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Geological Exploration of Beachrock through Geophysical Surveying on Yagaji Island, Okinawa, Japan

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This paper describes the knowledge obtained from a study of geophysical prospecting for beachrock. Previous studies on beachrock worldwide have been focused on the geochemistry. However, more knowledge of the chemical and physical properties is needed to elucidate the formation mechanism. In the present study, a direct current (DC) electrical survey and a surface seismic survey were conducted to detect the underground structure of the beachrock on Yagaji Island, Okinawa, Japan. This was a first attempt at conducting multiple geophysical surveys to investigate beachrock. In each survey, one survey line was set perpendicular to the seashore and two survey lines were set roughly parallel to the seashore. The results of each survey were observed in section of resistivity and seismic wave velocity. Furthermore, in order to estimate the effectiveness of the surveys, laboratory tests were conducted on the beachrock samples collected from the study site to measure the porosity, the resistivity, and the velocities of primary- (P-) waves and secondary- (S-) waves. There was a superior correlation between the sections and with the data on the study site. Hence, the features of the beachrock at the site are as follows: the resistivity is about 4–16 Ωm, the S-wave velocity is about 325 m/s, the thickness is about 1 m, and the thickness has a tendency to become greater toward the sea. One beachrock formation mechanism obtained by this study is close a currently accepted mechanism. [doi:10.2320/matertrans.M-M2013839]

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1. Introduction

Sea-level rise, which is said to be caused by global warming, causes coastal erosion around the world.[1,2] Concrete armor units are used as revetments for preventing coastal erosion, but this method has the disadvantage of damaging the environment and landscape. In addition, there is a continuing decline in the cost of Japanese public works projects, which means that new methods of bank protection should minimize the maintenance and operating costs of such projects. For the above reasons, the formation mechanism of beachrock is studied in order to develop a new method of bank protection that includes the ability to self-repair.

Beachrock is a sort of sedimentary bedrock that is formed from beach deposits and observed on seashores, mainly in tropical and subtropical regions[3,4] (Fig. 1). The cement materials of beachrock are mainly high-magnesium calcite and aragonite.[5,6] Table 1 lists the characteristics of beachrock according to the literature.[7–9] In general, bedrock forms over a long period of time, but it has been reported that the formation periods of some beachrocks were only a few decades.[7] In addition, it is assumed that if the formation period is longer, than the seismic wave velocities and the unconfined compressive strength are larger but the porosity and the permeability are smaller.[9] The most widely held theory of beachrock formation involves the deposition of $CaCO_3$ between coral sand and gravel by evaporation of seawater.[9–11]

There is much domestic and global literature on beachrock, but the majority of this concerns its geochemistry. In particular, its underground structure is not yet well understood. One of the few studies of this was by Psomiadis,[12] who used electrical resistivity tomography to map the beachrock on the island of Thassos, Greece. In spite of the general claim that comprehending the underground structure of beachrock is absolutely imperative to elucidating its formation mechanism, research has been restricted to areas near the surface at the seashore because of concerns about damaging the landscape with exploratory boring. In the present study, a DC electrical survey and a seismic surface-wave survey were conducted on Yagaji Island, Okinawa, Japan (Fig. 2). As a result of these surveys, a view of the structure around the seashore to a depth of more than 10 m was obtained. For clarity about the underground structure and solidification of the ground, an attempt was made to convert the resistivity sections into porosity sections by Archie's law. In order to estimate the effectiveness of surveys, laboratory tests were conducted to measure the resistivity, S-wave velocity, and porosity of the beachrock samples collected from the study site. The underground structure was estimated by making a comparison between the resistivity sections, the S-wave velocity sections, and the values measured in the laboratory tests. Furthermore, this paper addresses the effectiveness of using geophysical exploration to comprehend the underground structures of beachrock.

Table 1 Characteristics of beachrock according to the literature.

Sample	BR*1 (Maeda*2)	BR (Gima*3)	BR (KU*4)
Estimated age (yBP*5)	1250	2300	—
Saturated density (g/cm^3)	1.97	2.49	2.27
Porosity (%)	25.4	3.7	27
Unconfined compressive strength (MPa)	19.91	31.11	—
P-wave velocity (km/s)	3.69	4.07	2.29
S-wave velocity (km/s)	2.31	2.51	1.33
Dynamic Poisson ratio	0.178	0.193	0.245

*1BR: beachrock samples. *2Maeda: Maeda city in Okinawa.[9] *3Gima: Gima city in Okinawa.[9] *4KU: the study site. *5yBP: years before 1950.

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Fig. 1 Beachrock in Yagaji Island.

↓**This study**

Step 1 Geological surveying of beachrock by geophysical exploration

Step 2 Analysis of the formation process of beachrock

Step 3 Making a test piece of man-made beachrock
based on the formation process obtained from Step 2

Step 4 Practical scale experiment

Fig. 2 Flowchrat of entire study.

