Seismological Findings Using Real-Time Cabled Observatories

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Abstract – There are a number of seismological findings obtained using real-time cabled observatories, since such cabled systems bring invaluable data as continuous time series from the seafloor. These data cannot be acquired without cabled observatories. In Japanese water, there are already 7 cabled observatories installed for seismic and tsunamic observations. An M8 earthquake took place in September 2003 (The 2003 Tokachi-oki Earthquake) at one of locations for these observatories and gave a great opportunity to monitor all what took place at the time of megathrust earthquake occurrence. At the 2003 Tokachi-oki earthquake of M8, seafloor phenomena such as a generation process of tsunami, seafloor uplifts, etc., were observed. The seafloor uplifts were observed not before the main shock but continuously after the main shock. The uplifts were 0.35, 0.37, and 0.12 m for epicentral distances of 25.5, 31.4, and 81.8 km, respectively. Pressure fluctuations that took place co-seismically show about 100 times in amplitude to those observed as the uplifts. The uplift of the seafloor generated not only tsunami but high amplitude acoustic waves. Both the tsunami and acoustic waves were generated by the uplift and superposed to each other. After the main shock, a continuous uplift of the seafloor is observed at the all three pressure gauge locations and the rate of uplift was about 0.004 m/day. These phenomena imply that there was a change in the state of friction on the plate boundary interface by the main shock. We summarize the latest scientific results from monitored data produced by our cabled observatories and, then, to demonstrate advantages of such underwater seismic and tsunamic stations. It is clear that there are potentially and scientifically meaningful outcome from such observations. There are interesting scientific objectives for earthquake studies: crustal deformation processes due to accumulating stress at the plate boundaries, the design of early tsunami warning system as a part of future disaster mitigation methodologies, description of physical tsunami generation process, etc. Technical and theoretical development in offshore earthquake monitoring must be well considered for satisfying these objectives using offshore seismic and tsunami observations.

I. INTRODUCTION

There are number of researches that have been done at various occasions of plate boundary earthquakes [1]. In particular, source mechanisms, associated crustal deformations and tsunamis are of a great interest for the mitigation of disasters caused by recurrent plate boundary megathrust earthquakes. The 2003 Tokachi-oki earthquake, i.e., one of the plate boundary earthquakes, took place on September 25 2003, at 19:50 (UTC) at almost the same location as the 1952 Tokachi-oki earthquake [2]. In the focal area of the earthquake, a cabled observatory was deployed in 1999 and recorded, on the seafloor, both seismic and tsunamic fluctuations caused by this megathrust earthquake. The 2003 Tokachi-oki earthquake is the first one which took place near any cabled observatories.

The data acquired by the cabled observatory provided us indispensable information on what took place at the earthquake. Pressure gauge data brought new insight on tsunami generation process and crustal deformation. Also, the observatory is continously recording post-seismic crustal uplift even almost a year after the main shock [3]. This phenomena need to be also described for future monitoring of earthquakes taking place in seismogenic zones. Cabled observatories at a seismogenic zone could be used to reveal new phenomena what has not been observed, and it is necessary to summarize what were observed using our cabled observatory at the 2003 Tokachi-oki earthquake.

In this paper, we try to describe what were observed on the seafloor at the time of the M8 megathrust earthquake. The observations of the seafloor uplift associated with the earthquake are described based on acquired data on the seafloor. Unfortunately, there is no remarkable short-term precursory resolved until now in available data from the cabled observatory. As discussed in Watanabe et al. (2004) [2], the cabled observatory has proven the effectiveness of such observation system in the monitoring of earthquakes at the southwestern end of the Kuril seismogenic zone. Discussions finally make it clear that it is necessary to enhance the resolution or signal-to-noise ratio of observations on top of the existing technology of cabled observatories. Especially, much closer access should be tried to seismogenic zones to monitor deep processes or to detect any precursory of plate boundary megathrust earthquakes.

