

Improvement of earthquake locations with the Marine Cable Hosted Observatory (MACHO) offshore NE Taiwan

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Abstract In order to improve the locating capability for offshore earthquakes and tsunamis monitored off northeastern Taiwan, a cable-based ocean bottom seismographic observatory named “Marine Cable Hosted Observatory” (MACHO) was constructed and began operation at the end of 2011. The installed instruments of the observatory include a broadband seismometer, a strong-motion seismometer and a pressure gauge. In addition, various scientific instruments could be deployed for other purposes as well. At present, the seismic data are transmitted in real-time via a fiber cable, and integrated into the current inland seismographic network in Taiwan. The ocean bottom station has contributed to provide high quality seismic data already. According to observations from January 2012 to June 2013, there were a total of 15,168 earthquakes recorded by the system. By using the data from the ocean bottom station, the number of relocated earthquakes with an azimuth gap less than 180 degrees substantially increase about 34 %. Meanwhile, the root-mean-square of the time residual, the error in epicenter, and the error in depth of the earthquake locations decrease. Therefore, the implementation of MACHO has the advantage of extending the coverage of existing the Taiwan seismic network to the offshore, providing more accurate and real-time seismic data for offshore earthquakes monitoring. The results show that MACHO is crucial and necessary for monitoring seismic activities in northeastern Taiwan.

Keywords Offshore earthquake · Tsunami · Northeastern Taiwan · MACHO

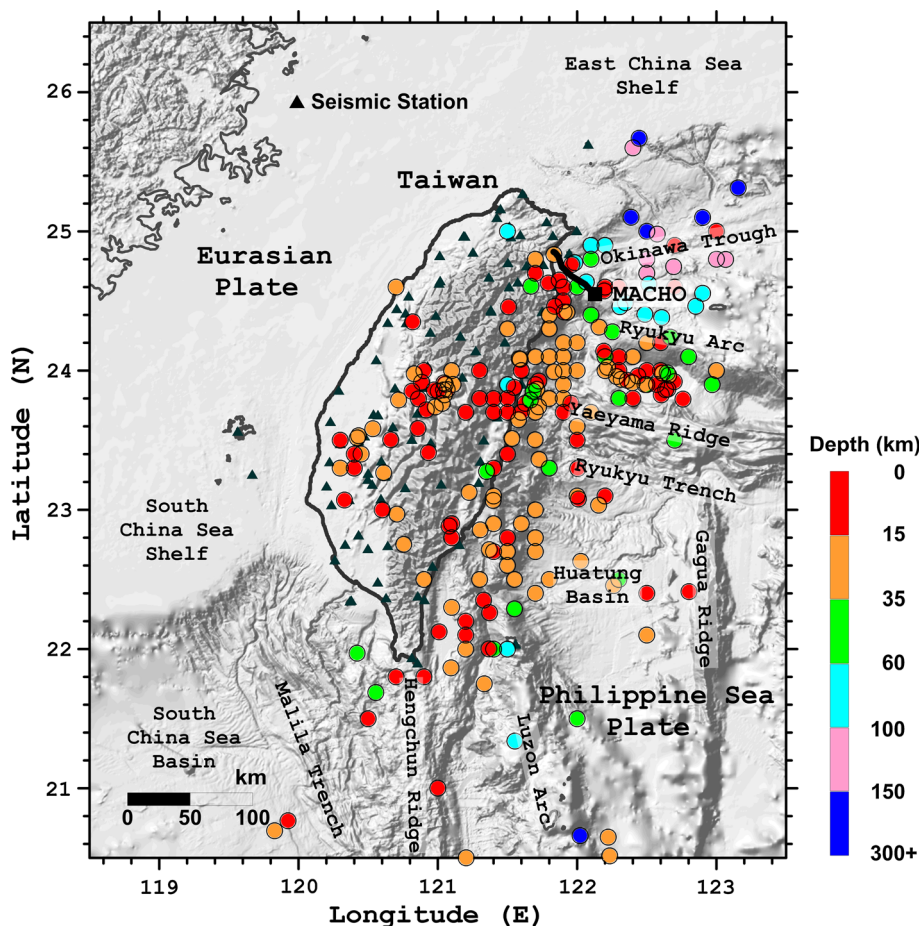
Introduction

Taiwan is located on the convergent boundary between the Eurasian Plate and the Philippine Sea Plate, part of the Circum-Pacific seismic belt. Due to the oblique collision and subduction between the two plates, numerous earthquakes occur in the surrounding regions. Frequent and destructive earthquakes usually result in huge loss of life and property, thus earthquake hazard is one of the most threatening natural disasters in Taiwan. For the sake of seismic hazard mitigation, a dense network of seismic stations has been implemented in the whole island and some offshore islets by the Central Weather Bureau (CWB), Taiwan (Fig. 1). Currently, there are 105 stations in operation, and 30 of them are borehole stations. At the stations, three types of seismic instruments are installed, either co-site or separately installed, including short-period seismographs, accelerometers, and broadband instruments. The different kinds of seismographs with different formats are all transmitted to the Earthworm system in the data center. The Earthworm system is a multi-functional seismic data processing system distributed by the United States Geological Survey (USGS). In CWB, the system is used as a common platform to integrate all real-time signals for integral processing (Hsiao et al. 2011). Those stations have been playing an important role in the earthquake monitoring in Taiwan. On average 20,000 seismic events are detected every year. The local magnitude of completeness (M_c) for the inland region is generally less than 2.0, whereas the M_c in the offshore region is between 2.5 and 3.2 due to poor network coverage (Chan et al. 2012). M_c is defined as the lowest magnitude above which all

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Fig. 1 The cable route and the connected submarine node (solid square) of the MACHO system implemented off NE Taiwan. The solid triangles indicate the locations of seismic stations on land. Colored circles are the epicenters of $M > 6$ earthquakes with different focal depths that have occurred in the Taiwan region since 1900. Most of the earthquakes took place in the offshore area of eastern Taiwan situated at the Ryukyu convergent plate boundary



earthquakes in a space–time volume are detected (Wiemer and Wyss 2000). It is usually used for assessing the performance of a seismic network and related to the studies of seismicity and seismic hazard assessment. Due to more than 70 % of the earthquakes occurred off eastern Taiwan, within the boundary of two tectonic plates. The performance of earthquake monitoring, including accuracy of the hypocenter determination and timeliness of earthquake response, previously were limited because only land-based stations were available.

