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Development of a Fiber-Optic Cable Monitoring System for Storm-Generated Bathymetric Change in the Surf Zone

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A monitoring system, called the optic sediment sensor (OSS), for study of the detailed processes of bathymetric changes in the surf zone has been developed. The OSS system consists of an array of fiber gap sensors (FGSs), a support structure (steel pipes), an electronics unit that transmits and receives light through fiber-optic cables, and a data acquisition system. The FGSs are mounted in a 2-m long vertical steel pipe; the sensor spacing is 10 cm. Steel pipes containing FGSs were embedded in the seafloor at two places at water depths of 4–5 m beneath a pier at the Hazaki Oceanographical Research Station (HORS) (Port and

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Airport Research Institute) on the Sudahama Coast, facing the Pacific Ocean, Japan. The electronics unit and the data acquisition system were installed in an observation room on the pier. The OSS systems successfully recorded well-defined and consecutive bathymetric changes caused by storm waves (maximum significant wave-height = 3 m); e.g. reversal of seabed erosion and deposition within a day could be recognized. If the OSS system could be installed in many more locations along the pier, the consecutive process of the formation, migration, and deformation of the whole of the longshore bar may be clarified.

Keywords: Optic sediment sensor; bathymetric change; monitoring; high-energy surf zone.

1. Introduction

Development of a monitoring system that can record the detailed processes of bathymetric change and sediment transport is necessary for progress in studies of nearshore morphodynamics, modern sedimentary processes, and coastal engineering works. In general, bathymetric changes and related sediment transport are studied on the basis of survey results obtained before and after an event such as a storm or tsunami [e.g. Yoshikawa and Nemoto, 2010, 2014; Goto *et al.*, 2011]. This method, however, cannot be used to clarify the timing, volume, and manner of sediment migration during a single event. Several devices have been created for continuous monitoring of nearshore features and sediment transport in the nearshore zone. For example, Traykovski *et al.* [1999] observed continuous morphological changes in wave orbital ripples for six weeks at a water depth of 11 m using an autonomous rotary side-scan sonar system mounted on a tripod. To estimate the suspended sediment concentration in the swash zone, optical backscatter sensors (OBS) have been developed [Downing *et al.*, 1981]. Masselink *et al.* [2007] investigated the dynamics of wave ripples using multiple sensors including a sand ripple profiler and OBS. Those systems provide very high-resolution data on morphological change and sediment transport, but are unsuitable for investigation of large-scale sediment erosion and deposition that produces a longshore bar generated by high-energy waves in the surf zone. If the change in water depth is large (e.g. more than 1 m) over a short time interval, the monitoring system will be destroyed, lost, or submerged. Once the monitoring system is buried below the seafloor, it cannot be used to observe bathymetric changes and sediment transport.

In this study, a new instrument containing plastic fiber-optic cables, which can be mainly used to monitor bathymetric changes in the high-energy shallow marine environment has been developed. Field testing was conducted at the Hazaki Oceanographical Research Station (HORS) (Fig. 1) owned by the Port and Airport Research Institute (PARI) on the Sudahama Coast, facing the Pacific Ocean, Japan. This area is suitable for our research objectives because active sediment transport that creates and deforms the longshore bar has been observed [e.g. Kuriyama, 2002; Kuriyama *et al.*, 2006].

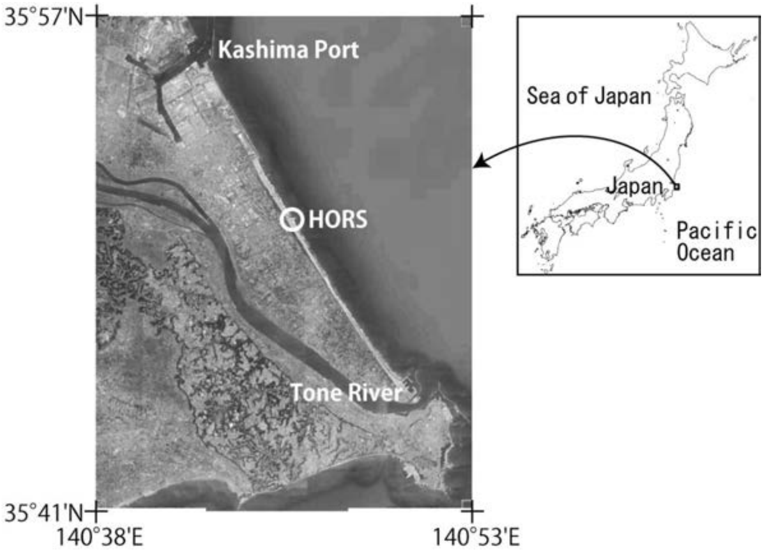

Fig. 1. Location of the study area. The newly developed monitoring system for research on storm-generated bathymetric change and sediment transport was placed at the Hazaki Oceanographical Research Station (HORS; http://www.pari.go.jp/en/about/facilities/hors.html) owned by the PARI on the Sudahama Coast, central Japan. The aerial photograph is a Google Earth image taken on 29 March 2012.

2. Instruments, Methods, and Study Site

2.1. *Concept of the sensing technique using light*

The backscatter intensity is important for observations of sediment transport and concentration in water using light [e.g. Downing *et al.*, 1981; Beach *et al.*, 1992; Foster *et al.*, 2000]. Herein, this method of detecting the backscatter intensity is called the twin fiber method (Fig. 2). Use of the method for detection of local migration of sandy particles has been established in laboratory experiments [Akutagawa *et al.*, 2014]. The equipment consists of two plastic fiber-optic cables with a diameter of 1 mm (Fig. 2). The first cable (Fiber-1) is used to supply light to the point of observation; the other cable (Fiber-2) collects light reflected back from surfaces of nearby particles and carries it back to a photosensor. Therefore, the area of observation at the tips of the fibers is on the scale of millimeters [Akutagawa *et al.*, 2014].