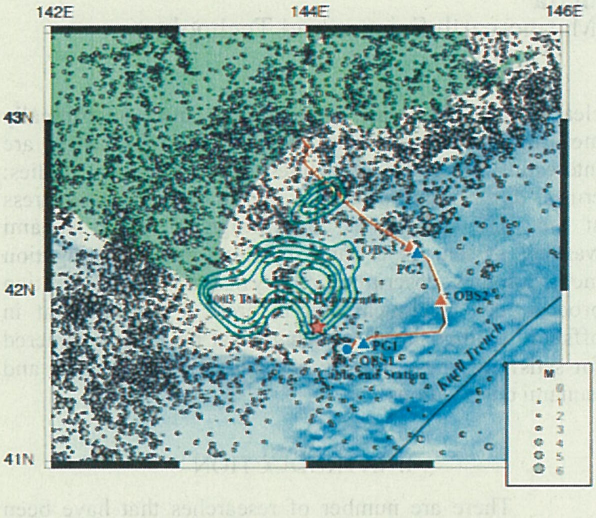

Figure 1 The locations of cabled observatory. Dots are for epicentral distribution of microearthquakes during a period from March 2000 to August 2003. Green contours [4] are drawn every one meter of fault slip at the plate boundary.

II. The 2003 Tokachi-oki earthquake

The focal area of the Tokachi-oki earthquakes is close to the southwestern end of the Kuril trench where an arc-arc junction from the Kuril to Japan trench began as a result of the southwestward migration of the Kuril forearc sliver [5]. The focal area is in a seismogenic zone of the North American and Pacific plates where the latter subducts beneath the former in an oblique direction with a rate of 8.5 cm/year [6]. The amount of dislocation of the 2003 Tokachi-oki earthquake was estimated from 3 to 5 m on the slip interface from an inversion analysis of teleseismic signals [4].

The crustal deformation is in progress [7] around the Hokkaido island caused by the plate motion of the three major plates, i.e., the Pacific, North American and Eurasian plates. The subduction zone, off Tokachi located at the boundary between the Pacific and Eurasian plates, has become a seismically inactive region compared to the other part of the Kuril trench seismogenic zone in the last decade [8]. At the same time, two disaster intraplate events, the 1993 Kushiro-oki [9], and the 1994 Hokkaido Toho-oki earthquakes [10], started to take place in the southern side of the Kuril subduction zone. A cabled observatory was deployed in the southwestern end of the Kuril subduction zone in 1999 and consists of three omni-directional tri-component seismometers, two high-precision pressure gauges, and a cable-end benthic environment monitoring sensors [11]. The two pressure gauges (PG1 and PG2) are located about about 31.4 km southeast (2283 m below sea level: denoted as mbsl hereafter) and 81.7 km northwest (2248 mbsl) from the epicenter, respectively (Fig. 1). The closest seismometer is located about 28.2 km in the epicentral distance from the hypocenter.

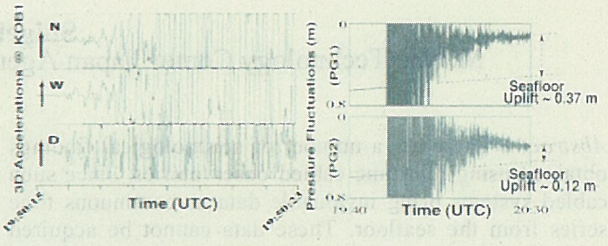

Fig.2 Recorded waveform and pressure fluctuations at the KOB1 and PG1/2 locations for the 2003 Tokachi-oki earthquake[1]. Full seismic waveforms were acquired without any saturation in amplitude at all sensors. Pressure fluctuations show that high-amplitude pressure fluctuations at the time of the mainshock were about 40 m and 30 m, and significant static changes in seafloor estimated as 0.37 m and 0.12 m at the PG1 and PG2 sites, respectively. These pressure gauges recorded crustal uplift, earthquake related oscillations, and tsunamogeic pressure fluctuations.

