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Recent seafloor seismic and tsunami observation systems for scientific research and disaster mitigation

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Recent seafloor seismic and tsunami observation systems for scientific research and disaster mitigation

Masanao Shinohara

Resumen

Debido a su posición entre varias placas tectónicas, Japón se encuentra ante un constante riesgo de desastres naturales tales como erupciones volcánicas, sismos y tsunamis. Estos últimos tienen un gran y destructivo impacto, ya que gran parte de la población japonesa vive sobre planicies costeras. La importancia de contar con sistemas de alerta temprana ha llevado a los científicos japoneses a dar una importancia particular al estudio del lecho marino y sus características tectónicas, esto con el objetivo de comprender mejor su composición geológica y poder crear mejores y más veloces sistemas de alerta temprana con las nuevas tecnologías de transmisión y recopilación de datos.

Abstract

Due to its position between various tectonic plates, Japan is at constant risk of natural disasters such as volcanic eruptions, earthquakes, and tsunamis. The latter have a great and destructive impact since a large part of the Japanese population lives on coastal plains. The importance of having early warning systems has led Japanese scientists to give particular importance to the study of the seabed and its tectonic characteristics, in order to better understand its geological composition, and to be able to create better and faster early warning systems with new technologies for transmission and data collection.

INTRODUCTION

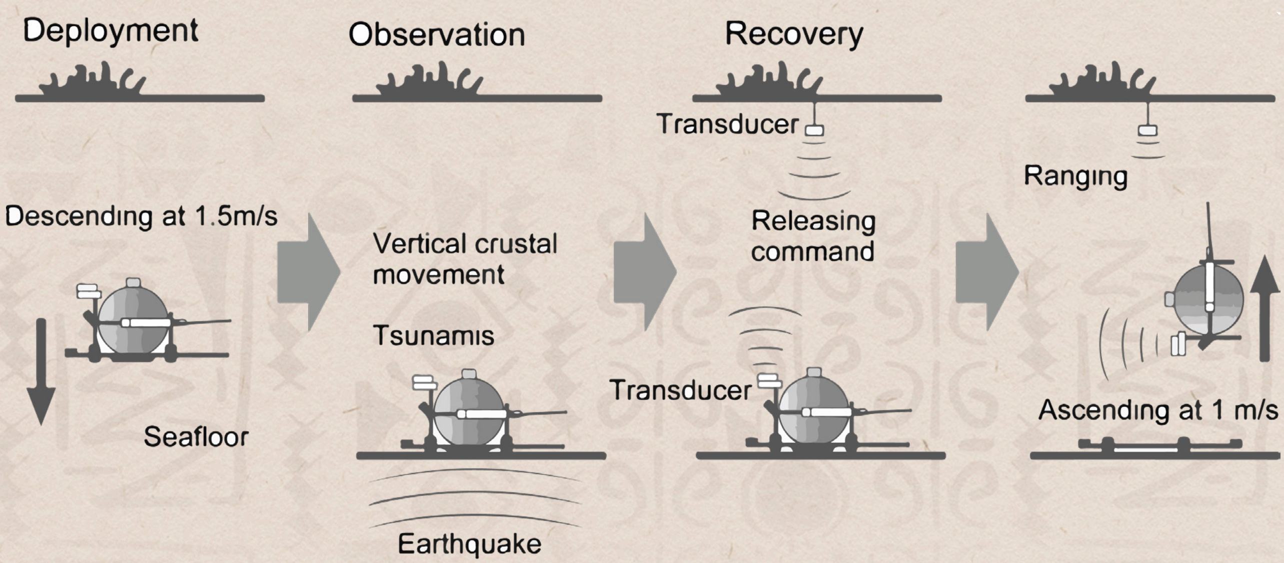
Large earthquakes cause damage to human society. The Japanese islands are positioned above the subduction zones. Destructive large earthquakes have repeatedly occurred at the plate boundary between landward plate and subducting oceanic plate. In addition, large earthquakes in marine areas often generate large tsunamis. An oceanic plate subducts below a landward plate, and a two plates interface is thought to be stuck together. The subducting oceanic plate pulls the landward plate down and strain is accumulated. When strain accumulation reaches a limit, the landward plate is rebounded. The movement of the seafloor due to the rebound of a landward plate causes tsunami. To understand exactly the generation of earthquakes, it is important to observe seismic activities and tsunamis on the sea floor just above these seismogenic zones. Marine observations have scientific advantages. We must carry out observation near events as close as possible for a precise understanding of crustal activity for researches of earthquake generation. From a view of disaster mitigation, marine observation can detect a generation of an earthquake and tsunami build up earlier than land observation. However, it is difficult to make observations in marine areas. There are some reasons. Since there is no power supply on the seafloor, the electric power that the equipment can use is limited. Generally, batteries are used for power supply for equipment on the seafloor. The equipment must be protected from seawater. Therefore, the equipment is usually installed into a waterproof capsule. In addition, large water pressure is applied to the vessel on the deep seafloor. The seawater is not transparent for radio waves and lights. We have no high-speed communication method to equipment on the seafloor. Finally, humans cannot go to the seafloor. Therefore, equipment must work autonomously.

For the last two decades, the technology of seafloor observation for earthquake, tsunami and crustal deformation has greatly progressed. As a result, various seafloor observations have been carried out and new geophysical findings have been obtained. Marine observational researche for earthquake generation and mitigation of disasters is enabled by the developments of innovative equipment. The seismic and geodetic observation systems for marine areas are broadly divided into two groups. One is the free-fall pop-up type seafloor observation systems, and the other is the observation systems using seafloor cables.

Free-fall pop-up type ocean bottom seismometer system

The Free-fall pop-up type Ocean Bottom Seismometer (OBS) is a stand-alone system. These are deployed on the seafloor by free-fall from a research vessel and are recovered by pop-up after releasing weights as a sinker. The advantage of the pop-up OBS is low-cost for the equipment and observations. In addition, they can be deployed anywhere. However, the data is obtained only after the recovery of the OBSs (Fig.1). In Japan, the development of pop-up OBS started in the late 1970s (Asada and Shimamura, 1974). Objectives of observation using OBSs are to obtain crustal and upper mantle seismic structure and the distribution of earthquakes. Early OBSs used a timer for the release of sinker weight. However, recovery was sometimes difficult due to stormy weather. In the 1980s, an acoustic release system was developed, and OBSs could be recovered during good weather (Kasahara *et al*., 1979; Kanazawa, 1986). Before the 1990s, the OBSs had analog recorder. At that time, analog recording system had advantage that they could record data continuously for more than two weeks. A disadvantage of the analog OBSs was their limited dynamic range per recording channel. A digital recording OBS emerged in the 1990's (e.g. Shinohara *et al*., 1993). The first digital OBS had the same recording duration as the analog OBSs. However, they obtained higher-quality data. The development of OBSs continues now, and pop-up OBSs can be classified by the type of sensor, and observation term.