In this study, a gap between two fiber cables aligned in a straight line is used to measure the attenuation of light intensity. In this way, a fiber gap sensor (FGS) is formed (shown in Fig. 2 as the "gap method.") The concept of the sensing technique is illustrated in Fig. 3. The light intensity at the emitting and receiving sides are denoted as L_E and L_R, respectively. As the light from the emitting side is scattered at a wide angle, L_R is generally smaller than L_E. When the gap is fully in seawater, L_R remains stable at a certain level. If suspended sediment particles enter the gap,

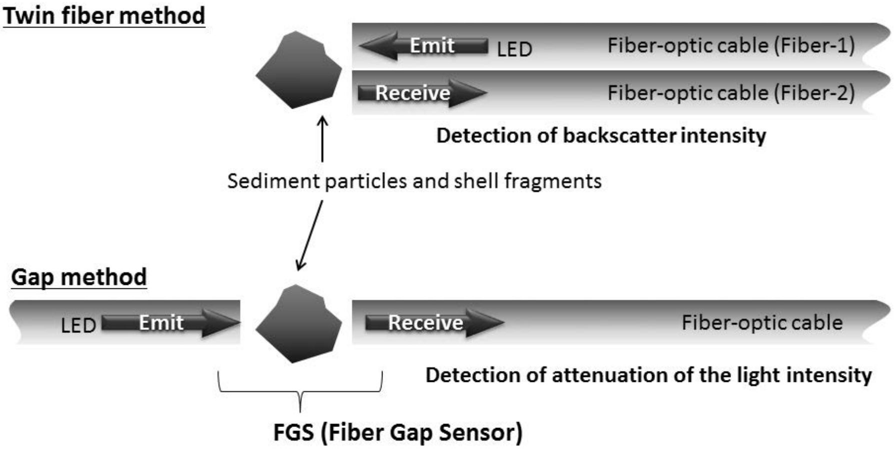

Fig. 2. Diagram showing the sensor created using fiber-optic cables and an LED.

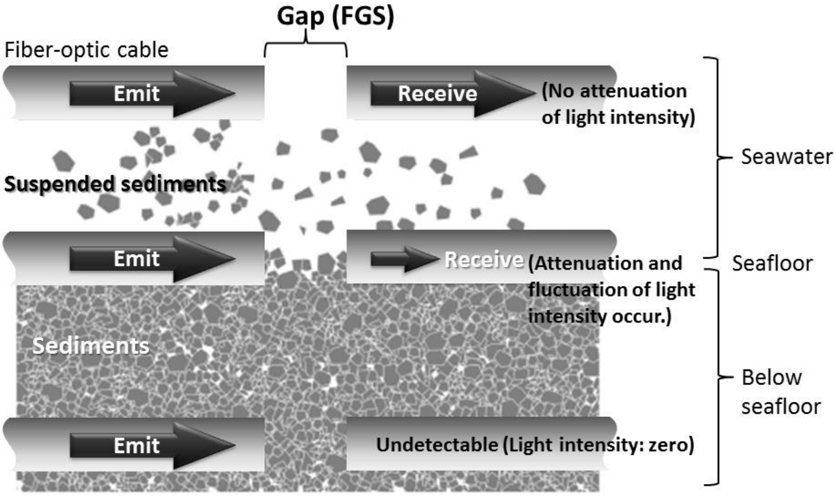

Fig. 3. Diagram illustrating the sensing technique using the gap method.

L_R is affected by the movement of those particles and its value is altered randomly. When the gap is completely filled by sediments below the seafloor, L_R becomes almost zero. Therefore, by monitoring fluctuations in L_R, it is possible to determine the location of the seafloor at any given time. In a strict sense, L_R is affected not only by L_E and the presence of sediment in the gap, but also by sunlight. However, it is demonstrated later that this effect is negligible in this study.

2.2. *OSS system configuration*

The newly developed device, called the optic sediment sensor (OSS) system, consists of four main components: An FGS array formed as a unit assembly with a 10-mm

