Behaviors of Electromagnetic Waves Directly Excited by Earthquakes

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***Abstract*—We detected electromagnetic (EM) waves directly excited by earthquakes in a deep borehole and confirmed them by simultaneous capturing of their waveforms and of seismic waves measured at the same observation site. Furthermore, the excitation mechanism of the EM pulse was confirmed as the piezoelectric effect by a laboratory experiment, in which a seismic P-wave was readily generated by a small stress impact, and the EM wave was simultaneously excited basically by the P-wave. Here, we show behaviors of seismic waves and of their excited EM waves when small and large earthquakes occurred. We also found that EM waves excited by seismic waves have leaked out of the ground surface.**

***Index Terms*—Electromagnetic (EM) radiation, observations in borehole, piezoelectric effect, seismic wave.**

I. Introduction

So far, many scientists have been trying to detect electromagnetic (EM) signals as a precursor of earthquakes [1]–[6]. Very recent studies have revealed that only low-frequency (i.e., around 1 Hz or lower) signals have a direct interrelation with earthquakes [7], [8]. In these studies, data of reliable seismic electric signals or EM signals are a prerequisite to the analysis in finding the relation with earthquakes. On the other hand, coseismic EM signals have been detected by magnetotelluric (MT) methods [9]–[11], in which shapes of their waveforms are similar to those of seismic waves. However, the physics of the relationship between these EM waves and earthquakes has remained unclear.

In order to find EM pulses as a precursor of earthquake, we first started with the observation of EM noise in the Earth, constructing an electrically nonconductive borehole of 100 m in depth in the campus of Kyoto Sangyo University, Kyoto, Japan [12]. Inserting an EM sensor system into the borehole, we had been observing EM waves. At 14:50 JST on January 6, 2004, we detected an EM pulse just when an earthquake of M5.4 occurred off the coast of Kumano-nada, Japan, which was about 130 km southeast of the EM observation site. From the frequency dispersion characteristic curve of the detected EM pulse, we estimated its propagation distance in the space between the ground surface and the ionosphere and concluded that the detected EM pulse had first leaked out of the ground surface of the seashore near the earthquake, then propagated in the space, and was detected by the sensor in the borehole [13]. For finding EM pulses directly excited by earthquakes, we have been observing EM noise in boreholes at various places such as on mountainsides and seashores. At the Shirahama observation site among them, we detected tremendous number of EM pulses of a few kilohertz with duration of a few milliseconds. From polarization analysis of these EM pulses detected both above the ground and in the borehole, we found that almost all of these EM pulses were generated by lightning, and others were artificial ones radiated from power lines [14], and we could not find any earthquake-related EM pulse at all.

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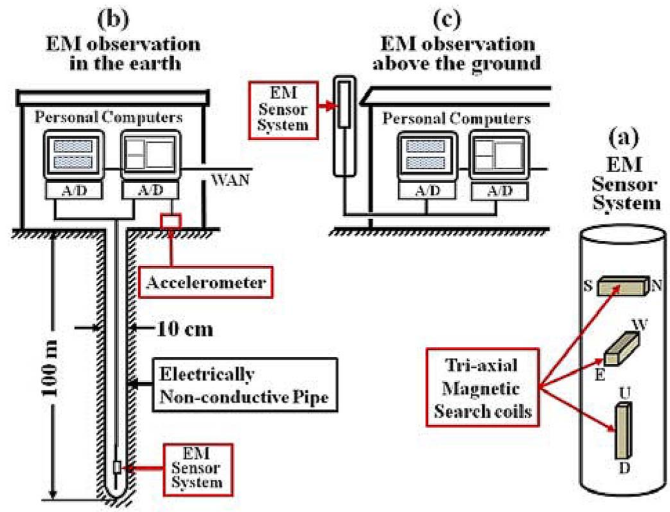

Fig. 1. Observation systems for detecting EM noise in the Earth and above the ground. (a) EM sensor systems composed of tri-axial magnetic search coils. (b) Observation booth with an electrically nonconductive borehole of 100 m in depth and 10 cm in diameter. An accelerometer is set near the borehole. (c) EM sensor system on the ground.