Figure 1. Schema of seafloor observation using free-fall pop-up type ocean bottom seismometer and/or pressure gauge

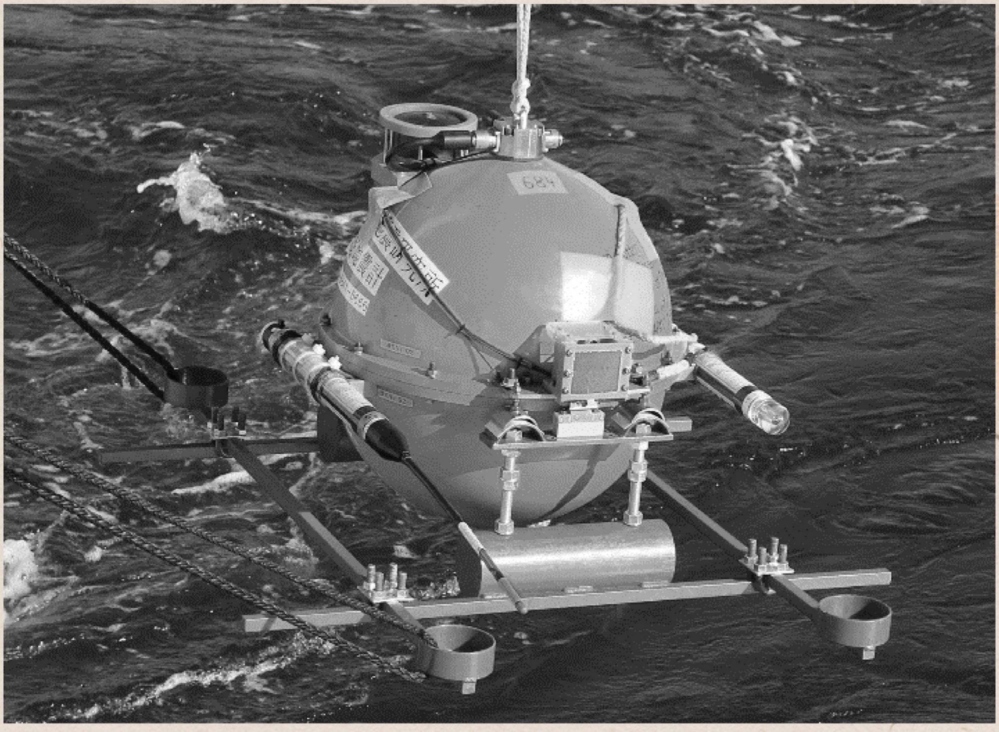


Source: Shinohara et al. (1993).

Long-term OBS

Long-term OBSs (LT-OBS) were developed at Earthquake Research Institute, the University of Tokyo to observe earthquakes continuously on the sea floor over more than one-year (Kanazawa *et al*., 2009). For the housing of the LT-OBS, a titanium-alloy sphere with 50 cm diameter was used, so as to avoid problems from corrosion of the pressure vessel (Fig. 2). The titanium-alloy vessel was tested for use at 6,000m depth. Lennartz's LE-3Dlite is used for the short-period sensors in this OBS operating with a velocity-proportional response in the frequency range between 1 and 80 Hz. Three component sensors are mounted on a leveling system. The leveling unit is equipped with two tiltmeters which have 0.1 degree accuracy. The outputs of the three seismometer components are amplified by a low-noise and low-power analog unit and are converted to 24-bit digital signals continuously. The sampling frequency is either 200Hz or 128Hz. Data is stored in memory temporarily. When the memory is full, the data on the memory is transferred to Hard Disk (HD) or SD-RAM. Power to all the electric circuits (CPU, sensors, leveling system, and HD/SD-RAM) is supplied by lithium battery cells. Each cell has a power capacity of 30Ah. Although the number of battery cells depends on the intended duration of the recording, approximately 50 battery cells are needed for one-year observations for recorders using HD. When we use the recorder with SD-RAM, a recording period reaches approximately two years. The LT-OBS is equipped with an acoustic release and communication system. The most important function of the acoustic system is to release weight for recovery. After an acoustic release command is sent from an interrogator on the ship, the acoustic system on the OBS provides electric power to a weight release unit, causing rapid electrical corrosion of the strap holding the weight. Another function of the acoustic system is communication between the seafloor and sea surface. The recording unit on the OBS can be controlled from the interrogator onboard, for example, starting or stopping recording, leveling the sensor, and checking the status of the recording unit.

Figure 2. Photograph of a long-term ocean bottom seismometer just before deployment
Orange sphere is made of titanium alloy and contains equipment for seismic observation.



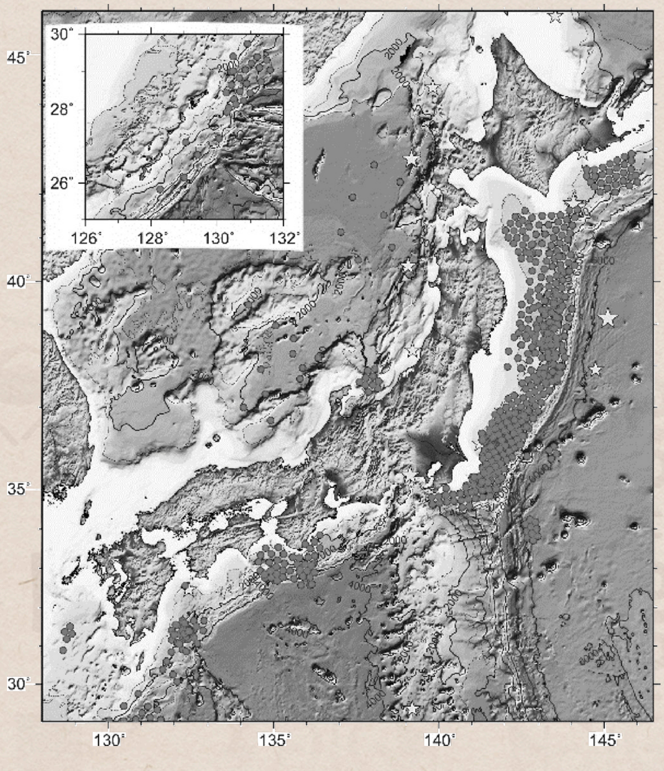
Source: Shinohara *et al*. (2018).

