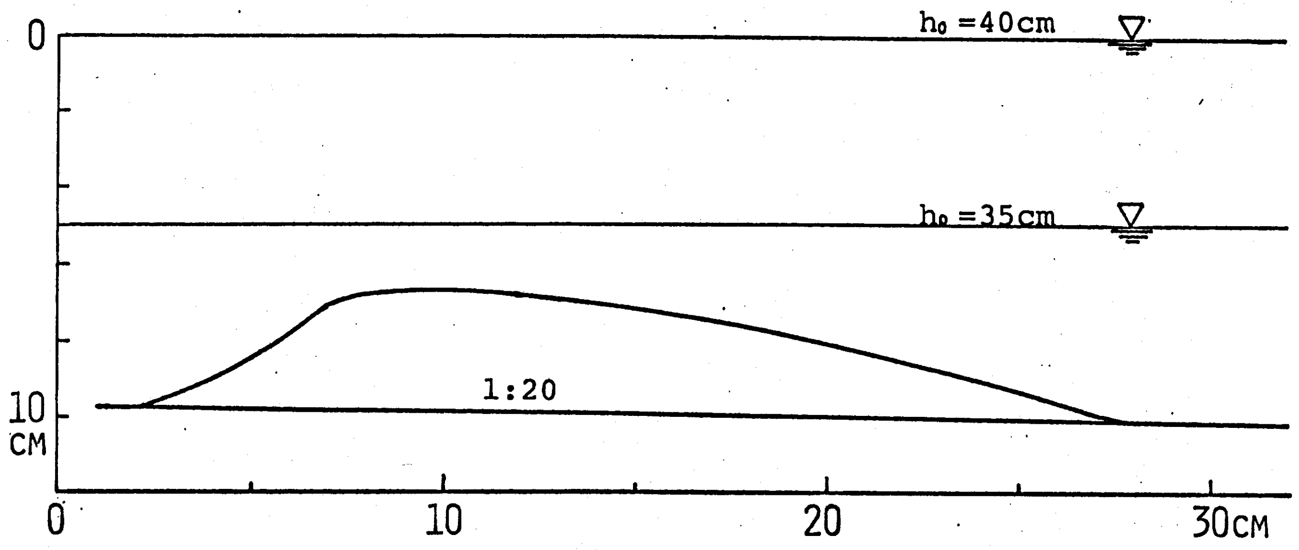
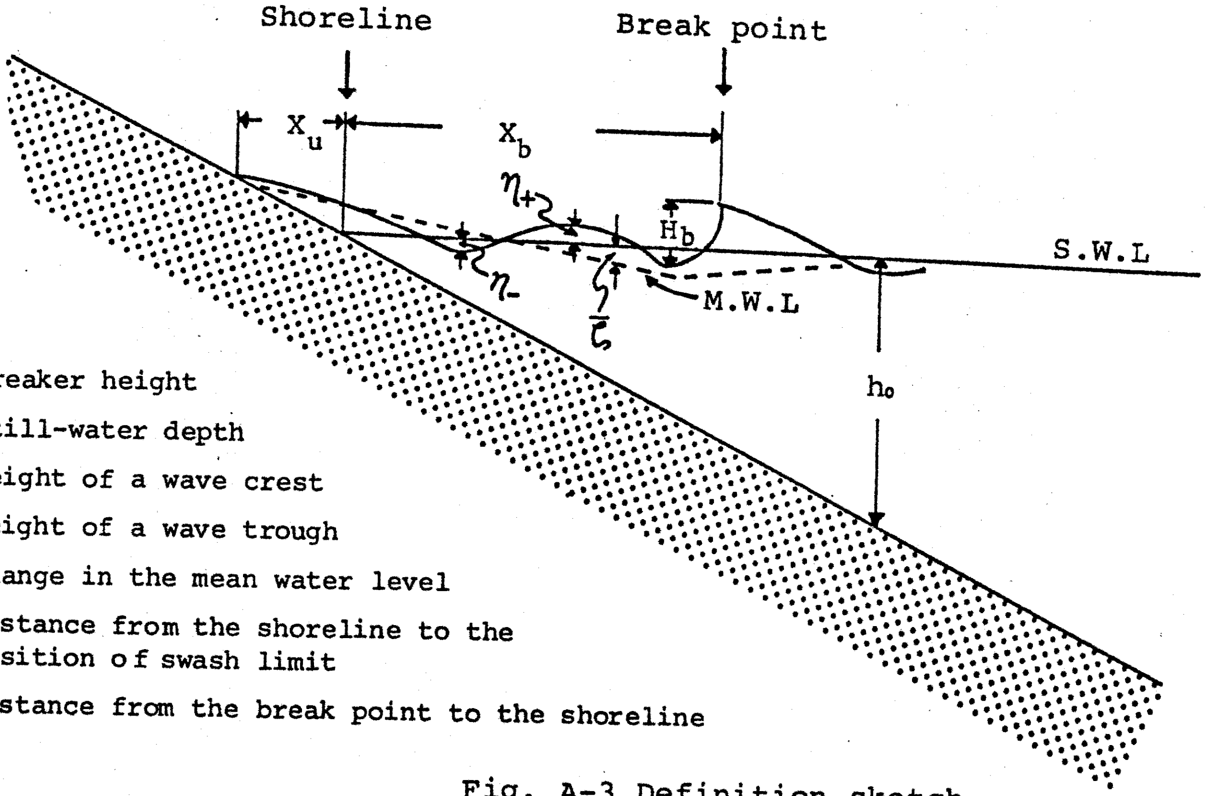


Fig. A-2 Bar profile.
h_0 : still-water depth



H_b: breaker height

h_o: still-water depth

η_+: height of a wave crest

η_-: height of a wave trough

$\bar{\zeta}$: change in the mean water level

X_u: distance from the shoreline to the position of swash limit

X_b: distance from the break point to the shoreline

Fig. A-3 Definition sketch.

Table A-1 Test cases and conditions.

CASE No.	still-water depth ho(cm)	wave period T(sec)	deep-water wave height Ho(cm)	deep-water wave steepness Ho/Lo	
A1-1	40.0	1.78	8.65	0.0175	
-2	"	"	6.88	0.0139	
-3	"	"	5.51	0.0111	
-4	"	"	2.95	0.0060	
A2-1	"	1.43	9.39	0.0295	
-2	"	"	5.99	0.0188	
-3	"	"	3.88	0.0121	
A3-1	"	1.00	8.66	0.0555	
-2	"	"	5.13	0.0329	
-3	"	"	3.63	0.0233	
B1-1	"	1.78	8.39	0.0170	Bar
-2	"	"	7.08	0.0143	"
-3	"	"	5.51	0.0111	"
-4	"	"	3.00	0.0061	"
B2-1	"	1.40	9.61	0.0314	"
-2	"	"	5.88	0.0192	"
-3	"	"	3.79	0.0124	"
B3-1	"	1.00	9.24	0.0592	"
-2	"	"	7.96	0.0510	"
-3	"	"	5.94	0.0381	"
-4	"	"	3.71	0.0238	"
C1	35.0	1.78	2.61	0.0053	"
C2	"	1.40	4.06	0.0133	"
C3-1	"	1.00	5.41	0.0347	"
-2	"	"	3.35	0.0215	"

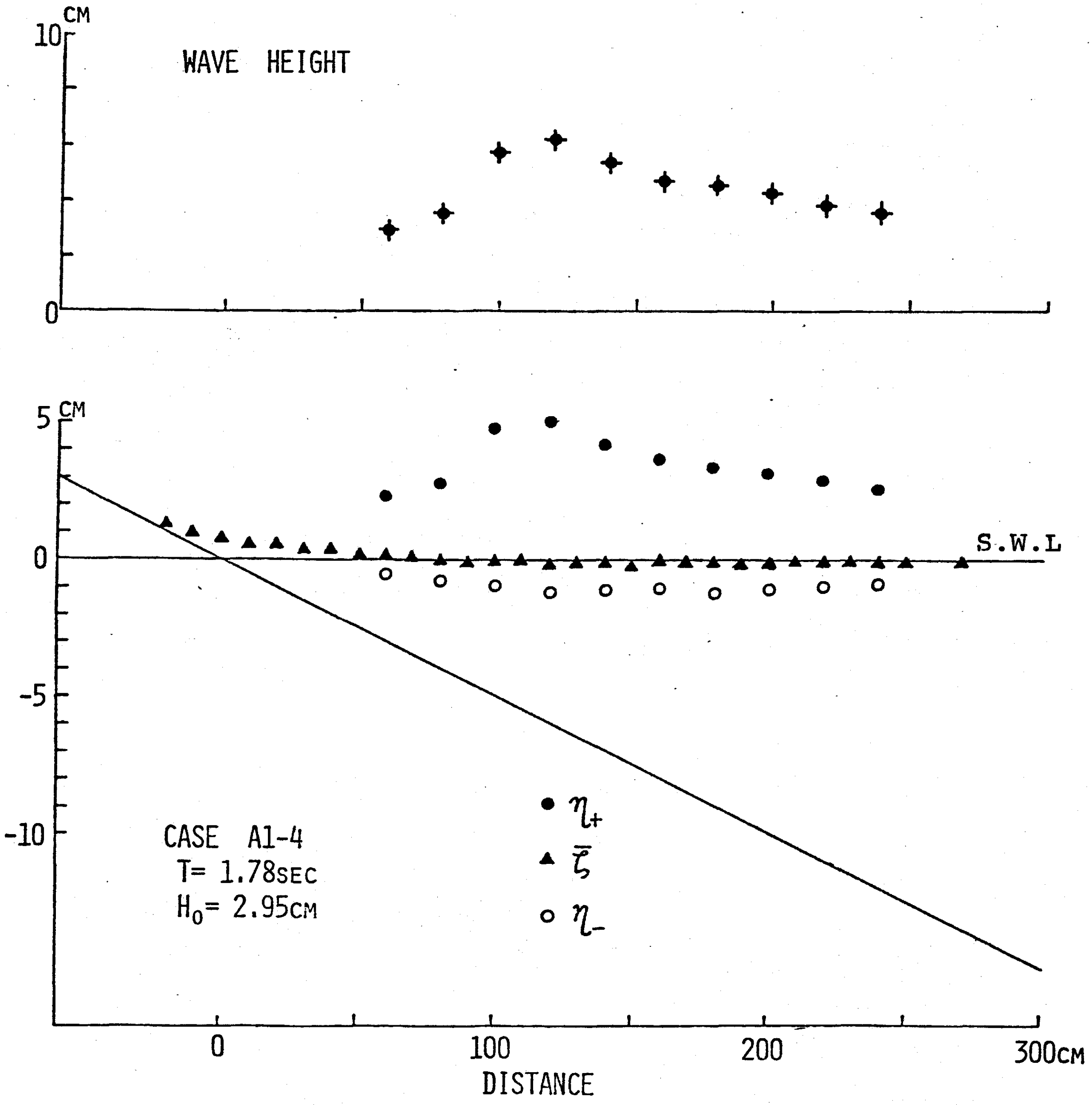


Fig. A-4 Mean water level on each measuring point.