In order to improve the capability for monitoring offshore earthquakes and tsunamis off eastern Taiwan, the CWB conducted a submarine cable-based ocean bottom seismograph (OBS) instrumentation project, named “Marine Cable Hosted Observatory” (MACHO) since 2007. To ensure the safety of the deployed cable, we have first conducted route survey to determine an adequate cable route and the site of submarine station. The investigations included bathymetry, geology, geophysics, ocean environment, and fishery activities. Then, a land station was set up at Toucheng city, as the cable landing site and operation room. Meanwhile, for the purpose of marine cable landing and land cable installation, a horizontal directional drilling at the onshore end and in-station cable ducts were prepared. Finally, the CWB

began the main part of the project, to build the submarine observatory, at the end of 2009. The tasks included cable and equipment manufacture, cable laying, equipment installation, and system approval.

The cable-based ocean bottom seismic observatory (Fig. 1) was constructed successfully and began operating at the end of 2011. Currently, the seismic data are transmitted via a fiber cable, and integrated into the existing seismographic network in real-time already. The observatory is considered a pilot submarine observatory system in Taiwan. According to the performances of operation, the CWB is planning to extend the current cable length and add more instruments in the future.

Geological setting

The Philippine Sea Plate moves and collides with the Eurasian Plate in the NW direction with a convergent rate of about 8 cm/year (Seno et al. 1993; Yu et al. 1997). Off eastern Taiwan, the Philippine Sea Plate subducts northward beneath the Eurasian Plate along the Ryukyu Trench, developing the Ryukyu subduction zone. From south to north, the Ryukyu Trench, fore-arc basins, Ryukyu Arc,

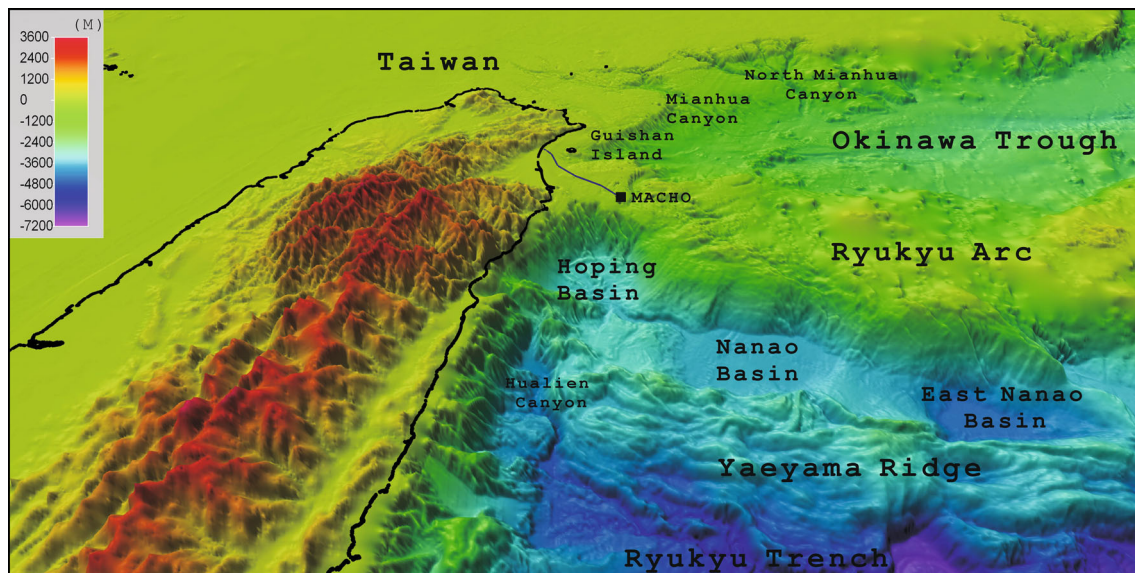


Fig. 2 Tectonic setting of the submarine observatory. The observatory, marked by the *square*, was located in the Ryukyu subduction zone. Aligned from south to north, the fore-arc basins, volcanic arc, and back-arc basin stand for three major submarine features off NE Taiwan

and Okinawa Trough are major tectonic elements off NE Taiwan (Fig. 2).

A series of fore-arc basins are situated at the southernmost portion of the Ryukyu subduction zone offshore east Taiwan. These basins, including the Hopping, Nanao, and East Nanao basins, become broader and deeper from the west to east in sequence. The water depths are between 2,000 and 4,000 m. This area, located near the interface of subduction, is considered one of the most seismically active zone in Taiwan. Many large earthquakes occurred in the past century (Fig. 1). For instance, a surface wave magnitude 8.1 earthquake (M_w estimated at 7.7, Theunissen et al. 2010) occurred on June 5, 1920 (Wang and Kuo 1995). It was the biggest earthquake ever recorded instrumentally in Taiwan. Besides, the tectonic characteristics of this area have the potential to generate great earthquakes (Hsu and Sibuet 2005; Hsu et al. 2012; Hsu et al. 2013).