Improvement of the system continues after the development of the LT-OBS. Since an LT-OBS is designed for high-sensitivity observation, OBS records of large earthquakes happening near an OBS are often saturated. Therefore, a new OBS to obtain accelerograms with low-sensitivity (strong-motion) was developed by installing of a small three-component accelerometer to LT-OBS (Shinohara *et al.*, 2009). Recently, compact broadband seismometers with low-power consumption have become available. Therefore, the short-period seismometer can be replaced with a compact broadband sensor. We adopt seismometers with a natural period of 20 seconds or 120 seconds (Shinohara *et al.*, 2018). A pressure gauge with high precision is useful to observe a temporal variation of water pressure, which corresponds to vertical crustal movement or tsunamis. Ocean Bottom Pressure gauge (OBP) has been developed using the technology of the LT-OBS and used for seafloor observation at the present. A recording period of the OBP with a 50 cm diameter pressure vessel reaches more than two years.

The appearance of the LT-OBS enables us to make long-term monitoring on the seafloor by replacing LT-OBSs. From 2003, dense seafloor earthquake observations using LT-OBSs in the landward slope of the Japan trench and Nankai trough where large interplate earthquakes occurred repeatedly have been performed (Fig. 3). As a result, we obtained the precise hypocenter distribution in the observation areas, and the precise hypocenter distribution of earthquakes that enabled us to estimate the geometry of the plate boundary. Additionally, seismic surveys using OBSs and controlled sources were carried out in these regions, and the seismic structures from marine surveys are useful as references of the position of the plate boundary. For example, the geometry of the subducting Pacific plate from the trench to the coast of Hokkaido and southern Tohoku Japan was estimated. The Pacific plate started to subduct with a small angle in the whole study area. The subducting angle of the Pacific plate rapidly increases where the plate reaches a depth of 30 km. It is inferred that a spatial spread of source the region of large earthquakes is related to the shape of the plate boundary. The seismic monitoring in the landward slope of the Japan trench using the LT-OBS continues after the 2011 Tohoku-oki earthquake.

Figure 3. Deployed positions of long-term Ocean Bottom Seismometers (LT-OBSs) from 2003 when the LT-OBS was developed

All positions of deployed LT-OBSs are shown until July, 2018. LT-OBSs were also deployed off Mexico, off Chile, and off New Zealand, back-arc basin of Mariana



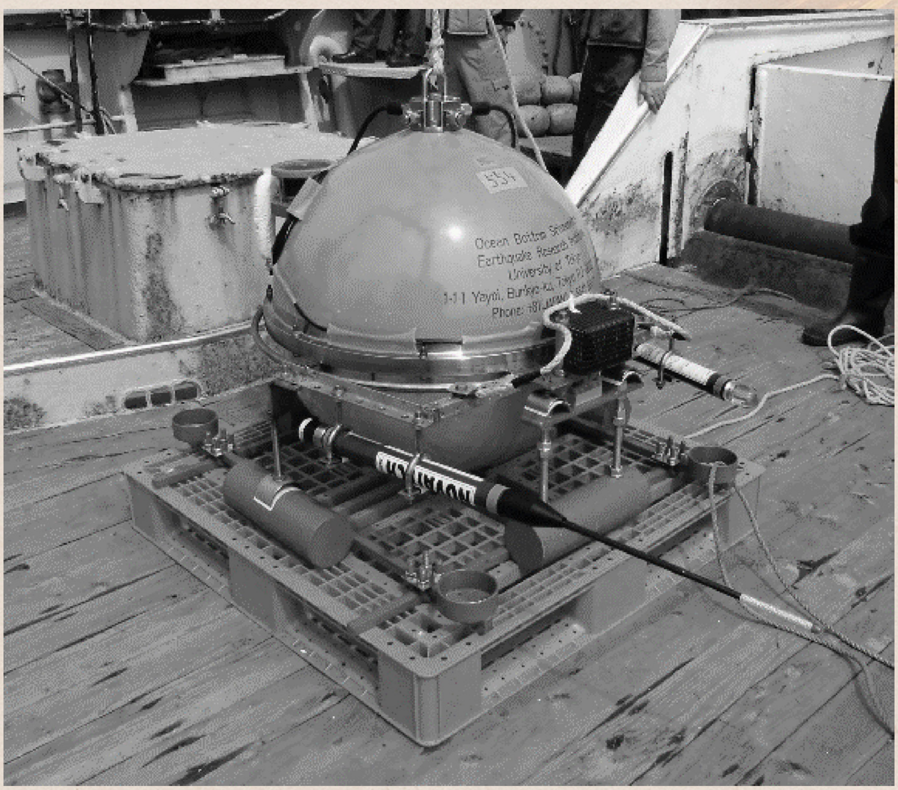
Source: Shinohara *et al*. (2018).

Large earthquakes occurred near the Pacific coast of Mexico by the subducting oceanic plate. In the subduction zone off and below the coast of the state of Guerrero, Mexico (Guerrero seismic gap), no large earthquakes have been known for at least 60 years. To obtain detailed crustal activities in marine area of the Guerrero seismic gap, seafloor seismic and geodetic observation in the Guerrero seismic gap is being performed as a part of the Science and Technology Research Partnership for Sustainable Development (SATREPS). Seven LT-OBSs and two LT-OBPs in November 2017 were deployed in cooperation with Instituto de Geofísica, Universidad Nacional Autónoma de México as a part of this marine observation (Cruz-Atienza *et al.*, 2018). Because it is known that large long-term slow-slip events occur approximately every 3.5 years in the gap, the OBS/P network also tries to observe slow earthquakes associated with slow-slip events. Recovery of installed LT-OBSs and LT-OBPs was performed in November 2018 and all equipment was successfully recovered.

