Development and Operation of an Ocean Bottom Cable Seismic and Tsunami (OBCST) Observation System in the Source Region of the Tohoku-oki Earthquake

Masanao Shinohara, Tomoaki Yamada, Kenji Uehira, Shin'ichi Sakai, Hajime Shiobara, and Toshihiko Kanazawa

Abstract  Cabled seafloor seismic and tsunami observation systems are ideal for marine geophysical monitoring because the data can be obtained in real time. We have developed a new compact seafloor-cable seismic and tsunami observation system using Information and Communication Technology (ICT). Our system achieves reliability through redundancy using ICT. A software-based system using up-to-date electronics technology contributes to cost reduction and production sustainability. The system named the Ocean Bottom Cable Seismic and Tsunami (OBCST) observation system was installed on the Pacific Ocean floor off Sanriku, northeast Japan, in September 2015, in the source area of the 2011 Tohoku-oki earthquake. The purpose of the installation is to monitor seismic activity better and to observe tsunami activity through spatially dense observation. The system has been continuously collecting the seismic and pressure data since the deployment. For the seismic data, ambient seismic noise is comparable to that from a previous cable observation system. One observation node is buried 1 m below the seafloor and has a lower noise level compared to nodes on the seafloor. Because the noise levels are stable, many local earthquakes and telesismic events have been recorded by the system. The data obtained by high-precision pressure gauges have a resolution of <1 hPa which is limited to environmental noise. The effectiveness of the buried pressure gauge is demonstrated by a recording of a tsunami. The system also continuously monitors its operating environment. The operating temperature is reasonably low and stable, which is optimal for long-term operation.

Plain Language Summary  Large magnitude earthquakes and tsunamis are significant hazards in marine subduction zones. A cable seafloor observation system is essential for research on and the mitigation of such hazards because it can provide observations in real time. We have developed a new compact cable seismic and tsunami observation system to increase the number of observation stations. The system uses Information and Communication Technology which also provides the flexibility to monitor the system and change observational parameters after deployment. In 2015, our system was deployed in the source region of the 2011 Tohoku-oki earthquake, and data have been gathered continuously since then. Long-term observational data show that the system consistently records high-quality seismic and pressure data. The system operates at a low and stable temperature which is ideal for reliable long-term observations.

1. Introduction

Many destructive earthquakes have occurred at plate boundaries around Japan due to the subduction of oceanic plates; thus, observations of seismic waves and tsunamis on the seafloor are essential for disaster mitigation. A seafloor-cable system is a powerful tool for the study of plate subduction and earthquake generation because it performs in real time and allows long-term sea-based reliable observations. Therefore, seafloor-cable systems with seismometers and tsunami meters were developed based on submarine telecommunication cable system technology and have been used for the past 25 years around Japan (Kanazawa & Hasegawa, 1997). In addition, cable systems are useful for oceanographic research and for addressing environmental problems such as climate change (e.g., Howe et al., 2019).
The Earthquake Research Institute (ERI) of the University of Tokyo installed the seafloor seismic and tsunami observation system, which used optical fiber for the first time in Japan, on the seafloor off Kamaishi City in the Sanriku region in 1996 (Figure 1). This seafloor-cable system is based on available telecommunication technology and is able to continuously observe seismic waves and tsunamis in real time. The system is positioned in the source region of the 2011 Tohoku-oki earthquake, which had a hypocenter located below a landward slope of the Japan Trench. For about 30 min after the mainshock, the system continued to transmit seismic wave and tsunami data to the ERI until its landing station were damaged by the tsunami. Data from the seafloor system were essential for accurately estimating source faults in the area and for evaluating the rupture process of the 2011 event (Fujii et al., 2011; Maeda et al., 2011). Although the landing station had been carried away by the tsunami, the cable end was found in the wreckage. Tests with an optical time domain reflectometer suggested that the system on the seafloor had little damage. We connected a temporary receiving system to the end of the fiber and applied power to the system. It was found that the cable system on the seafloor worked properly. The seafloor-cable system originally installed in 1996 was restored by the rebuilding of the landing station and receiving units of the cabled system in 2014.