The Ryukyu Arc is a long strip extending from Kyushu to Taiwan islands. In its southwestern end, volcanism linked to subduction is present (Lin et al. 2004). The sea floor gently undulates hundreds of meters, and some islets emerge above sea level. The Guishan Island is the westernmost and is located on the continental shelf off Ilan Plain. Active geothermal variations of heat flow have been observed (Chiang et al. 2010). Behind the Ryukyu Arc, the Okinawa Trough is a rifting back-arc basin due to the northward subduction of the Philippine Sea Plate. It is in the NEE to WSW orientation and terminates in the west in the Ilan Shelf (Liu et al. 1998; Clift et al. 2008). The water depth of the central trough is greater than 2,000 m and decreases toward the margins. Due to the rifting activity and local magmatic activity within this

region, the seismicity is very active (Lin et al. 2007). Submarine canyons and valleys exist in many places at the edge of the trough. Submarine landslides there may cause tsunamis that threaten the coastal area of NE Taiwan.

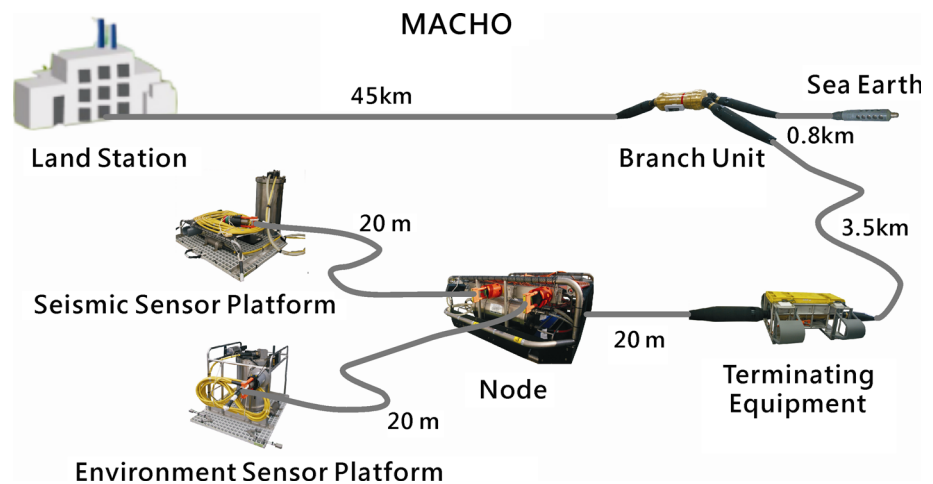
In general, the Ryukyu subduction zone is one of the most seismically active regions near Taiwan. Therefore, the implementation of a real-time submarine monitoring system has significant meaning for hazard mitigation in Taiwan.

Observatory configuration and equipment

The system configuration of the MACHO is shown in Fig. 3. The land station is situated at Toucheng, Ilan county, in the NE corner of Taiwan. Inside the station, facilities are equipped to provide functions of power supply, data transmission, time synchronization, system control and management for the observatory. The total power supply of the system is 1 kV in total, and the bandwidth of transmission exceeds 2 gigabyte.

The fiber cable is deployed from the land station toward the seafloor node. The total cable length is about 45 km, and the seafloor depth is within 300 m. At the end, the main cable is separated into two different cables with a Branch Unit (BU). One cable connects the Sea Earth to help form a power supply circuit in the sea water. The Sea Earth unit is mainly used for unilateral powered submarine cable systems to maintain voltage stability. The other cable connects the Terminating Equipment (TE), which is intermediate equipment deployed between cable end and submarine observation instruments. It can convert data

Fig. 3 Systematic diagram of the MACHO system. The system is mainly composed of land station equipments, Branch Unit, Sea Earth, Terminating Equipment, Node, and sensor platforms. Each instrumental unit is connected by a submarine fiber cable. The Sea Earth unit is mainly used for unilateral powered submarine cable systems to help form a power supply circuit to maintain voltage stability



packets from observation instruments into a fiber signal for data transmission via the fiber-optic cable.

Regarding the submarine observation instruments, one 4-port node connected to various kinds of instruments is used. The node is designed as network hub and power equipment deployed on the seafloor, used to provide the power supply, time synchronization, and two-way communication for the observation instruments. The power capacity for a node is designed up to 600 V, and the data bandwidth is 622 Mbps. Due to the main purpose of the system, a seismic sensor platform attached to seismometers and a pressure gauge (PG) is deployed. The seismometers consist of one broadband and one strong-motion seismometer, capable of monitoring small and large earthquakes simultaneously. The model of the broadband sensor is CMG-3TC, Guralp, and the strong-motion sensor is TSA-100s, METROZET. They are both 24-bit resolution sensors. The frequency response of the broadband sensor is from 360 s to 50 Hz, and full-scale range of strong-motion sensor is ± 4 g peak-to-peak. The PG is used to monitor tsunamis by detecting the change of seawater pressure. The type of PG is quartz crystal frequency output type and the measurement range is from 0 to 2,000 PSIA (13.79 MPa) full scale. In addition, for improving the developments in marine science and underwater technology in Taiwan, an environment sensor platform equipped with some scientific instruments are installed and connected to the node as well. Currently, a conductivity, temperature, and depth (CTD) recorder and a hydrophone are implemented. The CTD is used to measure conductivity (salinity), temperature, and level data of seawater. The hydrophone is deployed to record the voiceprints of marine animals.