2. Study Site

Yagaji Island is one of the islands located in the northern part of Okinawa Prefecture, Japan. Okinawa Prefecture lies in the subtropical zone between the Pacific Ocean and the East China Sea. The study site is on the north coast of Yagaji Island and to the west of the Kouri Bridge (see Fig. 3(a)). The lower bedrock depths greater than about 10 m is old limestone and volcanic rocks, while the upper bedrock is composed of sand, shingle, and coral reef deposits[13] (Fig. 3(c)). Beachrock covered the site for about 100 m in the east-west direction and 10 m in the north-south direction. The inclination was about 3° towards the sea.[14] According to Omoto,[14] the sea level of this site has not changed in less than about 5000 years. The coastline shown in Fig. 3(a) represents the low water mark on the survey day, and the fluctuations in tidal level during the survey were within about 50 cm from the low water mark.

In each survey, two survey lines (A-line and B-line) were set horizontal to the seashore, while another survey line (C-line) was set perpendicular to the seashore (Figs. 3(a) and 3(b)). The lengths of the A-line, B-line, and C-line were 44.5, 89, and 15 m, respectively. The B-line was made the longest line to detect the underground structure in perspective. GPS determined the coordinates of the survey lines as listed in Table 2. The beachrock outcrop along the A-line and B-line extends for 27.3 m eastward from the western edge of the A-line and for 16 m eastward from 27 m east of the western edge of the B-line (Fig. 3(a)). Along the C-line, the beachrock extends from the land edge to 7.25 m seaward. In addition, there is beachrock interspersed above the B-line.

3. Methods

The sections of resistivity and S-wave velocity were obtained from a DC electrical survey and a seismic surface-wave survey that were conducted in the field. Additionally,

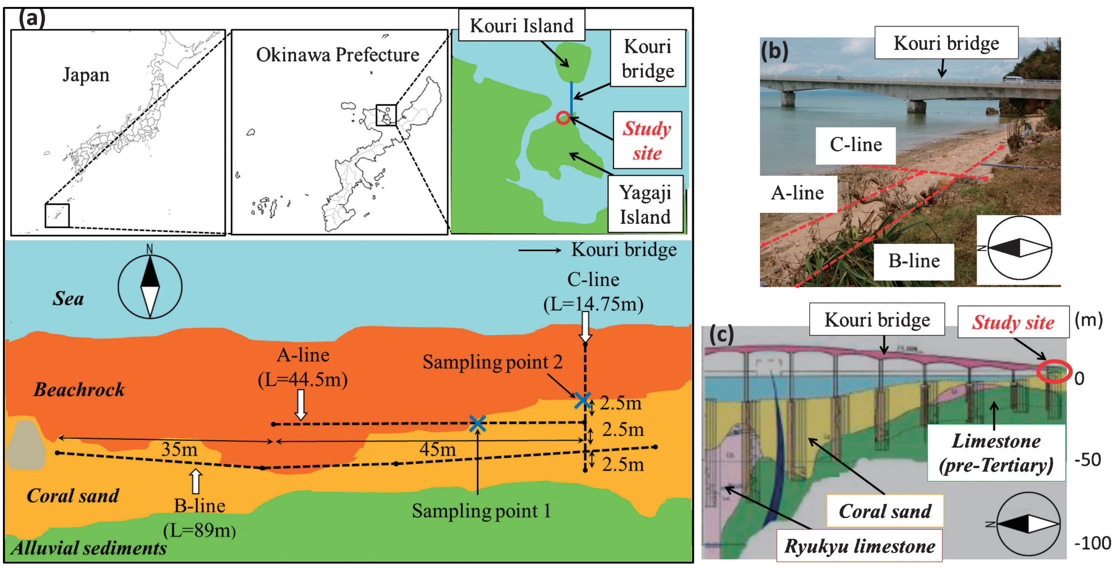

Fig. 3 (a), (b) Study area and survey lines, (c) Geological section along the Kouri Bridge near the study site.[13]

Table 2 Coordinates of survey lines.

	A-line	B-line	C-line
GPS	(26°40.44′N, 128°00.42′E)–(26°40.48′N, 127°59.57′E)	(26°40.43′N, 128°00.40′E)–(26°41.25′N, 128°00.56′E)	(26°40.56′N, 127°59.09′E)–(26°40.53′N, 127°59.03′E)
<Electrical survey>			
Electrode interval	1.0 m	0.5 m	0.25 m
Line length	44.5 m	89 m	14.75 m
<Surface wave survey>			
Shot point interval	1.0 m	2.0 m	0.5 m
Line length	45 m	90 m	17 m

laboratory tests were conducted to examine the influences of saturation on the resistivity, S-wave velocity, and P-wave velocity of the beachrock samples collected from the study site (Fig. 3(a)).