Considering the reason why earthquake-related EM pulse could not be detected in the Earth, we found that the amplitude of EM pulses excited in the Earth would be strongly decayed during their propagation due to high electrical conductivity of the Earth's medium. The decay rate is given by a specific distance called "Skin depth δ" through which the amplitude of EM wave decays to $1/e$ $(e = 2.718)$ [15]. Since the distance δ is inversely proportional to the square root of frequency, high-frequency EM waves would decay and fade out in a short distance, but those of lower frequency could propagate for a long distance. Therefore, we shifted down the monitoring frequency from a few kilohertz range to a few tens of hertz below the frequency of power lines. As a result, we have finally detected earthquake-excited EM pulses in boreholes and above the ground. From these observed results, we have clarified behaviors of EM waves directly excited by seismic waves.

II. Observation and Analysis System

Fig. 1 show a schematic illustration of observation systems (at 35.07° N, 135.75° E) in the campus of Kyoto Sangyo

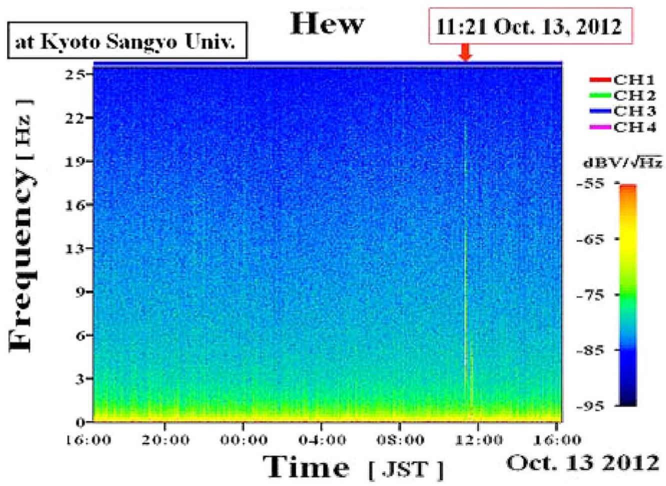

Fig. 2. Example of spectrogram used for continuous monitoring of EM noise. A slightly bright spectral line seen at 11:21 on October 13, 2012 was an EM pulse excited by an earthquake (M3.8) at 26.5 km north of the EM observation site.

University. We have accomplished sensor systems for the present observation. The EM sensor system is composed of tri-axial magnetic induction (search) coils for detecting tri-axial magnetic field components (east–west $\mathrm{H_{ew}}$, north–south $\mathrm{H_{ns}}$, and vertical $\mathrm{H_{v}}$). The coils were wound by a wire of 26 000 turns around a permalloy core of 8 cm in length and 1.2 cm in diameter. Each coil is connected to a preamplifier with an amplification factor of 808. One EM sensor system was hung in a borehole with an electrically nonconductive pipe of 100 m in depth and 10 cm in diameter. The hanging by a long cable makes it hard to travel the seismic vibration to the magnetic search coil near the bottom of the borehole. Another sensor system was set on the ground. The calibration of signal intensity of detected magnetic field was completed in advance by measurements of each search coil set in a double Helmholtz coil forming known magnetic field intensity. Output signals from the preamplifiers were led to a 16-bit analog-to-digital converter installed in personal computers on the ground. Thus, the resolution of detected magnetic flux density is 3 pT.

For continuous monitoring of EM noise environment, we used an analysis system embedded in the personal computers, which can display spectrograms (see Fig. 2) in a range of up to 25 Hz versus time (spanning 24 h), in which vertical spectral lines with color-coded intensity are scrolled every 160 s. Other computers with a clock synchronized with the GPS time can capture waveforms of all magnetic components and of seismic accelerations measured by an accelerometer installed near the borehole. These signals were acquired with a sampling frequency of 512 Hz by delayed-triggering timing for a signal exceeded preset amplitude of the $\mathrm{H_{ew}}$ component.