Broadband OBS

Based on long experience with the short-period short-term OBS, a broadband OBS (BBOBS) has also been developed at ERI, the University of Tokyo (Kanazawa *et al.*, 2009). BBOBS is equipped with broadband sensors. This system is also mobile, compact, reliable and easy to operate and enables long-term observations. These BBOBSs have been used since 1999, obtaining scientific results and offering more opportunities for observations, especially in the long-period range. The design of the BBOBS (Fig. 4) is the same as that of the LT-OBS. A sphere-type pressure vessel contains all units. A method of installation and recovery also adopts a free-fall and pop-up system for the BBOBS. Low power consumption of the sensor and logger, including the accurate clock, is important for long-term observation on the seafloor. A light weight for the sensor and recording system of the BBOBS contributes to keep positive buoyancy during recovery despite a limited volume of the pressure vessel. The titanium-alloy pressure vessel has a diameter of 65 cm, which is slightly larger than the LT-OBS, as required to contain the broadband seismic sensor with its larger volume and additional batteries needed to power the broadband sensor. The sensor was specially made for the active leveling unit. The mechanical part of the sensor and the electronics board for the sensor control can be physically separated to implement the active leveling system. When the BBOBS is deployed at the deep seafloor, the inside of the housing is an ideal operating environment for the sensor (and also the crystal-oscillator clock) because of the small temperature variations experienced and the absence of human activity compared to land observatories. The amount of the data stored is about 4 GB for one month if the sampling rate is 200 Hz for three components and when using a completely recoverable compression method.

Figure 4. Photograph of the Broadband Ocean Bottom Seismometer (BBOBS) before deployment
The shape of the BBOBS is similar to that of the LT-OBS, however, the pressure vessel is larger due to sensor size.



Source: Shinohara *et al*., (2018).

Geodetic observation on the seafloor becomes more important for large earthquakes research occurring at plate boundaries. A new system to extend the observation period toward long periods by adding a precise absolute pressure gauge (APG) to the BBOBS was developed (Shiobara *et al*., 2014). To increase the resolution of pressure measurement, counting the APG's signals is based on the highly stable frequency source inside the OBS recorder. The BBOBS with APG (BBOBSP) can observe micro-earthquakes, teleseismic events and vertical crustal movement simultaneously.

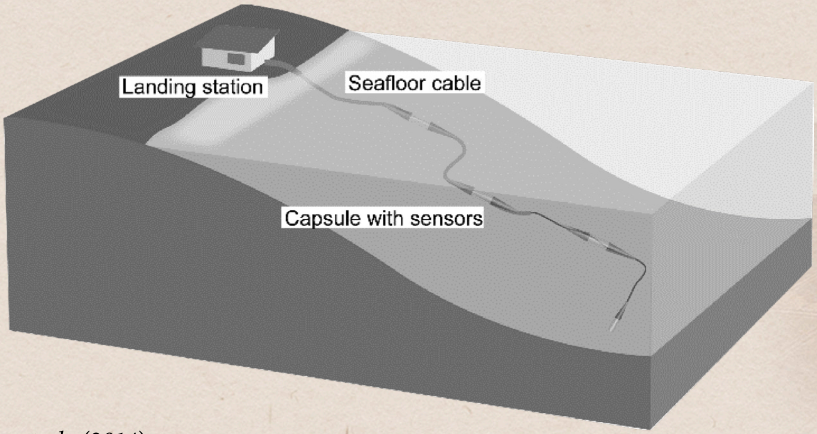
Seafloor cabled observation system

A seafloor cabled system where sensors are equipped in a hermetically-sealed pressure capsule and these cases are connected with cables (Fig. 5), can make monitoring in real-time for long-term in marine environment. Especially seismic and tsunami observations by using a seafloor cabled system are useful from views of disaster mitigation. In Japan, the Pacific plate is subducting below northeastern Japanese islands, and several destructive earthquakes occurred at a boundary between the Pacific plate and landward plate. Disaster mitigation needs to recognize occurrence of a large earthquakes as early as possible. A seafloor cabled system is also a powerful tool for studying of the plate subduction and earthquake generation. Therefore, a seafloor cabled system with seismometers and tsunami-meters was developed based on a submarine telecommunication cable system, and have been used over the past 25 years around Japan (Kanazawa and Hasegawa, 1997). In Japan, the development and installation of cabled observation systems were started in the 1980s. The first generation of seafloor cable systems used analog telecommunication technology for data transmission, and high reliability was kept on individual electric and mechanical parts. During the 1990s, optical fiber for digital data transmission was used (The second generation of seafloor cable system). The first system of the second generation was deployed by ERI, the University of Tokyo off the Izu Peninsula. The second generation is mainstream for the cabled observation system in Japan at the present. During the 2010s, large-scale seafloor cable networks were constructed based on the second-generation technology (Fig. 6).

The ense Oceanfloor Network system for Earthquakes and Tsunamis (DONET) was installed in the landward slope of the Nankai Trough. The objectives of DONET are monitoring crustal activities and tsunamis before a large earthquake in the Nankai Trough. DONET system consists of two subsystems. Each subsystem is an expandable cable system that has a back-born cable with high reliability and a branch unit connecting to the back born cable. After the deployment of the back born cable, an underwater robot connects sensors to the cable system (Kaneda *et al*., 2015; Kawaguchi *et al*., 2015). Installation of DONET1 started in 2006 and the construction was completed in 2011. The DONET1 has 22 observation stations and each station has various types of sensors, e.g. strong motion meter, broadband seismometer, absolute pressure gauge. As of 2010, DONET2 was under construction in the western part of DONET1. DONET can be connected to a seafloor borehole observatory. Pore pressure data from a seafloor borehole revealed that small slow slips occur repeatedly near the trench at the Nankai trough (Araki *et al*., 2017).

Figure 5. Schema of seafloor cabled observation system

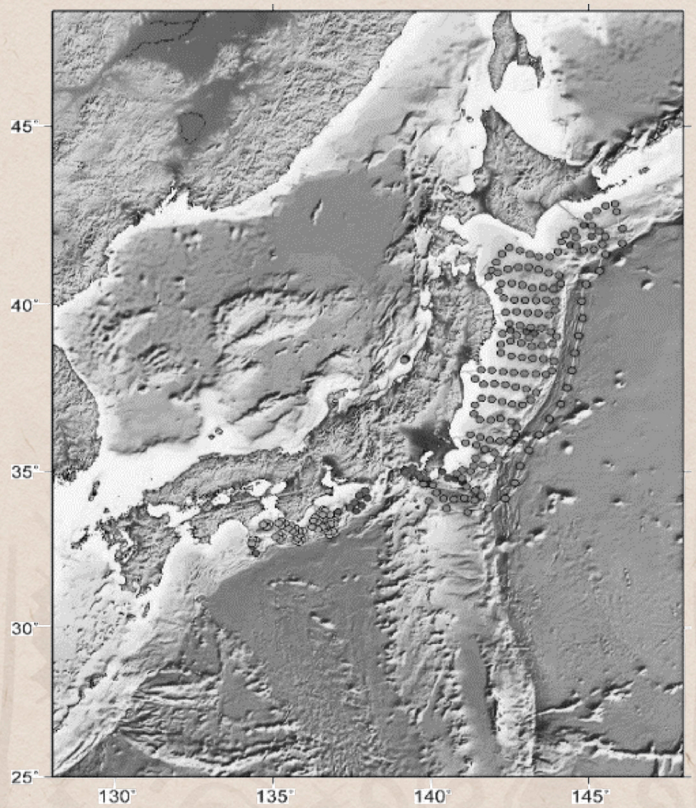
A sealed capsule contains seismometers and/or pressure gauge as tsunami-meter. Capsules are generally connected in series by seafloor cable (in-line system).