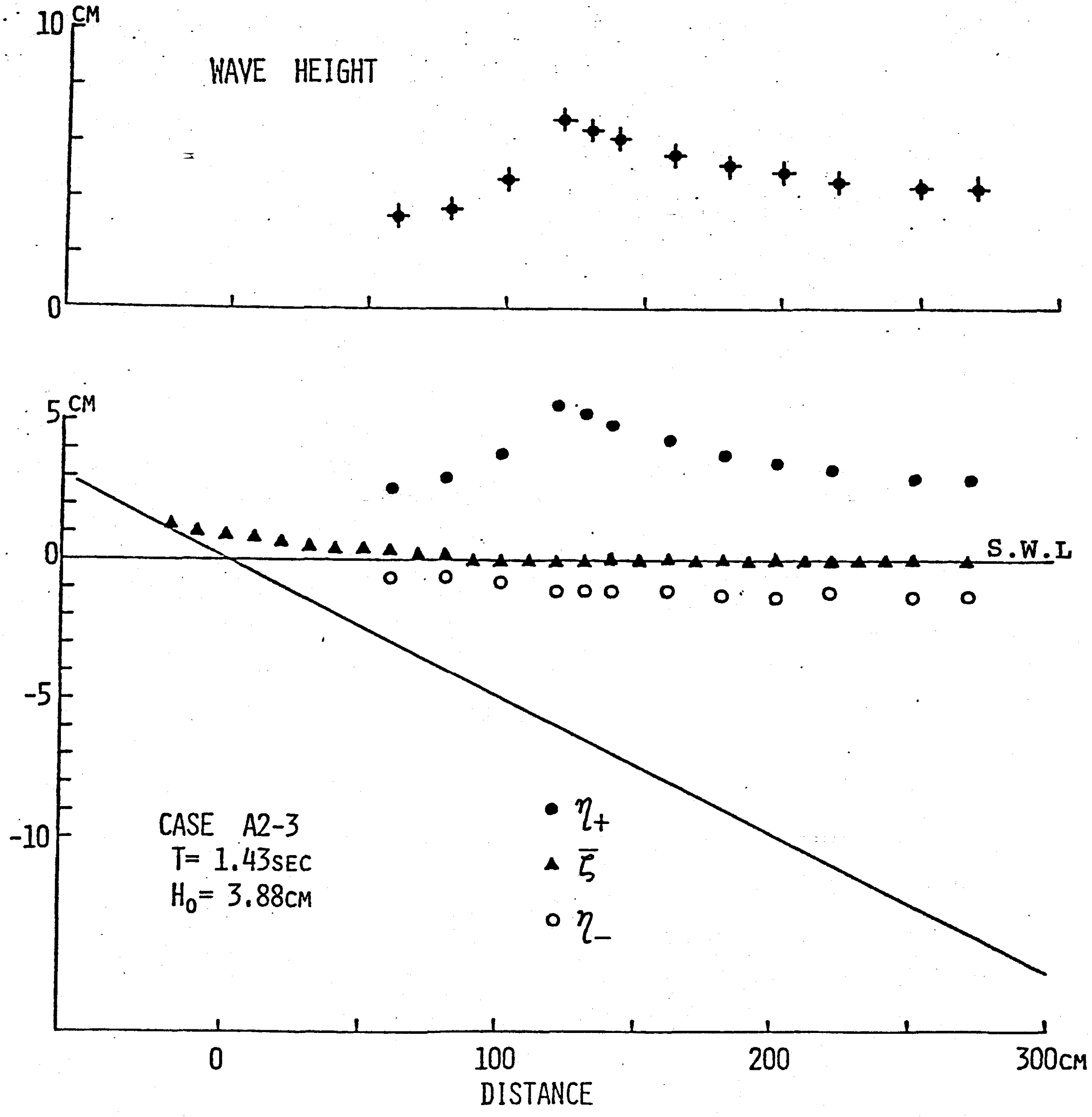


Fig. A-5 Mean water level on each measuring point.

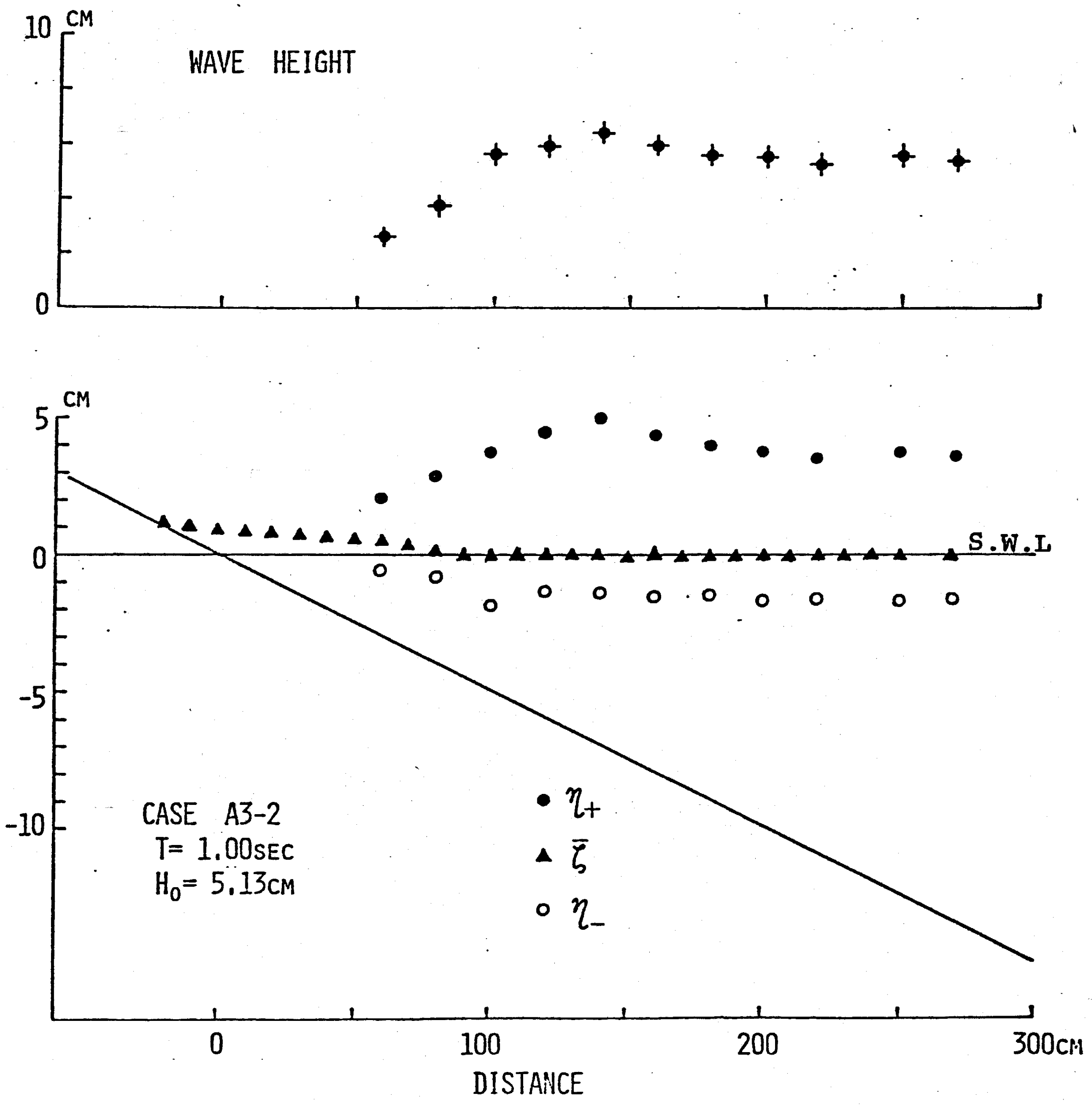


Fig. A-6 Mean water level on each measuring point.

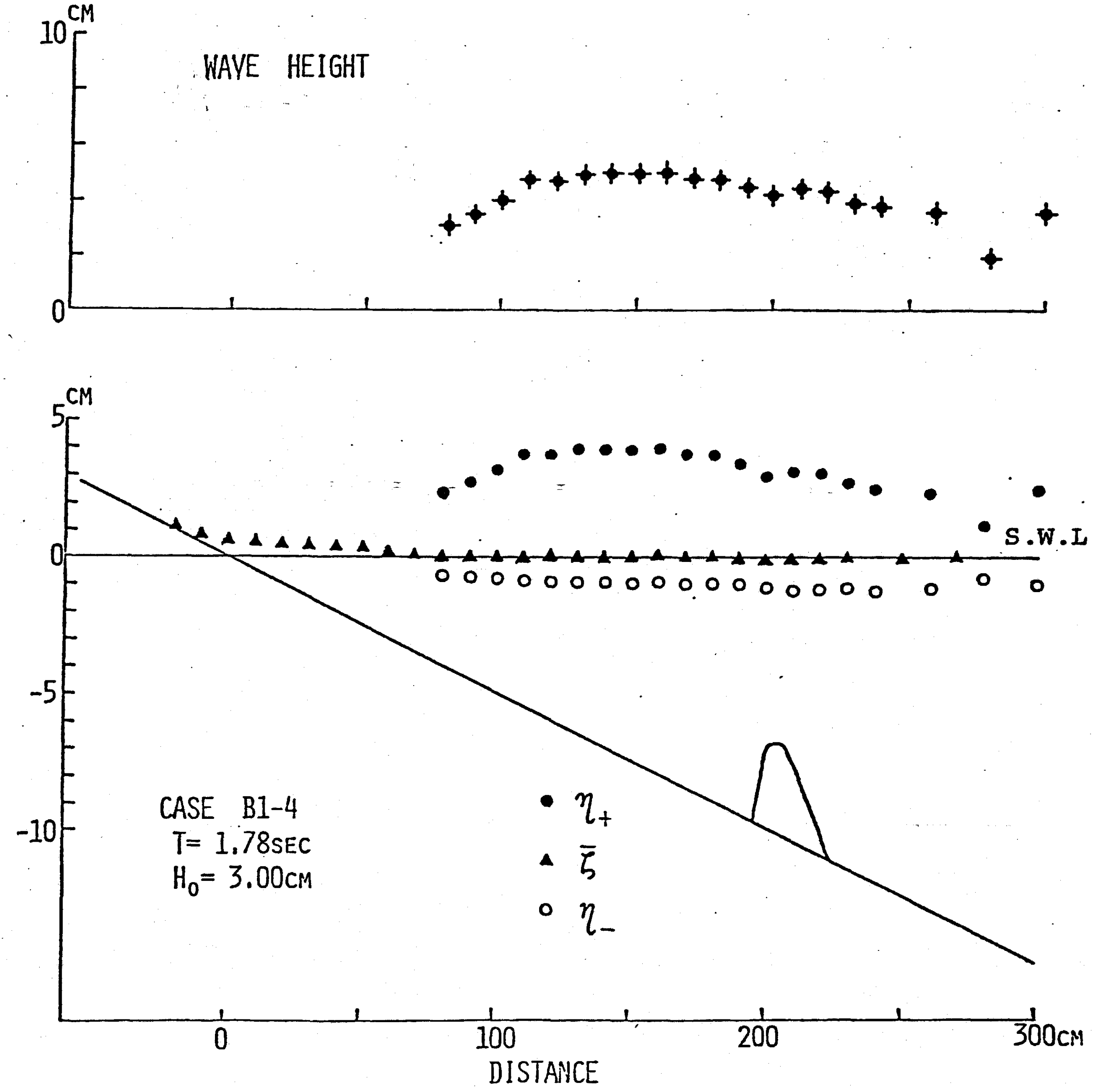


Fig. A-7 Mean water level on each measuring point.

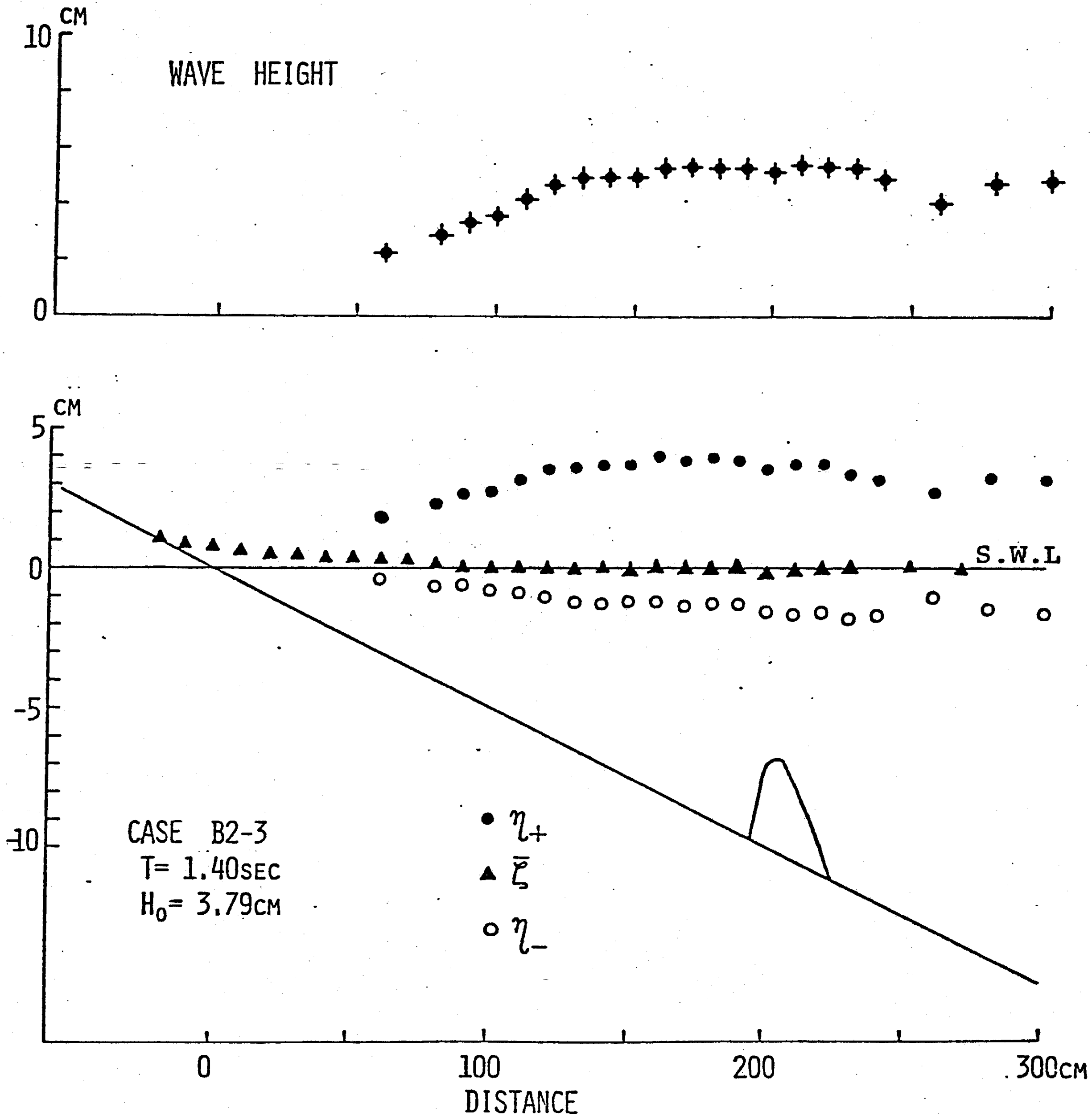


Fig. A-8 Mean water level on each measuring point.