The submersible instruments, including node and observation platforms, were deployed and connected to each other by remotely operated vehicle (ROV). The instruments were all equipped with submersible connectors. Therefore, the

operations for wiring can be conducted by ROV underwater. If there is any replacement or repair needed, or the future expansion of system, the task could be executed in the same manner.

Seismological observation

The seismic data of ocean bottom seismometers are transmitted to the land station via a submarine fiber cable in real-time. Meanwhile, through an IP virtual private network (IP-VPN), the data are sent back to the CWB headquarters simultaneously. At the headquarters, the OBS data are combined together with exiting seismic stations in the Earthworm system for integrated processing. Figure 4 shows the example of a June 7, 2013, $M_L 6.2$ off eastern Taiwan earthquake. In this case, the OBS is the nearest station about 81 km away from the epicenter, and the broadband data are combined with that of the existing land stations for effective operation. It is helpful to enhance the accuracy of earthquake location and reduce the necessary time of automatic data processing. The OBS station has already contributed to the monitoring of offshore earthquakes in NE Taiwan.

Figure 5 shows another case of the broadband seismogram recorded by the OBS. For the same earthquake, a recording from a borehole seismometer in Toucheng is also plotted together for comparison. The earthquake occurred at 23:51 UTC on June 28, 2013, off the east coast of Taiwan. The local magnitude is 5.7. Except for the high frequency component in the OBS data, the trends of the waveforms for these two stations are similar. It indicates that the OBS records good-quality seismic data. The borehole seismometer was installed in a 300 m dry well and the background environment is very quiet. The minor high-frequency disturbances at the OBS station are likely caused by the

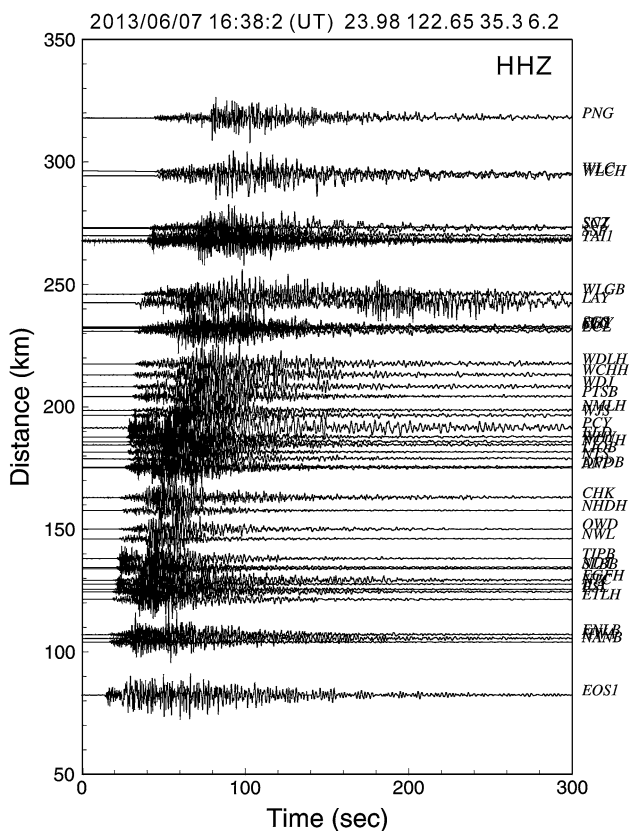
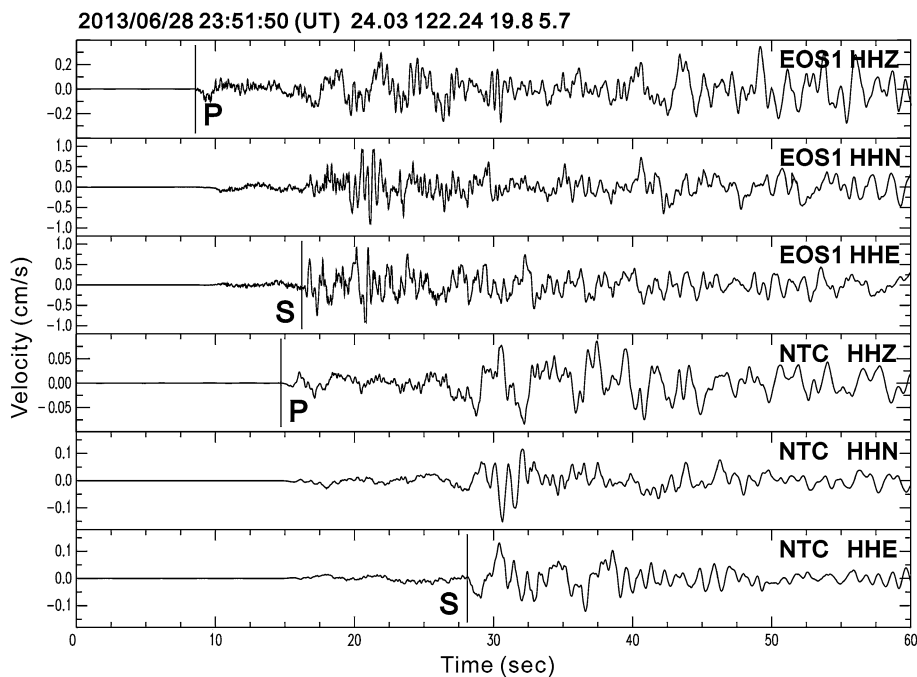


Fig. 4 Vertical broadband seismograms of the June 7, 2013, M_L 6.2 off eastern Taiwan earthquake recorded by the OBS station (EOS1) and other 44 land stations. The OBS is the nearest station and all the seismograms are displayed as a function of the distance