Source: Shinohara *et al*., (2014).

Figure 6. Positions of seafloor cabled stations around Japan as of March 2019

Blue and red circles indicate stations of the 1st and 2nd generation system, respectively. Yellow and green circles denote stations of DONET and S-net, respectively. Orange circles mean stations of the 3rd generation system which introduces ICT.



Source: Shinohara *et al*., (2014).

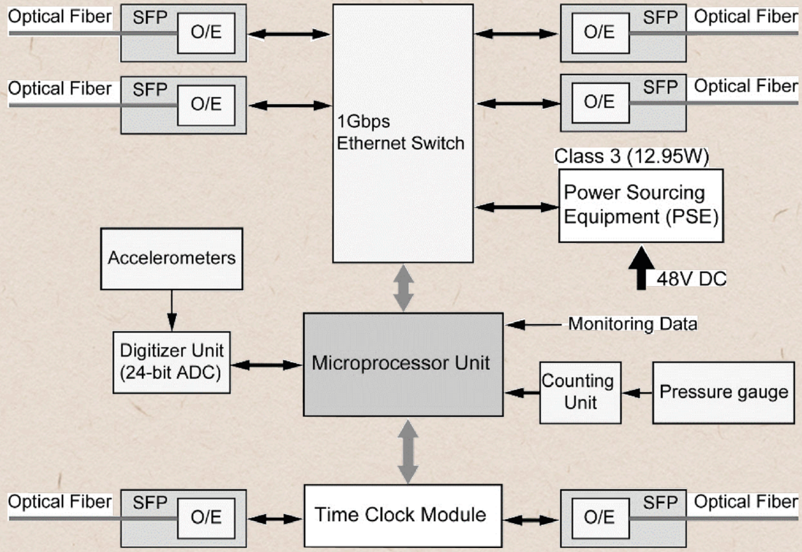
The seafloor observation network for earthquakes and tsunamis along the Japan trench (S-net) was constructed for early detection of earthquakes and tsunamis occurring near the Japan trench (Kanazawa et al., 2016; Mochizuki *et al*., 2017). In this region, the Tohoku-oki earthquake occurred in 2011 and caused a lot of damage to human society. The S-net consists of six subsystem. The subsystems have a cable length of 730 - 1470 km and 22 - 28 observation units are inserted in a seafloor cable (in-line system). The S-net has 150 observation stations in total. An interval of station is about 30 km in the east-west direction that is roughly perpendicular to the Japan Trench axis and is 50-60 km in the north-south direction. Each observation unit has short-period seismometers, accelerometers, and absolute pressure gauges which are useful for tsunami detection. Subsystems covered within the region from off-Hokkaido to off-Boso Peninsula. One subsystem was deployed in the outer rise region of the Pacific plate. Both ends of the cable for each subsystem are landed for redundancy in view of power supply and data transmission. Construction of the S-net began in 2013. In 2017, deployment of all subsystems was finished and started to collect the data. The S-net system is buried in coastal areas to avoid social activity. Seismological noise levels recorded by the buried observation units are generally smaller than those recorded by the observation units on the seafloor (Uehira *et al*., 2018).

Several observation stations in marine areas are still smaller than that of land seismic networks, although large scale seafloor cable observation systems have been deployed and operated. The spatial high-density observation is preferred for monitoring seismic activities and research of earthquake generation in marine areas. In addition, there are seismogenic areas without a seafloor cable network system around Japan. Limitation of several sensors and lack of seafloor networks mainly cause cost of a system. In addition, the existing seafloor cabled system does not have sufficient flexibility of measurements after installation. To obtain precise seismic activities and tsunami generation, the observational network with seismometers and tsunami gauges must cover the source region of a large earthquake with high spatial density. Moreover, the system has high-flexibility of observation and low maintenance costs. The cost of the system should be minimized. For these reasons, development of a new system was started. The new system should be compact and low-cost with high reliability. To satisfy the objectives, Internet Communication Technology (ICT) and up-to-date electronics technology are introduced (The third generation of seafloor cable system). The observation unit consists of sensors, CPU with Operation System and Ethernet switch (Kanazawa *et al*., 2007). Based on this concept, a new compact cabled observation system with low cost was designed. Observation unit of the new system was downsized by introducing a software which controls the system and processes the observed data. Because the system has redundancy which is easily implemented using the ICT, the system keeps reliability (Yamazaki *et al*., 2012). The first system based on this concept was developed as the Ocean Bottom Cabled Seismometer (OBCS) system and deployed in the Japan Sea (Kanazawa and Shinohara, 2009; Shinohara *et al*., 2014).

Earthquake Research Institute, the University of Tokyo had installed a seismic and tsunami observation system using seafloor optical fiber in the off-Sanriku area for seismological study in 1996. This seafloor cabled system is based on the telecommunication technology (the second generation system), and seismic waves and tsunamis had been observed continuously in real-time since the deployment of the system. The 2011 Tohoku-oki earthquake has the largest magnitude in the instrumental record of Japan, and the hypocenter was positioned at a plate boundary between the Pacific plate and the landward plate below a landward slope of the Japan Trench. The system observed seismic waves and tsunamis generated by the 2011 Tohoku-oki earthquake and sent data to the ERI until about 30 minutes after the mainshock. However, the landing station of the system was damaged by the huge tsunami, and an observation has been discontinued. The data from the system are essential to estimate the accurate position of the source faults and the source process of the 2011 event (Fujii *et al*., 2011). Because the system is dispensable to obtain data from the seafloor in real-time, restoration of the existing system was decided. In addition, development and installation of the new system using ICT was planned for additional observation and/or replacement of the existing system.