3.1 Field tests

3.1.1 DC electrical survey

Archie[15] showed correlations among the rock resistivity, the pore water resistivity, the porosity, and the degree of saturation. Subsequently, many researchers have advanced this research into the relationship between the electrical resistivity and the other physical characteristics of rocks.[16,17)]

Archie's law states

$$\rho_R = a \cdot \varphi^{-m} \cdot S^{-n} \cdot \rho_W$$

where ρ_R is the rock resistivity, φ is the porosity, S is the saturation, ρ_W is the pore water resistivity, and a, m, and n are constants that depend on the rock type. In this law, there is a negative correlation between the rock resistivity and the degree of saturation, and there is a relationship between the rock resistivity and the pore water resistivity. The rock resistivity increases as the degree of saturation decreases or the pore water resistivity increases. Furthermore, the resistivity section obtained through a DC electrical survey can be converted into sections of other physical properties, if each physical property is replaced using Archie's law.[18] For these properties, a DC electrical survey is used to determine lateral and vertical variations in the conductivity of the ground by measuring differences in electrical potential.[19,20] The exploration depth is influenced by the distance between the electrodes.

In this survey, spikes were used as electrodes (about 5 mm in diameter and 15 cm in length). The spikes were driven in with a hammer to a depth of about 4 cm in the sand and about 1 cm in the beachrock. There were 90 electrodes at 0.5 m intervals along the A-line, 90 electrodes at 0.5 m intervals along the B-line, and 60 electrodes at 0.25 m intervals along the C-line as given in Table 2. The intervals along the C-line were set shorter to detect the thickness of the beachrock. The alternating direct current (period 0.4 s) was carried at 200 or 350 mA with fourfold stacking by means of the Wenner and Eltran arrays. The resistivity sections were derived from the measured data using the 2D inversion technique. This method involves numerical calculation of the electric field and constrained smoothing by a non linear least-squares method.[21,22]

3.1.2 Seismic surface-wave survey

The surface-wave velocity was measured by multi-channel analysis of surface wave (MASW) methods and converted analytically into the S-wave velocity section for comparison with the results of the laboratory tests. The velocities elastic waves have been widely used for ground exploration in the fields of civil engineering and construction. This is especially true of the S-wave velocity, which has a recognized close relationship with the physicomechanical properties of rocks.[23] In general, the harder the rocks, the higher the wave velocity. S-wave velocities are affected by the strength and pore structure of rock, meaning that the wave field is correlated with the geological structure of the rock through which S-waves propagate. The exploration depth is determined by the frequency of the surface waves.

In this survey, at most 24 geophones (4.5 Hz) were deployed along each line at 1.0 m intervals. The multiple geophones used (Shinki Land Streamer Cable; OYO Corp., Japan) were attached to 24 spindles at 1 m intervals on a cloth belt to increase the working efficiency through high mobility. The source point is located 2.0 m from the rear geophone in the direction against the movement. The instrumentation was shifted every 1.0, 2.0, and 0.5 m along each line, respectively, with end-on spread (Table 2). The ends of the survey lines were measured by shifting only the source point. Assuming that the study site is a horizontal multilayer, the dispersion curves of the phase velocity obtained in this survey were analyzed by the 1D inversion technique (SeismicImager/SW; OYO Corp., Japan).[24] The intervals of the inversion points were 2.0, 2.0, and 1.0 m on each line, respectively.

3.2 Laboratory tests

For laboratory tests, beachrock samples were gathered at two points: one about 27 m east from the western edge of the A-line (Sample 1), and the other where the C-line meets the south edge of the beachrock outcrop (Sample 2). The samples brought to the laboratory were trimmed into rectangular parallelepipeds with a rock-cutting machine (Fig. 4). Sample 1 was 2.7 cm × 2.4 cm × 5.8 cm and Sample 2 was 3.8 cm × 3.2 cm × 4.6 cm.

First, the specimens were soaked in artificial sea water (Aquamarin: Yashima Pure Chemicals Co., Japan) for 24 h in a vacuum. Then, the specimens were tested for changes in resistivity, P-wave velocity, S-wave velocity and mass during a natural evaporation at room temperature (25°C). Once the

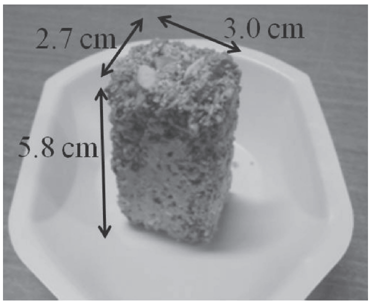

Fig. 4 Beachrock sample 1.

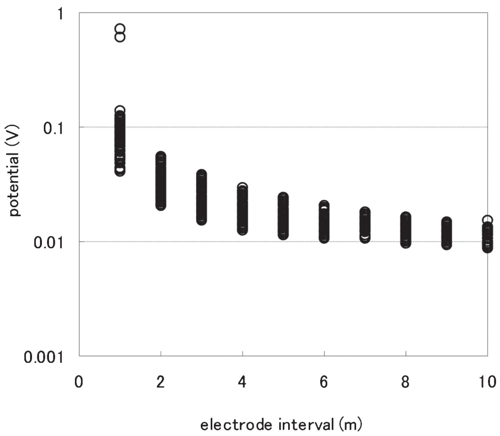

Fig. 5 Relationship between the electrode interval and the potential on B-line.

evaporation process slowed down, these tests were continued while the specimens were heated to and held at 40°C in a constant-temperature drying oven. Finally, tests were carried out with the specimen heated to 110°C for 24 h. Three times at each water content, the saturated density of the specimen was measured by the "Test Method for Bulk Density of Rock"[25] and the resistivity was measured with a resistivity meter (miniOHM; OYO Corp., Japan). In measuring resistivity, the specimens were placed between two sets of electrodes: one set consisted of two electrodes that were less than 0.5 mm thick, and the other set consisted of two sheets of filter paper soaked in the artificial seawater. Twice at each water content, the P- and S-wave velocities were measured (SonicViewer-SX; OYO Corp., Japan).