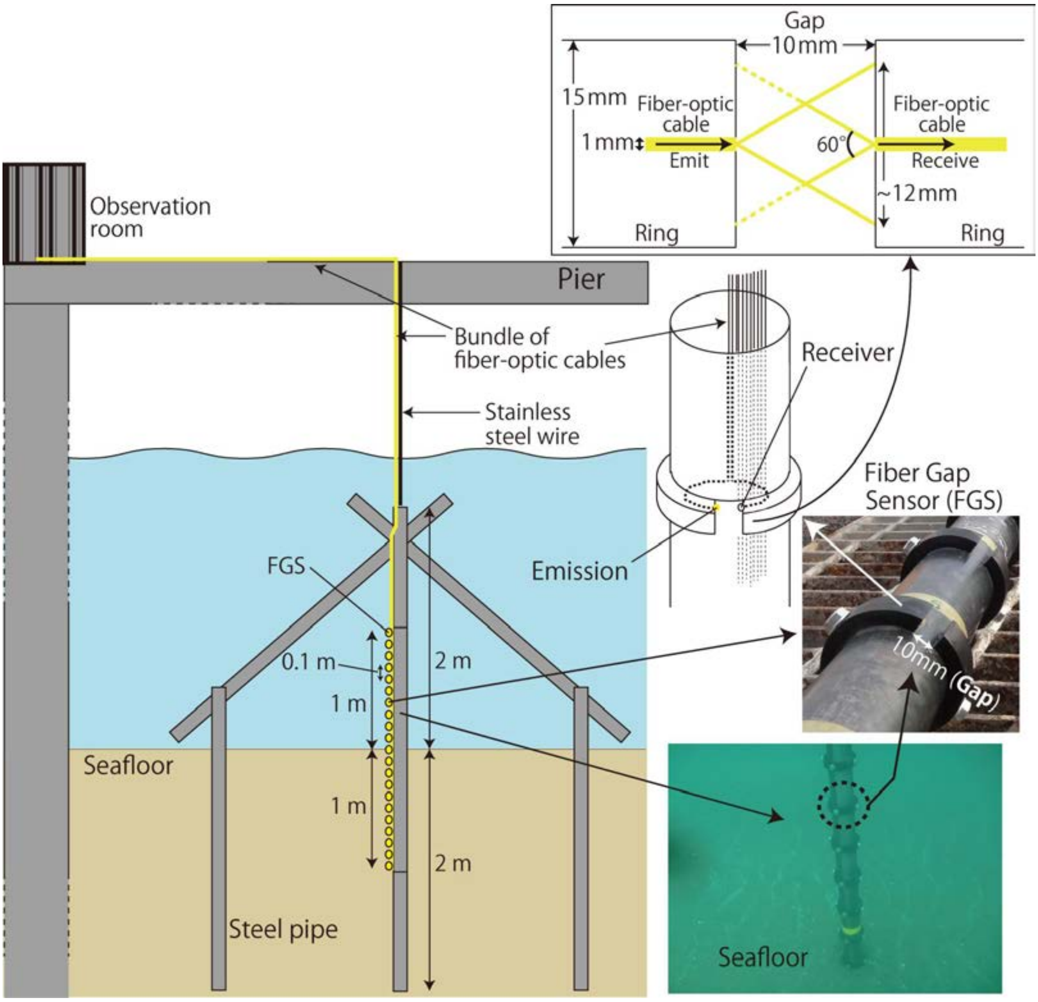

Fig. 4. Illustrations and photographs of the undersea system of the monitoring device. The diffusion and reception of light by the fiber-optic cables within the gap is also illustrated at the top of the figure.

gap between the emitting and receiving sides of fiber-optic cables supported in a ring made of polyoxymethylene (Fig. 4); a support structure (steel pipes); an electronics unit that transmits light from the LED (OSM5XNE1E1S, http://www.optosupply.com/EN/search.asp; Opto Supply Ltd.) and receives returning light through the fiber-optic cables (PGS-CD1002-22-E, http://www.toray.co.jp/english/electronic/index.html; TORAY Industries, Inc.); and a data acquisition system. The diameter of the steel pipe that composes the FGS array is 48.6 mm. A schematic representation of the undersea OSS system is illustrated in Fig. 4.

The gap spacing of the FGS was decided upon based on the following reasoning: (1) shell fragments and some gravels would probably be easily caught in the gap if the spacing was less than 10 mm; (2) the desire to avoid the diffusion of the light (described below), and (3) the light intensity (L_R) becomes high as the distance between the emitting and receiving sides decreases. In the present system, the effect of inter-channel (FGS) interference on the light intensity (L_R) is thought to be small because of the range of the acceptance angle (maximum 60°) and numerical aperture (0.5) of the present fiber cable, the vertical length of the ring that supports the FGS (15 mm), and the gap spacing (Fig. 4). Even if the angle of light diffusion from the emitting side reaches 60°, the diffusion area is still within the ring, as shown in the uppermost part of Fig. 4.

The newly developed FGSs were mounted in a 2-m long vertical steel pipe; the space between the sensors was 10 cm (Fig. 4). The FGS-containing steel pipes were embedded in the seafloor at two locations at water depths of 4–5 m beneath a pier at HORS. The pier is aligned perpendicular to the coastline. The systems on the seafloor were called OSS systems No. 1 and No. 2, with system No. 1 being 15 m nearer to the shore. A bundle of fiber-optic cables with stainless steel wire ran from the steel pipe on the seafloor to the pier, and the cables were routed into an observation room on the pier (Fig. 4). The digital processing unit was installed in this room.

The digital processing unit is composed of the electronics unit and the data acquisition system. The electronics unit consists of two sensor boxes (Box 1 and 2). Box 1 contains light emitting diodes (LEDs) that emit light through the emitting parts of the FGSs through the fiber-optic cables. The photosensors in Box 2 receive light from the receiving parts of the FGSs, yielding amplified electrical currents that are finally converted into digital signals. These signals are processed by a microcomputer in Box 2. The digital signals are transferred from Box 2 to the data acquisition system (PC). The PC controls the processing in Box 2; i.e. the sampling rate can be changed by the PC.

During the survey period by the OSSs, remote-control operation of the digital data acquisition system was conducted from an office in Yokosuka city, about 115 km west-southwest of HORS.

2.3. *Sediments around the survey site*

Near the HORS, the bottom sediment from shoreline to a water depth of about 6 m is mainly composed of fine to medium sand (0.18–0.5 mm in median diameter) based on repeated sediment sampling along the pier with a cross-shore interval of 10 m [Katoh *et al.*, 1990]. The beach sediments that are the likely source of the shallow seafloor sediments near the HORS are mainly chert, shale, sandstone, quartz, shell fragments, and iron minerals [Sudo, 2006].

3. Laboratory Experiments

Laboratory experiments were conducted to determine the detection ability of sensors using the gap method, the difference in the detection ability of the gap method

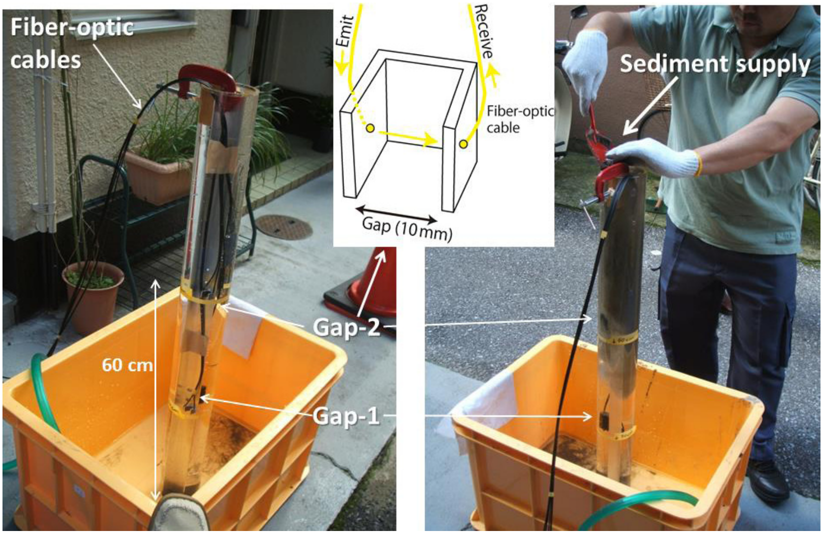

Fig. 5. Photographs of the experiment using a cylinder and sandy sediments obtained on the seafloor at HORS. An illustration of the sensors using the gap method for the experiment is also shown.

