Distributed Acoustic Sensing measurement by using seafloor optical fiber cable system off Sanriku for seismic observation

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***Abstract*—Recently Distributed Acoustic Sensing (DAS) measurement which utilizes an optical fiber itself as a sensor becomes popular. In 1996, a seafloor seismic tsunami observation system using an optical fiber cable was deployed off Sanriku by Earthquake Research Institute, the University of Tokyo. The system has spare (dark) optical fibers without repeaters. We start development of a seafloor seismic observation system by the DAS technology with Sanriku cable observation system as a next generation of marine seismic observation system. In February 2019, we made a pilot observation of a DAS measurement using a dark fiber of Sanriku seafloor observation system. The data were collected continuously for about 46 hours and many earthquakes including micro-earthquakes and a deep earthquake were recorded.**

Keywords—Seafloor cable observation system; Distributed Acoustic Sensing; Earthquake observation

I. INTRODUCTION

A seafloor cabled system has advantage in marine environment for real-time and long-term observations. Seismic and tsunami observations by using a seafloor cabled system are important from views of disaster mitigation. The Pacific plate is subducting below northeastern Japanese islands, and several destructive earthquakes occurred at a boundary between the Pacific plate and a landward plate. A seafloor cabled system is also a powerful instrument for study of the plate subduction and generation of earthquakes. Therefore a seafloor cabled system with seismometers and tsunami-meters was developed based on a submarine tele-communication cable system, and have been used over the past 25 years around Japan [1, 2]. The early seafloor seismic and tsunami observation systems have a limited number of seismometers and tsunami-gauges. Although the seafloor cable observation systems are useful [3-6], the number of the equipped seismometers and tsunami-gauges for the existing seafloor cabled systems is not enough for detailed researches of seismic activities in marine area. Limitation of a number of sensors mainly causes a cost of a system. Recent cable observation systems transmitted seismic and tsunami data digitally from scientific sensors to landing stations by using technologies of commercial seafloor telecommunication. Although the early system adopted peer to peer data transmission, recent system uses Wavelength Division Multiplexing (WDM) method for communication between a node and a landing station.

A. *Deployment of large scale cable observation system*

According to efforts to lower a cost by using up-to-date technology, a number of sensors for a cable system is increasing. Since 2010, seafloor cable observation system becomes a large-scale and is being enlarged as a sensor network (Fig. 1). Dense Oceanfloor Network system for Earthquakes and Tsunamis (DONET) is large scale seafloor observation system deployed in the Nankai Trough region. DONET1 was completed in 2011 and was installed off Kii Peninsula where Tonankai Earthquake occurred. DONET1 has twenty-two geophysical stations and each station has a strong motion meter, a broadband seismometer, absolute and differential pressure gauges, a hydrophone and a precise temperature meter. A significant feature of the DONET system is an expandable cabled system. DONET system has a back-born cable with a high reliability which is achieved by using the seafloor tele-communication technology and can be connected a scientific node by using an underwater vehicle after the installation[7, 8]. From 2010, construction of DONET2 which is covered with Kii Strait had been started. Some improvements were applied to the DONET2 for connection of more stations and longer cable length. DONET system can be connected to a seafloor borehole geophysical observatory for long-term monitoring. Pore-pressure data from the seafloor borehole observatory revealed that small slow-slip events on the plate interface recurred[9]. The Tohoku-oki Earthquake with a magnitude of 9.0 occurred on March 11,

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2011 and gave a large damage to human society. There is a possibility that large aftershocks follow and generate tsunami again. Construction of Seafloor observation network for earthquakes and tsunamis along the Japan Trench (S-net) was started in 2013 to detect generation of a large earthquake and tsunami as early as possible[10,11]. The S-net consists of six subsystems and subsystems have cable lengths of 730 km to 1470 km and 22 to 28 observation nodes. The sensor (observation node) is connected to seafloor cable in serial (in-line system). Each node has short-period seismometers, accelerometers, and absolute pressure gauges. Both ends of the cable are basically connected to landing stations to duplicate power supply and data communication. Five subsystems are deployed in the landward slope of the Japan Trench off Boso Peninsula of Chiba Prefecture, off Ibaraki-Fukushima Prefectures, off Miyagi-Iwate Prefectures, off northern Sanriku, off Hokkaido-Aomori Prefecture. One subsystem is installed on the Pacific plate. Six subsystem were completed in 2016 and immediately started data collection. The system is buried in costal areas to avoid a conflict with social activities. Seismological noises of buried nodes are smaller than those of nodes on seafloor. This means that observation using a buried node has an advantage for earthquake observation [12].