III. Observed Data

The two high-precision pressure gauges (maximum resolution of 0.3 mm) records 0.1 Hz sampled pressure fluctuations in water depth. They all recorded invaluable abrupt changes in pressure, i.e., the water depths, at the time of the earthquake at these three locations. After a tide compensation method [12], it has become clear that the pressure gauges have recorded vertical uplift of seafloor. The vertical displacements caused by the main shock at these sensor locations are estimated as 0.37 and 0.12 m, respectively at the PG1 and PG2 locations (Fig. 2). This is the first time to record such a crustal uplift in the offshore at the time of plate-boundary earthquakes in the past. The model for the synthetic tidal pressure fluctuations matches quite well with the observed before the earthquake. At the time of the main shock, the pressure gauges recorded high amplitude pressure fluctuations with a period of 6 seconds as shown in Fig. 3. The amplitudes of these fluctuations are ca. 50 and 5 meters in peak-to peak in equivalent water depth at PG1 and PG2 locations, respectively. Therefore, the ratio of pressure fluctuations against the crustal uplifts might be about 50 independently from the location on the seafloor. Tsunamis are generated by uplift or subsidence of seafloor through transportation of a potential energy of water column, and periods of tsunami waves are order of several tens of minutes. Therefore, the observed high pressure fluctuations cannot be explained by the tsunami.

After the main shock, tidal gauge data show a linear trend in the difference between the synthetic and observed water depth (Fig. 3). The rate of the linear uplifts at the pressure sensor locations are estimated as 4.1 and 3.9 mm/day respectively at the PG1 and PG2 locations over a period of two months after the main shock. Although the difference between the observed and estimated was almost constant before the main shock, the fluctuation of the difference became unstable after the main shock and the uplift of the seafloor continues.

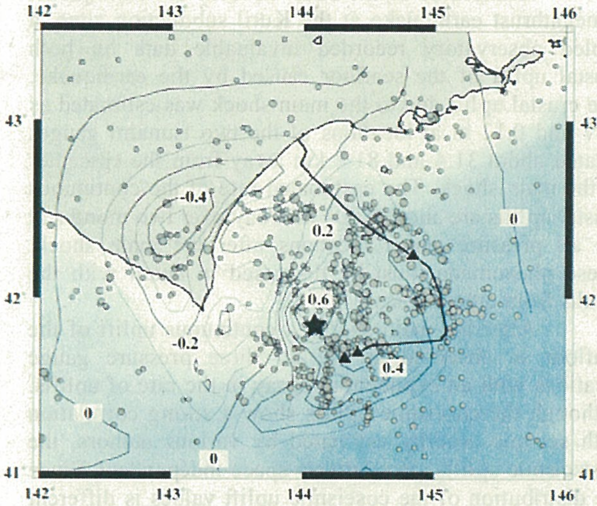

Figure 3 Estimated coseismic uplift at the time of the 2003 Tokachi-oki earthquake using the slip model [13]. Because of displacement distribution for the plate boundary, large area of vertical displacement is found in the offshore and relatively minor subsidence takes place along the coastline. The numbers on the contours are in meter and solid circles are for post-seismic events [14] whose estimated magnitudes are more than three.

IV. Crustal uplift and pressure gauges

One of the observatories at the time of the 2003 Tokachi-oki earthquake was the coseismic uplift of the seafloor as shown in Fig. 2. If we estimate the distribution of seafloor uplift using one of the rupture models obtained by seismic waveform studies, the recorded static uplift can be well explained as shown in Fig. 3. In Fig. 3, we could see that the major part of coseismic deformation is located in the offshore and that there is a tendency in the distribution of aftershocks to be located beneath uplifted zone of the rupture area.

Long-term variations also indicate that preseismic subsidence and postseismic uplift took place in before and after the mainshock (Fig. 4). These pressure fluctuations are now recognized as a preseismic seafloor subsidence and a postseismic seafloor uplift before and after the earthquake, respectively. The cabled observatory was installed in 1999, i.e., four years before the mainshock, and pressure gauge data recorded about 3 cm/yr of the continuous subsidence of the seafloor before the mainshock. After the mainshock, a continuous uplift was observed at a rate of 4 mm/day at the beginning and the rate of uplift asymptotically diminished in a year.