and the twin fiber method, and the effect of sunlight on the light intensity. The experiments used a cylinder about 1-m long and sediments obtained from the seafloor at HORS. In the cylinder, the gaps were placed at heights of 30 and 60 cm, and are called Gap-1 and Gap-2 (Fig. 5). The gap between the emitting and receiving sides of the fiber-optic cables was 10 mm. This was the same setting for the device as used in the field experiments. Experiments were conducted outside the laboratory in sunlight, and inside the laboratory with the lights turned off. The latter condition simulates field measurements obtained at night.

First, the sediments were slowly fed into the top of the cylinder at a time. Changes in light intensity (L_R) during sediment settling were detected at Gap-1 and Gap-2 (Fig. 6). At Gap-1, a high amplitude of L_R with attenuation of the intensity resulting from passage of sediment through the gap was observed. The higher L_R values during the fluctuations indicate lower concentration of sediments at the Gap-1 depth at that time, resulting in minor disturbances in the amount of light between the emitting and receiving parts of the gap. In the second round of sediment supply to Gap-2, the sediments were also fed slowly at a time. At Gap-2 (a height of 60 cm), a similar change to that at Gap-1 occurred. A drop in L_R immediately before the second round was caused because small quantity of the sediments had been dropped from the top of the cylinder. The L_R values in the gaps become zero when the gaps are completely buried in the sediment.

In addition, the L_R measured using the gap method is about 10 times higher than that measured using the twin fiber method, indicating that the former method is more useful for studies of sediment concentrations. A higher initial value is desirable for measurement of the L_R because attenuation of the light intensity (transmission

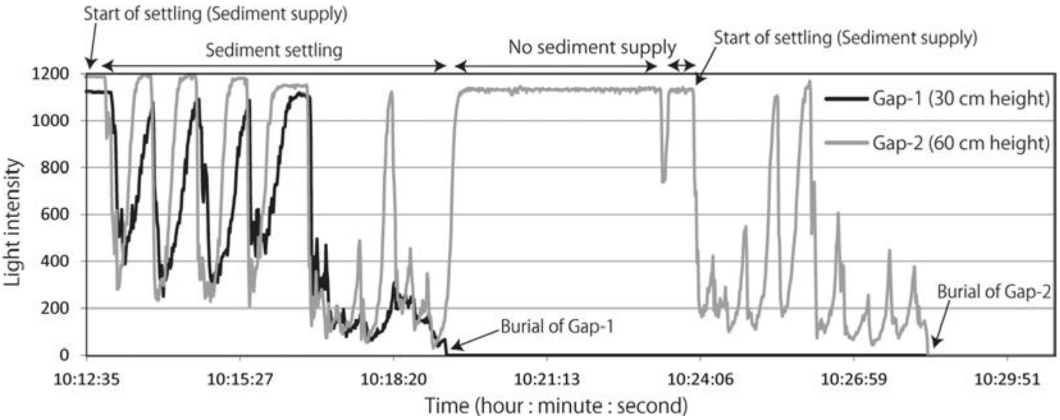

Fig. 6. Result of the experiment based on the sensors using the gap method. The light intensity is a dimensionless value.

loss) becomes large on increasing the length of the plastic fiber-optic cables. Furthermore, Akutagawa *et al.* [2014] reported that fluctuation in the light intensity was detected by the twin fiber method even if the tip of the cables are completely within fine-grained sediments (90% of the particles are smaller than 0.25 mm on average); a sensor (tip of the cable) reacted to slight motions of the sediments in front of the tip when the fiber cable was inserted into, and removed from the sediments. The reaction seen using the twin fiber method is unfavorable for monitoring the seabed in the present study area. The seafloor and sub-seafloor sediments are unstable because of high energy waves and currents.

Regardless of the presence or absence of sunlight, the same results were observed. The initial values of L_R at the gaps were similar: the value of L_R in sunlight is approximately 1120 at Gap-1 and 1190 at Gap-2; L_R is approximately 1135 at Gap-1 and 1230 at Gap-2 inside the laboratory with the lights turned off.

4. Field Experiments

In this research, the field data consist of data obtained by the OSS systems, wave observation data, and weekly bathymetric cross sections investigated by PARI. The measurements from the OSS systems were obtained between 20 January and 3 March, 2014, although OSS system No. 1 was destroyed on 16 February because of breakage of the fiber cables, probably due to storm waves. Based on the bathymetric cross section data, there was no significant change in the bathymetry between 20 January and 3 February, and a longshore bar developed between 3 February and 3 March (Fig. 7). The wave data observed at the pier (Fig. 8), about 30 m offshore from OSS system No. 2, indicate that high incident waves (significant wave-height > 2 m) that are likely to have been related to the formation of the longshore bar were frequently observed in the latter period (from 3 February to 3 March), particularly between 4 and 18 February because of the passage of several low-pressure systems.