4. Results

4.1 Field tests

First, the reliability and reproducibility of the results of the DC electrical survey are discussed. Figure 5 shows the relationship between the electrode interval and the potential on the B-line. The longest electrode interval was 10 m and its potential was 0.01 V, but the results of the DC electrical survey are reliable because the resolution of the exploratory devices is about 0.001 mV in the absence of noise. Furthermore, the results are reproducible, because the standard deviation is less than 1% in the case of the longest electrode interval. The reliability and reproducibility of the results hold for surveys conducted on A-line and C-line.

Figures 6(a1), 6(b1), and 6(c1) show the velocity sections along each survey line, while Figs. 6(a2), 6(b2), and 6(c2) show the resistivity sections along each survey line. The results of the two surveys essentially show that the study site has three areas vertically between the surface and 15 m in depth. As shown below, these areas were tentatively identified as the beachrock, the sand layer, and the bedrock, in order from the surface.

The near-surface areas (less than about 1 m from the surface) include the highest velocity areas (more than 325 m/s) at about 2–40 m on the A-line (Fig. 6(a1)), 30–47 and 88–90 m on the B-line (Fig. 6(b1)), and 12–14 m on C-line (Fig. 6(c1)) and include the highest resistivity areas (more than 4.0 Ωm) at about 0–32 and 39–43 m on the A-line (Fig. 6(a2)), 38–42 and 62–88 m on the B-line (Fig. 6(b2)), and 0–15 m on the C-line (Fig. 6(c2)). Furthermore, the observed beachrock outcrops coincide relatively well with the high resistivity areas and the high velocity areas (Figs. 3 and 6). Hence, it is considered that the two surveys detected the beachrock outcrop at the study site and revealed that this beachrock was not solidified horizontally against the coastline. Moreover, it is very likely that the surveys detected the buried beachrock. The examples seen are the surface areas at about 27–44.5 and 43–89 m on the A-line and the B-line, respectively. On the C-line, there is the area of higher resistivity (more than 4.0 Ωm) in the range 0–3 m, even though the beachrock outcrop (Fig. 6(c2)) is not observed. This is due to the drying of sand by evaporation.

The areas deeper than the near-surface areas on both, A-line and C-line are also the areas lower in resistivity (less than 4.0 Ωm) and the areas lower in velocity (less than 250 m/s). In spite of there being no higher area at a depth of about 1–5 m under the observed beachrock outcrop on the A-line set near the B-line, there is a higher resistivity area at the same depth on the B-line (Fig. 6(b2)). This can be attributed to the effect of bedrock because B-line has a deeper detecting depth than A-line. Comparison with the other results indicated that a higher resistivity area does not exist at a depth of about 1–5 m under the observed beachrock outcrop on the B-line. Comparison with the geological map of this site leads to the probablility that these areas of lower resistivity and velocity indicate unconsolidated sand saturated with sea water (Fig. 3(c)).

Additionally, in the much deeper areas (more than 5 m from the surface), the resistivity and velocity tend to increase, while the porosity tends to decrease. These tendencies are assumed to constitute a detection of the bedrock and roughly agree with the results of the geological surveyor that explored the site for the construction of the Kouri Bridge[13] (Fig. 3(c)).

Based on the above, it is deduced that the two surveys detected the beachrock, the unconsolidated area, and the bedrock. Likewise, it is deduced that the beachrock at the study site has a thickness of about 1 m, surface-wave velocity of about 325 m/s, and resistivity of about 4–16 Ωm.

4.2 Laboratory tests

Table 3 lists the dry density, wet density, and porosity of each specimen. The results of the experiment are shown in Fig. 7, which indicates the relationship among the saturation, P-wave velocity and S-wave velocity, and electrical resis-