A large-scale cable observation system with telecommunication technology (S-net) was recently deployed off northeast Japan (Mochizuki et al., 2017). A cable system with Underwater Mateable Connectors (UMCs) for seafloor sensors (DONET) was also installed in the Nankai Trough (Kaneda et al., 2015; Kawaguchi et al., 2015). In Canada, cabled ocean observatories with diverse instruments were deployed (Barnes et al., 2013). A cabled array of instruments was also installed off the coast of Oregon (Smith et al., 2018). However, for detailed monitoring for scientific purposes and disaster mitigation, a network of seismometers and tsunami meters distributed at a higher spatial density than that of the existing system around Japan is required. Aside from the need for higher-density networks, weaknesses in existing in-line systems that use telecommunications technology have become apparent: they lack sufficient flexibility of measurements after installation (Kanazawa & Shinohara, 2009), and they become more difficult to maintain the system with the difficulty of finding older parts for repair due to the rapid advances in telecommunications technology.

A next-generation system that used Information and Communication Technology (ICT), that is, Internet Protocol (IP) on the seafloor, called the Ocean Bottom Cable Seismometer (OBCS) system, was introduced in 2010. Observation nodes (ONs) of the OBCS system were downsized by introducing state-of-the-art electronic devices that need firmware to control the system and process the observed data. Reliability was assured by redundancy, which is easily implemented using ICT (Kanazawa et al., 2006; Yamazaki et al., 2012). The OBCS system was designed for low-cost production and installation. A smaller ON leads to lower costs and a larger seafloor footprint, providing a more comprehensive view of deep-sea processes by the broad distribution of nodes.

Figure 1. Location of the OBCST system installed in 2015 and previously deployed cable system in 1996. Squares and red line indicate position of observation nodes and cable route, respectively, for the OBCST system. Circles show seismometers and tsunami meters in the older system. Colored circles mark epicenters during 2018 determined by the Japan Meteorological Agency. The landing station is common to both cable systems. OBCST, Ocean Bottom Cable Seismic and Tsunami observation system.
installation costs because sufficiently small ONs may be installed without cable ships. The OBCS system has dual communications capabilities: ring configuration and doubled route configuration, which are implemented as a double ring network on a single seafloor cable (Shinohara, Kanazawa, et al., 2014; Yamazaki et al., 2012). Ethernet, the de facto standard in ICT, is used for data transmission and monitoring of the system. The practical OBCS system was produced and deployed in the Japan Sea. A commercial cable ship that usually installs submarine telecommunication cables, deployed the system in 2010 off Niigata, central Japan, in the Japan Sea. The system has a seafloor cable with a total length of 25 km and four stations with 5 km intervals (Shinohara, Kanazawa, et al., 2014).

It was considered a preliminary implementation because it included only seismometers as scientific sensors and had minimum ICT capabilities for data transmission and system control. Expansion of the system was anticipated.

2. Development and Installation of the OBCST System

In 2012, we started development on an improved version of the OBCS system, called it the Ocean Bottom Cable Seismic and Tsunami (OBCST) observation system that would include, at each node, a tsunami meter and a connector to add new sensors on the seafloor after deployment. The system and the installation of the OBCST are summarized here because characteristics of the system and its installation in the marine area have already been reported (Shinohara, Yamada, et al., 2014; Shinohara et al., 2016a, 2016b).

The control unit has a microprocessor (SH-4, Renesas Electronics Corp.) and the operating system is Linux. The implementation of a CPU, Field Programable Gate Arrays (FPGAs), and the introduction of Linux allow a modification of measurement parameters for scientific sensors and upgrade of firmware and software on the ONs after deployment. Indeed, some programs on the Linux operating system were replaced after the installation. For the seismometers, we chose conventional force balance accelerometers that are identical to those of the OBCS system and other seafloor-cable systems in Japan (JA-5, Japan Aviation Electronics Industry, Ltd). The accelerometer responds to signals with frequencies ranging from DC to more than 300 Hz and has a resolution of less than 9.81 × 10⁻⁶ m/s². This resolution determines the noise level of the sensor. The control unit interfaces to the digitizer for the FPGA. Analog signals from the three accelerometers as a seismic sensor are synchronously digitized by sigma-delta A/D converters with a resolution of 24 bits and a sampling rate of 1 kHz. For the tsunami meter, we chose a high-precision pressure gauge that uses a quartz crystal resonator with a frequency of oscillation that varies with changes in pressure (Series 8B, Paroscientific Inc.). The adopted pressure gauge has a depth rating of 4,000 m. The pressure gauge senses changes in pressure using frequency of crystal oscillation. The frequency of the output signal from the pressure gauge is measured by a counting unit programed on the FGPA (Figure 2). For a pressure gauge with frequency output, a time window of 1 ms is applied for counting the pulses of the output signal from the pressure gauge, which has a measurement resolution of <1 mm. To avoid counting errors, outputs from a pressure gauge are counted including fractional cycle within a time window of 1.0 ms using a reference clock with a frequency of 32.768 MHz. In normal operation, the reference clock signal is sent from the landing station. The ON transmits counting values including fractional cycle to the landing station, and the workstation in the landing station processes the counting data to obtain pressure and temperature in real time.