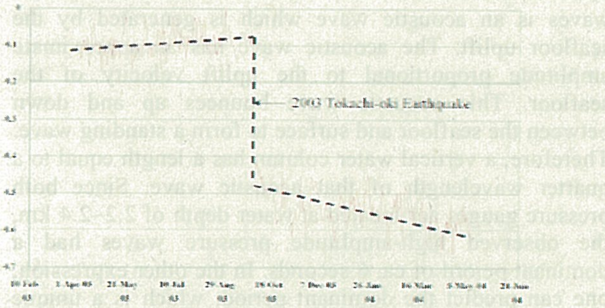

Figure 4 Postseismic crustal uplift at PG1. The rate of postseismic change has been gradually decreasing, but is still on-going. The vertical axis depicts relative subsidence in meters.

Earthquake monitoring requires a set of geophysical measurements and geodetic observations are one of indispensable schemes to help understanding what really takes place in the invisible intratelluric earth. Megathrust earthquakes take place in general in the offshore and it could be said that it still is very difficult to achieve such geodetic measurements until contemporary methodologies will have been well established [15]. This time in the analysis of pressure gauge data, acquired data have shown the effectiveness of pressure measurements in the offshore. The extension of this study for one of the other cabled observatories have shown that pressure gauges would be a good measure to monitor seafloor subsidence and uplift as indicated in some literature although the quality of the measurements [1]. Also, the importance of long term observations to cope with real geodetic phenomena should be mentioned to understand both pre- and post-period of earthquakes taking place with recurrence periods of 100 years. The 2003 Tokachi-oki earthquake has proven that pressure gauges have capability to detect crustal uplift in the offshore. Although already several months have passed since the main shock, the uplift of the seafloor still continues with gradual asymptotic rate change.

V. Cause of coseismic pressure fluctuations

As mentioned earlier, there was high-amplitude pressure fluctuations of ca. 30-40 m equivalent water depths observed at the time of the mainshock. The pressure fluctuations had a dominant period of 6 seconds and were monochromatic oscilations with variant amplitudes. In the earthquake or Tsunami studies, there have been no record of such high-amplitude pressure waves in the past. Finally, we realized that these fluctuations should be a common phenomena in the generation of tsunamis by seafloor uplift or subsidence.

Kajiura (1970) formulated the generation of tsunami using a linear wave equation [16]. Using his formulation for a case of uniform uplift in a rectangular region, we could derive qualitative estimates of dynamic pressure fluctuations for basically two kinds of waves. If we assume a constant velocity uplift of the seafloor for a time duration of T, one may see that the first wave has the waveheight on the sea surface equal to the total uplift value of the seafloor, i.e., a tsunami. The other kind of waves is an acoustic wave which is generated by the seafloor uplift. The acoustic wave has an approximate amplitude proportional to the uplift velocity of the seafloor. This acoustic wave bounces up and down between the seafloor and surface to form a standing wave. Therefore, a vertical water column has a length equal to a quarter wavelength of that acoustic wave. Since both pressure gauges aer located at water depth of 2.2~2.4 km, the observed high-amplitude pressure waves had a dominant peiord of ca. 6 seconds. In the other expression, one can predict the dominant period, which is a unique quantity defined by the water depth, of acoustic waves generated by seafloor uplift or subsidence [16].

V. Discussions

There might be two types of findings in our study on data acquired by the cabled observatory.