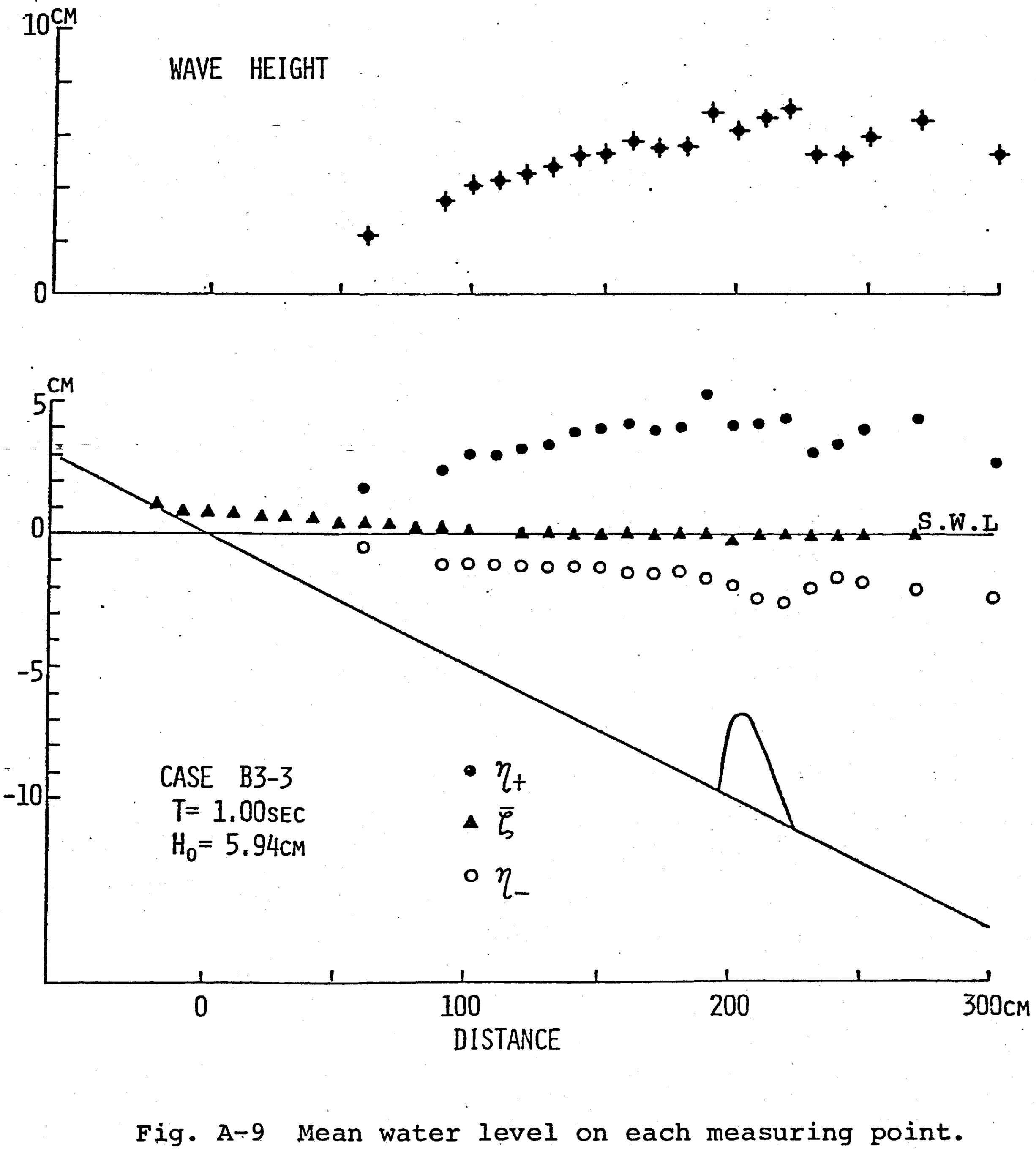


Fig. A-9 Mean water level on each measuring point.

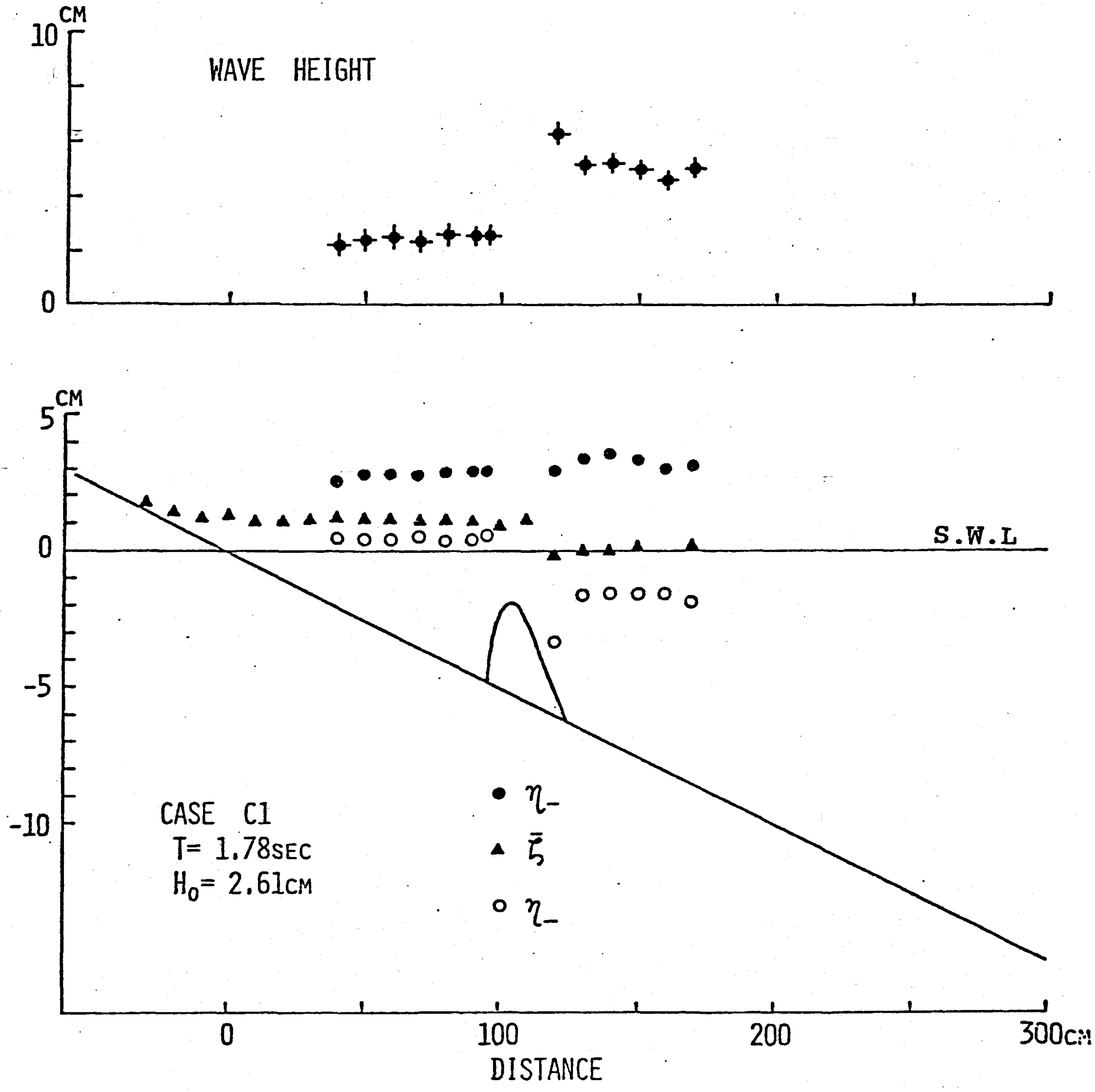


Fig. A-10 Mean water level on each measuring point.

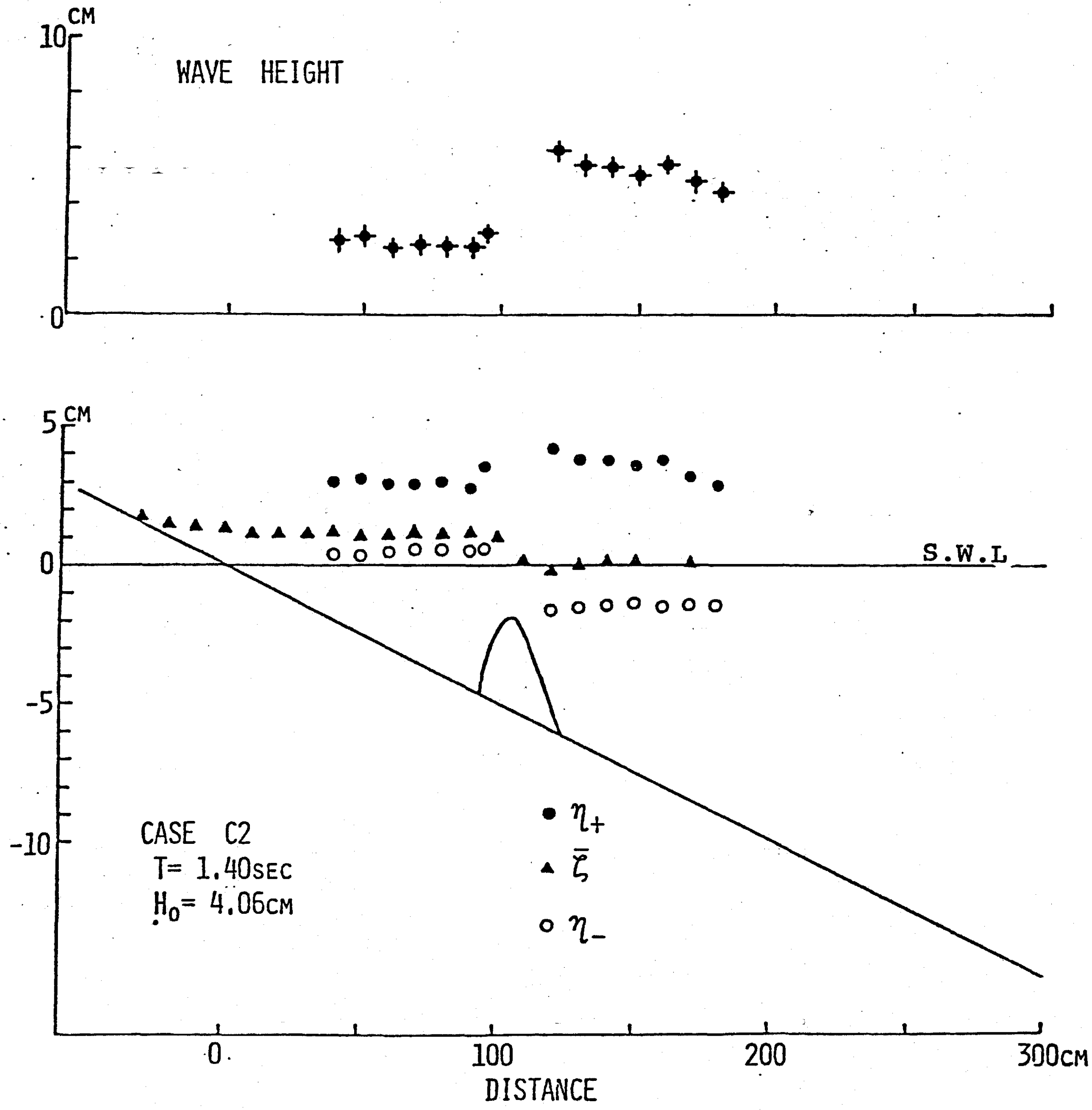


Fig. A-11 Mean water level on each measuring point.