The OBCST system implements a standard TCP/IP protocol with a speed of 1 Gbps for data transmission, system control, and system monitoring. High-speed data transmission allows the collection of larger amounts of data. One of the features of our system is the direct utilization of TCP/IP protocols for communication, similar to a computer network in a small office. Although some other subsea systems have TCP/IP functionalities, many systems implement a TCP/IP protocol on a telecommunication system such as Synchronous
Figure 3. Upper: A cross section of the Type FA ON of the developed OBCST system. The pressure gauge is protected using a small canister filled with silicon oil, and the inside section of the vessel where the canister of the gauge exists is inundated with sea water. Sea water pressure transmits to the inside of the canister through a soft plastic film installed on the canister. Observation unit contains three-component accelerometers. Lower: photograph of ONs of the OBCST system. A pressure vessel has a diameter of 26 cm and a length of about 1.3 m. The deployed system has two types of node: (1) Type FA has accelerometers and a built-in pressure gauge and (2) Type FB has accelerometers and a PoE interface through UMC. Lower left: an ROV view of an observation node of Type FB on seafloor (YOB3). The ROV dived to the seafloor on October 11, 2016. Water depth was about 1,570 m. PoE port and pressure node of Type FB on seafloor (YOB3). The ROV dived to the seafloor on PoE interface through UMC. Lower: photograph of ONs of the OBCST system. A pressure vessel has a diameter of 26 cm and a length of about 1.3 m. The deployed system has two types of node: (1) Type FA has accelerometers and a built-in pressure gauge and (2) Type FB has accelerometers and a PoE interface through UMC. Lower left: an ROV view of an observation node of Type FB on seafloor (YOB3). The ROV dived to the seafloor on October 11, 2016. Water depth was about 1,570 m. PoE port and pressure gauge attached before the deployment are shown. ON, observation node; PoE, Power over Ethernet; UMC, Underwater Mateable Connector; ROV, Remote Operated Vehicle.

Digital Hierarchy. The system, which utilizes TCP/IP directly, can support up to about 100 ONs on a single channel with a reasonable latency and occupancy from a point of view of network performance (Yamazaki et al., 2012). We used Wavelength Division Multiplexing (WDM) technology to reduce the number of optical-electro conversion modules and optical fibers. Small Form-factor Pluggable (SFP) is used as an optical-electro conversion module for TCP/IP communication (Figure 2).

Because precision timing is critical for seismic observation, a clock signal with an accuracy of <10−8 is delivered through a dedicated fiber to all ONs from a GPS receiver on the landing station. Precision timing is also required for the pressure gauges, which use the delivered clock signal to obtain an accurate time window for counting the pulses of the output signal. When the TCP/IP system is unavailable, the lines for clock delivery are also used for communication between the Linux system on the ONs and the landing station. If the delivery of the reference clock from the landing station fails, an atomic clock module (SA.45S CSAC, Symmetricom) with an accuracy of <10−8 is used instead. In addition, an IEEE-1588 standard (Precision Time Protocol) is implemented for the OBCST system to synchronize the real-time clock on the ONs to the land-based system clock driven by GPS through a TCP/IP protocol. Because the Ethernet switch in the ONs is composed on the FPGA, the hardware necessary for IEEE-1588 was implemented without difficulty. We evaluated the clock accuracy of the implemented IEEE-1588 and found a timing bias through the switches of <300 ns (Shinohara et al., 2016a). The electric power is supplied using Zener diodes inserted in a power line of the seafloor cable. In a normal operation, the CPU unit and TCP/IP modules consume a power of ~10 W. Six optical modules (SFPs) and the FPGA account for a large proportion of the power consumption. Each ON has six Zener diodes for power supply with Zener voltages of 5.1 V.