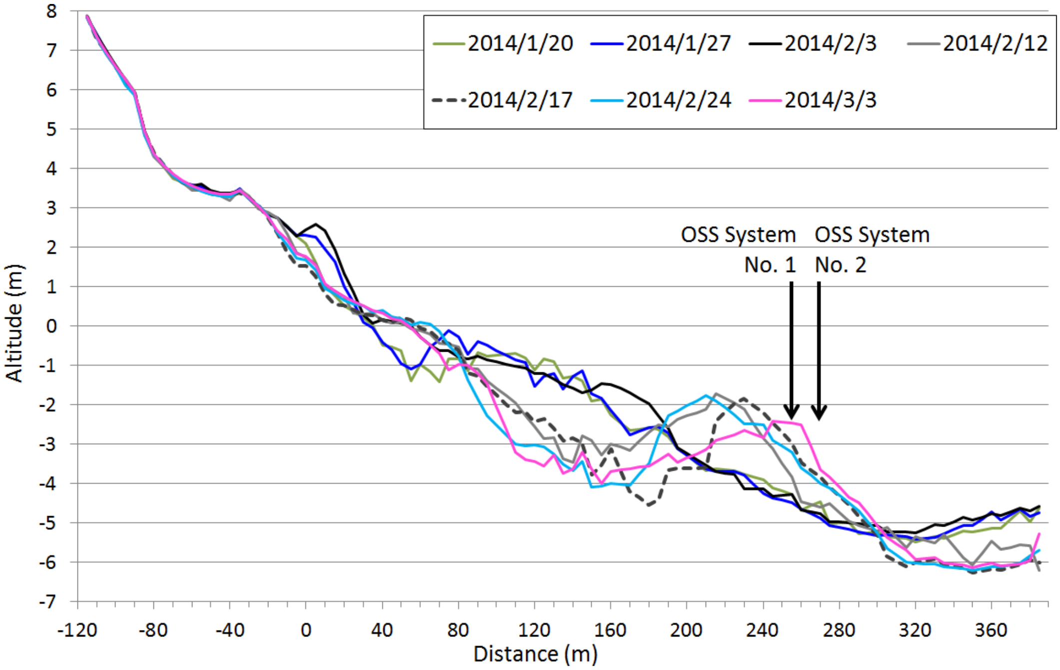

Fig. 7. Temporal changes in the bathymetric cross section, surveyed by PARI. The locations of OSS systems No. 1 and No. 2 are also shown.

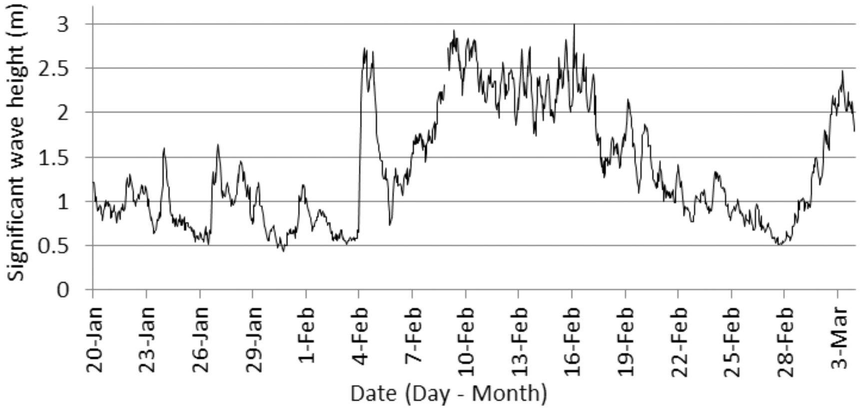

Fig. 8. Wave conditions (measured by PARI) during the survey period of the OSS systems.

This section presents the bathymetric changes identified by the OSS systems between 3 and 17 February, when the most remarkable development of the longshore bar was observed based on the data shown in the cross section (Fig. 7). The data obtained during this period are suitable for confirming the availability of the systems, because the OSS systems were located in the depositional zone of formation of the longshore bar and its offshore-directed migration (Fig. 7). The FGS channel numbers increase upward: ch 1–21 are in OSS system No. 1, and ch 23–43 are in OSS system No. 2. It should be noted that the initial values in these channels are not the same, because the optical axis alignments of the fibers on the emitting and receiving sides were not necessarily perfect. The difference in the length of the fiber cables, the degree of cable bending between the sensor box in the observation room and sensor array in the seafloor, and the processing accuracy of planarization of the end face of the cables are also possible causes of the difference in the initial value of the light intensity (L_R). However, the amount of change relative to the initial value should be obtained in the present system, in contrast to the general measurement that evaluates the absolute value.

The OSS data described below can be interpreted in the same way as the results of the laboratory experiments: L_R of the given channels is zero when the channels are buried completely below the seafloor, although no attenuation of L_R will be observed for channels located above the seafloor where suspended materials are rarely present. In addition, the attenuation rate depends on the increase or decrease in the amount of suspended sediment at the depth of the given FGS channels. Figures 9–11 show time-series of the position of the FGS channel immediately above the seafloor based on the L_R value and the threshold L_R value (tentatively defined in this study). When the L_R value is greater than 1, the FGS channel is located just on or above the seafloor. L_R values fluctuate from zero to > 1 when a given FGS channel is located near the seafloor, because of repeated exposure and burial of the FGS channel at this surface. Thus, the particular channel immediately above the seafloor will frequently vary (Fig. 9).

On 4 February, when the significant wave-height briefly reached approximately 2.7 m (Fig. 8), ch 7, 8, 30–32 were exposed above the seafloor (Fig. 9); i.e. about 20 cm of erosion occurred at OSS system No. 1, and 30 cm of erosion at OSS system No. 2. The exposure was instantaneous. When an FGS is located near the seafloor, a high amplitude of L_R is observed, as shown in the intensity values for ch 7, 8, 33, and 34. Rapid attenuation was occasionally observed in ch 8 (10 am and 4 pm on 5 February; Fig. 9), despite fluctuations in the L_R value in ch 7. This may have resulted from spatial and temporal variations in the suspended sediment concentration near the seafloor. Gradual attenuation of L_R, as observed in ch 33 and 34, during the period between 11 pm on 4 February and midnight on 6 February may have been caused by bending of the fiber-optic cables by waves and wind. Similar attenuations or fluctuations were observed after this period.

Between 6 and 10 February, when the significant wave-height increased from about 0.7 to 2.9 m (Fig. 8), burial of ch 7–13 and ch 30–33, and subsequent exposure of ch 10–13 and ch 30–33, were observed (Fig. 10). The transition time from deposition to erosion was 16 h in OSS system No. 1, and about 10 h in OSS system No. 2.