Development of the new system started in 2012. The new system is placed in the second system of the third generation and is named Ocean Bottom Cabled Seismometer and Tsunami-meter (OBCST) system. The OBCST system has both seismometers and tsunami-meters as scientific sensors. A seismometer is a conventional force balance accelerometer (JA-5TypeIII, Japan Aviation Electronics Industry, Ltd.), and three accelerometers are used for three-component observation. A high-precision pressure gauge, using a crystal oscillator (Paroscientific Inc. series 8B), was adopted as a tsunami-meter. A pressure gauge outputs measurement as changes of frequency of oscillation. A microprocessor unit has an interface of a pressure gauge and counting unit of frequency of oscillation (Shinohara *et al*., 2014). The microprocessor unit consists of a processor of SH-4 and an FPGA which handles the interface to a digitizer for seismometers and pressure gauge (Fig. 7). The Linux system is implemented on the measurement unit to control all the system. Analog signals from three accelerometers are synchronously digitized by 24-bit sigma-delta A/D converters with a sampling rate of 1 kHz. A time window for counting frequency of oscillation from pressure gauges is 1 ms and a reference clock for counting is sent from a GPS clock in a landing station. Resolution of pressure gauge corresponds to less than 1 mm height change of sea surface. The OBCST uses standard TCP/IP protocol with a speed of 1 Gbps for data transmission, system control and system monitoring. The Wavelength Division Multiplexing (WDM) is introduced to reduce several optical fibers.

Figure 7. System block diagram of the observation unit for the OBCST system



Source: Shinohara *et al*. (2014).

Timing with high precision is important for seismic observation. A clock signal is delivered to all observation units from the GPS receiver on a landing station using dedicated simple dedicated fibers. The clock lines are also used for communication to the Linux system when the TCP/IP network is not available. The observation unit also has an atomic clock module with an accuracy of less than 10^{-8} in case a clock from a landing station has a problem. In addition, IEEE-1588 (Precision Time Protocol, PTP) is implemented in the OBCST system to synchronize a real-time clock in the observation units to a land-based system clock driven by GPS through TCP/IP protocol. We evaluated the clock accuracy of the implemented IEEE-1588, and found that an error of timing is less than 300 ns through the switches (Shinohara *et al*., 2014).

Two types of observation units were developed. Both types have three accelerometers as seismic sensors for a three-component ground motion observation. One type (Type FA) has a pressure gauge as a tsunami sensor. Another type (Type FB) has an external port for additional observation sensors. The power for additional sensors on the seafloor is supplied by using Power over Ethernet (PoE) technology. Because the system has an Ethernet switch in an observation unit (Fig. 7), it is not difficult to implement a PoE port. The power sourcing equipment (PSE) unit for PoE was developed. The PSE provides electric power of about 12 W to an additional sensor and 10 Mbps Ethernet is used for data transmission and communication. Because an underwater mateable connector (UMC) is used for the external port, an additional sensor can be replaced after the deployment of the cable system. For both types, four electric lines must penetrate the pressure capsule. Feed-through technology for four metal conductors was reproduced. Therefore, the pressure capsule does not use an underwater dry connector at all. A smaller size of the standard canister of telecommunication seafloor cable system is used to reduce cost. The capsule for the observation node has a diameter of 26 cm and length of about 1.3 m. This small size of the canister has an advantage for burying the system below seafloor (Fig. 8).

Figure 8. Photograph of observation units of the OBCST system, which was deployed off Sanriku, Japan in 2015

The size of the pressure vessel is comparable with that of a repeater for an ordinary optical seafloor communication system.

Source: Shinohara *et al*. (2014).

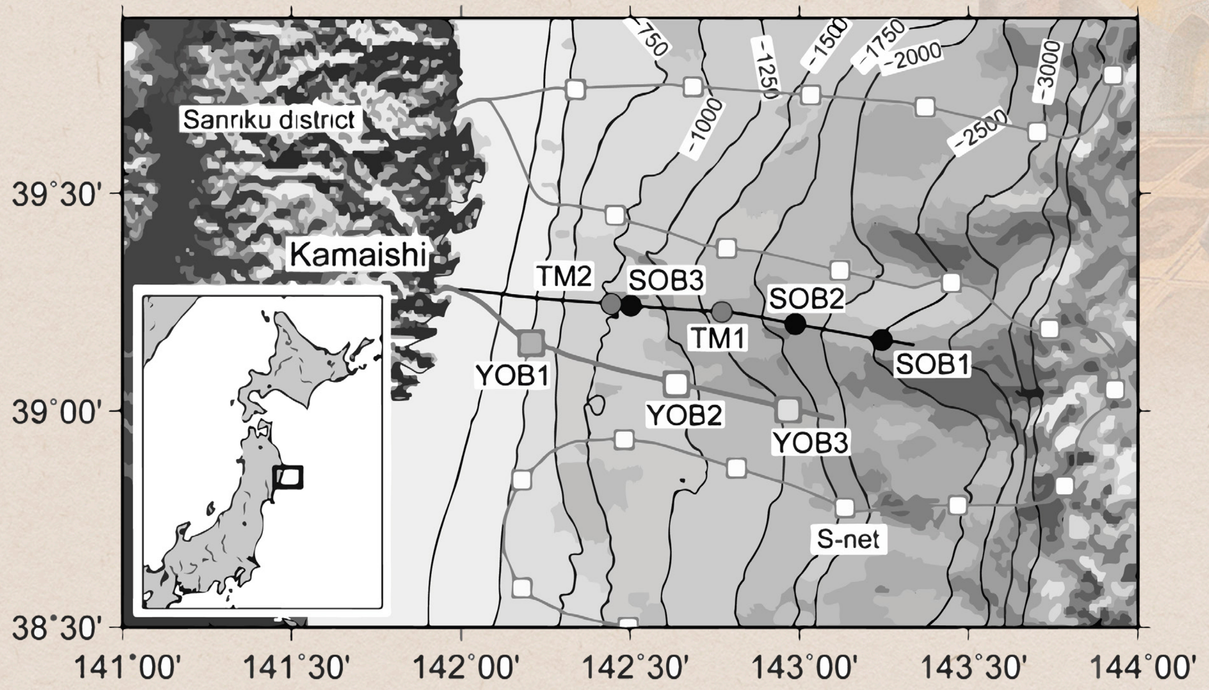
The new system has a total cable length of 105 km and three observation units with 30 or 40 km spacing. Two units are type FA, and the furthest unit is Type FB. At the deployment of the cable system, we attached a precise pressure gauge with digital output to Type FB. Consequently, all the observation units have a three-component accelerometer and pressure gauge as a tsunami-meter. A route for the OBCST system was selected considering of those of the existing cable and plans for another new cable system, and a route survey was carried out in 2013.