We produced two types of ONs for the OBCST system: Type FA and Type FB. Both types have three orthogonal accelerometers. The Type FA ON is equipped with a pressure gauge housed inside a vessel. The pressure gauge is housed in a small canister that is filled with silicon oil to prevent corrosion and provide electrical insulation and has a small hole covered with soft plastic to transfer pressure from the outside. This canister is housed inside a section of the pressure vessel that is open to sea water through a penetrating hole (Figure 3). The in-line nodes in other systems in Japan do not introduce sea water into the pressure vessel. The Type FB ON lacks an internal pressure gauge but has an external port for attaching an additional observation sensor. Communication and power for additional sensors connected through the external port are provided using Power over Ethernet (PoE) technology. PoE can provide ~12 W of electrical power to the external sensor and Ethernet communication at 10 Mbps. The implementation of PoE is not difficult due to the adoption of TCP/IP technology for the system. Because an UMC is used for the external port, external sensors can be replaced even after the installation of the cable system. The UMC was provided by Teledyne Oil & Gas (ODI) and has four metal pins. Ethernet communication at 10 Mbps can be performed through the UMC. The power for external sensors is supplied at 48 V through the UMC, and the depth rating of the UMC is 5,000 m. An isolation-type DC/DC converter supplies the power to external components exposed to seawater. If an external component short to seawater, the processing unit turns off a power switch on the power line to isolate the PoE unit. For both types of ON, four electric lines must penetrate the pressure capsule. A commercial penetrator has been discontinued, and our capsule has no connector, so we developed feed-through technology for the four metal conductors in cooperation with Fujitsu Limited. The advantage of our system is the use of PoE for an interface. Other plug-in systems in Japan have no PoE capabilities. The use of the PoE interface contributes to the low-cost development of external components. The capsule for
the ON has a diameter of 26 cm and a length of about 1.3 m (Figure 3). We selected the smallest-sized standard canister used in the telecommunication seafloor-cable systems for the pressure vessel. The choice of a small-sized canister reduces installation costs. The fibers and single copper conductor in the cable penetrate the pressure vessel using the standard feed-through technology for seafloor telecommunication systems. The use of both Type FA and Type FB ONs distinguishes the OBCST system. Because S-net is an in-line system, a Remote Operated Vehicle (ROV) is not necessary to start observations. However, exchanging a sensor is difficult. On the other hand, a plug-in system such as DONET needs an ROV for the installation and maintenance of sensors. The OBCST is a hybrid system that has in-line nodes and a plug-in node that provides modest flexibility that would require an ROV. For a Type FB node, the exchange and service of instruments after the installation are allowed, although a sensor package can be attached at deployment.

The electronics unit of the ON is built largely from commercial components. Our system achieves reliability by redundancy using ICT. The SFP has a high rate of Failure In Time (FIT) of ∼1,500. It is important to operate this component at low temperatures since this reduces the FIT number and increases reliability. On the other hand, semiconductors and passive components (registers, capacitors, etc.) have low FIT numbers. Our ON except SFPs and an atomic clock module has a FIT number of about 1,000 totally. Based on our successful experience using geophysical sensors for long deployments in marine environments, we decided to further improve reliability by implementing multiple communication paths. The ON has six SFPs for dual-channel Ethernet and clock transmission. Each Ethernet channel and clock line has a ring configuration (Shinohara et al., 2016a). Although each communication unit includes SFPs with high FIT numbers, the redundancy ensures reliability of the system. Adoption of components for consumer use allows for the cost-effective production of the ON. In addition, the utilization of standard components and technology for telecommunications seafloor-cable systems contributes to lower production and installation costs for the system. Communication to the ONs using the TCP/IP protocol also lowers the cost of receiving units at the landing station.

The seafloor-cable seismometer and tsunami observation system, installed in 1996 off Kamaishi, was damaged by the 2011 Tohoku-oki earthquake. The indispensable nature of real-time observations on the seafloor led to the decision to restore the existing system and deploy an OBCST system for additional observation and/or replacement of the existing system. The first practical OBCST system has a total cable length of 105 km and three ONs with 30 or 40 km spacing. The two ONs closest to the shore are Type FA, and the one farthest from the shore is Type FB. A precise pressure gauge with an RS-232 interface (Series 8B, Paroscientific Inc.) was attached to the PoE interface on the Type FB ON via an interface module at the deployment of the cable system so that each ON has both a three-component accelerometer and a pressure gauge as a tsunami meter. A seafloor route for the new OBCST was selected with reference to the system installed in 1996 and plans for S-net deployment. The results of a route survey carried out in 2013 were also considered.