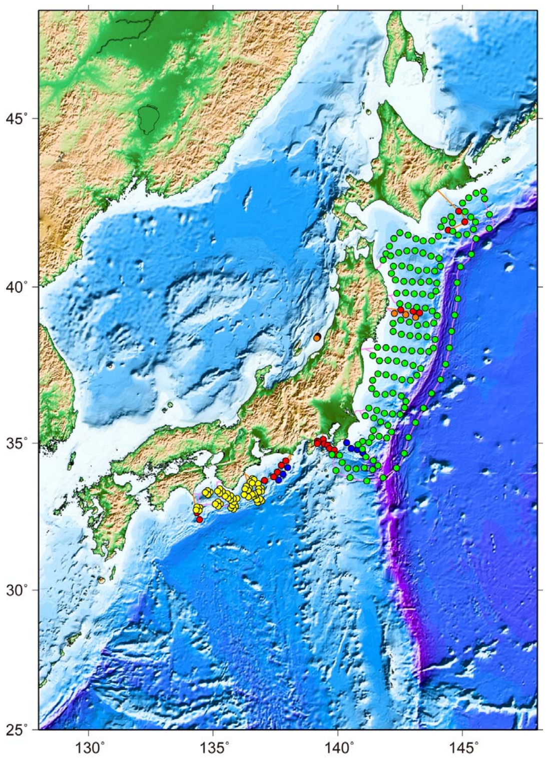

Fig. 1 Positions of seafloor observational stations around Japan as of March 2019. Blue and red circles indicate stations of the systems deployed before 2010. Yellow and green circles denote stations of DONET and S-net, respectively. Orange circles mean stations of the system introducing Internet Communication Technology (After [13]).

B. Cable observation system using ICT

A number of real-time seafloor stations has increased rapidly by installation of the DONET and S-net after the Tohoku-oki Earthquake, and monitoring methods using seafloor data are developing at the present. However a number of seafloor stations is still much smaller than that of land stations on the Japan islands. A number of seafloor real-time station must be increased from views of scientific researches and real-time warnings of earthquake and tsunami. A cable observation system with more stations by up-to-date technology is being expected.

Development of seafloor cabled system of the next generation using Information and Communication Technologies (ICT) is carried out from late 2000's [14]. The ICT system aims for low costs in both production and installation to deploy many observation nodes in target areas. In addition, the ICT system has a flexibility for installation, observation and maintenance. The developed system is in-line type and uses up-to-date technology for commercial purposes. The ICT system has two dual methods for communication. One is a ring configuration, and another is a doubled ring configuration. High reliability is accomplished by redundant system which is easily constructed by ICT. Because a Central Processing Unit (CPU) and Field-Programmable Gate Array (FPGA) can decrease the number of circuits and parts, the cost of the system can be reduced. Introduction of a CPU leads a software based system for flexibility of system. The first system based on this concept was developed as Ocean Bottom Cabled Seismometer (OBCS) system and deployed in Japan Sea [14-15]. Development of the second ICT system which has both seismometers and tsunami-meters as scientific sensors started from 2012 [16]. A seismometer is a conventional force balance accelerometer which is also used for other cable systems. A high-precision pressure gauge using crystal oscillator which has been widely applied for seafloor observations was selected as a tsunami-meter. The system is controlled by a processor of SH-4 and an FPGA handles the interface to a digitizer for seismometers and pressure gauge. The system uses standard TCP/IP protocol with a speed of 1 Gbps for data transmission, system control and system monitoring. Data transmission with large capacity enables us to collect larger amount of data. The WDM is also introduced to reduce a number of optical fibers. Clock is delivered to all observation nodes from the GPS receiver on a landing station using simple dedicated lines. In addition, IEEE-1588 (Precision Time Protocol) is implemented to synchronize a real-time clock in nodes to a land-based system clock driven by GPS through TCP/IP protocol. There are two types of nodes. Both types have three accelerometers as seismic sensors. One type equips a pressure gauge as tsunami sensor. Another type has an external port for additional observation sensor. Power of additional sensors on seafloor is supplied using Power over Ethernet (PoE) technology. In September 2015, the system was installed off Sanriku, northeastern Japan where the Tohoku-oki Earthquake occurred in 2011 (Fig. 2). In this region, a seismic and tsunami observation system using conventional technology has been already installed in 1996. The objectives of the observation are to obtain exact seismic activity related to plate subduction and to observe tsunami on seafloor using two cable observation systems. The new system has a total length of 105 km and three stations. Two stations have a built-in tsunami sensor. Another has an external port. At the deployment of the system, we connected a tsunami gauge as an external sensor. The seismic data from the deployed system shows the noise levels are comparable to those at the existing cabled system off Sanriku. In addition, the burial sensor below the seafloor has low noise environment. Pressure gauges have 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. A sensibility of buried pressure gauge seems to not change for a period of a tide [16].