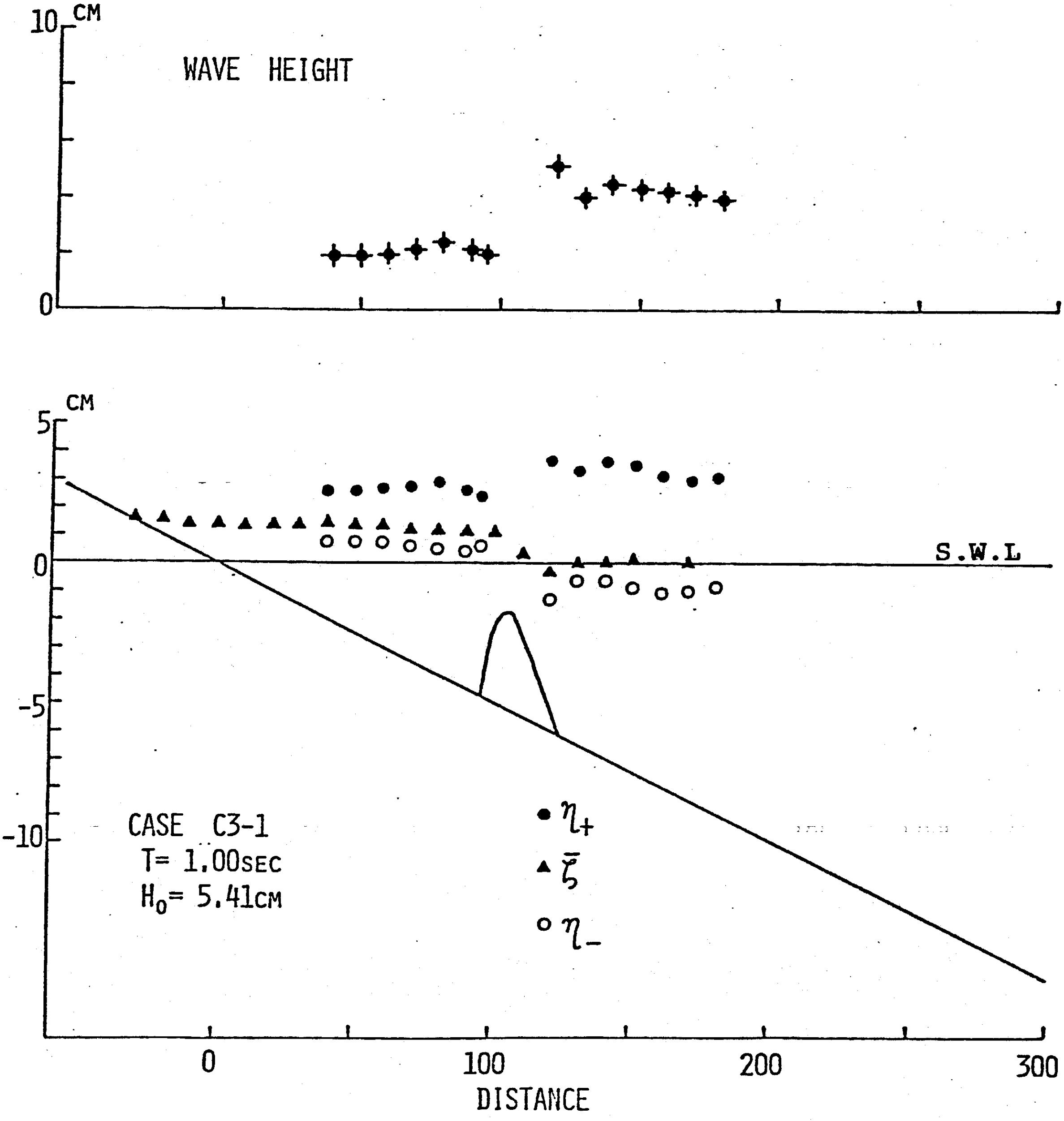


Fig. A-12 Mean water level on each measuring point.

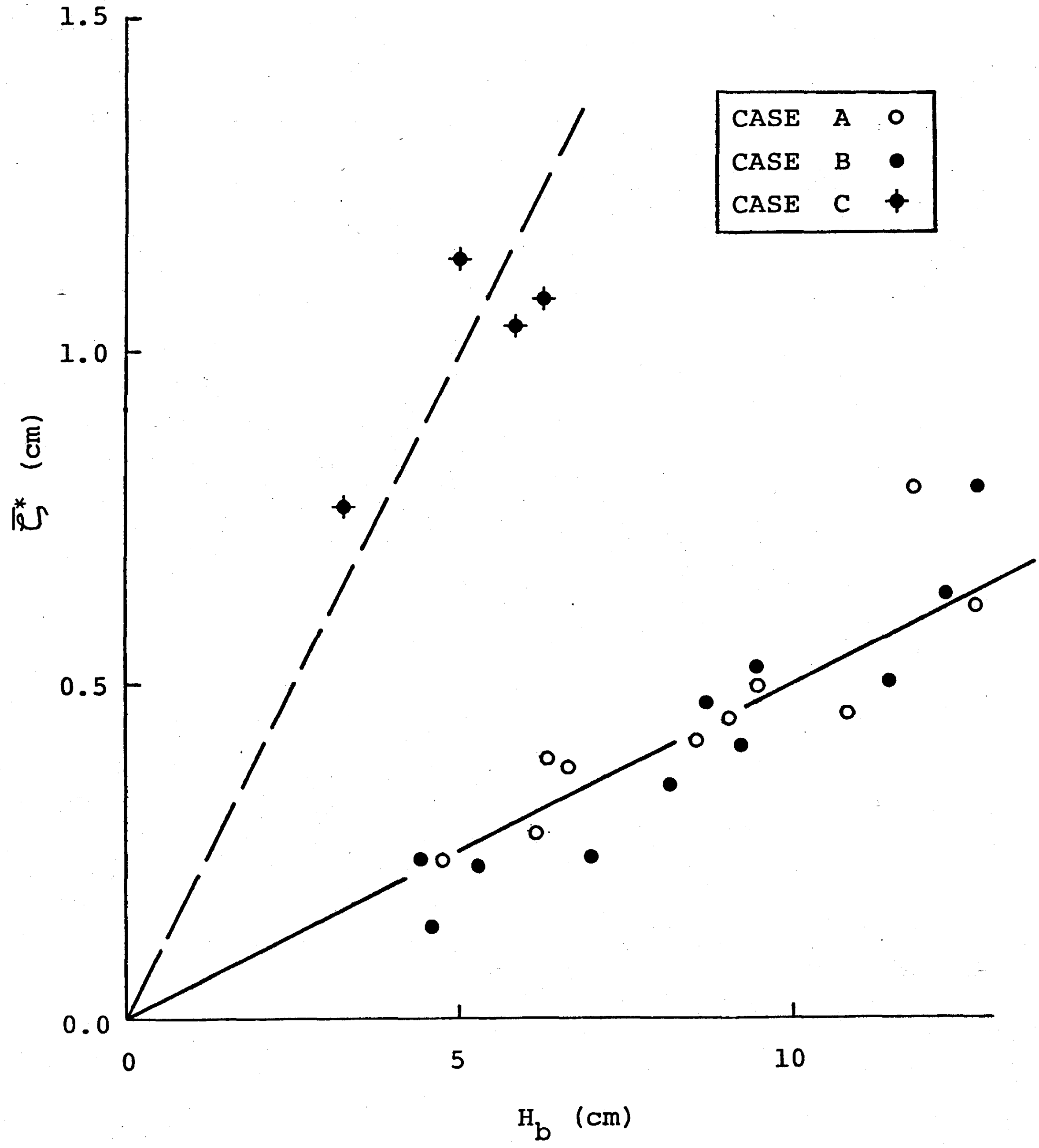


Fig. A-13 Relation of $\overline{\zeta}^*$ and H_b.

Table A-2 Wave characteristics and the elevation of the mean water level at each measuring point.

CASE A1-1 Xu=60cm X_b=285cm

X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
285*	14.25	12.75	9.75	-3.00	-
270	13.50	-	-	-	-0.15
250	12.50	10.88	8.25	-2.63	-0.15
240	12.00	-	-	-	-0.20
230	11.50	8.63	6.00	-2.63	-0.25
220	11.00	-	-	-	-0.15
210	10.50	7.32	5.01	-2.31	-0.10
200	10.00	-	-	-	0.00
190	9.50	7.44	5.40	-2.04	+0.05
180	9.00	-	-	-	+0.05
170	8.50	6.62	4.74	-1.88	+0.05
160	8.00	-	-	-	+0.15
150	7.50	5.78	4.11	-1.67	+0.20
140	7.00	-	-	-	+0.25
130	6.50	5.96	4.29	-1.67	+0.35
120	6.00	-	-	-	+0.40
110	5.50	4.80	3.33	-1.47	+0.45
100	5.00	-	-	-	+0.45
90	4.50	4.24	3.05	-1.19	+0.60
80	4.00	-	-	-	+0.80
70	3.50	3.68	-	-	+0.90
60	3.00	-	-	-	+1.00
50	2.50	-	-	-	+1.10
40	2.00	-	-	-	+1.20
30	1.50	-	-	-	+1.30
20	1.00	-	-	-	+1.40
10	0.50	-	-	-	+1.55
0	0.00	-	-	-	+1.65
-10	-0.50	-	-	-	+1.75
-20	-1.00	-	-	-	+1.90
-30	-1.50	-	-	-	+2.00

* break point

Table A-2 (continued)

CASE A1-2 Xu=51cm X_b=240cm

X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
270	13.50	9.43	7.05	-2.38	-0.10
250	12.50	10.22	7.82	-2.40	-0.10
240*	12.00	10.80	8.36	-2.44	-0.05
230	11.50	-	-	-	-0.15
220	11.00	10.58	8.31	-2.27	-0.20
210	10.50	-	-	-	-0.20
200	10.00	9.32	7.35	-1.97	-0.20
190	9.50	-	-	-	-0.25
180	9.00	8.12	6.21	-1.91	-0.25
170	8.50	-	-	-	-0.20
160	8.00	6.43	4.76	-1.67	-0.20
150	7.50	-	-	-	-0.20
140	7.00	5.55	4.05	-1.50	-0.10
130	6.50	-	-	-	+0.05
120	6.00	5.01	3.75	-1.26	+0.10
110	5.50	-	-	-	+0.20
100	5.00	4.37	3.36	-1.01	+0.25
90	4.50	-	-	-	+0.40
80	4.00	3.92	3.10	-0.82	+0.55
70	3.50	-	-	-	+0.60
60	3.00	3.55	3.09	-0.46	+0.70
50	2.50	-	-	-	+0.90
40	2.00	-	-	-	+0.95
30	1.50	-	-	-	+1.10
20	1.00	-	-	-	+1.20
10	0.50	-	-	-	+1.30
0	0.00	-	-	-	+1.45
-10	-0.50	-	-	-	+1.55
-20	-1.00	-	-	-	+1.65
-30	-1.50	-	-	-	+1.75

* break point

Table A-2 (continued)

CASE A1-3 Xu=44cm X_b=180cm

X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
270	13.50	6.81	4.95	-1.86	-0.15
250	12.50	6.81	4.93	-1.88	-0.10
240	12.00	6.95	5.19	-1.76	-0.10
230	11.50	-	-	-	-0.10
220	11.00	7.42	5.81	-1.61	-0.15
210	10.50	-	-	-	-0.20
200	10.00	7.82	6.02	-1.80	-0.15
190	9.50	-	-	-	-0.15
180*	9.00	8.55	6.75	-1.80	-0.10
170	8.50	-	-	-	-0.05
160	8.00	8.54	6.83	-1.71	-0.15
150	7.50	-	-	-	-0.20
140	7.00	6.82	5.34	-1.48	-0.15
130	6.50	-	-	-	-0.05
120	6.00	5.67	4.28	-1.39	-0.15
110	5.50	-	-	-	+0.05
100	5.00	5.16	4.03	-1.13	+0.05
90	4.50	-	-	-	+0.20
80	4.00	3.92	2.99	-0.93	+0.25
70	3.50	-	-	-	+0.35
60	3.00	3.15	2.51	-0.64	+0.45
50	2.50	-	-	-	+0.55
40	2.00	-	-	-	+0.65
30	1.50	-	-	-	+0.85
20	1.00	-	-	-	+0.95
10	0.50	-	-	-	+1.05
0	0.00	-	-	-	+1.20
-10	-0.50	-	-	-	+1.40
-20	-1.00	-	-	-	+1.50