The OBCST system shares the landing station with the older cable system. Only one end of the cable is landed, and as a result the Ethernet channels are turned at the seaward end of the cable to create a ring configuration, from the perspective of network topology. A single fiber is used for each Ethernet channel by employing WDM technology. The seafloor cable has six fibers. We implement two Ethernet channels and one clock delivery system because a fiber pair is needed to make a ring configuration. Any ON can receive/send information in both directions due to the ring configuration. At the landing station, the data are stored in a large disk unit. Collected data are decimated at the landing station and transmitted through a land-based network for data distribution. System monitoring and control can be performed remotely. Collection of seismic and tsunami data began immediately upon deployment of the system in September 2015 (Figure 1). The system was deployed using a commercial telecommunication cable ship. In the region where the water depth is less than 1,000 m, the seafloor cable and the ON (YOB1) were simultaneously buried at a depth of 1 m below the seafloor to avoid obstructing fishing activities. The installation, including burial by a cable ship, is almost identical to that for telecommunication cables. The YOB3 (Type FB ON) is mounted in a frame to allow an ROV to access the external port of the UMC. For installation of the YOB3, the seafloor cable was taken out from the cable engines for deployment, and then the YOB3 was deployed. Since this procedure is similar to the installation of a branch unit of a telecommunication system, it does not take a long time. If burial of the system is not needed, the system could possibly be deployed using an ordinal ship such as an offshore mobile platform. Positions of the stations are summarized in Table 1. One
The rotation angle (θ) is estimated using the equation
\[ \theta = \tan^{-1}\left(\frac{A_y}{A_x}\right) \]
Quick changes of the angle correspond to occurrences of earthquakes. It was reported that large ground motions during earthquakes sometimes cause the rotation of cylindrical pressure vessels of the cable observation system (e.g., Nakamura & Hayashimoto, 2019). Angles of pressure vessels change slowly over long periods of time. There is a possibility that long-term variations of the rotation are caused by a drift of the accelerometers or an attitude change of the pressure vessel due to deformation of the seafloor. The observed pressure is not affected by the small rotation of the canisters (Figure 4). Since the YOB3 has a frame attached to a cylindrical vessel (Figure 3), there is little possibility of rotation of the vessel. Consequently, a large rotation of the cylindrical vessels is not observed.

Table 1
Coordinates (WGS 84) of the ONs for the OBCST System Installed in 2015

| Station | Latitude (°North) | Longitude (°East) | Depth (mbsl) |
|---------|------------------|------------------|--------------|
| YOB1    | 39.15968         | 142.20556        | 495          |
| YOB2    | 39.06454         | 142.63959        | 1,188        |
| YOB3    | 39.00555         | 142.97364        | 1,573        |

Note. mbsl, meters below sea level; OBCST, Ocean Bottom Cable Seismic and Tsunami observation system.

Table 2
Seismic Sensor Directions Estimated Using the Acceleration Data on January 1, 2017 for the OBCST System

| Station | Sensor | Azimuth (°) | Dip (°) |
|---------|--------|-------------|---------|
| YOB1    | X      | 27          | -6      |
|         | Y      | 27          | 84      |
|         | Z      | 117         | 0       |
| YOB2    | X      | 103         | -19     |
|         | Y      | 193         | 71      |
|         | Z      | 193         | 0       |
| YOB3    | X      | 13          | -81     |
|         | Y      | 193         | -9      |
|         | Z      | 103         | 0       |

Note. Dip means angle from horizon and plus value indicates down dip.

Three accelerometers are orthogonally mounted on the frame of the observation unit, which is directly fixed to the pressure vessel. The attitude of the pressure vessel can be estimated using the outputs of the three orthogonal accelerometers because there is no leveling system for the accelerometers and the accelerometers sense gravity. The azimuths of the pressure vessels were estimated during the deployment by the cable ship and a sensing direction of an accelerometer for the Z-component is parallel to a longitudinal axis of the cylinder. Using this information, we estimated the azimuth and dip angle of each accelerometer (Table 2). For the approximate estimation of attitude of the pressure vessel, it is assumed that the pressure vessels are laid horizontally on the seafloor, in other words, pitch angles of the vessel are thought to be small. There is a possibility of rotation around the longitudinal axes of the pressure vessels because the pressure vessel of the ONs has cylindrical shape and is not fixed on the seafloor. The rotation of the vessel results in changes in the dip angle for the accelerometers.