The pressure gauge data indicate that seafloor uplift in the eastern sensor (PG2) was about one third of that of the eastern sensor (PG1) at the time of the main shock. The initial slip on the fault plane was larger in the western side of the focal region [4], and aftershocks started eastward migration six hours after the mainshock. It is reported that the post-seismic slip took place adjacent to but different from the coseismic fault rupture of the main shock analyzing land-based GPS data [3]. Postseismic seafloor uplift for two pressure gauge locations show almost identical rate and uplift values. The present results from offshore cabled observatory would provide supplementary but definite data to further analyses of slip motion at the plate boundary [17]. These results might imply that the seismic fault plane has not only spatial variations but also time-scale variations in frictional properties. Post-seismic slip could be regarded as a reinforced procedure in stress redistribution along the fault plane. If the steady-state slippage is kept on a surface at the other areas than the asperity of the mainshock, the existence of low frictional surfaces or continuous pressurization in the subsurface could be considered. Detailed discussions on the localization and thickening of aftershock zones should be done and might require much data including land GPS observations as shown to the 1994 Hokkaido Toho-oki earthquake [18].

As demonstrated in the above section on the tsunami generation process, we have recorded acoustic standing waves caused by the seafloor uplift for the first time. Also it was shown that approximate pressure fluctuations can be expressed by seafloor uplift velocity and displacement under the assumption of constant velocity uplift. Both the tsunami and acoustic pressure fluctuations are caused by the same uplift, one constrains the other in the real estimation of the seafloor movement. If we take the current approximate amplitude estimation, we would be able to obtain ca. 3 seconds for effective duration of the seafloor uplift. We think that the change in water depth would be more abrupt than having been considered. The amplitude of the tsunami at each pressure gauge location is the same as the uplift amount of the seafloor and the amplitude of the acoustic pressure fluctuations is proportional to uplift velocity. We think that the pressures observed on the seafloor would be explained by superposed fluctuations such as tsunami and acoustic waves. Note that the pressure fluctuations due to incident seismic waves are within a few meters in equivalent water depths and the most dominant wave in the recorded pressure signals would be of the acoustic wave.

VI. Summary

At the time of the 2003 Tokachi-oki earthquake, a megathrust earthquake at the Kuril subduction zone, a cabled observatory recorded invaluable data on both crustal uplift of the seafloor caused by the earthquake. The crustal uplift due to the main shock was estimated as 0.37 and 0.12 m at locations of the two tsunami gauges located about 31.4 and 81.7 km away from the epicenter of the main shock. The eastimated rate of the continuous crustal uplifts are about 0.004 mm/day over two months at the all pressure gauge locations after the main shock. These phenomena must be discussed in detail with the results from other means.

After the main shock, a continuous uplift of the seafloor is observed at the all three pressure gauge locations with an exponential decay in the rate of uplifts. Although the coseismic uplifts show a strong correlation with seismic asperity estimated by various authors, the postseismic uplifts are relatively space-independent. Since the distribution of the coseismic uplift values is different from that of the postseismic, we preclude that mechanisms of these seafloor uplifts could be caused by two different causes. Since the postseismic continuous uplifts are observed at all the pressure gauge locations, we think that one of the possible cause of the post-seismic uplift would be of a slip of the plate boundary supplementary to coseismic one. Through the analysis of the data, we now think that there might be at least two directions in observation efforts in future seismogenic studies. One is to deploy long-term observatories to cover as long time as possible compared to the recurrence cycle of plate boundary megathrust earthquakes, and the other to access as close as possible to real seismogenic zone to improve the signal-to-noise ratio in observation properties.

Pressure fluctuations we observed on the seafloor at the time of the earthquake were analyzed for possible cause of high amplitude signals whose magnitude is about several tens of the real seafloor uplift. We think the most predominant signals in the pressure would be caused by acoustic waves caused by the uplift. The order estimate of their amplitude led us to a new insight that the abrupt change in water depth has taken place in a time duration of several seconds. Since both tsunami and acoustic waves are caused by the same phenomena, it would be important to relate them to each other to obtain real seafloor uplift in a time series.

We would like to conclude that all the above observations are all new findings that could be obtained since there was a cabled observatory witnessed the occurrence of the plate boundary earthquake. For any further seismological development for plate boundary earthquakes taking place in the offshore, one should think of making seafloor observations satisfactory to get reliable data to monitor necessary phenomena invisible or unknown in the past.

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