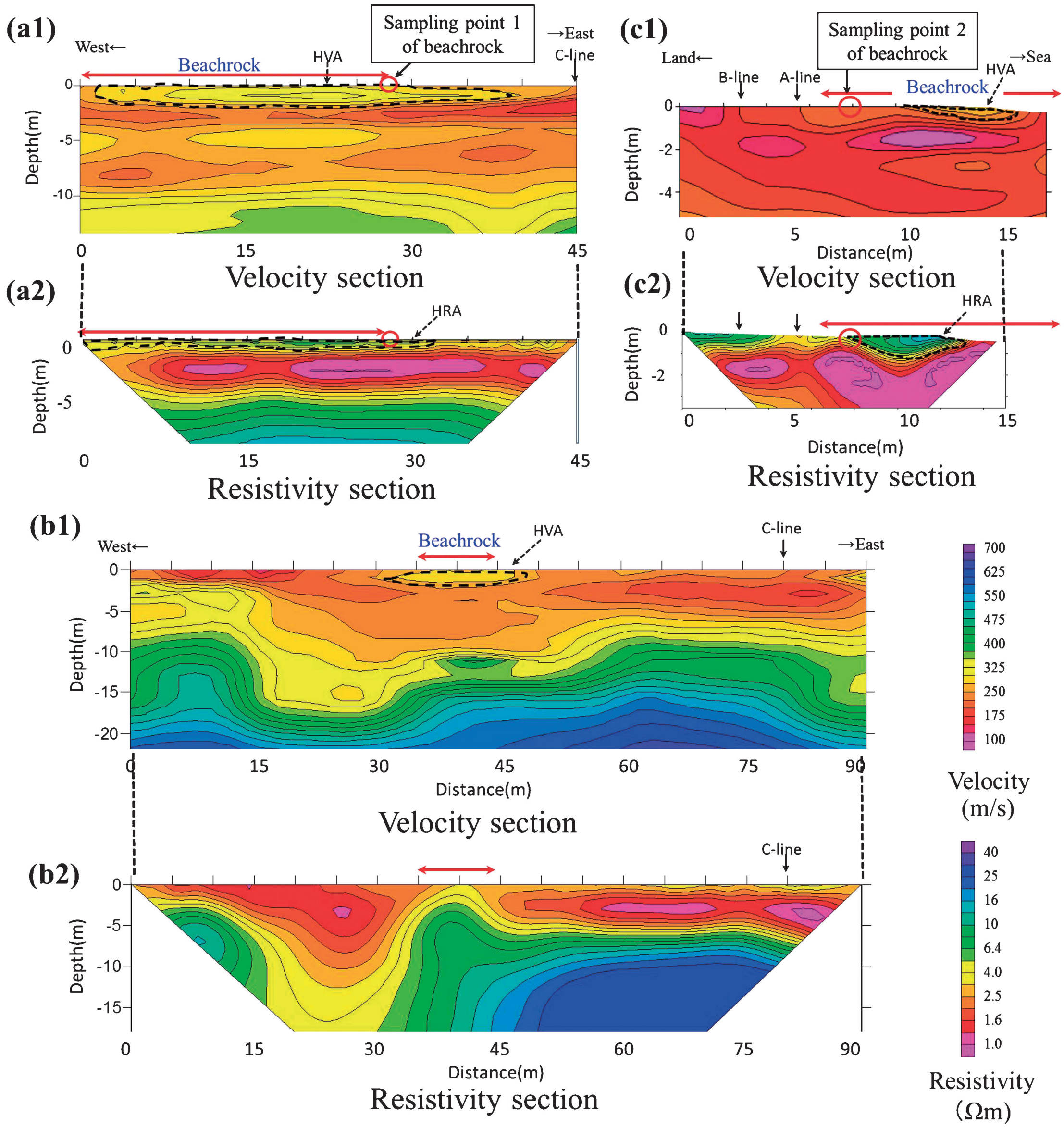

Fig. 6 Results of surveys. (a1) S-wave velocity section of A-line, (a2) Resistivity section of A-line, (b1) S-wave velocity section of B-line, (b2) Resistivity section of B-line, (c1) S-wave velocity section of C-line, (c2) Resistivity section of C-line. HVA: high velocity area. HRA: high resistivity area.

Table 3 Results of physical measurements of beachrock samples.

	Dry density (g/cm^3)	Wet density (g/cm^3)	Porosity (%)
Sample 1	2.0	2.3	27.4
Sample 2	2.0	2.3	28.3

tivity. Figures 7(a1) and 7(b1) show the results for Sample 1, while Figs. 7(a2) and 7(b2) show the results for Sample 2. It was found that the electrical conductivity and specific gravity of the solution saturating the specimens were 5.85 S/m and 1.02 g/cm^3, respectively. The S-wave velocity and P-wave velocity of Sample 1 were about 1.1–1.5 km/s (average 1.3 km/s) and 2.0–2.6 km/s (average 2.3 km/s), respectively (Fig. 7(a1)), and those of Sample 2 were about 1.0–1.6 km/s (average 1.2 km/s) and 1.8–2.6 km/s (average 2.2 km/s), respectively (Fig. 7(a2)). There is a large difference of about 1.0 km/s between the S-wave velocity assumed for detecting the beachrock in the field and that measured in the laboratory tests. The electrical resistivity was about 5.0 Ωm at 100% saturation and increased drastically when the saturation was less than about 20% (Figs. 7(b1) and 7(b2)). The resistivity at the sampling points that corresponded to rock saturated with seawater was about 6.4 Ωm (Figs. 6(a1) and 6(c1)). The resistivity agreed roughly with the results of laboratory tests when the saturation was greater than 20% (Figs. 7(b1) and 7(b2)). The relationship between the saturation and electrical resistivity of rock can be approximated by a log–log linear regression if the electrical resistivity obeys Archie's law.[15] However, compliance with the linear relationships was confined to saturations less than about 20% in this test.