Temperatures at the semiconductor modules (e.g., CPU) and optical modules are continuously monitored to check the system status. The monitoring data are sent to the landing station where they are stored. The CPU on each ON maintains a low temperature (<30°C) and the temperatures are stable (Figure S1). Similarly, an integrated circuit on the electric board, such as FPGA, has low-temperature levels. The buried ON (YOB1) shows a larger temperature variation over long periods compared to the other ONs. On the other hand, the ONs on the seafloor (YOB2 and YOB3) show smaller temperature variations over short periods that are not observed on the buried ON. We infer that the small variations of the temperature for YOB2 and YOB3 are caused by changes in sea water temperature because the power consumption of the ONs has little variation. The temperature of the CPU in the YOB1 rises a few degrees during winter. Since YOB1 is closest to land, there is a possibility that the temperature of the YOB1 is affected by seasonal temperature changes on land. Optical modules have the highest temperature among the electrical units, and there is little variation in temperature. The working temperatures of the optical module in the ONs are sufficiently low to remain in the specified operational temperature range. A low-temperature environment is essential for maintaining long-term operation. A design of pressure vessels that features effective heat conduction is important for long-term observations.
3. Long-Term Observation Using the OBCST System

The OBCST system was used for observations immediately following its deployment in 2015, and it sends seismic, pressure, and system monitoring data. The seismic data are decimated to 100 Hz from 1 kHz, transmitted to ERI, and distributed, using the internet in real time, to research institutions for scientific studies and agencies for disaster mitigation. The latency for distribution is generally less than 1 s. For pressure measurements, original data from the ON are also stored at the landing station as are converted values of pressure and temperature in real time that are sent to the ERI at the University of Tokyo. The monitoring data of the system consist of various information such as electrical voltages on the circuits, laser light power on data transmission units, and temperature of the electrical circuit board in the ONs. The monitoring data of the system are used to understand the status of the system. Data have been obtained from the OBCST system for more than 5 years.

3.1. Seismic Data

Seismic data from the OBCST system off Sanriku allow the study of seismic noise. The ambient noise was estimated using short-term data after the deployment and preliminary results showed that noise levels of the OBCST system were low enough for a seismic observation (Shinohara et al., 2016a, 2016b). We obtained the ambient seismic noise levels for the OBCST system using long-term data to research the noise environment. First, we calculated the power spectra for each seismometer with a time window of about 262 s and performed averaging using a smoothing frequency band of 0.02 Hz. The power spectra were estimated using the records for each day in 2017 and 2018 at midnight in Japan Standard Time (JST). Using the estimated spectra, we calculated the probability density functions of power spectra (McNamara & Buland, 2004; McNamara & Boaz, 2006). It was found that the seismic noises are temporally stable. The noise levels are low at frequencies of >2 Hz and <∼0.1 Hz (Figure 5). This level of ambient seismic noise is close to the system noise level, which is mainly determined by sensor sensitivity and is similar to noise levels for the cable system installed in 1996. Seismic noise levels observed by S-net are comparable (Uehira et al., 2018). The ON buried below the seafloor (YOB1) has lower noise levels than the other ONs. It is known that burial of the sensor package is effective in reducing seismological noise (Shinohara, Kanazawa, et al., 2014; Stephen et al., 2003; Sutton et al., 1981). In addition, the peak frequency of microseisms for the buried station (YOB1) appears to be higher than those for stations on the seafloor. Although a large variation of spectrum levels at frequencies of >1 Hz from earthquakes is clearly seen, seismic noise levels at this frequency band seem to be stable. On the other hand, large temporal variations in levels for periods of around a few seconds are recognized as changes in the magnitude of the microseisms. Some ONs have noise with monochromatic frequencies (Figure 5) that are higher than 8 Hz and appear frequently. Although levels of the monochromatic noise varied by individual accelerometers, the largest level of the noises is smaller than a level of the high noise model (Peterson, 1993). The pressure vessel of the ON is thought to have a higher resonant frequency compared to the observation frequency band, and the monochromatic noises were not identified before the deployments. There is a possibility that a small mechanical vibration of the ON is induced by connecting the seafloor.