Fig. 5 (Top) Broadband seismograms of the June 28, 2013, M_L 5.7 earthquake off eastern Taiwan earthquake recorded by the OBS. **(Bottom)** For the purpose of comparison, with the same earthquake, a recording of the downhole seismometer in Toucheng is arranged together. The onsets of P wave and S wave are marked in the plot



influence of ocean currents. Additionally, for the timeliness, the picking times of P wave and S wave of OBS data are earlier than on the land record by 6.2 and 11.9 s, respectively. In the current development, P waves are used as the key parameter to determine the issuance of earthquake early warning (Hsiao et al. 2011). In the case of this earthquake, it provides about 20 s to response in advance. Besides, at the OBS station, broadband and strong-motion seismometers are simultaneous installed. Figure 6 shows the seismograms of an earthquake. Both the broadband and strong-motion waveforms are displayed. The earthquake occurred on June 28, 2013, and the local magnitude was 6.6. So far, this is the biggest earthquake recorded by the OBS. Due to the epicentral distance being only 20.8 km from the station, the horizontal component of the broadband sensor was clipped by the strong shaking. However, the strong-motion data were all within measurement range of the instrument. Therefore, the system is capable of providing high quality data during big earthquakes for the purpose of seismic hazard mitigation.

Tsunami monitoring is another main task of the MACHO project. A magnitude 7.6 earthquake occurred at 12:47 UTC on August 31, 2012, off the east coast of the Philippines. The distance is about 1,600 km to the submarine station. Figure 7 shows the record of the pressure gauge. The PG data were converted from pressure values to actual variations of sea level, with the long-term tidal effects removed by a bandpass filter. As the result, the seismic and tsunami signals are both clearly recognizable. The first seismic wave arrived at 12:51 UTC, which was 4 min after the origin time. Two

Fig. 6 The broadband (*top*) and strong-motion (*bottom*) seismograms of the June 9, 2012, M_L 6.6 earthquake off eastern Taiwan earthquake recorded by the OBS. The horizontal records of broadband sensor clipped due to the strong shaking, whereas the strong-motion ones were within measurement range of the instrument

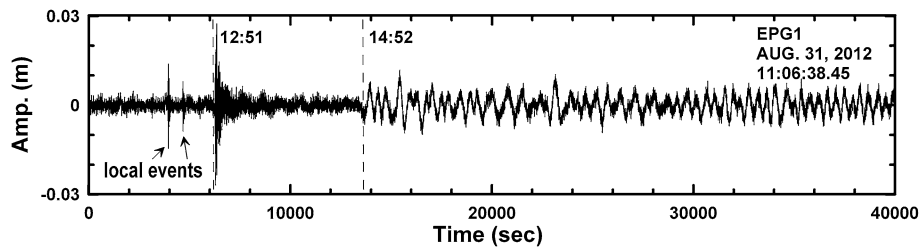
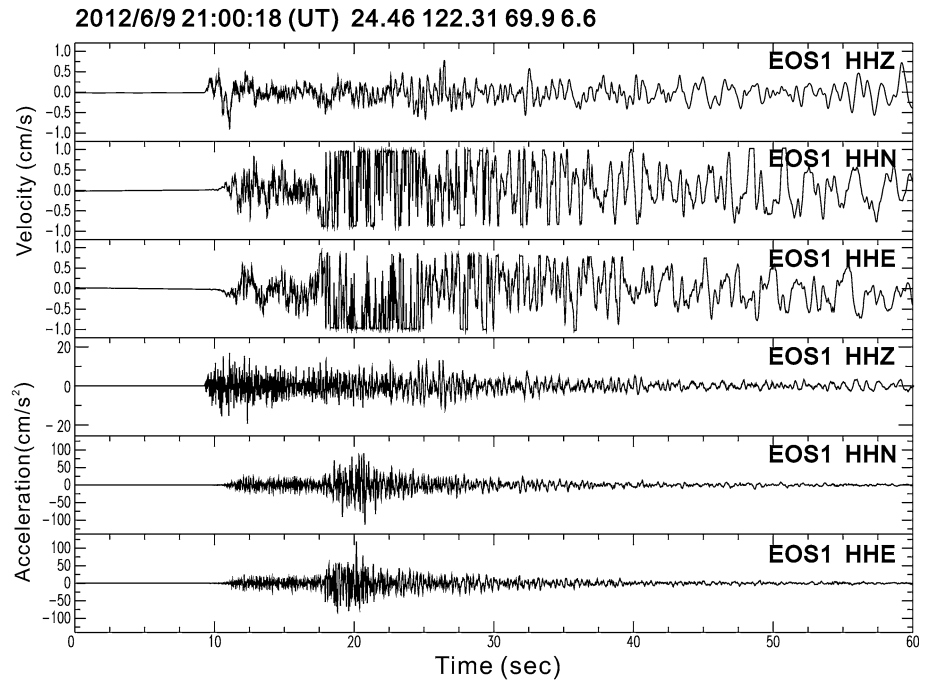


Fig. 7 Pressure gauge record of the August 31, 2012, M_w 7.6 off eastern Philippines earthquake. The data were converted from pressure values to actual variations of sea level, and the long-term tidal effects were removed by a bandpass filter. The signals of the

seismic and tidal wave are clearly recognizable in the record. Moreover, two prior local events were recorded as well. Local magnitudes of these two earthquakes were 5.0 and 4.8, respectively

hours later, the tsunami waves reached the submarine observatory at 14:52 UTC (Fig. 7). The period was about 12 min, and the maximal amplitude was 0.01 m. In addition, two prior local events were recorded as well. The magnitudes of local earthquakes were 5.0 and 4.8, respectively, and the epicentral distances were about 130 km for both. The high resolution of PG data is approved as a very useful tool for tsunami observation off NE Taiwan.