* break point

Table A-2 (continued)

CASE A1-4 Xu=32.0cm X_b=120cm

X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
270	13.50	-	-	-	-0.15
250	12.50	-	-	-	-0.10
240	12.00	3.52	2.53	-0.99	-0.15
230	11.50	-	-	-	-0.15
220	11.00	3.90	2.83	-1.07	-0.15
210	10.50	-	-	-	-0.15
200	10.00	4.23	3.08	-1.15	-0.20
190	9.50	-	-	-	-0.20
180	9.00	4.56	3.32	-1.24	-0.20
170	8.50	-	-	-	-0.10
160	8.00	4.73	3.64	-1.09	-0.15
150	7.50	-	-	-	-0.25
140	7.00	5.35	4.18	-1.17	-0.20
130	6.50	-	-	-	-0.20
120*	6.00	6.17	4.95	-1.22	-0.20
110	5.50	-	-	-	-0.15
100	5.00	5.75	4.74	-1.01	-0.15
90	4.50	-	-	-	-0.15
80	4.00	3.53	2.71	-0.82	-0.10
70	3.50	-	-	-	+0.05
60	3.00	2.82	2.23	-0.59	+0.15
50	2.50	-	-	-	+0.20
40	2.00	-	-	-	+0.30
30	1.50	-	-	-	+0.40
20	1.00	-	-	-	+0.50
10	0.50	-	-	-	+0.50
0	0.00	-	-	-	+0.70
-10	-0.50	-	-	-	+0.90
-20	-1.00	-	-	-	+1.20

* break point

Table A-2 (continued)

CASE A2-1 Xu=49cm X_b=230cm

X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
270	13.50	11.10	8.08	-3,02	-0.29
250	12.50	11.59	8.72	-2.87	-0.12
240	12.00	-	-	-	-0.30
230*	11.50	11.80	8.91	-2.89	-0.19
220	11.00	11.31	8.59	-2.72	-0.18
210	10.50	-	-	-	-0.17
200	10.00	9.92	7.39	-2.53	-0.12
190	9.50	-	-	-	-0.18
180	9.00	8.89	6.94	-1.95	-0.15
170	8.50	-	-	-	0.00
160	8.00	6.53	4.99	-1.54	+0.15
150	7.50	-	-	-	+0.30
140	7.00	6.00	4.93	-1.07	+0.45
130	6.50	-	-	-	+0.47
120	6.00	5.44	4.39	-1.05	+0.55
110	5.50	-	-	-	+0.62
100	5.00	4.63	4.09	-0.54	+0.80
90	4.50	-	-	-	+0.85
80	4.00	3.68	3.57	-0.11	+1.02
70	3.50	-	-	-	+1.14
60	3.00	3.02	3.09	+0.07	+1.25
50	2.50	-	-	-	+1.37
40	2.00	2.31	2.74	+0.43	+1.40
30	1.50	-	-	-	+1.45
20	1.00	-	-	-	+1.55
10	0.50	-	-	-	+1.60
0	0.00	-	-	-	+1.70
-10	-0.50	-	-	-	+1.75
-20	-1.00	-	-	-	+1.90
-30	-1.50	-	-	-	+2.05

* break point

Table A-2 (continued)

CASE A2-2 Xu=38cm X_b=190cm

X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
270	13.50	7.50	4.97	-2.53	-0.13
250	12.50	7.62	5.13	-2.49	-0.15
240	12.00	-	-	-	-0.17
230	11.50	-	-	-	-0.15
220	11.00	8.21	6.02	-2.19	-0.09
210	10.50	-	-	-	-0.10
200	10.00	8.69	6.66	-2.03	-0.10
190*	9.50	9.06	6.98	-2.08	-0.15
180	9.00	8.61	6.73	-1.88	-0.15
170	8.50	-	-	-	-0.16
160	8.00	6.98	5.29	-1.69	-0.15
150	7.50	-	-	-	-0.17
140	7.00	5.53	3.98	-1.55	-0.15
130	6.50	-	-	-	-0.12
120	6.00	4.86	3.68	-1.18	-0.06
110	5.50	-	-	-	+0.10
100	5.00	4.41	3.43	-0.98	+0.24
90	4.50	-	-	-	+0.30
80	4.00	3.67	2.76	-0.91	+0.40
70	3.50	-	-	-	+0.55
60	3.00	3.08	2.32	-0.76	+0.60
50	2.50	-	-	-	+0.74
40	2.00	-	-	-	+0.84
30	1.50	-	-	-	+0.95
20	1.00	-	-	-	+1.00
10	0.50	-	-	-	+1.15
0	0.00	-	-	-	+1.25
-10	-0.50	-	-	-	+1.35
-20	-1.00	-	-	-	+1.43

* break point

Table A-2 (continued)

CASE A2-3 X_u=30cm X_b=120cm

X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
270	13.50	4.24	2.87	-1.37	-0.08
250	12.50	4.26	2.87	-1.39	-0.08
240	12.00	-	-	-	-0.06
230	11.50	-	-	-	-0.05
220	11.00	4.45	3.23	-1.22	-0.02
210	10.50	-	-	-	-0.03
200	10.00	4.82	3.47	-1.35	0.00
190	9.50	-	-	-	-0.05
180	9.00	5.06	3.75	-1.31	-0.08
170	8.50	-	-	-	-0.12
160	8.00	5.41	4.28	-1.13	-0.10
150	7.50	-	-	-	-0.13
140	7.00	6.02	4.84	-1.18	-0.13
130	6.50	6.35	5.21	-1.14	-0.15
120*	6.00	6.64	5.48	-1.16	-0.12
110.	5.50	-	-	-	-0.14
100	5.00	4.60	3.77	-0.83	-0.05
90	4.50	-	-	-	-0.03
80	4.00	3.54	2.89	-0.65	+0.08
70	3.50	-	-	-	+0.13
60	3.00	3.28	2.56	-0.72	+0.25
50	2.50	-	-	-	+0.32
40	2.00	-	-	-	+0.37
30	1.50	-	-	-	+0.45
20	1.00	-	-	-	+0.58
10	0.50	-	-	-	+0.73
0	0.00	-	-	-	+0.86
-10	-0.50	-	-	-	+0.97
-20	-1.00	-	-	-	+1.23

* break point

Table A-2 (continued)

CASE A3-1 Xu=33cm X_b=250cm

X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
300	15.00	8.78	6.36	-2.42	-
270	13.50	9.32	6.94	-2.38	-0.22
250*	12.50	9.44	6.96	-2.48	-0.23
240	12.00	-	-	-	-0.16
230	11.50	-	-	-	-0.18
220	11.00	8.94	6.60	-2.34	-0.15
210	10.50	-	-	-	-0.16
200	10.00	7.90	5.91	-1.99	-0.16
190	9.50	-	-	-	-0.16
180	9.00	6.75	4.95	-1.80	-0.14
170	8.50	-	-	-	-0.08
160	8.00	5.85	4.26	-1.59	-0.04
150	7.50	-	-	-	-0.03
140	7.00	4.58	3.36	-1.22	+0.10
130	6.50	-	-	-	+0.22
120	6.00	4.34	3.28	-1.06	+0.36
110	5.50	-	-	-	+0.45
100	5.00	3.57	2.93	-0.64	+0.60
90	4.50	-	-	-	+0.72
80	4.00	3.02	2.82	-0.20	+0.78
70	3.50	-	-	-	+0.84
60	3.00	2.16	2.13	-0.03	+0.90
50	2.50	-	-	-	+0.94
40	2.00	1.94	2.13	+0.19	+0.96
30	1.50	-	-	-	+0.96
20	1.00	-	-	-	+1.05
10	0.50	-	-	-	+1.20
0	0.00	-	-	-	+1.30
-10	-0.50	-	-	-	+1.36
-20	-1.00	-	-	-	+1.50
-30	-1.50	-	-	-	+1.62

* break point

Table A-2 (continued)

CASE A3-2 Xu=28cm X_b=140cm

X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
270	13.50	5.25	3.56	-1.69	-0.10
250	12.50	5.44	3.66	-1.78	-0.14
240	12.00	-	-	-	-0.08
230	11.50	-	-	-	-0.15
220	11.00	5.16	3.47	-1.69	-0.08
210	10.50	-	-	-	-0.04
200	10.00	5.46	3.75	-1.71	-0.03
190	9.50	-	-	-	-0.08
180	9.00	5.44	3.94	-1.50	-0.12
170	8.50	-	-	-	-0.08
160	8.00	5.82	4.27	-1.55	-0.10
150	7.50	-	-	-	-0.14
140*	7.00	6.31	4.90	-1.41	-0.14
130	6.50	-	-	-	-0.16
120	6.00	5.80	4.41	-1.39	-0.12
110	5.50	-	-	-	-0.16
100	5.00	5.59	3.68	-1.88	-0.06
90	4.50	-	-	-	-0.03
80	4.00	3.68	2.84	-0.84	+0.13
70	3.50	-	-	-	+0.27
60	3.00	2.59	2.00	-0.59	+0.42
50	2.50	-	-	-	+0.52
40	2.00	-	-	-	+0.62
30	1.50	-	-	-	+0.70
20	1.00	-	-	-	+0.77
10	0.50	-	-	-	+0.82
0	0.00	-	-	-	+0.92
-10	-0.50	-	-	-	+0.97
-20	-1.00	-	-	-	+1.12

* break point

Table A-2 (continued)

CASE A3-3 Xu=22cm X_b=100cm

X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
270	13.50	3.59	2.32	-1.27	-0.12
250	12.50	3.23	1.92	-1.31	-0.15
240	12.00	-	-	-	-0.14
230	11.50	-	-	-	-0.14
220	11.00	3.37	2.20	-1.17	-0.06
210	10.50	-	-	-	-0.02
200	10.00	3.57	2.44	-1.13	-0.00
190	9.50	-	-	-	-0.08
180	9.00	3.65	2.50	-1.15	-0.13
170	8.50	-	-	-	-0.02
160	8.00	3.94	2.77	-1.17	-0.05
150	7.50	-	-	-	-0.12
140	7.00	4.00	2.95	-1.05	-0.12
130	6.50	-	-	-	-0.18
120	6.00	4.22	3.20	-1.02	-0.20
110	5.50	-	-	-	-0.18
100*	5.00	4.72	3.70	-1.02	-0.12
90	4.50	-	-	-	-0.12
80	4.00	4.31	3.27	-1.04	-0.08
70	3.50	-	-	-	-0.06
60	3.00	2.87	2.02	-0.85	+0.04
50	2.50	-	-	-	+0.25
40	2.00	-	-	-	+0.32
30	1.50	-	-	-	+0.42
20	1.00	-	-	-	+0.52
10	0.50	-	-	-	+0.68
0	0.00	-	-	-	+0.74

* break point

Table A-2 (continued)

CASE B1-1 Xu=57cm X_b=250cm

X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
300	15.00	11.71	9.05	-2.66	-
280	14.00	11.52	8.89	-2.63	-
270	13.50	-	-	-	-0.20
260	13.00	12.18	9.23	-2.95	-
250*	12.50	12.30	9.53	-2.77	-0.14
240	12.00	10.55	8.17	-2.38	-
230	11.50	8.72	6.43	-2.29	-0.18
220	9.92	9.64	7.32	-2.32	-0.18
210	7.55	9.86	7.15	-2.71	-0.32
200	7.00	7.77	5.71	-2.06	-0.30
190	9.50	6.23	4.67	-1.56	+0.02
180	9.00	7.92	6.38	-1.54	+0.20
170	8.50	6.68	5.25	-1.43	+0.28
160	8.00	6.20	4.85	-1.35	+0.34
150	7.50	6.05	4.72	-1.33	+0.34
140	7.00	6.05	4.88	-1.17	+0.40
130	6.50	5.46	4.36	-1.10	+0.40
120	6.00	5.25	4.18	-1.07	+0.40
110	5.50	4.92	3.88	-1.04	+0.48
100	5.00	4.62	3.60	-1.02	+0.48
90	4.50	4.37	3.56	-0.81	+0.58
80	4.00	4.04	2.94	-1.10	+0.74
70	3.50	-	-	-	+0.88
60	3.00	3.00	2.65	-0.35	+0.94
50	2.50	-	-	-	+1.02
40	2.00	-	-	-	+1.10
30	1.50	-	-	-	+1.16
20	1.00	-	-	-	+1.18
10	0.50	-	-	-	+1.40
0	0.00	-	-	-	+1.48
-10	-0.50	-	-	-	+1.54
-20	-1.00	-	-	-	+1.72
-30	-1.50	-	-	-	+1.82