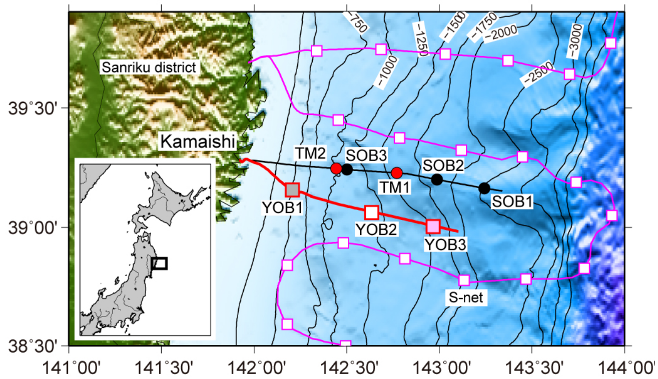

Fig. 2 Positions of the cable observation systems off Sanriku. Black and red lines indicate the 1996 system and the ICT system deployed in 2015, respectively. Pink lines denote S-net. (After [16]).

II. New Method of Semsic Observation Using Seafloor Optical Cable

Recently Distributed Acoustic Sensing (DAS) measurement which utilizes an optical fiber itself as a sensor becomes popular for security surveillance, monitoring of oil pipe line system, etc. In addition, DAS measurement begins to be applied to seismic prospecting such as vertical seismic profiling for an exploration of energy resources [17]. Because DAS measurement is thought to be useful for earthquake observation, there were some trials for an observation of earthquakes using an optical fiber deployed on the land or the seafloor[18]. However, seismic observation using DAS technology on seafloor does not become popular at the present. A DAS measurement is one of optical fiber sensing technologies. A coherent laser pulse is launched into to a single mode optical fiber repeatedly, and the backscattered light is observed as a function of time at the launching end. When a small deformation of a fiber occurs by a vibration near fiber, a pattern change of the backscattered light is observed. Travel time of light and pulse length correspond to distance of measurement point and spatial resolution, respectively. Spatial sampling of the observation is a few meters in the highest case. From these characteristics, a DAS measurement enables a dense seismic observation as a linear array. A length of the array which has a short interval of sensor corresponds to a length of a deployed optical fiber. According to the present technology, the maximum length of a DAS measurement reaches more than 70 km. On the other hand, development of data processing is needed because the principle of measurement by the DAS differs from that of conventional seismic measurement using a pendulum.

III. Practical Measurement Using DAS Technology

In 1996, a seafloor seismic tsunami observation system using an optical fiber cable was deployed off Sanriku by Earthquake Research Institute, the University of Tokyo (Fig.2). The system has three seismic stations and two tsunami-meters, and a length of the cable is approximately 120 km. The system still continues the observations experiencing an interruption by a damage of the 2011 Tohoku-oki Earthquake. The system has six spare (dark) optical fibers for future extension. Because the dark fibers have no repeater, the seismic array by a DAS measurement using a dark fiber of Sanriku cable observation system covers from the landing station to the end of the cable with a high spatial density. In addition, the dark fibers are suitable for DAS measurement because a type of the dark fibers are dispersion shifted single mode. Therefore, we start development of a seafloor seismic observation system by the DAS technology with Sanriku cable observation system as a next generation of marine seismic observation system. The observation system using the DAS technology can increase a spatial resolution incredibly on a seafloor seismic observation.