Between 10 and 17 February, the significant wave-height was mostly 2–3 m (Fig. 8). Changes in water depth were small until the night of 12 February, when

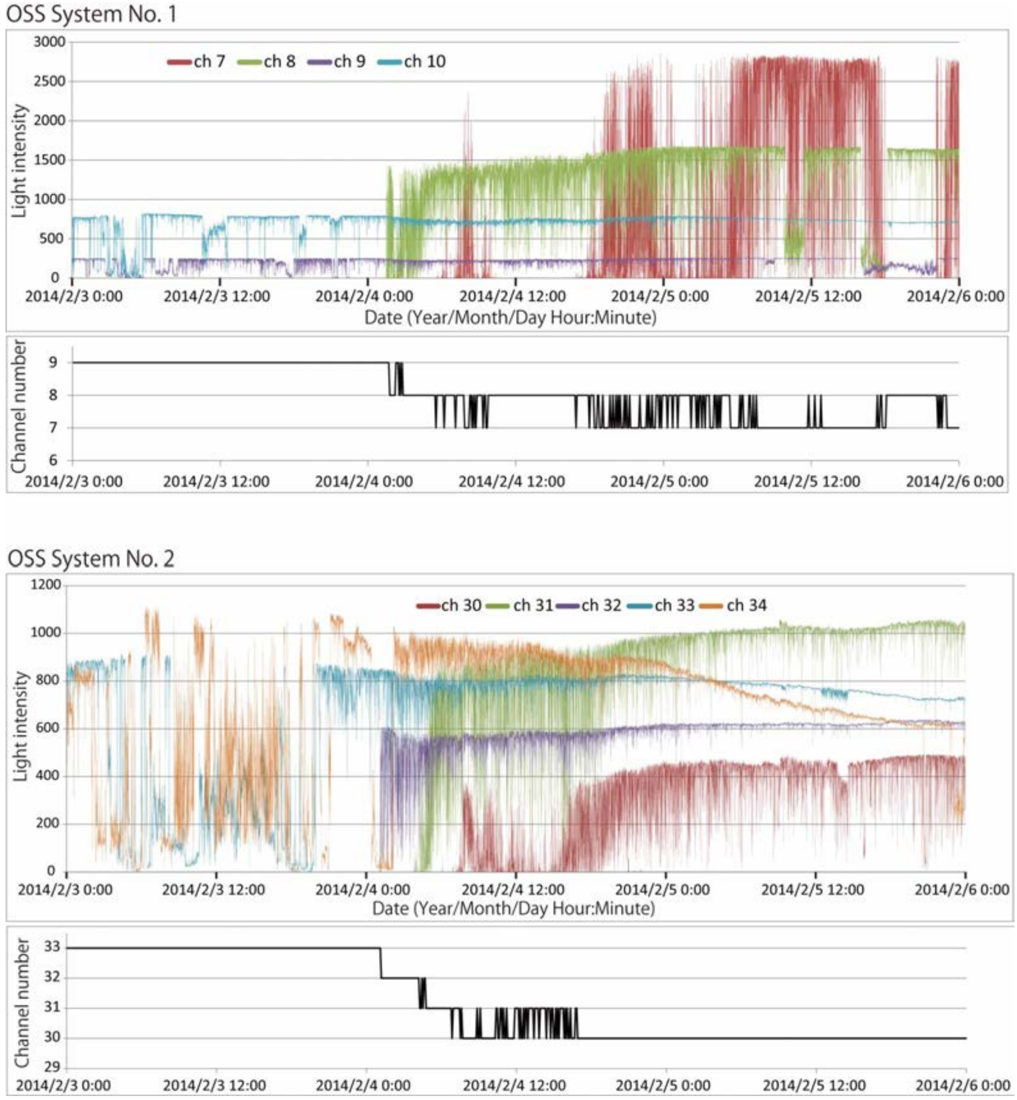

Fig. 9. Changes in light intensity detected by the OSS systems between midnight on 3 February and midnight on 6 February. The light intensity is a dimensionless value. The sampling interval is 20 s during this period. The number of the FGS channel immediately above the seafloor (measured at 5 min intervals) is shown in the lower portions of the two figure parts.

ch 9 and 10 were buried. In OSS system No. 2, no channels were buried or exposed during this period (Fig. 11). In contrast, dramatic changes in water depth were observed between 13 and 17 February. Burial of ch 12–21 occurred over about 21 h, and burial of ch 29–34 over 26 h, although the upper limit of deposition in OSS system No. 1 is uncertain because no FGSs were placed above ch 21. Rapid deposition in OSS system No. 1 began approximately 3 h before the start of the deposition in OSS system No. 2. In addition, seafloor erosion after the substantial deposition