* break point

Table A-2 (continued)

CASE B1-2 Xu=54cm X_b=210cm

X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
300	15.00	9.27	6.83	-2.44	-
280	14.00	8.77	6.46	-2.31	-
270	13.50	-	-	-	-0.20
260	13.00	10.04	7.21	-2.83	-
250	12.50	-	-	-	-0.16
240	12.00	10.80	8.17	-2.63	-
230	11.50	10.59	8.13	-2.46	-0.20
220	9.92	10.61	8.05	-2.56	-0.14
210*	7.55	11.45	8.60	-2.85	-0.34
200	7.00	10.07	7.92	-2.15	-0.44
190	9.50	8.90	7.20	-1.70	-0.12
180	9.00	7.18	5.55	-1.63	-0.10
170	8.50	7.30	5.86	-1.44	-0.08
160	8.00	7.37	6.03	-1.34	+0.10
150	7.50	5.42	4.05	-1.37	+0.02
140	7.00	5.60	4.25	-1.35	+0.08
130	6.50	5.55	4.23	-1.32	+0.18
120	6.00	5.63	4.38	-1.25	+0.20
110	5.50	5.27	4.02	-1.25	+0.28
100	5.00	5.19	3.96	-1.23	+0.28
90	4.50	4.53	3.41	-1.12	+0.32
80	4.00	4.19	2.81	-1.38	+0.40
70	3.50	-	-	-	+0.56
60	3.00	3.22	2.47	-0.75	+0.64
50	2.50	-	-	-	+0.74
40	2.00	-	-	-	+0.84
30	1.50	-	-	-	+0.96
20	1.00	-	-	-	+1.00
10	0.50	-	-	-	+1.16
0	0.00	-	-	-	+1.32
-10	-0.50	-	-	-	+1.38
-20	-1.00	-	-	-	+1.54
-30	-1.50	-	-	-	+1.66

* break point

Table A-2 (continued)

CASE B1-3 Xu=40cm X_b=210cm

X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
300	15.00	6.81	4.99	-1.82	-
270	13.50	6.69	4.88	-1.81	-0.14
250	12.50	7.19	5.08	-2.11	-0.14
240	12.00	7.55	5.70	-1.85	-
230	11.50	8.12	6.14	-1.98	-0.12
220	9.92	8.12	6.23	-1.89	-0.14
210*	7.55	9.25	6.98	-2.27	-0.24
200	7.00	7.95	6.41	-1.54	-0.42
190	9.50	7.16	5.82	-1.34	-0.18
180	9.00	6.73	5.46	-1.27	-0.06
170	8.50	6.03	4.65	-1.38	-0.08
160	8.00	6.74	5.52	-1.22	-0.04
150	7.50	5.18	4.10	-1.08	+0.06
140	7.00	5.32	4.33	-0.99	+0.02
130	6.50	4.66	3.73	-0.93	+0.14
120	6.00	4.42	3.52	-0.90	+0.22
110	5.50	4.30	3.38	-0.92	+0.22
100	5.00	3.91	3.02	-0.89	+0.22
90	4.50	3.46	2.72	-0.74	+0.24
80	4.00	3.17	2.54	-0.63	+0.30
70	3.50	-	-	-	+0.38
60	3.00	2.65	2.21	-0.44	+0.46
50	2.50	-	-	-	+0.62
40	2.00	-	-	-	+0.64
30	1.50	-	-	-	+0.74
20	1.00	-	-	-	+0.82
10	0.50	-	-	-	+0.98
0	0.00	-	-	-	+1.12
-10	-0.50	-	-	-	+1.26
-20	-1.00	-	-	-	+1.12
-30	-1.50	-	-	-	+1.68

* break point

Table A-2 (continued)

CASE B1-4 Xu=28cm X_b=210cm X_b^*=150cm

X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\overline{\zeta}$(cm)
300	15.00	3.58	2.48	-1.10	-
280	14.00	1.91	1.06	-0.85	-
270	13.50	-	-	-	-0.06
260	13.00	3.58	2.37	-1.21	-
250	12.50	-	-	-	-0.06
240	12.00	3.81	2.50	-1.31	-
230	11.50	3.88	2.68	-1.20	-0.02
220	9.92	4.27	3.02	-1.25	-0.02
210*	7.55	4.40	3.12	-1.28	-0.08
200	7.00	4.19	2.99	-1.20	-0.18
190	9.50	4.41	3.40	-1.01	-0.08
180	9.00	4.71	3.71	-1.00	-0.04
170	8.50	4.79	3.75	-1.04	-0.02
160	8.00	4.90	3.92	-0.98	0.00
150*	7.50	4.92	3.94	-0.98	-0.02
140	7.00	4.90	3.94	-0.96	-0.08
130	6.50	4.84	3.91	-0.93	-0.06
120	6.00	4.63	3.71	-0.92	-0.02
110	5.50	4.65	3.72	-0.93	-0.06
100	5.00	3.97	3.14	-0.83	-0.04
90	4.50	3.42	2.66	-0.76	-0.02
80	4.00	3.01	2.35	-0.66	0.00
70	3.50	-	-	-	+0.06
60	3.00	-	-	-	+0.12
50	2.50	-	-	-	+0.30
40	2.00	-	-	-	+0.30
30	1.50	-	-	-	+0.40
20	1.00	-	-	-	+0.46
10	0.50	-	-	-	+0.54
0	0.00	-	-	-	+0.60
-10	-0.50	-	-	-	+0.78
-20	-1.00	-	-	-	+1.00

* break point

Table A-2 (continued)

CASE B2-1 Xu=50cm X_b=230cm

X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
300	15.00	11.88	8.73	-3.15	-
280	14.00	11.24	8.73	-2.51	-
270	13.50	11.25	8.72	-2.53	-0.26
260	13.00	10.78	8.33	-2.45	-
250	12.50	11.16	8.45	-2.71	-0.22
240	12.00	12.02	9.00	-3.02	-
230*	11.50	12.73	9.74	-2.99	-0.16
220	9.92	11.36	8.56	-2.80	-0.22
210	7.55	11.13	7.68	-3.45	-0.52
200	7.00	8.29	6.33	-1.96	-0.48
190	9.50	5.97	4.56	-1.41	-0.04
180	9.00	7.40	6.07	-1.33	+0.26
170	8.50	6.26	4.93	-1.33	+0.46
160	8.00	5.26	4.07	-1.19	+0.46
150	7.50	5.62	4.57	-1.05	+0.46
140	7.00	5.43	4.41	-1.02	+0.62
130	6.50	4.88	4.11	-0.77	+0.68
120	6.00	4.80	4.08	-0.72	+0.68
110	5.50	4.35	3.81	-0.54	+0.82
100	5.00	3.95	3.49	-0.46	+0.82
90	4.50	3.89	3.53	-0.36	+0.86
80	4.00	3.69	3.24	-0.40	+1.02
70	3.50	-	-	-	+1.12
60	3.00	2.96	2.93	-0.03	+1.14
50	2.50	-	-	-	+1.22
40	2.00	-	-	-	+1.28
30	1.50	-	-	-	+1.34
20	1.00	-	-	-	+1.36
10	0.50	-	-	-	+1.48
0	0.00	-	-	-	+1.56
-10	-0.50	-	-	-	+1.62
-20	-1.00	-	-	-	+1.72
-30	-1.50	-	-	-	+1.86

* break point

Table A-2 (continued)

CASE B2-2 Xu=36cm X_b=210cm

X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
300	15.00	7.29	4.90	-2.39	-
280	14.00	6.65	4.58	-2.07	-
270	13.50	-	-	-	-0.18
260	13.00	6.11	4.28	-1.83	-
250	12.50	-	-	-	-0.14
240	12.00	7.16	4.76	-2.40	-
230	11.50	7.39	5.00	-2.39	-0.12
220	9.92	8.05	5.70	-2.35	-0.08
210*	7.55	8.15	5.67	-2.48	-0.28
200	7.00	7.79	5.73	-2.06	-0.36
190	9.50	7.22	5.64	-1.58	-0.10
180	9.00	6.56	4.99	-1.57	-0.06
170	8.50	-	-	-	-0.06
160	8.00	6.15	4.69	-1.46	+0.08
150	7.50	-	-	-	0.00
140	7.00	5.29	4.08	-1.21	+0.08
130	6.50	-	-	-	+0.12
120	6.00	4.61	3.60	-1.01	+0.12
110	5.50	-	-	-	+0.20
100	5.00	3.84	3.10	-0.74	+0.22
90	4.50	-	-	-	+0.26
80	4.00	3.27	2.64	-0.63	+0.36
70	3.50	-	-	-	+0.46
60	3.00	2.70	2.41	-0.29	+0.50
50	2.50	-	-	-	+0.56
40	2.00	-	-	-	+0.64
30	1.50	-	-	-	+0.70
20	1.00	-	-	-	+0.80
10	0.50	-	-	-	+0.94
0	0.00	-	-	-	+0.96
-10	-0.50	-	-	-	+1.06
-20	-1.00	-	-	-	+1.16

* break point

Table A-2 (continued)

CASE B2-3 Xu=30cm X_b=190cm

X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
300	15.00	4.87	3.18	-1.69	-
280	14.00	4.68	3.20	-1.48	-
270	13.50	-	-	-	-0.12
260	13.00	3.88	2.71	-1.17	-
250	12.50	-	-	-	-0.04
240	12.00	4.88	3.18	-1.70	-
230	11.50	5.21	3.37	-1.84	-0.10
220	9.92	5.32	3.67	-1.65	0.00
210	7.55	5.37	3.66	-1.71	-0.12
200	7.00	5.16	3.53	-1.63	-0.24
190*	9.50	5.27	3.88	-1.39	-0.02
180	9.00	5.24	3.93	-1.31	-0.04
170	8.50	5.26	3.88	-1.38	-0.06
160	8.00	5.25	3.96	-1.29	0.00
150	7.50	4.93	3.64	-1.29	-0.10
140	7.00	4.94	3.63	-1.31	-0.06
130	6.50	4.84	3.58	-1.26	-0.04
120	6.00	4.63	3.54	-1.09	-0.04
110	5.50	4.14	3.18	-0.96	0.00
100	5.00	3.48	2.68	-0.80	0.00
90	4.50	3.23	2.61	-0.62	+0.04
80	4.00	2.91	2.25	-0.66	+0.10
70	3.50	-	-	-	+0.24
60	3.00	2.28	1.80	-0.48	+0.30
50	2.50	-	-	-	+0.28
40	2.00	-		-	+0.36
30	1.50	-	-	-	+0.44
20	1.00	-	-	-	+0.46
10	0.50	-	-	-	+0.62
0	0.00	-	-	-	+0.72
-10	-0.50	-	-	-	+0.80
-20	-1.00	-	-	-	+1.00

* break point

Table A-2 (continued)

CASE B3-1 Xu=33cm X_b=210cm

X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
300	15.00	7.78	5.34	-2.44	-
270	13.50	8.66	6.02	-2.64	-0.22
250	12.50	-	-	-	-0.28
240	12.00	-	-	-	-0.30
230	11.50	8.17	6.21	-1.96	-0.28
220	9.92	8.91	6.19	-2.72	-0.34
210*	7.55	9.46	6.62	-2.84	-0.42
200	7.00	7.32	5.19	-2.13	-0.44
190	9.50	6.04	4.11	-1.93	-0.16
180	9.00	6.93	4.28	-2.65	-0.16
170	8.50	5.94	4.25	-1.69	+0.20
160	8.00	4.23	2.63	-1.60	+0.18
150	7.50	4.69	3.17	-1.52	+0.22
140	7.00	4.69	3.08	-1.61	+0.36
130	6.50	4.58	3.21	-1.37	+0.46
120	6.00	4.52	3.22	-1.30	+0.42
110	5.50	4.21	3.06	-1.15	-
100	5.00	3.91	2.78	-1.13	+0.56
90	4.50	3.30	2.51	-0.79	+0.60
80	4.00	-	-	-	+0.64
70	3.50	-	-	-	+0.70
60	3.00	2.10	2.03	-0.07	+0.72
50	2.50	-	-	-	+0.78
40	2.00	-	-	-	+0.88
30	1.50	-	-	-	+0.94
20	1.00	-	-	-	+1.00
10	0.50	-	-	-	+1.04
0	0.00	-	-	-	+1.06
-10	-0.50	-	-	-	+1.16
-20	-1.00	-	-	-	+1.26