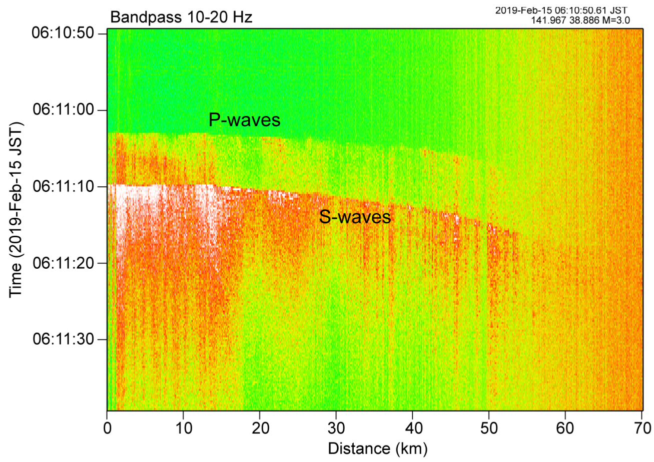

Fig. 3 Example of records of an earthquake by the DAS measurement using Sanriku seafloor cable observation system. P- and S- wave arrivals can be clearly seen.

In February 2019, we made a pilot observation of a DAS measurement using a dark fiber of Sanriku seafloor observation system. Before a DAS measurement, we confirmed a good condition of the dark fibers using Optical Time Domain Reflectometer. An interrogator for the DAS measurement was installed in the landing station temporarily, and data were recorded for 100 km length with spatial resolution of 5 m and sampling frequency of 500 Hz. The gauge length was set to 10 m or 40 m. The data were collected continuously for about 46 hours. As a result, many earthquakes including micro-earthquakes occurring near the cable system (Fig.3) and a deep earthquake below the Japan Sea were recorded. We can compare the data obtained by the DAS measurement and the data from seismometers of Sanriku seafloor observation system. The data by the DAS measurement is comparable to those from seismometers. We will develop data processing for seismic observation by the DAS measurement using the obtained data.

IV. CONCLUSIONS

A seafloor cabled system can perform real-time and long-term observation in marine environment. Especially seismic and tsunami observations by using a seafloor cabled system are useful from views of disaster mitigation. Therefore a seafloor cabled system with seismometers and tsunami-meters was developed based on a submarine tele-communication cable system, and has been used over the past 25 years around Japan. The early seafloor seismic and tsunami observation systems have a limited number of seismometers and tsunami-gauges. According to efforts to lower a cost by using up-to-date technology, a number of sensors for a cable system is increasing. Since 2010, a seafloor cable observation system becomes a large-scale and is being enlarged as a sensor network. The DONET systems were deployed in a region of the Nankai Trough to monitor crustal activities and detect occurrence of earthquakes and tsunamis. The feature of the DONET is an expandable cabled system and the system has approximately 50 stations in total. The S-net was installed near the Japan Trench and consists of six subsystems and each subsystem has 22 to 28 observation nodes. The observation node is connected to seafloor cable in serial. In addition. development of the ICT system is being carryed out. The ICT system aims for low costs in both production and installation to install more number of observation node in target areas. The ICT systems were deployed in Japan Sea and off-Sanriku. The developed system is in-line type and uses up-to-date technology for commercial purposes.

Distributed Acoustic Sensing (DAS) measurement which utilizes an optical fiber itself as a sensor becomes popular and there were some trials for an observation of earthquakes on the land or the seafloor. A DAS measurement enables a dense seismic observation as a linear array. A length of the array which has a short interval of sensor corresponds to a length of a deployed optical fiber. In February 2019, we made a pilot observation of a DAS measurement using a dark fiber of the Sanriku seafloor observation system installed in 1996. Data were recorded for 100 km length with spatial resolution of 5 m and sampling frequency of 500 Hz. The gauge length was set to 10 m or 40 m. As a result, many earthquakes including micro-earthquakes and a deep earthquake were recorded. Earthquake observation using DAS measurement on seafloor cable is promising for seafloor observation with spatially high density .

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