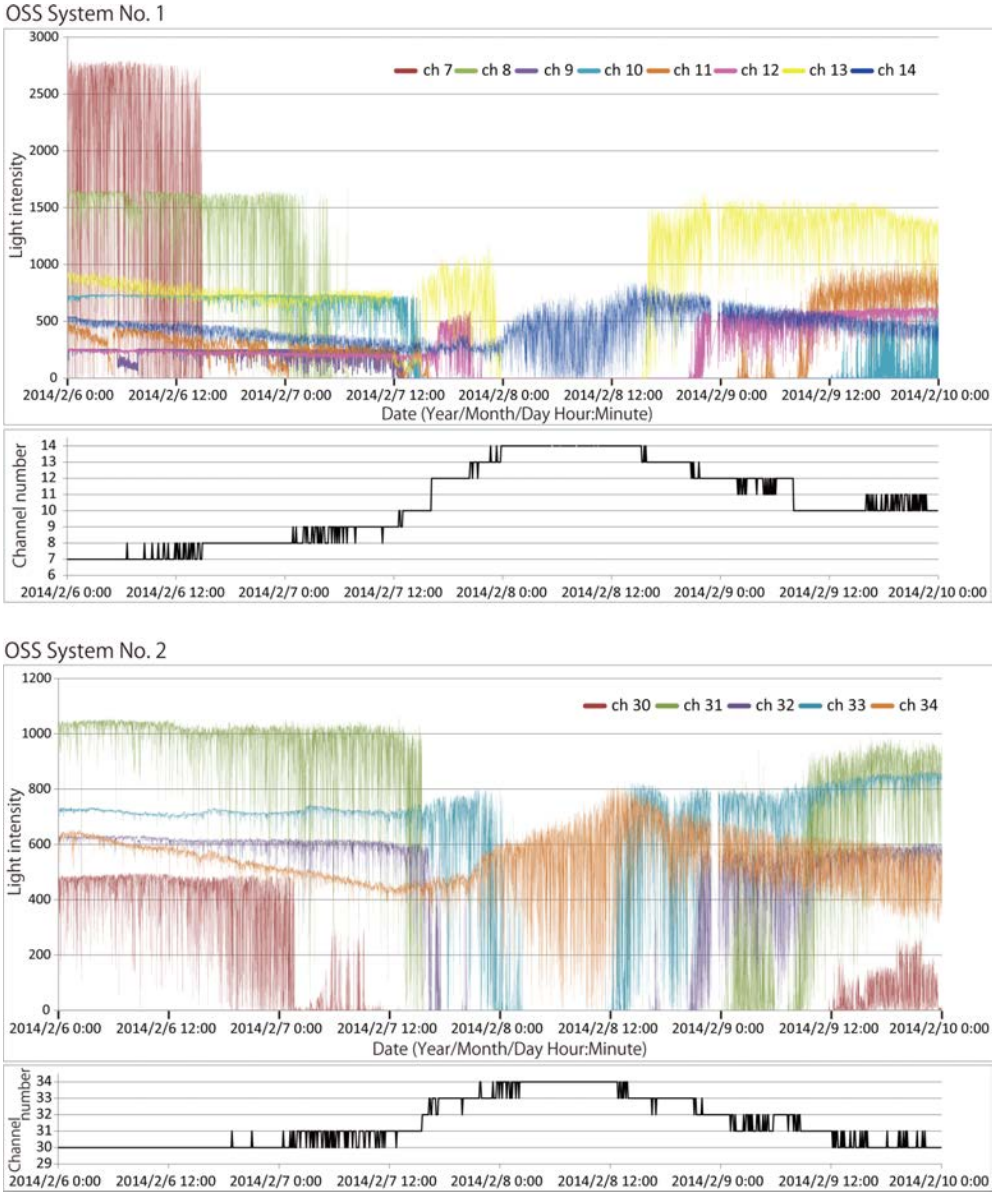

Fig. 10. Changes in light intensity detected by the OSS systems between midnight on 6 February and midnight on 10 February. The light intensity is a dimensionless value. The sampling interval is 30 s during this period. The number of the FGS channels immediately above the seafloor (measured at 5 min intervals) is shown in the lower portions of the two parts of the figure.

was recognized during this period as well as between 6 and 10 February. The time required for burial and exposure of one FGS channel was practically instantaneous (a few seconds).

The change in the number of the FGS channel immediately above the seafloor is generally consistent with the change based on the survey of the bathymetric cross