* break point

Table A-2 (continued)

CASE B3-2 Xu=29cm X_b=210cm

X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\overline{\zeta}$(cm)
300	15.00	6.27	4.13	-2.14	-
270	13.50	7.72	5.17	-2.55	-0.12
250	12.50	7.12	5.09	-2.03	-0.20
240	12.00	-	-	-	-0.22
230	11.50	7.49	5.20	-2.29	-0.18
220	9.92	8.46	5.95	-2.51	-0.18
210*	7.55	8.70	5.98	-2.72	-0.32
200	7.00	7.37	5.51	-1.86	-0.38
190	9.50	5.93	4.22	-1.71	-0.02
180	9.00	-	-	-	-0.10
170	8.50	5.93	4.48	-1.45	+0.12
160	8.00	-	-	-	+0.14
150	7.50	4.67	3.30	-1.37	+0.12
140	7.00	-	-	-	+0.24
130	6.50	4.01	2.88	-1.13	+0.38
120	6.00	-	-	-	+0.36
110	5.50	3.50	2.62	-0.88	-
100	5.00	-	-	-	+0.46
90	4.50	2.71	2.09	-0.62	+0.52
80	4.00	-	-	-	+0.54
70	3.50	-	-	-	+0.68
60	3.00	2.12	2.06	-0.06	+0.66
50	2.50	-	-	-	+0.72
40	2.00	-	-	-	+0.80
30	1.50	-	-	-	+0.88
20	1.00	-	-	-	+0.92
10	0.50	-	-	-	+0.96
0	0.00	-	-	-	+1.00
-10	-0.50	-	-	-	+1.06
-20	-1.00	-	-	-	+1.12

* break point

Table A-2 (continued)

CASE B3-3 Xu=23cm X_b=220

X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\overline{\zeta}$(cm)
300	15.00	5.20	2.63	-2.57	-
270	13.50	6.47	4.29	-2.18	-0.02
250	12.50	5.87	3.92	-1.95	-0.08
240	12.00	5.17	3.39	-1.78	-0.12
230	11.50	5.20	3.04	-2.16	-0.10
220*	9.92	6.95	4.32	-2.63	-0.12
210	7.55	6.66	4.16	-2.50	-0.16
200	7.00	6.14	4.04	-2.10	-0.30
190	9.50	6.85	5.21	-1.64	-0.02
180	9.00	5.41	3.99	-1.42	0.00
170	8.50	5.48	3.89	-1.59	-0.02
160	8.00	5.68	4.18	-1.50	-0.04
150	7.50	5.27	3.91	-1.36	-0.08
140	7.00	5.20	3.84	-1.36	-0.04
130	6.50	4.72	3.34	-1.38	+0.06
120	6.00	4.46	3.15	-1.31	+0.06
110	5.50	4.23	2.98	-1.25	-
100	5.00	4.09	2.92	-1.17	+0.12
90	4.50	3.56	2.38	-1.18	+0.20
80	4.00	-	-	-	+0.20
70	3.50	-	-	-	+0.32
60	3.00	2.19	1.70	-0.49	+0.28
50	2.50	-	-	-	+0.38
40	2.00	-	-	-	+0.50
30	1.50	-	-	-	+0.58
20	1.00	-	-	-	+0.64
10	0.50	-	-	-	+0.68
0	0.00	-	-	-	+0.72
-10	-0.50	-	-	-	+0.82
-20	-1.00	-	-	-	+0.98

* break point

Table A-2 (continued)

CASE B3-4 Xu=21cm X_b=75cm

X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
300	15.00	3.10	1.41	-1.69	-
270	13.50	3.88	2.11	-1.77	+0.02
250	12.50	3.35	1.70	-1.65	-0.08
240	12.00	-	-	-	-0.06
230	11.50	3.04	1.61	-1.43	-0.08
220	9.92	4.00	2.15	-1.85	-0.04
210	7.55	3.51	1.83	-1.68	-0.12
200	7.00	3.48	1.85	-1.63	-0.14
190	9.50	4.13	2.66	-1.47	-0.04
180	9.00	4.58	3.09	-1.49	-0.06
170	8.50	4.23	2.78	-1.45	-0.02
160	8.00	4.38	2.94	-1.44	-0.02
150	7.50	3.95	2.65	-1.30	-0.04
140	7.00	4.33	2.99	-1.34	-0.04
130	6.50	4.53	3.16	-1.37	-0.00
120	6.00	4.47	3.06	-1.41	-0.10
110	5.50	4.27	2.81	-1.46	-
100	5.00	4.06	2.59	-1.47	-0.10
90	4.50	4.24	2.75	-1.49	-0.06
80	4.00	-	-	-	-0.12
70	3.50	-	-	-	-0.06
60	3.00	3.31	2.11	-1.20	-0.06
50	2.50	-	-	-	+0.12
40	2.00	-	-	-	+0.26
30	1.50	-	-	-	+0.42
20	1.00	-	-	-	+0.50
10	0.50	-	-	-	+0.58
0	0.00	-	-	-	+0.66
-10	-0.50	-	-	-	+0.76

* break point

Table A-2 (continued)

CASE	C1	Xu=41cm	X_b=120cm		
X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
170	8.50	4.96	3.08	-1.88	+0.02
160	8.00	4.56	2.98	-1.58	-
150	7.50	4.92	3.27	-1.65	+0.02
140	7.00	5.09	3.47	-1.62	0.00
130	6.50	5.03	3.35	-1.68	-0.08
120*	4.92	6.24	2.84	-3.40	-0.26
110	2.55	-	-	-	+1.16
100	2.00	-	-	-	+0.88
95	4.75	2.43	2.84	+0.41	-
90	4.50	2.50	2.89	+0.39	+1.04
80	4.00	2.47	2.84	+0.38	+1.08
70	3.50	2.34	2.75	+0.41	+1.08
60	3.00	2.45	2.81	+0.36	+1.14
50	2.50	2.38	2.75	+0.37	+1.10
40	2.00	2.11	2.52	+0.41	+1.16
30	1.50	-	-	-	+1.16
20	1.00	-	-	-	+1.16
10	0.50	-	-	-	+1.14
0	0.00	-	-	-	+1.22
-10	-0.50	-	-	-	+1.14
-20	-1.00	-	-	-	+1.38
-30	-1.50	-	-	-	+1.66

CASE	C2	Xu=40cm	X_b=120cm		
X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
180	9.00	4.37	2.82	-1.55	-
170	8.50	4.69	3.18	-1.51	+0.02
160	8.00	5.29	3.70	-1.59	-
150	7.50	4.93	3.46	-1.47	+0.02
140	7.00	5.20	3.71	-1.49	+0.02
130	6.50	5.30	3.77	-1.53	-0.06
120*	4.92	5.82	4.19	-1.63	-0.22
110	2.55	-	-	-	+0.08
100	2.00	-	-	-	+0.86
95	4.75	2.88	3.43	+0.55	-
90	4.50	2.28	2.73	+0.45	+1.06
80	4.00	2.42	2.88	+0.46	+1.12
70	3.50	2.43	2.88	+0.45	+1.08
60	3.00	2.40	2.87	+0.47	+1.12
50	2.50	2.69	3.05	+0.36	+1.12
40	2.00	2.60	2.95	+0.35	+1.20
30	1.50	-	-	-	+1.16
20	1.00	-	-	-	+1.12
10	0.50	-	-	-	+1.14
0	0.00	-	-	-	+1.28
-10	-0.50	-	-	-	+1.36
-20	-1.00	-	-	-	+1.44
-30	-1.50	-	-	-	+1.68

* break point

Table A-2 (continued)

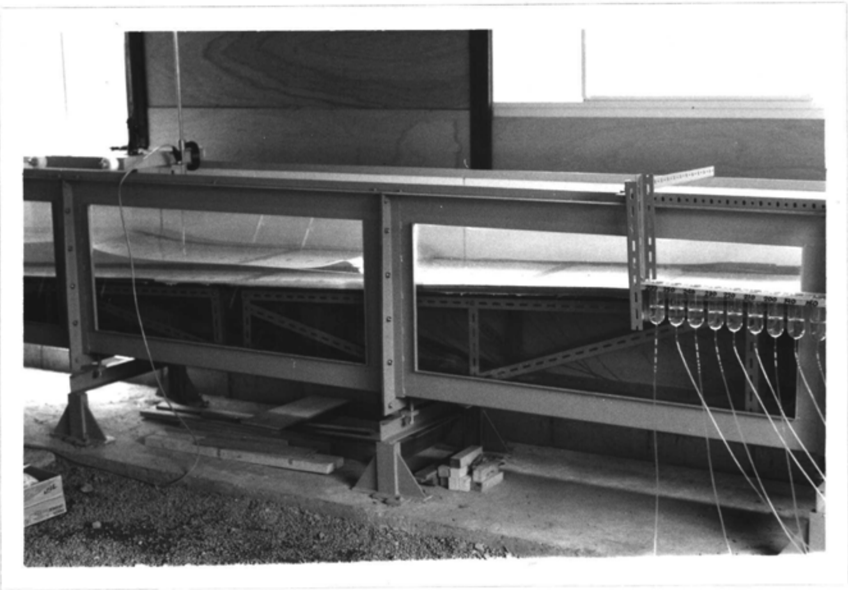
CASE	C3-1	Xu=35cm	X_b=120cm		
X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
180	9.00	3.92	3.00	-0.92	-
170	8.50	4.03	2.96	-1.07	0.00
160	8.00	4.18	3.02	-1.16	-
150	7.50	4.23	3.44	-0.97	+0.04
140	7.00	4.40	3.64	-0.76	0.00
130	6.50	3.98	3.21	-0.77	-0.08
120*	4.92	5.02	3.66	-1.36	-0.32
110	2.55	-	-	-	+0.26
100	2.00	-	-	-	+1.02
95	4.75	1.90	2.39	+0.49	-
90	4.50	2.13	2.54	+0.41	+1.16
80	4.00	2.37	2.82	+0.45	+1.18
70	3.50	2.13	2.73	+0.60	+1.20
60	3.00	1.93	2.61	+0.68	+1.28
50	2.50	1.82	2.50	+0.68	+1.26
40	2.00	1.83	2.50	+0.67	+1.36
30	1.50	-	-	-	+1.32
20	1.00	-	-	-	+1.30
10	0.50	-	-	-	+1.30
0	0.00	-	-	-	+1.38
-10	-0.50	-	-	-	+1.40
-20	-1.00	-	-	-	+1.48
-30	-1.50	-	-	-	+1.58

CASE	C3-2	Xu=27cm	X_b=120cm		
X(cm)	h(cm)	H(cm)	η_+(cm)	η_-(cm)	$\bar{\zeta}$(cm)
180	9.00	2.72	1.38	-1.34	-
170	8.50	2.52	1.24	-1.28	+0.02
160	8.00	2.82	1.32	-1.50	-
150	7.50	3.12	1.41	-1.71	+0.04
140	7.00	3.15	1.55	-1.60	+0.04
130	6.50	2.64	1.15	-1.49	0.00
120*	4.92	3.24	1.36	-1.88	-0.16
110	2.55	-	-	-	+0.20
100	2.00	-	-	-	+0.72
95	4.75	1.80	1.82	+0.02	-
90	4.50	1.72	1.71	-0.01	+0.78
80	4.00	1.74	1.73	-0.01	+0.86
70	3.50	1.65	1.61	-0.04	+0.82
60	3.00	1.56	1.64	+0.08	+0.90
50	2.50	1.63	1.72	+0.09	+0.82
40	2.00	1.58	1.77	+0.19	+0.92
30	1.50	-	-	-	+0.90
20	1.00	-	-	-	+0.84
10	0.50	-	-	-	+0.82
0	0.00	-	-	-	+0.94
-10	-0.50	-	-	-	+0.98
-20	-1.00	-	-	-	+1.14

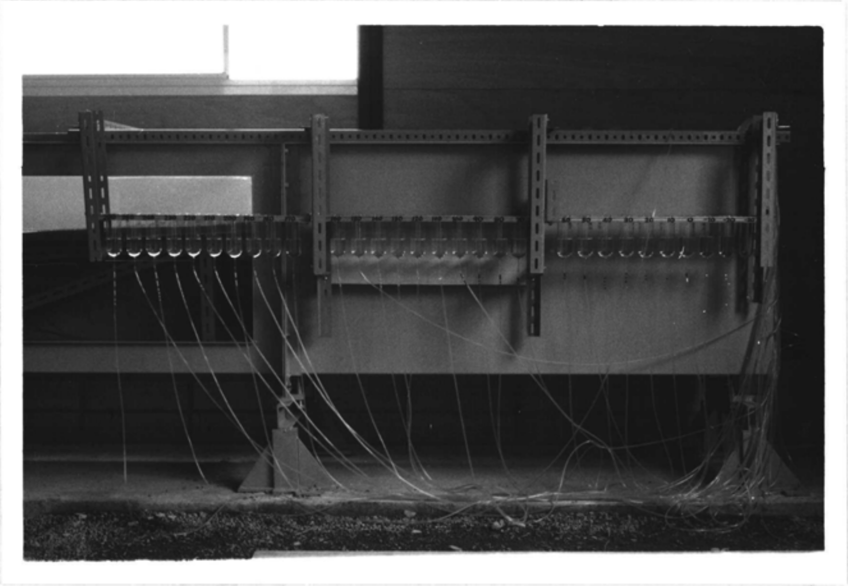
* break point

PHOTOGRAPHS (APPENDIX A)

Photograph	
A-1	Main part of the experimental equipment.
A-2	Water gage.