5. Discussion

5.1 Characteristics of the beachrock at the study site

First, a comparison is made between the characteristics of beachrock obtained from the present surveys and those of

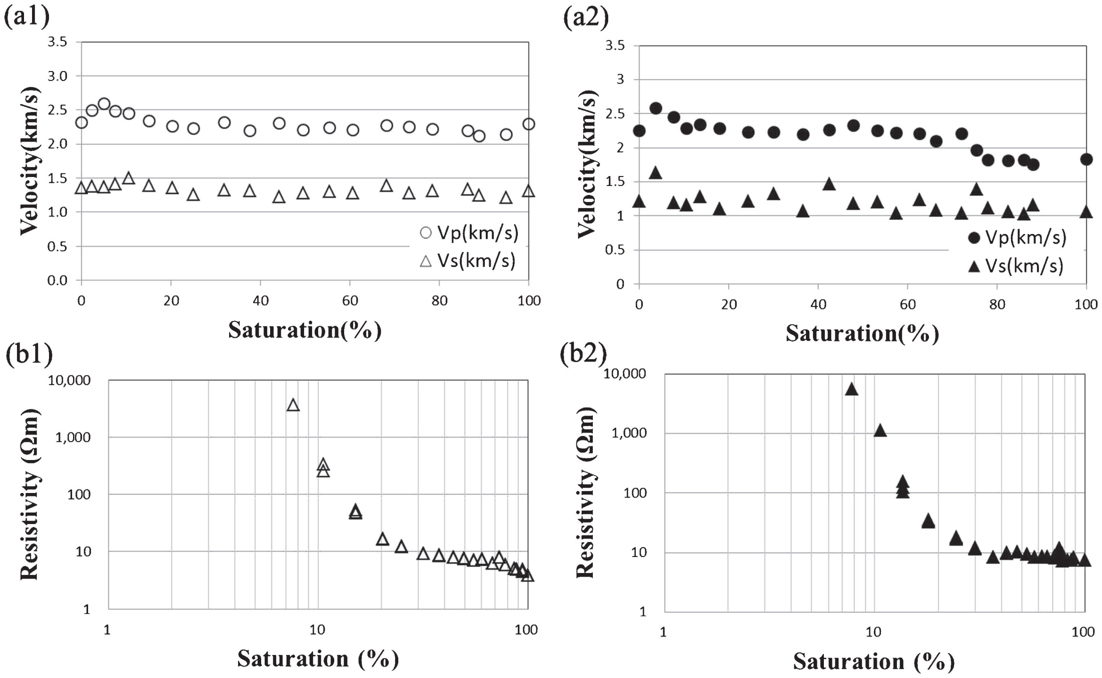

Fig. 7 Results of laboratory tests. (a1), (a2) Relationship between saturation and and seismic velocity. "Vp" and "Vs" indicate P and S wave velocity. (b1), (b2) Relationship between saturation and specific resistivity.

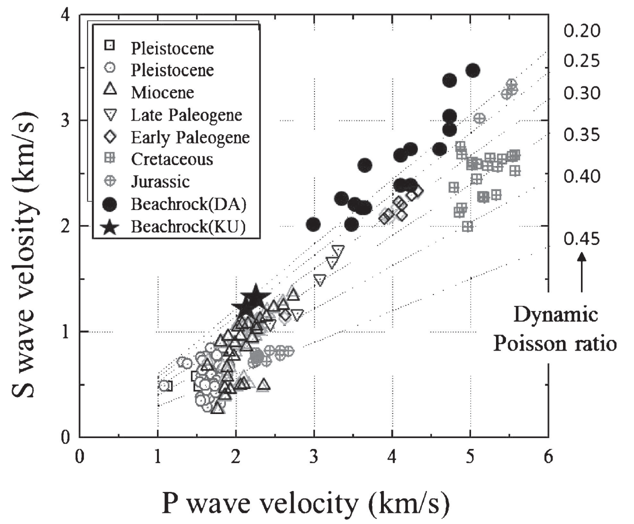

Fig. 8 Comparison of the geophysical properties of the sedimentary rocks and the beachrock. (a) The relationship between P wave velocity and S wave velocity for sedimentary rocks.[26] Beachrock (DA) is the beachrock studied by Danjo *et al.*,[9] shown in Table 1, and Beachrock (KU) is the beachrock examined in this study.

beachrock at other sites. The resistivity of the beachrock on the island of Thassos, Greece, is about 2–15 Ωm according to Psomiadis,[12] whereas that on Yagaji island, Japan, is about 4–16 Ωm (Fig. 6). The thickness of the beachrock is about 1 m at either study site.