In order to examine the effectiveness of the OBS data, we collected in total 15,168 earthquakes recorded by the OBS station from January 2012 to June 2013. Figure 8 shows the distribution of these earthquakes. Most earthquakes occurred off the NE coast of Taiwan. The magnitudes range from 0.6 to 6.6. We first inspected the gap angle of each earthquake while the OBS data were used in focal determinations. The gap is defined as the largest azimuthal angle between two adjacent stations. It is measured in degrees at the epicenter of an earthquake. In general, the smaller this angle, the more

reliable the determined location of the earthquake. The gap of an earthquake exceeding 180 degrees typically has large deviation in focal determination. Based on the same earthquake dataset with and without OBS data, Fig. 9 shows the statistics of earthquake number with different gap angles. The percentage of earthquake number in which the azimuth gap was less than 180 degrees has substantially increased, by 34 %. Based on the study of Wu et al. (2013), the gap is the major factor in the uncertainty of earthquake location in Taiwan. Therefore, the submarine observatory is crucial for earthquake monitoring in NE Taiwan. The seismic network with OBS effectively enclosed many offshore earthquakes.

Figure 10 shows the diagrams of the numbers of earthquakes versus RMS (root-mean-square of time residual) in seconds, ERH (error in epicenter) in km, and ERZ (error in depth) in km. These parameters are usually used to assess the quality of earthquake location. If the same velocity model is used, a smaller number indicates a better fit of the data. By using the

Fig. 8 Distribution map showing the earthquakes recorded by the MACHO OBS from January 2012 to June 2013. In total, there were 15,168 earthquakes measured. The earthquakes are displayed by *colored circles* with different focal depths. Sizes of *circles* correspond to different ranges of magnitudes. Earthquakes with magnitude greater than 6 are shown by *solid stars*

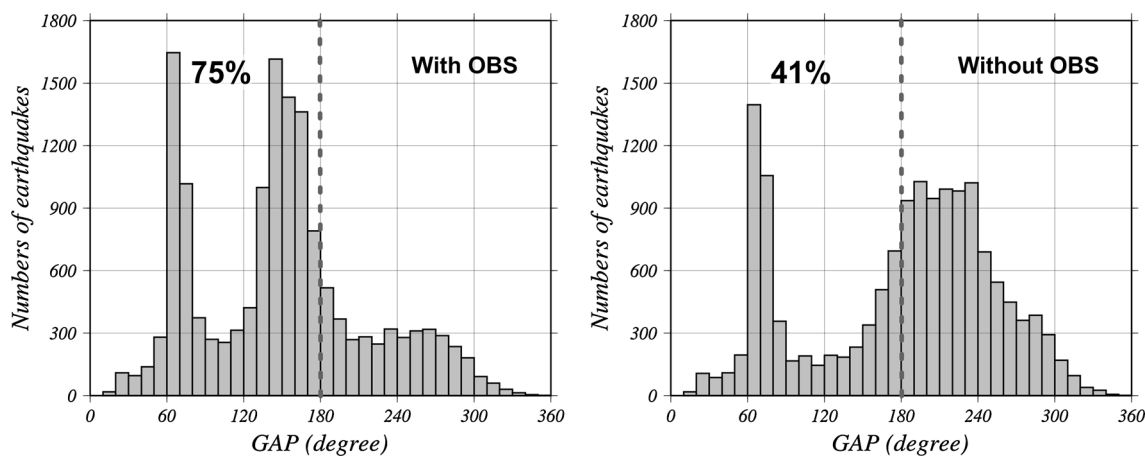
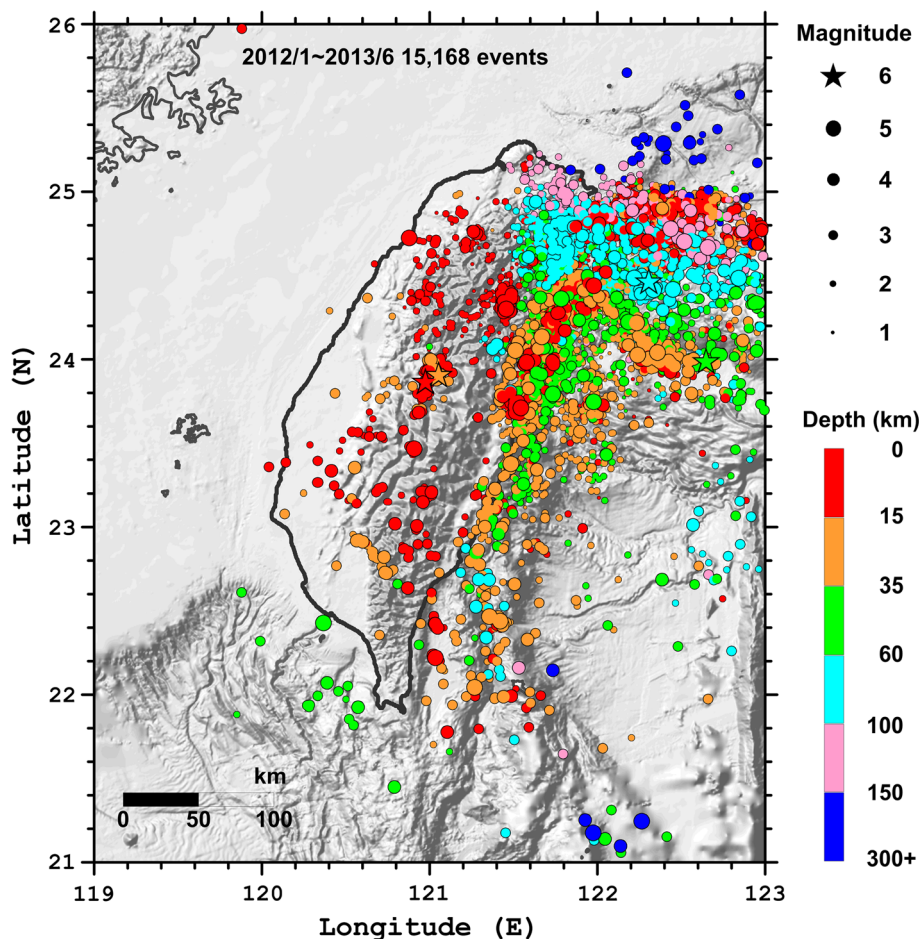