A–1



A–2

APPENDIX B

INVESTIGATION RESULTS IN THE SPRING OF 1978

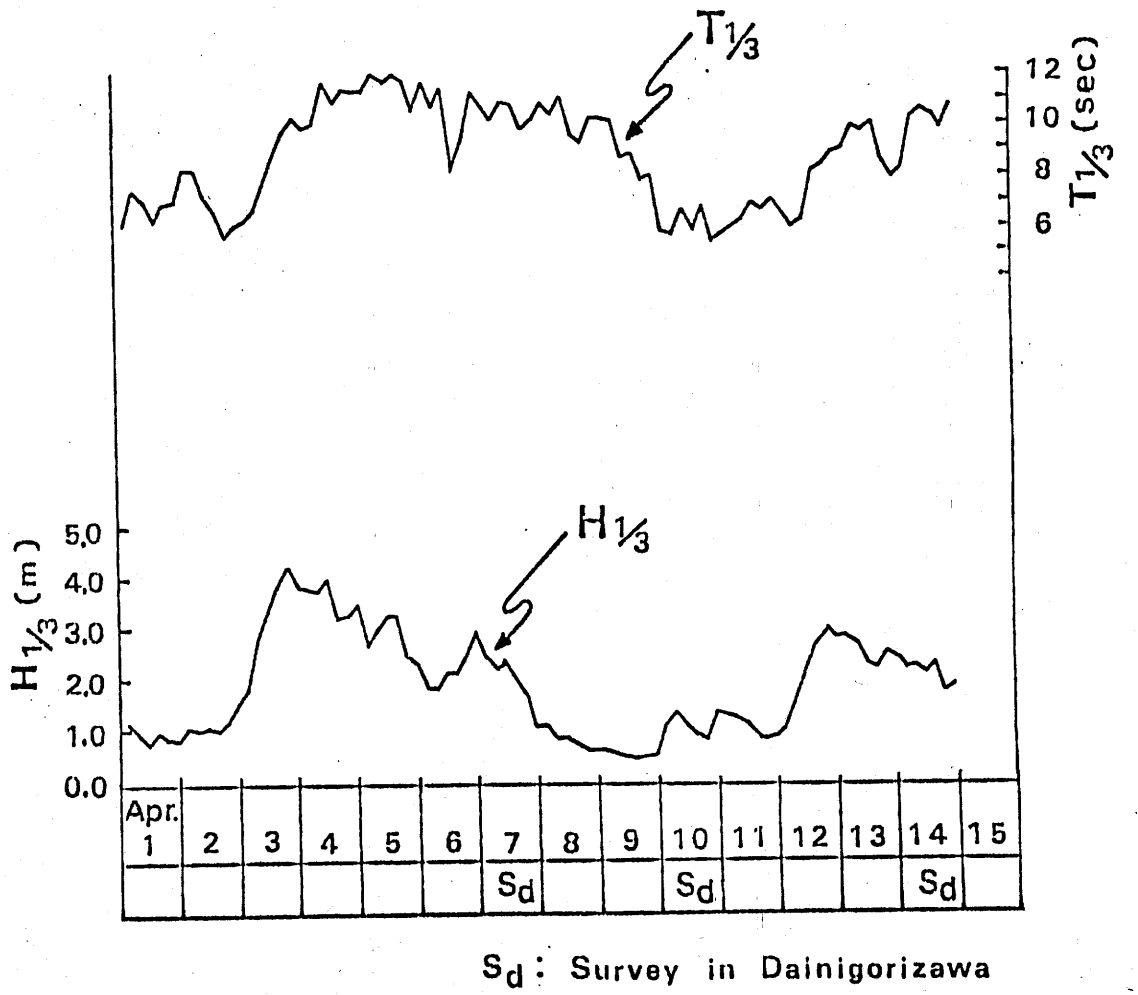
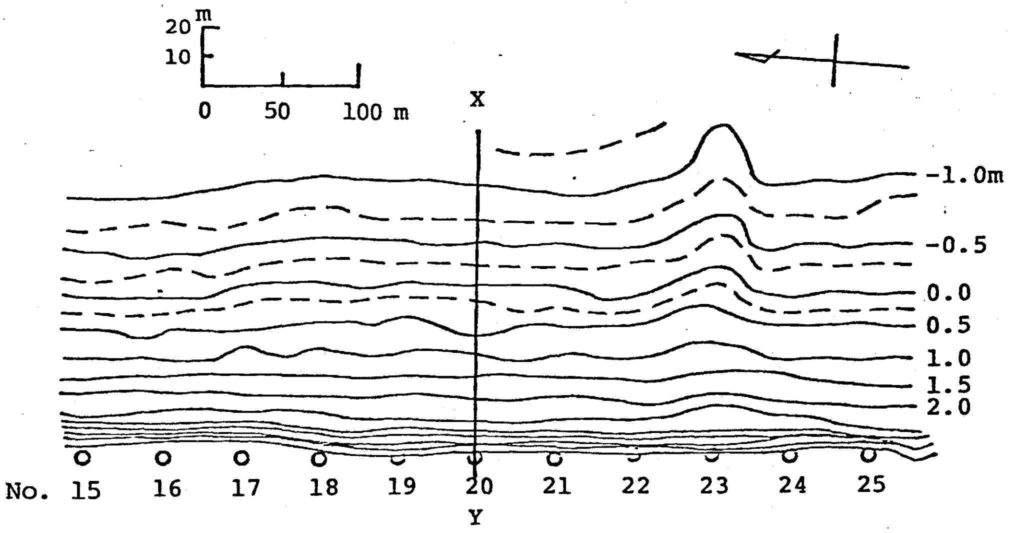
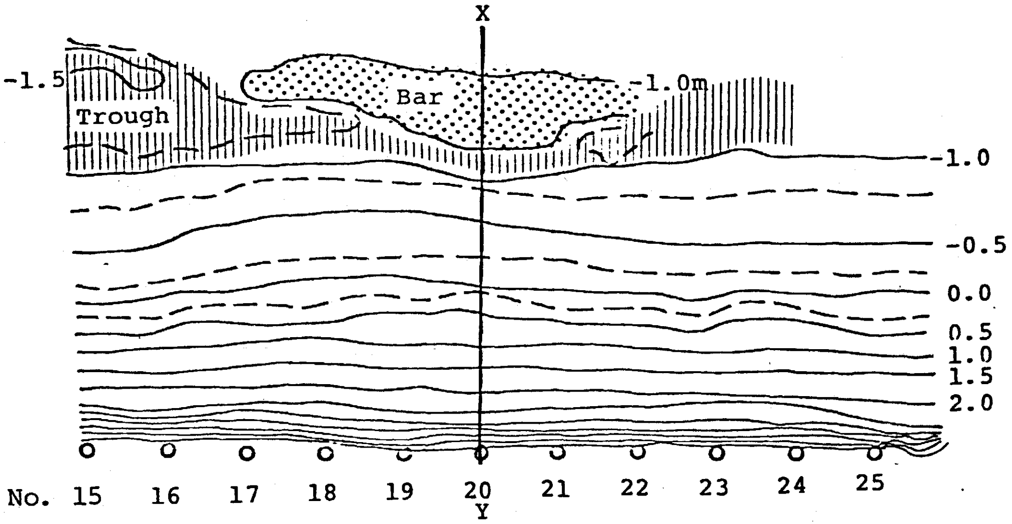


Fig. B-1 Wave conditions during the spring survey of 1978.
(by the construction work office of Kashima Port)



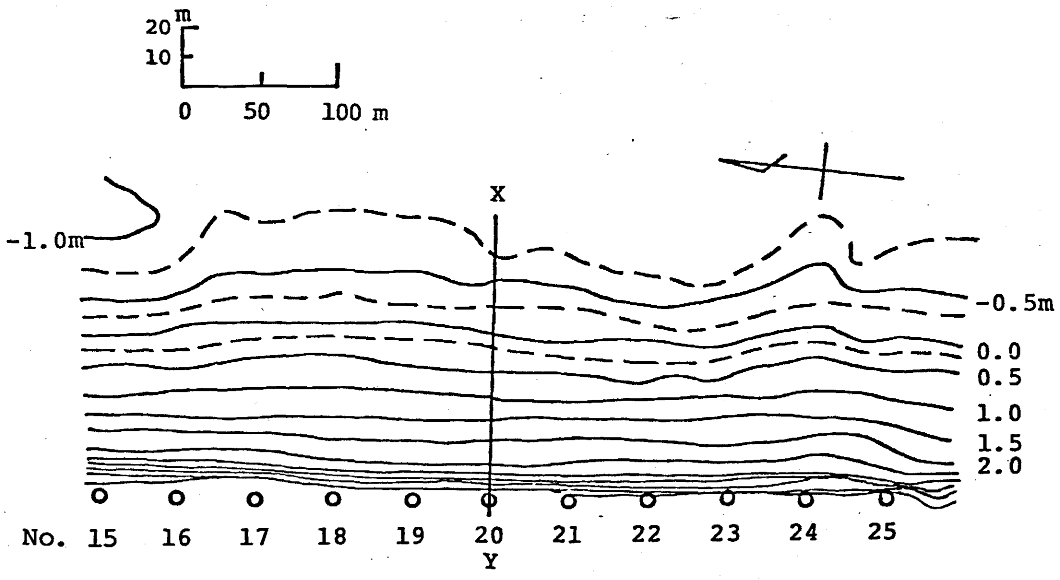
Apr. 7, 1978 (8:27-11:37)

Fig. B-2 Foreshore zone topography (Dainigorizawa).



Apr. 10, 1978 (8:45-12:11)

Fig. B-3 Foreshore zone topography (Dainigorizawa).



Apr. 14, 1978 (10:15-12:34)

Fig. B-4 Foreshore zone topography (Dainigorizawa).

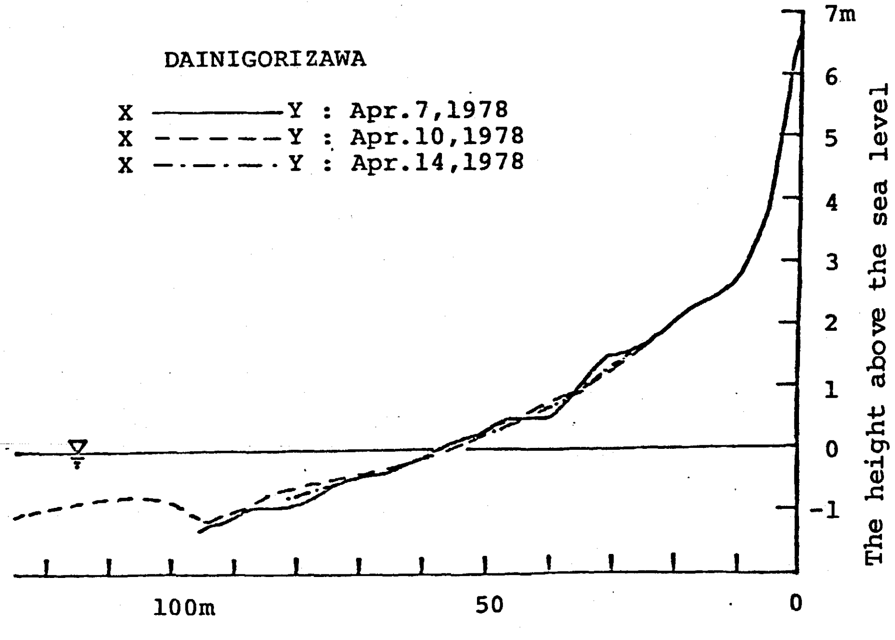


Fig. B-5 Changes in beach profile on the traverse No. 20 (Dainigorizawa, 1978).