There is a common theory[9] that if the formation period of beachrock is longer, then its solidification will be more progressed, but this does not hold for the beachrock samples from the study site. Figure 8 shows a comparison of the geophysical properties of sedimentary rocks[26] and beachrock.[9] The tendency of the P- and S-wave velocities of the beachrock at the study site was close to that of Miocene rocks (from 23 to 5.3 Ma ago), whereas that of the beachrock studied by Danjo *et al.*[9] was close to that of Early Paleogene rocks (from 65.5 to 55.8 Ma ago) and Jurassic rocks (from 201 to 145 Ma ago). This implies that the beachrock at the study site is newer than the other beachrock and thus is not as solidified. However, based on carbon-14 dating,[14,27,28] the formation of the beachrock at the site began about 1800–2200 yr ago and that of the beachrock studied by Danjo *et al.*[9] began about 800–2000 yr ago. Hence, the formation period of the beachrock at the study site is longer than that of the other beachrock. Presumably, the reason that the solidification of the beachrock at the study site is not in proportion to the formation period is associated with the composition and the cement material.

Next, the results of the present surveys are compared with the existing opinion on the formation mechanism of beachrock. In this survey, beachrock was not found in areas that were always saturated by seawater under the mean low water or in areas that were not always saturated by seawater over the mean high water (Fig. 9). Meanwhile, it is widely accepted that beachrock exists in or on the sand layer and becomes solidified by repeated immersion in sea water and evaporation of pore water.[9–11] Kawakami *et al.* and Kubo reported that sands were solidified by repeated immersion and evaporation of artificial seawater.[29,30] The reason why the results of this study support that opinion is as follows.

The reason that the immersion in seawater is important for the solidification of beachrock is as follows. Comparing the resistivity sections of the survey lines, the higher resistivity areas of the beachrock seem larger to the seaward side (the north side). The resistivity of the surface area that reveals the beachrock outcrop in the range 0–27 m on the A-line (nearer the sea than the B-line) is higher than that of its counterpart on the B-line, a result determined by comparing the resistivity sections of the A-line with those of the B-line

(Figs. 6(a2) and 6(b2)). This tendency is the same as that on the C-line, except for the unsaturated area in the range of about 0–5 m (Fig. 6(c2)). In particular, the area of higher resistivity (more than 16 Ωm) is about 10–15 m seaward on the C-line. Hence, it is deduced that the harder beachrock underwent the more ample immersion in seawater.

The reason that the evaporation of pore water is important for the solidification of beachrock in addition to the immersion in seawater is as follows. There is no beachrock in the areas always saturated by sea water. From the results of each survey, the sandy areas on the bedrock are assumed to be saturated and not to solidify (Fig. 6), because there is seawater within these areas regardless of the rise and fall of the tides.[31,32] Hence, it is deduced that the harder beachrock underwent the more ample evaporation of pore water. Therefore, it is highly probable that repeated immersion in sea water and evaporation of pore water is important to solidify the sand.

5.2 Conversion into porosity sections

The porosity of rock is considered an important indicator of the solidification. Making porosity sections, is thus helpful for understanding the solidity distribution of ground. In this study, the resistivity section obtained from a DC electrical survey was converted into a porosity sections by using Archie's law[18] because it was assumed that this law was established when the pores of the beachrock samples became more than about 80% saturated by seawater as mentioned in Section 4. For this conversion, each parameter was selected as follows: $S = 1.0$, $\rho_W = 0.3$, $a = 1.0$, and $m = 1.35$. These values were determined by the widely known standard values for sandstone[33] and assumption that the survey site was almost fully saturated with seawater. In addition, laboratory tests revealed that the beachrock's resistivity remained almost unchanged when the pores of the beachrock samples became more than about 80% saturated by seawater (Figs. 7(b1), 7(b2)). Furthermore, the porosity at the sampling points was found to agree roughly with the results of the laboratory tests. Figure 10 shows the porosity sections along each survey line. From these sections, it is deduced that the porosity of bedrock at depths greater than about 10–15 m is less than 10% and that of the unconsolidated sand is more than 20%.

The reason that the linear relationship between the saturation and specific resistivity of rock was confined to saturations less than about 20% in the test (Fig. 3(b)) is presumably that the interior of the specimen never became unsaturated and homogenous during the natural evaporation at room temperature (25°C). That is, an electrical conduct in the form of a saturated column apparently persisted inside the specimen until less than about 20% saturation was reached.

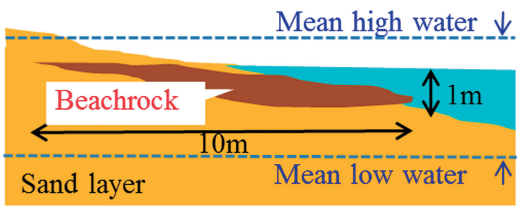

Fig. 9 Cross section of beachrock.

5.3 Applying geophysical surveys to geological exploration of beachrock

In this study, the velocity sections coincide relatively well with the resistivity sections, in spite of each survey measuring a completely different physical property. The time taken for the work on the A-line and the B-line was about 3 h and the surveys on the C-line were shorter than the others. Given these times, the two surveys in this study are reasonable in terms of the working hours expended. Furthermore, there is every possibility of detecting buried beachrock.