Fig. 9 Using the 15,168 earthquakes located, the statistical charts of earthquake number with respect to gap angle are plotted. (*Left*) The results are obtained with OBS data and (*right*) without OBS data. The

percentage of earthquakes with the gap less than 180 degrees has substantially increased, by 34 %

OBS data, the qualities of earthquake locations are improved. We found that the errors and their corresponding deviations in epicenter and depth both decreased, the average ERH and ERZ

are reduced from 1.23 ± 1.56 to 1.04 ± 1.23 km, and 1.44 ± 2.54 to 1.27 ± 2.07 km, respectively. Besides, the average RMS is reduced slightly from 0.34 ± 0.14 to 0.34 ± 0.13 s.

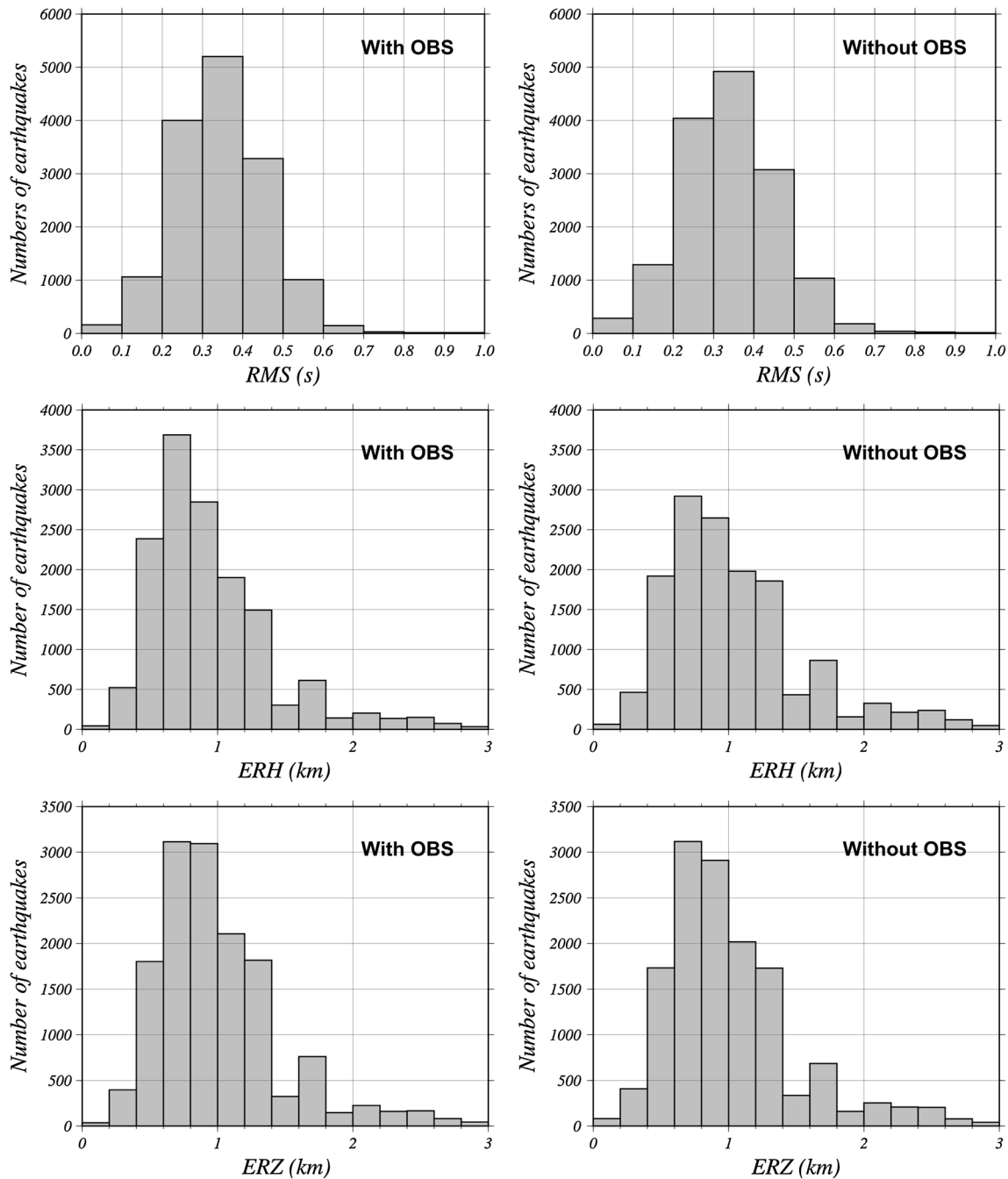


Fig. 10 Statistical charts of earthquake numbers versus RMS (root-mean-square of time residual), ERH (error in epicenter), and ERZ (error in depth). Charts in left column are the results with the OBS

data. The results in right column are the results without OBS data. By using the OBS data, the qualities of earthquake locations are improved