A number of local earthquakes were clearly recorded by both the OBCST system and the previous system installed in 1996, reflecting a low and stable noise environment (Figure 6). Because the accelerometers installed into the ONs remain sensitive for long periods, many teleseismic events are also recorded (Figure S2). Earthquakes with magnitudes greater than 7.5 and epicentral distances greater than 120° were often observed. From the records of teleseismic events, the buried accelerometer seems to have better a signal-to-noise ratio for periods longer than 2 s. These records are useful in studying a deep structure below the subduction zone.
3.2. Pressure Data

A primary objective of the pressure gauge is the observation of tsunamis. Tsunami waves have periods longer than 1 min and microtsunamis have wave heights of 1 cm (e.g., Hino et al., 2001). The high-precision pressure gauges for the OBCST systems are based on the principle of crystal oscillation. The variation of oscillation frequency with stress induced by changes in pressure is recorded. The OBCST system has one pressure sensor (YOB1) buried 1 m below the seafloor and two sensors (YOB2 and YOB3) on the seafloor. Sensors in both the YOB1 and YOB2 directly output analog signals from the crystal oscillator. A pressure gauge attached to the PoE port on the YOB3 has a processor to calculate pressure, and pressure data are outputted in a digital format. Water pressures are simultaneously observed by both the system installed in 1996 and the OBCST system.

The pressure gauges used for the OBCST system have another crystal oscillator to measure the temperature of the sensor because a crystal oscillator is sensitive to temperature. Pressure is estimated using the frequency from the crystal oscillator, which measures pressure with compensation of the temperature obtained simultaneously by another crystal oscillator. Therefore, it is possible to compare the temperature fluctuations at the seafloor sensors with those at the buried sensor. The temperature of the buried sensor is strongly affected by heat generated by the ON. After deployment, the buried sensor takes time to warm up and then mutes short-term temperature fluctuations, while the seafloor sensors show short-term fluctuation.
tations due to changes in sea water temperature (Figure S3). Because the pressure gauges observe temperatures continuously from the point of deployment, long-term variation in temperatures are also noticed. The variations of the temperature of the pressure gauges are believed to correspond to the temperature of the sea water near the seafloor (Figure 7). There is another possibility that variations of the temperature measured by the pressure gauge are related to the temperature change of internal electronics due to variations in power consumption. However, power consumption at the ON is believed to be stable because the system has a constant load. The temperature at the buried sensors rises by ~2° while the system is in operation. However, YOB1 has a large change in temperature over a period longer than a month. The sensors of YOB2 and YOB3 are deployed at a depth of greater than 1,000 m in the seafloor. On the other hand, YOB1 is installed at a depth of 495 m in the seafloor. The large temperature variation of YOB1 over the long period may be related to a temperature change near the coast. Since the variations in temperature of the sensors during operation are sufficiently small, pressure can be correctly compensated using temperature data.

Data from the pressure gauges clearly recorded the tides on each sensor (Figure S4). Using the records of tides just after the deployment, Shinohara et al. (2016a, 2016b) reported that the sensitivity of the buried pressure gauge is comparable to that of the seafloor gauges. The pressure records from YOB1, which is buried 1 m below the seafloor and YOB2 on the seafloor were compared. Power spectra for both records were estimated, and coherency was calculated to evaluate the effect of sensor burying (Figure S4). Waveforms of tides recorded by YOB1 and YOB2 are almost identical. Moreover, the power spectra and amplitude of YOB1 and YOB2 are very similar. This is confirmed by the coherency. The records from YOB1 and YOB2 for the periods longer than 10,000 s are identical, and coherency decreases for the period shorter than 10,000 s. However, the average coherency for a shorter period is not as small. The distance between the YOB1 and YOB2 is about 40 km, and therefore, the tides should be different. Wang and Davis (1996) showed that burial at a shallow depth does not have a large effect on the pressure sensor for amplitude. The burying of the pressure gauge (YOB1) does not have a large effect at longer periods based on the observations of tides.