The existing system has a single landing station. The OBCST system shares the landing station, which was rebuilt for the existing system. Therefore, the Ethernet channel is adapted to be turned at the seaward end of the cable. Due to the introduction of the WDM for the OBCST system, only one fiber is needed for one Ethernet channel. Since the seafloor cable has six optical fibers, four fibers are used for the Ethernet channels and two fibers are employed for the clock delivery. The data transmission channel using the Ethernet is duplicated and both of the Ethernet channels are placed at the ON farthest from the landing station for the ring configuration. The clock module also has a duplicated channel for redundancy. The data from an observation unit are transmitted to the landing station. At the landing station, the data is stored in a large hard disk. Decimated data is transmitted to the Data Center in Nagano for data distribution. When a remarkable event occurs, all the data from the event can be retrieved via the Internet. The system control commands are sent from the ERI.

Deployment of the OBCST system was carried out in September 2015 by using a commercial telecommunication cable ship (Fig. 9). First, the cable ship swept the seafloor along the cable route to remove obstacles on the seafloor. the cable end was landed at the landing station and the cable ship started deployment of the cable system offshore. In the region where the water depth is less than 1,000 meters, the submarine cable and the observation unit (YOB1) were simultaneously buried using a plough-type burial machine. Burial depth is 1 meter below the seafloor. Finally, a remote operated vehicle (ROV) buried the submarine cable around the landing point. After finishing the deployment, data recording was immediately started (Shinohara *et al.*, 2016).

Figure 9. Positions of the deployed ITC system

Large squares indicate the position of observation units for the OBCST system. Block and red circles indicate seismic stations and tsunami observation stations of the previous cable system deployed in 1996 by The University of Tokyo, respectively. Small squares denote stations of S-net.

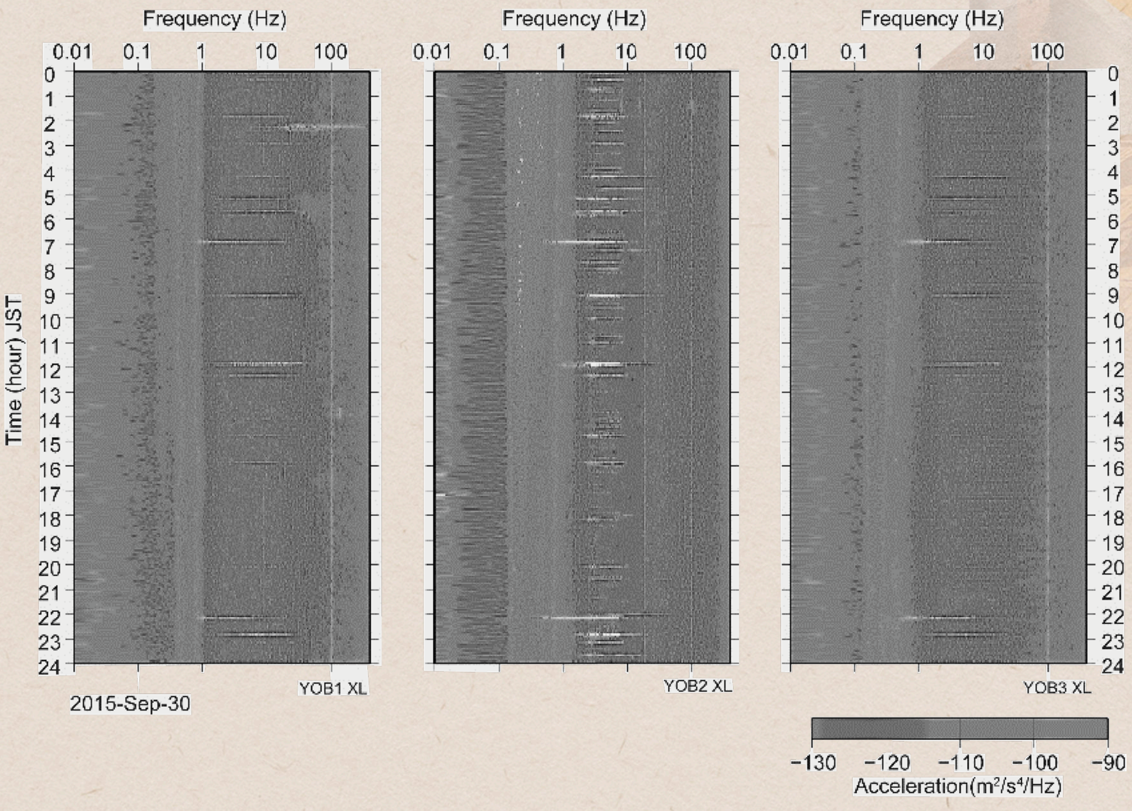


Source: Shinohara *et al*. (2016).

The seismic data from the OBCST system enable us to study the seismic noise. The spectrum of the ambient seismic noise is calculated (Fig. 10). It is found that the noise levels at the OBCST system are low at frequencies greater than 2 Hz and smaller than 0.1 Hz. This level of ambient seismic noise is close to a typical system noise. In addition, the noise levels at the OBCST system are comparable to those at the existing cabled system. The burial observation unit below the seafloor (YOB1) has a low noise environment. It is known that burial of the sensor package is effective for seismological noise reduction. Reflecting a low noise environment, a small earthquake was recorded clearly by the OBCST system.

Figure 10. Running spectra of the records from the OBCST system. Spectra were calculated using one-day records on September 30th, 2015

The spectra for low-gain channel of an X component are shown for all the observation units. There is little change in noise levels above 1 Hz. Many earthquakes are visible on the running spectra.