III. Observation Results

From December 2011, we began to monitor EM noise environment in the Earth by spectrograms. One example of the $\mathrm{H_{ew}}$ component is shown in Fig. 2, in which a slightly bright vertical spectral line of the detected EM pulses can be seen at 11:21 JST when an earthquake occurred on October 13, 2012. As the first step, a relation between earthquakes and EM pulse detection was examined from spectrograms. During a period from December 2011 to March 2013, we had 19 earthquakes of magnitude greater than 2 $(\mathrm{M} > 2)$ occurred in the area around the EM observation site. A spatial distribution of these earthquakes is shown in Fig. 3. Thirteen earthquakes denoted by red dots among them were confirmed by the bright spectral lines in spectrograms. They were within a circle of 40 km in radius centered at the EM observation site, in which earthquakes with larger magnitude were at far distances from the EM observation site. Seismic intensities at the EM observation site by these earthquakes were mostly 1 or less. This suggests that EM waves could be detectable for earthquakes that caused vibrations of seismic intensity greater than 1 at the EM observation site.

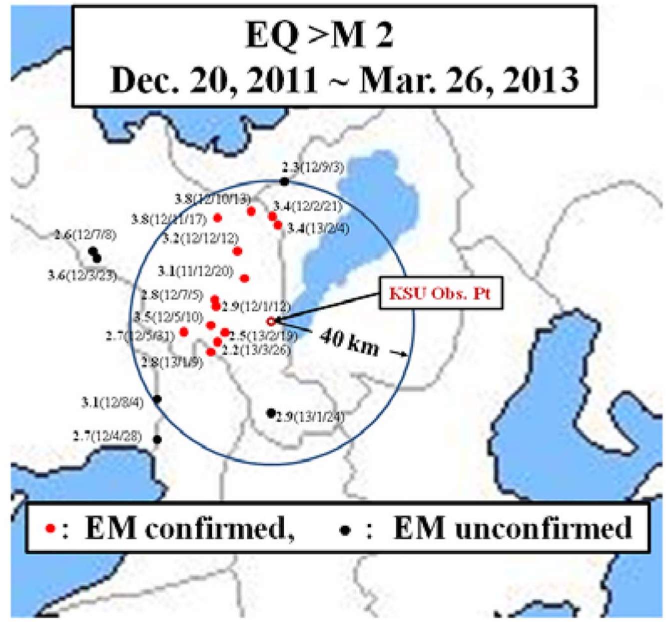

Fig. 3. Distribution of 19 earthquakes occurred in an area around the EM observation site during 15 months from December 20, 2011 to March 26, 2013. The red dots denote earthquakes confirmed by bright spectral lines in spectrograms.

From March 2013, we began simultaneous capturing of waveforms of the seismic acceleration $\mathrm{S_{ns}}$ and tri-axial magnetic components $\mathrm{H_{ew}}$, $\mathrm{H_{ns}}$, and $\mathrm{H_{v}}$ of EM pulses detected both in the borehole and above the ground.

A. *For a Small Earthquake*

A small earthquake (M2.2) occurred at 6.5 km-depth of 34.99N, 135.61E at about 16 km west of the EM observation site at 03:19:53.6 JST on March 26, 2013. The official occurrence point and time of the earthquake was taken from the Japan Meteorological Agency Earthquake Catalogue. Fig. 4(a) shows captured waveforms of the magnetic $\mathrm{H_{ew}}$ component of an EM pulse detected in the borehole and of the north–south component $(\mathrm{S_{ns}})$ of seismic acceleration. The waveform of $\mathrm{H_{ew}}$ is drawn as the magnetic flux density $\mathrm{B_{ew}}$. At 03:19:59.89 JST, which is 6.29 s after the occurrence of the earthquake, the amplitude of $\mathrm{B_{ew}}$ became large just when the seismic S-wave arrived at the EM observation site as seen in the waveform of $\mathrm{S_{ns}}$. The primary tremor part of $\mathrm{B_{ew}}$ shown by small amplitude (0.08 nT) begun at 2.03 s before 03:19:59.89 JST, which would