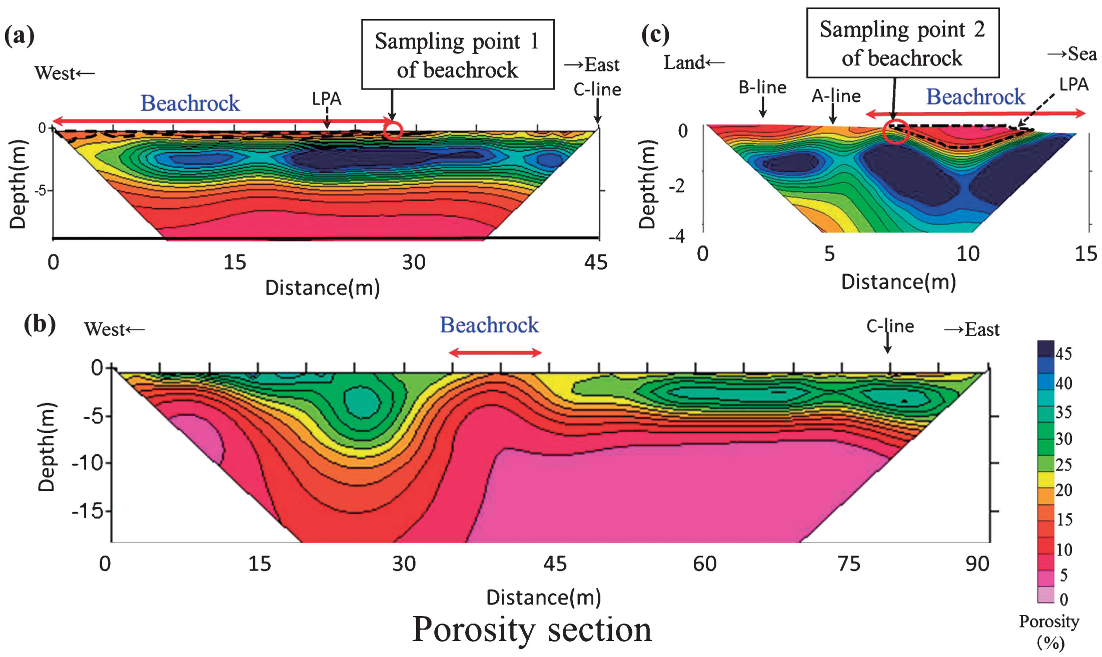

Fig. 10 Porosity sections. (a) Porosity section of A-line, (b) Porosity section of B-line, (c) Porosity section of C-line. LPA: low porosity area.

Table 4 Features of each survey.

	Surface seismic survey	DC electrical survey
Advantage	The effect of pore water is insignificant.	The workload is low during measurements.
Disadvantage	The workload is high during measurements: transfer geophones, oscillation by hammer.	The effect of pore water is significant.
Features if applied to beachrock	The problems to be solved are the detection of higher velocity areas and improvements to the resolution.	Setting electrodes is easy. The problem yet to be solved is improvement of the resolution.

Some future tasks are proposed for both surveys. In the case of the seismic surface-wave survey of the beachrock, there was a great difference between the S-wave velocity in the laboratory tests (about 1.3 km/s) and the S-wave velocity that had been assumed for detecting the beachrock in the field (about 0.3 km/s). The cause of this discrepancy is presumably that the area of highest frequency (highest velocity) along the survey line could not be detected, because the high frequencies had been attenuated by putting all the geophones on the beachrock. As a countermeasure, it is proposed that the sensitive geophones be placed into holes made in the ground. Moreover, in the case of either survey, there is a desire to adjust the interval between the electrodes or geophones. For example, in a DC electrical survey of beachrock that is about 1 m thick, such as that at the study site, it is necessary to shorten the interval between electrodes to less than 0.25 m. This is because it was possible to observe the distribution of resistivity within the area of high resistivity (more than 16 Ωm) only along the C-line, where the interval between electrodes was 0.25 m (Fig. 6(c1)).

Finally, the opportunity for exploratory boring is limited, because the surroundings of beachrock are often a tourist spot. It seems that geophysical prospecting, in which underground structures are surveyed without damaging the landscape can be an extremely effective way to study the distribution of beachrock. To give an overall impression of geophysical surveying applied to geological exploration of beachrock, Table 4 summarizes the advantages, disadvantages, and features of each surveying method as gained through this investigation into beachrock.

6. Conclusion

The features of the beachrock at the study site and the effectiveness of using geophysical surveys to comprehend the underground structures of beachrock are as follows:

(1) The resistivity of the beachrock at the study site was about 4–16 Ωm and the S-wave velocity was about 325 m/s. The thickness was about 1.0 m and had a tendency to become greater toward the sea. It is highly probable that repeated immersion of the sand in seawater, resulting in repeated evaporation of the pore water, is important to solidify the sand.

(2) There was a good correlation between the results from the DC electrical survey and the seismic surface wave survey. These two surveys detected the buried beachrock over a wide area without damaging the landscape of the study site. In addition, understanding the solidity distribution of the ground was facilitated by converting the results of the DC electrical survey into the porosity sections. It seems that geophysical prospecting is an extremely effective way to study the distribution of beachrock.

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