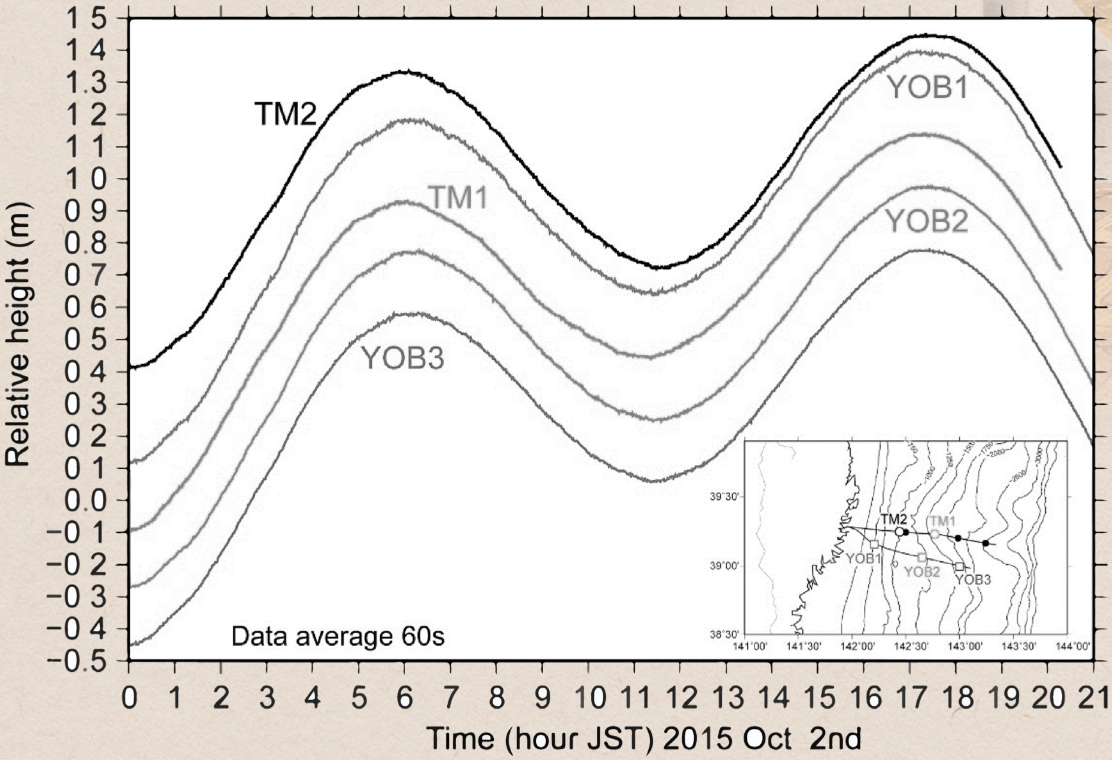


Source: Records from the OBCST system on September 30th, 2015.

Water pressures are simultaneously observed by high-accurancy pressure gauges from both the OBCST system and the existing system. Since a crystal oscillator type pressure gauge is temperature sensitive, the sensors also observe the temperature. It is found that the temperature of the buried observation unit (YOB1) does not change. Other sensors on the seafloor have small variations of temperature which may have originated by the change of seawater temperature near the seafloor. Comparing data from each pressure gauge for tidal change, it is also found that the sensibility of the pressure gauge which is buried does not have a large change compared to that on the seafloor (Fig. 11). From the data, the pressure gauge has a resolution of less than 1 hPa, which corresponds to a change of water height of less than 1 cm, and data from all the sensors are consistent.

Figure 11. Records from pressure gauge by the OBCST system and the existing system

The data are averaged using 60 seconds windows and pressure values are converted to variation of sea surface height. Pressure gauges have a resolution of less than 1 hPa.



Source: Records from pressure gauge by the OBCST system

Conclusions

The technology for ocean bottom seismic and tsunami observation has been greatly developed for the past twenty years. As a result, various seismic and tsunami observations have been carried out around Japan and new geophysical findings are obtained. For seafloor seismic and pressure observation, long-term ocean bottom seismometer (LT-OBS) and broadband ocean bottom seismometer (BBOBS) were developed. At the present, LT-OBS and BBOBS have large variations of equipping sensors. As a result of long-term observations, precise seismic activities including low-frequency events in marine areas, especially under the landward slope of trenches, are revealed.

A seafloor cabled system, where the sensors are equipped in a hermetically-sealed capsule and these capsules are connected with seafloor cable, is the best solution for real-time observation in marine areas. During the 1990s, the system with optical fiber for digital data transmission was developed and installed. The system using this technology is popular for the cabled observation system in Japan even at the present. During the 2010s, large-scale seafloor cable networks were constructed based on the technology. Dense Oceanfloor Network system for Earthquakes and Tsunamis (DONET) which is an expandable system on the seafloor was installed in the landward slope of the Nankai Trough. A seafloor observation network for earthquakes and tsunamis along the Japan trench (S-net) with 150 observation units was constructed for early detection of earthquakes and tsunamis occurring near the Japan trench.

A new seafloor cabled observation system named the Ocean Bottom Cabled Seismometer and Tsunami-meter (OBCST) system was developed and installed in the source region of the 2011 Tohoku-oki earthquake in September 2015. The OBCST system is characterized by the application of ICT technologies. By using the ICT, the system becomes compact and less expensive. IP access and an upgrade of software in the system are enabled. The OBCST has a three-component seismometer and pressure gauge. In addition, Power can be added over the Ethernet interface. Reliability of the system is kept by using a redundant system which is easily constructed using the ITC. The total length of the seafloor cable is 105 km and there are three observation units. The seismic data from the OBCST system shows the noise levels are comparable to those at the existing cabled system. Pressure gauges have a resolution of less than 1 hPa, which corresponds to a change of water height of less than 1 cm.

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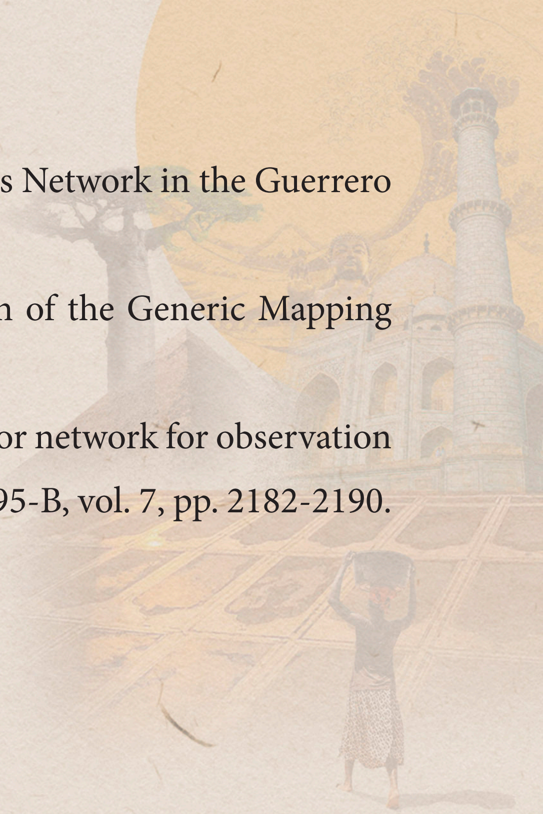

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