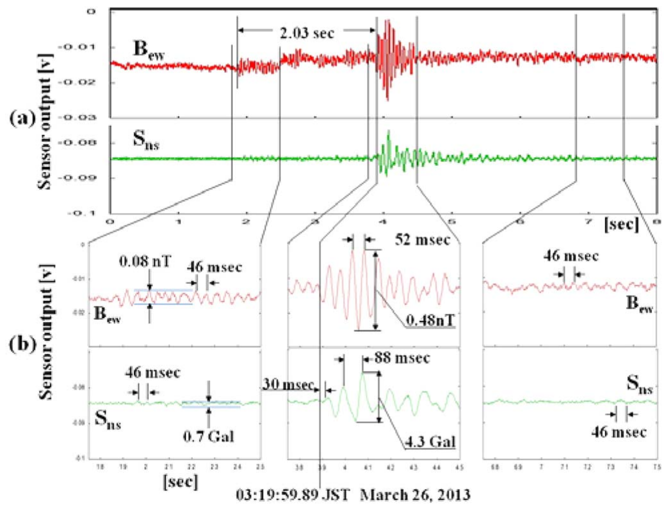

Fig. 4. (a) Waveforms of magnetic flux density B_{ew} of east–west component H_{ew} of EM pulse detected in the borehole and of north–south component S_{ns} of seismic acceleration at around 03:19:59.89 JST on March 26, 2013 after an earthquake (M2.2) occurred at 16 km west of the EM observation site at 03:19:53.6 JST on March 26, 2013. (b) Time-expanded waveforms of B_{ew} and S_{ns}.

be excited by the seismic P-wave, although P-wave fluctuation is not clearly seen in the waveform of S_{ns}. The time span of 2.03 s is consistent with the difference in arrival times between P- and S-waves for the distance of about 17 km from the earthquake hypocenter to the EM observation site, which was calculated using their propagation velocities of 5.3 and 3.3 km/sec, respectively.

Fig. 4(b) shows time-expanded waveforms of three parts in B_{ew} and S_{ns}. They are parts before S-wave arrival, during the S-wave passage, and after its passage. In the waveforms before and after the S-wave arrival, fluctuations with a dominant period of about 46 ms are seen in both B_{ew} and S_{ns}. Thus, B_{ew} could be regarded as a coseismic wave basically excited by the seismic P-wave. During the passage of the S-wave with a period of ∼88 ms, the amplitude of B_{ew} became large, and its period was modified to 52 ms. The difference in periods between B_{ew} and S_{ns} during the S-wave passage suggests that the B_{ew} signal was not induced by the earthquake dynamo mechanism, as described in [9] and [10].

B. For a Big Earthquake

At 05:33:17.7 JST on April 13, 2013, a big earthquake (M6.3) occurred at 14.8 km-depth of 34.4N, 134.8E in Awaji-shima island, which was 115 km southwest of the EM observation site (35.07N, 135.75E) at Kyoto Sangyo University. Although, regrettably, computers could not capture waveforms of the EM pulse at that time; they captured waveforms of tri-axial magnetic components (B_{ew}, B_{ns}, B_v) detected above the ground (shown in the upper part in Fig. 5) at around 05:33:39.921 JST, which was 22.221 s after the rupture time of the earthquake. Furthermore, at 13.063 s later, another computer captured waveforms of seismic S-wave (S_{ns}) and of magnetic east–west component (B_{ew}) detected in the borehole simultaneously at 05:33:52.984 JST (shown at the bottom part in Fig. 5). We displayed these waveforms in a frame with the same time scale in Fig. 5. The time interval of 13.063 s from the detection of the EM pulse above the ground at 05:33:39.921 JST to the detection of the seismic vibration in S_{ns} and its excited B_{ew} at 05:33:52.984 JST has provided us important information on the behaviors of the seismic wave and its excited EM waves, which is discussed below. The long duration of about 4 s of waveforms after 05:33:39.921 JST shown in the upper part in Fig. 5 is also explained in Section IV.