The pressure gauges have ambient noise at short periods (less than 1 min) of less than one hPa, which corresponds to a change of water height of less than 1 cm (Shinohara et al., 2016a, 2016b). An event with a magnitude of 7.4 occurred off Fukushima on November 22, 2016 and generated a moderate tsunami. The cabled systems observed the tsunami clearly (Figure 8 upper). High frequency pressure from the seismic waves of an aftershock was observed at around 06:40 JST by both YOB1 and YOB2 followed by the arrival of tsunami with periods around 15 min. The reflected tsunami from the Japan island coast is recognized at around 7:40 JST. The data collected contributed to the estimate of a focal solution (Gusman et al., 2017). According to the analysis by Gusman et al. (2017), the deployment below the seafloor does not seem to affect the sensitivity of the pressure gauge. We compare power spectra of tsunami waves observed by the buried pressure gauge, YOB1 and the seafloor pressure gauge, YOB2 to estimate the difference of the observation data for a frequency range of the tsunami waves (Figure 8 lower). The waveform of the tsunami observed by the buried sensor, YOB1 has a higher signal-to-noise ratio for short periods. The spectra of tsunami waves with periods longer than 1 min are consistent. It is concluded that the buried pressure gauge, YOB1 has the same quality and quantity as the seafloor pressure gauge for periods of tsunami waves. Power spectra of records from the buried sensor at periods shorter than 10 s are lower than those from the sensor on seafloor.

Figure 6. Example of seismograms of a local earthquake recorded by both the OBCST system and the system installed in 1996. Three components with a high-pass filter (2s) are shown. Note that orthogonal three components of X, Y, and Z do not correspond to vertical component and two horizontal components. The origin time of the event was 06:10:50.6, February 15, 2019, JST. Focal depth and magnitude were ~50 km and 3.0, respectively, according to Japan Meteorological Agency. Epicenter was positioned below a deployment area of the cable systems. JST, Japan Standard Time. OBCST, Ocean Bottom Cable Seismic and Tsunami observation system.
4. Conclusions

We developed a seafloor-cable seismic and tsunami observation system named OBCST and installed it off Tohoku, northeast Japan. A new feature of our system is the application of ICT technology, which allows it to be more compact and less expensive. The system also has IP access and software upgrade capabilities. The OBCST has other new features: Gigabit Ethernet, IEEE1588, WDM, and PoE. System reliability is achieved through redundancy, which is easily implemented using ICT. ONs on the seafloor can be accessed through TCP/IP from land. A CPU and FPGAs are implemented in the ONs, which allow the measurement parameters of the sensors to be modified and the firmware and software on the ONs to be upgraded after deployment. We installed the OBCST system in September 2015. The system has three ONs and a length of 105 km. Two of the ONs have built-in tsunami meters, and the third has an external port to which a pressure gauge was connected as an external sensor during deployment. The data from each ON are sent to our institute and data distribution center via a landing station using a TCP/IP protocol. The data are also stored at the landing station. Rotation of the cylindrical pressure vessel around a longitudinal axis may occur due to its shape. Using long-term data from the accelerometers, rotation around the longitudinal axis was estimated. No large rotation of the cylindrical vessel was observed during the observation period. Temperatures at the semiconductor modules and optical modules are continuously monitored to check system status. According to the monitoring data, temperatures of electrical and optical parts are sufficiently low and stable. Low power consumption of the system and effective heat conduction of a vessel are important because low working temperature has an advantage for long lifetime of electronics. We are able to evaluate ambient noise levels of seismic data using long-term data. Seismic data from the OBCST showed that noise levels are low enough to ensure meaningful seismic observations and stability. The ON buried below the seafloor has a lower noise environment than the ON on the seafloor. Given the low and stable noise environment, the system observed many local earthquakes and large teleseismic events. These records are useful in studying the structure and seismicity in the subduction zone. Water pressures are simultaneously observed by high-precision pressure gauges with a resolution of <1 hPa (10 mm), evaluated by practical observation. Because the pressure gauge using a crystal oscillator is sensitive to temperature, the temperature of the sensor is also recorded. Long-term variations of temperature were reasonably small. Therefore, pressure data can be correctly compensated using temperature data. A tide was clearly recorded by each pressure gauge, and the sensors clearly observed the tsunami triggered by an earthquake with a magnitude of 7.4 in November 2016. Through the evaluation of records of tides and a tsunami, it is estimated that the buried pressure gauge records data with the same quality and amplitude as the pressure gauge on the seafloor.

Data Availability Statement

The seismic data from the OBCST system are available online at http://www.hinet.bosai.go.jp/?LANG=en, and the data used to create the figures in this study are stored at http://www.eri.u-tokyo.ac.jp/people/mshino/ESS20Data/.
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