Discussion and conclusions

The MACHO is the first ocean bottom observatory providing real-time data for the purposes of seismic hazard mitigation and marine environment research in Taiwan. Although only one observatory node is implemented currently, the performance of the seismic observation has improved. By using the same data set, Fig. 11 shows the

spatial distribution diagrams of earthquakes using the OBS data for location and the ones without the OBS data. The range is from 23.5°N to 25.5°N and from 121°E to 123°E. The focal depth is within 200 km. An apparent subducted Wadati-Benioff zone is shown in both diagrams. In comparison, the space distribution of earthquakes using OBS data seems to be better focused, especially for the earthquakes between the Okinawa Trough and the Ryukyu

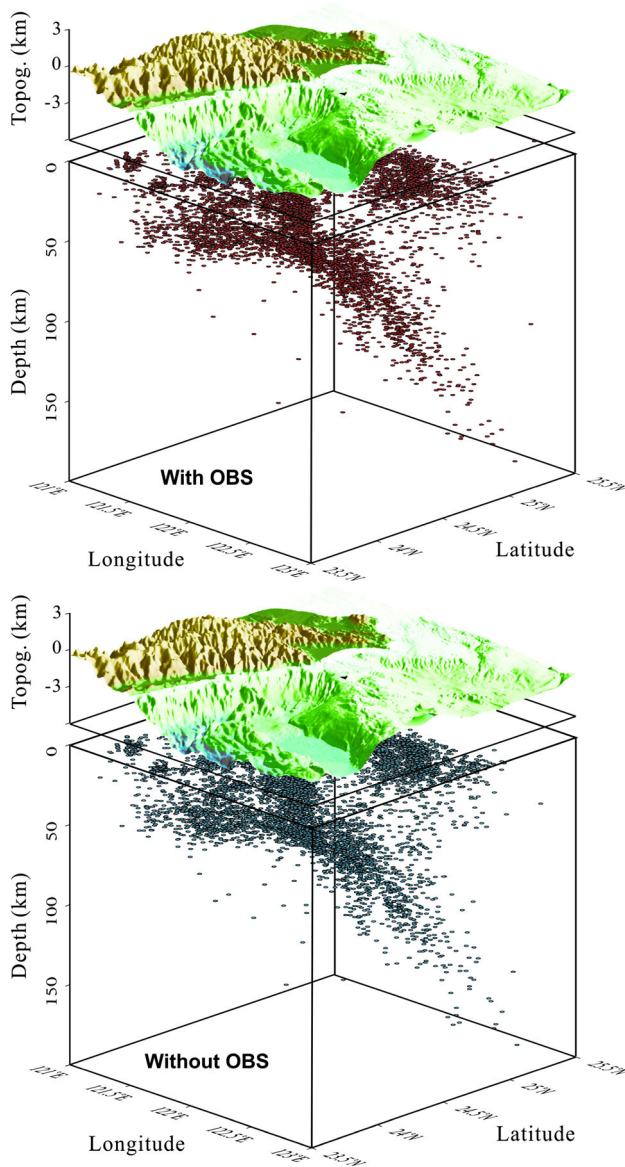


Fig. 11 Spatial distribution maps showing the locations of earthquakes by using MACHO OBS data (*top*) and the ones without OBS data (*bottom*). The range of the demonstrated earthquakes is from 23.5°N to 25.5°N, and from 121°E to 123°E. The focal depth is limited within 200 km. Improvement of earthquake locations between the Okinawa Trough and the Ryukyu subducted slab is especially evident

subducted slab. Supposing that more OBS stations can be implemented off eastern Taiwan in future, the earthquake locations can be much better improved.

After the March 11, 2011, M_w 9.0 earthquake off Tohoku, Japan earthquake, the subject of monitoring offshore earthquakes near plate boundaries has received increasingly attention. The sufficiently and precise seismic database provided by the MACHO will be helpful to understand the tectonic behavior offshore of the NE Taiwan area. An active plate boundary occurs beneath the

OBS station (Tsai et al. 1977), and the plate convergence is intensely active in this area. The significant crustal deformation showed by the steep submarine topography, as well as the abundant earthquakes recorded indicated that the convergent stress is active there. For these reasons, the potential of damaging earthquakes is high offshore of the NE Taiwan area. In order to understand the earthquake hazards in the future, a sufficient and precise seismic database is essential to know the detailed slip behaviors where the seismic gap might represent a pre-seismic locking area and the possible location of damaging earthquakes if tectonic stress has been accumulating (Campos et al. 2002; Moreno et al. 2010; Ruegg et al. 2009). Although the precise local earthquakes measured have been few until now, the seismic database will be expanded sufficiently as time goes on and used for tectonic investigation by implementation of the MACHO system.

The implementation of the current system has the advantage of extending the coverage of the existing Taiwan CWB seismic network to the offshore, providing more accurate and real-time seismic data for offshore earthquakes monitoring. Meanwhile, through the pressure gauge deployed on the ocean bottom, timely information for rapid response of tsunamis can become available. Additionally, the system can provide real-time monitoring data for submarine volcanic activities in the vicinity of Guishan Island. All of these system capabilities help to mitigate possible natural damage in NE Taiwan. Furthermore, the research capabilities of marine and earth sciences are improved and expanded. Our result reveals that the submarine OBS stations are crucial and necessary in the offshore area of NE Taiwan.

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