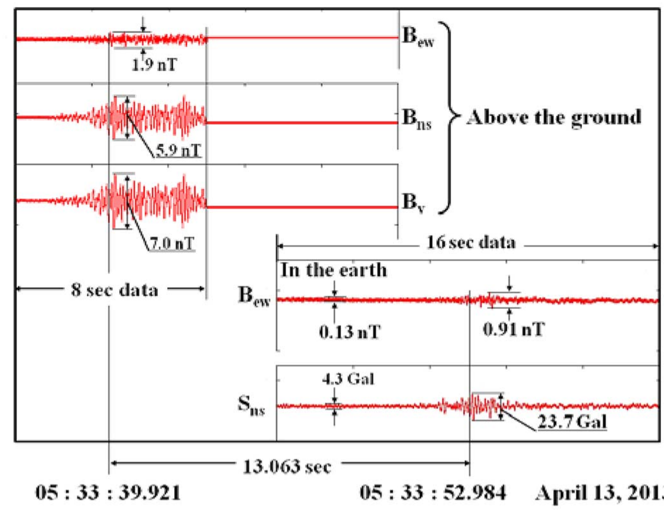

Fig. 5. Waveforms of magnetic components of an EM pulse excited by seismic waves detected after the occurrence of a big earthquake (M6.3) at Awaji-shima island at 05:33:17.7 JST April 13, 2013. (Upper part) Waveforms of tri-axial magnetic flux densities detected above the ground at the EM observation site at around 05:33:40 JST, which was 22.2 s after the rupture time of the earthquake. (Lower part) Waveforms of B_{ew} in the Earth and of seismic acceleration S_{ns} detected at the EM observation site at around 05:33:53 JST.

C. Laboratory Experiment

Before discussing the behaviors of the seismic waves and their excited EM pulses, we need to confirm the mechanism of EM wave excitations. Since we have been considering its mechanism to be a piezoelectric effect, we tried to confirm it by a laboratory experiment, which was conducted in the Research Center for Earthquake Prediction, Disaster Prevention Research Institute, Kyoto University [16].

The experimental setup for confirming excitations of EM pulses in a granite pillar due to the piezoelectric effect is schematically shown in Fig. 6(a). For detection of EM fields radiated from the granite pillar (10 cm × 10 cm × 50 cm), we used four sets of the EM sensor system composed of a cross-electric dipole antenna of 5 cm tip-to-tip and a magnetic search coil. They were arrayed along the granite pillar every 7-cm spacing without contact to the granite surface. Waveforms of 12 channel signals from the EM sensors passing through preamplifiers were captured into digital oscilloscopes.

For giving stress impacts to the granite pillar to cause the piezoelectric effect in it, we used a method of negative stress impact, which was caused at the fracture of a glass ball of 2 cm in diameter set on the top of the granite pillar. At the fracture of the glass ball by gradually increasing pressure loaded to the glass ball and granite pillar in series, EM fields were excited in the granite due to the piezoelectric effect and radiated from it. The captured waveforms are shown in Fig. 6(b). Although we measured many EM signals with various fluctuation periods,

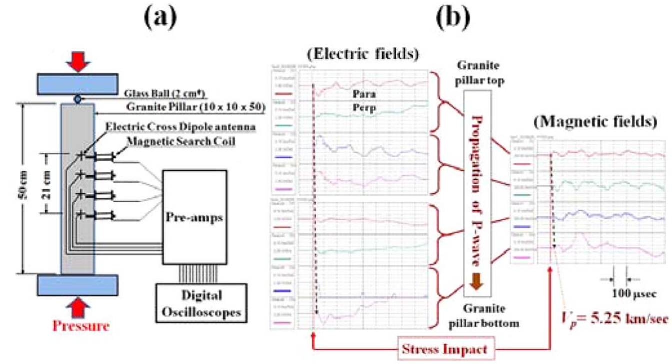

Fig. 6. (a) Schematic illustration of the experimental setup for confirming EM pulse excitations in a granite pillar (10 cm × 10 cm × 50 cm). EM fields radiated from the granite pillar were detected by four sets of the sensor system arrayed every 7-cm spacing along the granite pillar, and waveforms of detected signals were captured by digital oscilloscopes. A glass ball of 2 cm in diameter is set on the top of the granite pillar. A negative stress impact can be given to the granite top when the glass ball was fractured. (b) Waveforms of EM fields detected at each sensor position. The starting times of EM field detection in each waveform have delayed in accordance with their sensor positions from top to bottom. The delay time of 40 μs for 21-cm distance results in a propagation velocity of 5.25 km/s.