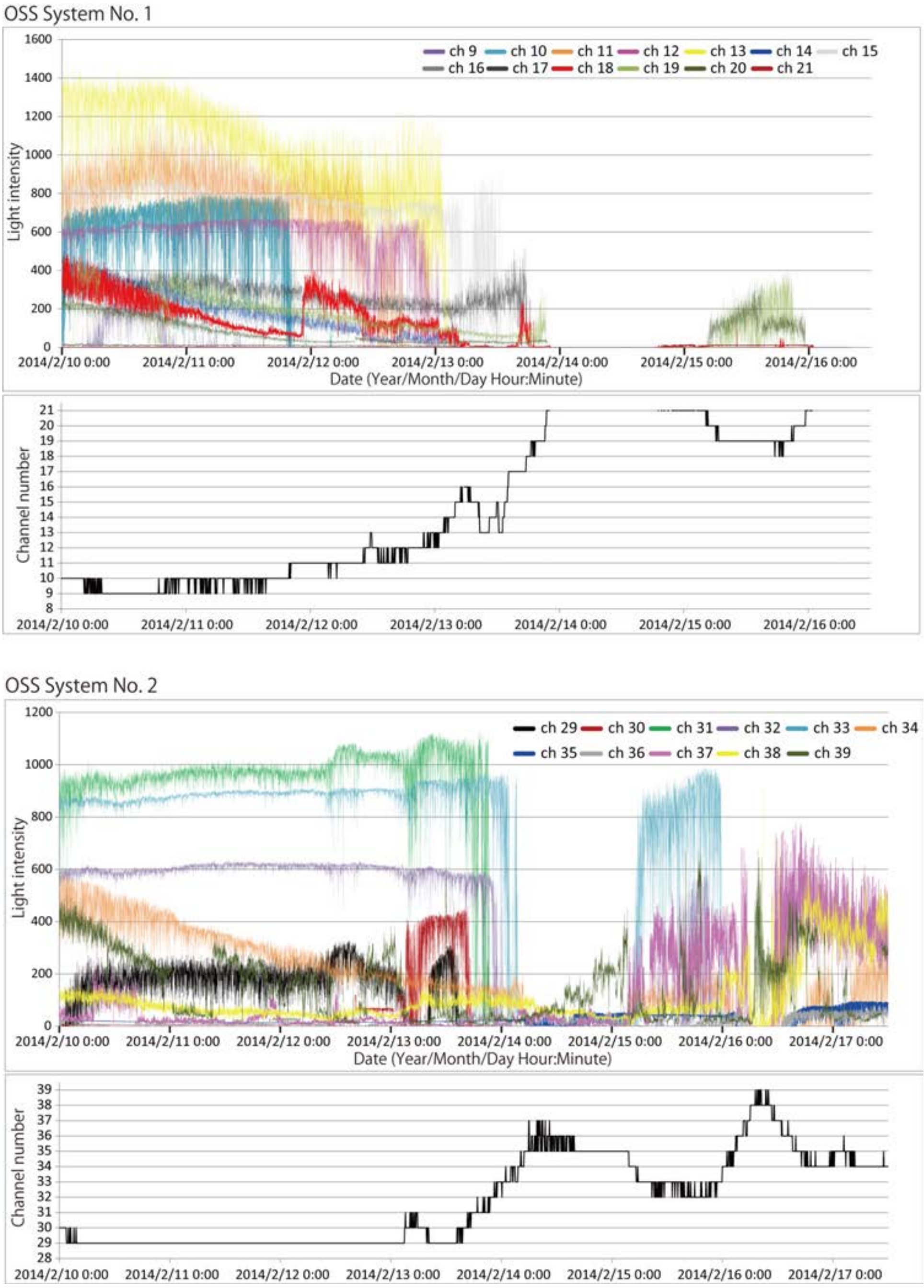

Fig. 11. Changes in light intensity detected by the OSS systems between midnight on 10 February and noon on 17 February. The light intensity is a dimensionless value. The sampling interval is 60 s during this period. The number of the FGS channel immediately above the seafloor (measured at 5 min intervals) is shown in the lower portions of the two parts of the figure.

section near the OSS system, although a minor difference (ca. < 20 cm) in the measured depth value between both datasets remains. For example, on 20 and 27 January, and 3 and 12 February, the water depth was 4.27, 4.49, 4.29 and 3.84 m, respectively, near OSS system No. 1, whereas the channel number immediately above the seafloor was ch 10 on 20 January, ch 8 on 27 January, ch 9 on 3 February, and ch 12 on 12 February in OSS system No. 1. These channel numbers were the locations at about 11 am on the given days, when the surveys were conducted by PARI. The reason for the minor difference in each water depth value probably relates to the distance (about 3.5 m) between the location of the bathymetric survey by PARI and that of the OSS system; the former survey was conducted on the south side of the pier, but the OSS system was on the north side.

5. Discussion and Conclusions

A new monitoring system, the OSS, was designed using fiber-optic cables and LEDS. The system is designed to mainly investigate the detailed processes of storm-generated bathymetric change. Fiber-optic sensors have often been used for multidisciplinary research projects. In research on sediment transport and bed level change, fiber-optic sensors have been used for measurements of the backscatter intensity of light as described above, fluctuations in temperature between flowing water and saturated soil [Manzoni *et al.*, 2011], and strain [Zarafshan *et al.*, 2012]. Two of the latter type of sensor are used for the monitoring of bridge pier scouring, and were based on a fiber Bragg grating (FBG) sensor. The main difference between the FGB and the OSS used in the present study is whether the cut in the sensor cable that transmits and receives the data signal is present or not. In contrast to the FGB system, which has sensors in various places in the cable, the tips of the cables are the sensing parts in the OSS system. The proposed OSS system, if installed at an existing pier, is likely to be of value in monitoring within the high-energy surf zone, because dramatic changes in the water depth caused by the passage of low-pressure systems can be clearly monitored without breakdown of the OSS or collapse of the steel pipes, apart from breakage of the fiber-optic cables. As the distance between the FGSs can probably be decreased to about 1.5 cm based on the consideration of their inter-channel interference, a higher-resolution of seabed level change will be possible by increasing the number of FGS used.

The data from the OSS system indicate that the longshore bar at HORS was formed by repeated sediment erosion and deposition over very short time intervals during storms, whereas the bathymetric cross sections indicate that the formation and offshore-directed migration of the bar results simply from sediment deposition. In addition, reversal of seabed erosion and deposition within a day could be recognized using the data from the OSS systems. Instantaneous exposure and burial of one channel was also observed. This information could not have been obtained using previous survey methods. If the OSS systems can be installed in many more locations (e.g. 20–30 m intervals) along a pier, and so perpendicular to the shoreline, where a longshore bar is present, such as the HORS, the consecutive process of the formation, migration, and deformation of the whole of the bar will be clarified. In addition, the OSS system should be suitable for monitoring local erosion around the base of coastal structures; e.g. jetties, offshore breakwaters, and piers. However, an online system for sending data wirelessly from the seafloor, or an offline approach using automatic data acquisition and storage within the underwater system, will have to be developed if sensor cables cannot be run from the seafloor above the surface (or on land) because of the lack of an observation room near the measurement system (unlike HORS).

In future, it will be necessary to develop measures to protect the fiber-optic cables against damage, and this may avoid attenuation of the initial value of light intensity. One possible countermeasure against cable damage is as follows. As the breakage of the fiber cables occurred near the sea surface, all of the fiber cables could be taken out from the lower part of the FGS array below the seafloor, and then covered with a protecting tube. They could then be routed from the array to the bottom of the support structure of the pier. Then, the cables with the tube attached to the support structure can run from the seafloor to the pier. Their burial depth should be below the lower limit of seafloor erosion, as determined from previous bathymetric data obtained at the HORS. Furthermore, monitoring any change in the position of the pipes during the survey period may also be required, although a change in the position of the pipes probably did not occur in the present survey period as: (1) the stainless steel wires were keeping the position that were ran from the steel pipes on the seafloor to right above the pier; and (2) observations by divers revealed that the pipes had not moved. Moreover, the OSS systems must have a high withdrawal resistance for the pipe because the penetration depth below the seafloor of the pipes, including the support pipes, is 2 m initially. The convex structures of the FGS rings are an additional factor for increase of the withdrawal resistance for the sensor pipe.

In addition, examination of the relationship between light intensity and sediment concentration will be required using OSS field data and data measured simultaneously by a turbidity meter, or sampling of the suspended sediment within seawater [Sternberg *et al.*, 1986; Katayama *et al.*, 1999], or a combination of these. For example, Katayama *et al.* [1999] reported a time-series of suspended sediment concentration and grain size distribution in sediment from continuous seawater sampling by pump at HORS. As the fluctuations in light intensity can be measured immediately above the seafloor during storms, the OSS system may be a promising device for the study of both bathymetric change and sediment concentration in water, although the effect of flow modification probably caused by the steel pipe and the ring of the FGS on measurement of suspended sediment concentration must be examined further.

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