it is not so important to discuss a relation between fluctuation periods measured in the observation and in the experiment, because scale sizes in both situations are quite different. On the contrary, we found a physically basic point showing a relation between the dynamic movement of the granite and excitation of EM waves. It was starting time of EM signal detection at each sensor position for the passage of shock waves propagating in the granite pillar. The detection times have delayed in accordance with their sensor positions from top to bottom. The delay time for the span of 21 cm from the top sensor to the bottom one was $\sim$40 μs, which results in a velocity of $\sim$5.25 km/s. This velocity coincides with that of the seismic P-wave in the granite. This experimental result showed that the EM fields were surely excited in the granite pillar after the passage of wave-front of the P-wave and showed that the stress impact generating P-wave was extremely small compared with that for breaking the granite.

IV. Discussion

A. Behaviors of Seismic Waves and Their Excited EM Waves

By the laboratory experiment, we have confirmed important facts that the stress impacts given to the granite pillar readily generated seismic P-wave in it and the P-wave simultaneously excited EM waves. Therefore, $\mathrm{B_{ew}}$ with a period of $\sim$46 ms shown in Fig. 4 is considered to have been basically excited by vibrations of the seismic P-wave. Furthermore, due to large distortions of the Earth's crust by large amplitude of the S-wave, the amplitude of the EM signal would become large, and its period would be modified. A possible generation mechanism of these coseismic signals was proposed by Huang [17].

At 22.2 s after the rupture time (05:33:17.7 JST) of the big earthquake on April 13, 2013, waveforms of tri-axial magnetic components of the EM pulse were captured above the ground at the EM observation site at around 05:33:40 JST (shown in the upper part in Fig. 5), and further, at 13.063 s later, the amplitude of the $\mathrm{B_{ew}}$ component in the Earth was magnified by the S-wave arrival at the EM observation site at around 05:33:53 JST (shown in the lower part in Fig. 5). From these results, we can imagine behaviors of the seismic S-wave and of its excited EM waves.

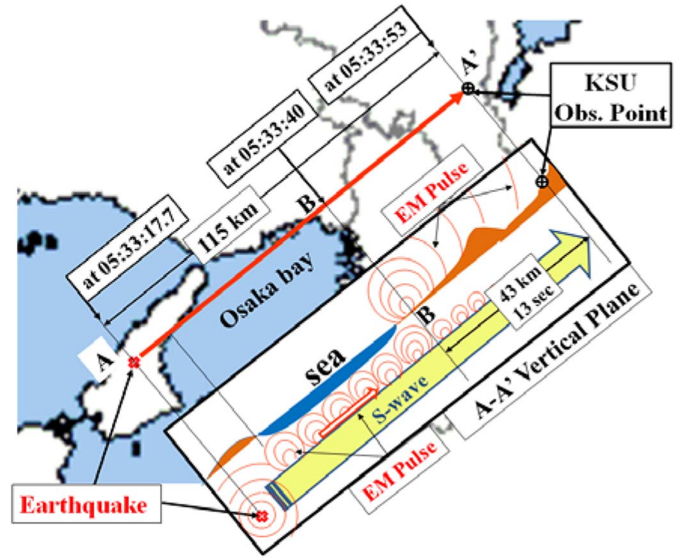

Fig. 7. Schematic illustration of behaviors of seismic wave and of excited EM pulses derived from the waveforms shown in Fig. 5. The earthquake (M6.3) occurred at 05:33:17.7 JST on April 13, 2013. When the seismic S-wave was propagating underneath the Osaka bay, the EM pulse radiated from Earth's crust could not leak out of the seawater. After the arrival of the S-wave at the seashore (area B in the figure), the EM pulse leaked out of the ground surface and spread onto the free space with the light velocity and was detected above the ground at the EM observation site at around 05:33:40 JST. The S-wave that had been propagating was detected at the EM observation site at around 05:33:53 JST.

Fig. 7 shows a schematic illustration of their behaviors. After the occurrence of the earthquake, seismic P- and S-waves were propagating in the Earth's crust, and large-amplitude EM pulses excited by the S-wave could be radiated from the Earth's crust along with S-wave propagation. EM pulses radiated underneath the Osaka bay, however, could not leak out of the sea surface due to the EM shielding effect of the seawater. When the seismic S-wave passed through the Osaka bay underneath and arrived at the seashore (area B indicated in the figure), the EM pulse could leak out of the ground surface and spread into the free space with the light velocity. Conducting a numerical simulation by the finite-difference time-domain method in space (from the deep Earth to the air via sea–land surface), we had confirmed the EM wave leaking out of the ground at seashore. Then, the EM pulse was detected by the EM sensor system on the ground at the EM observation site at around 05:33:40 JST. On the other hand, the seismic S-wave had been propagating with its velocity of $\sim$3.3 km/s in the Earth's crust and arrived at the EM observation site at 05:33:53 JST, where waveforms of seismic S-wave and their excited EM waves were captured as shown in the lower part in Fig. 5. The propagation distance of the seismic S-wave during the time interval of 13.063 s became 43 km, which was the distance from area B to the EM observation site.

The rather long duration of about 4 s of waveforms seen after 05:33:39.921 JST (shown in Fig. 5) would be resulted by detection of superposed waveforms leaked out of a long area of B along the propagating path of the S-wave toward the EM observation site.

Recently, we have had two earthquakes. One (M3.5) occurred at 22 km south of the EM observation site where the seismic intensity was 1, and an EM pulse was first detected above the ground at about 0.19 s before its detection in the borehole. Another one (M3) occurred at 5.4 km north of the EM observation site. In this case, an EM pulse was detected above the ground at 0.12 s after its detection in the borehole. These results suggest that the earthquake-excited EM pulses are readily radiated from the ground.

B. Measurements Hereafter

From the present study, we have confirmed that EM waves were readily excited even by the weak seismic vibrations in the Earth's crust and were sensitively detected both above and under the ground surface.

It was found, from the result of the laboratory experiment, that the seismic P-wave can be readily generated even by small stress impact to the granite at the fracture of the glass ball. This stress impact was extremely small compared with that for breaking granite. We can imagine that this situation is analogous to a microfracture in active faults, where small glass balls in the experiment can be replaced by small rocks laid in a fragmentation layer in active faults. Therefore, under the situation of gradually increasing pressure loaded to the Earth's crusts, EM pulses could be excited at the fractures of these small rocks. For increasing pressure, many rocks could be fractured, and the intensity of EM pulses would become large. Since the increasing pressure might lead to rupture of an earthquake, detection of these EM pulses would provide us important information on the situation of pressure loaded to the Earth's crust. Therefore, EM measurements in the deeper Earth would become an important future subject.

V. Conclusion

In the present study, we have confirmed that EM waves directly excited by seismic wave were detected both above and under the ground surface although we could not find EM pulses before and at ruptures of earthquakes. We can conclude that the coseismic EM signals detected by the MT method [9]–[11] would be excited due to the piezoelectric effect by the vibrations of the seismic waves in the Earth's crust.

We deeply recognized that measurements of EM signals in a deep borehole are very important for this research, because interference of unnecessary EM noise filled above the ground can be reduced in the deep Earth. Measurements of EM waves above the ground in addition to that in the deep Earth would provide us important information on EM phenomena excited by earthquakes. Finding EM pulses that might be excited before and at the time of rupture of earthquakes would be the next subject.

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