SEISMIC SEICHE OCCURRED AT LAKE SAIKO DUE TO THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE

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SUMMARY:
A phenomenon similar to tsunami was observed by anglers and inhabitants right after the 2011 off the Pacific coast of Tohoku earthquake at Lake Saiko in Japan, which is one of the five lakes located on the foot of Mt. Fuji. In order to clarify the mechanism of this phenomenon, the author interviewed with the witnesses first and found that high waves had come on lake shores with over a period of 2 minutes. Earthquake ground motions observed near the lake were examined next and it was found that the surface wave exhibiting the feature of Rayleigh wave with a period around 60 seconds in the observed motion was predominant. A shaking experiment was conducted using a Lake Saiko model and it revealed that a resonant fluctuation of water surface in the short side of the rectangular shape of the lake with a period just about 60 seconds had made the shift to that in the long side with a period close on 200 seconds. Then, the author confirmed that the phenomenon had been caused by a seismic seiche.

Keywords: 2011 off the Pacific coast of Tohoku earthquake, Seiche, Observed ground motions, Experiment

1. INTRODUCTION

Mcgarr and Vorhis (1968) stated that a term seiche was first applied by Forel to standing waves set up on the surface of water of Lake Leman by wind and changes in barometric pressure in 1895. Meanwhile, a term seismic seiche was first used by Kvale in discussing oscillation of lake levels in Norway and England caused by the Assam earthquake of August 15, 1950 (Mw=8.6). In the old days, the phenomenon of a seismic seiche in Scotland and England due to 1755 Lisbon earthquake, Portugal (Mw=8.5~9.0) was reported. In recent years, a seismic seiche due to 2004 Sumatra-Andaman earthquake (Mw=9.1) was reported in India, Bangladesh, Nepal and Thailand. A seismic seishe is used to stand for standing waves set up on rivers, reservoirs, ponds, bays and lakes at the time of passage of seismic waves due to an earthquake. A seismic seiche is characterized by two representative features. The first one is that the magnitude of earthquakes which brings about a seismic seiche is larger than 8.5. The second is that a seismic seiche is observed far-distant from epicenters.

2011 off the Pacific coast of Tohoku earthquake was occurred in Japan on March 11, 2011. Huge tsunami attacked the eastern coast of Tohoku region and about 19,000 people were lost or missing. The magnitude of this earthquake was measured as 9.0 (Mw), which is the largest in the history of earthquakes in Japan. Crustal movement was observed all over the main island of Japan and the largest displacement 5.3 m in the horizontal direction and 1.2 m in the vertical direction was measured at Ojika peninsula, Miyagi prefecture. The Geospatial Information Authority of Japan reported continuous crustal movements monitored using the GPS-based control points due to the earthquake. They clearly showed the state of propagation of surface waves from fault ruptures to all over Japan.

A phenomenon similar to tsunami was observed right after the earthquake by anglers and inhabitants at Lake Saiko, which is one of the five lakes located on the foot of Mt. Fuji in Japan. In this paper, the author tries to verify that the phenomenon was caused by a seismic seiche from an engineering point of view, by examining earthquake ground motions observed near the lake and conducting vibration experiment using a Saiko model. Figure 1 shows the location of Lake Saiko and its positional relation to the hypocentral region of the 2011 off the Pacific coast of Tohoku earthquake.

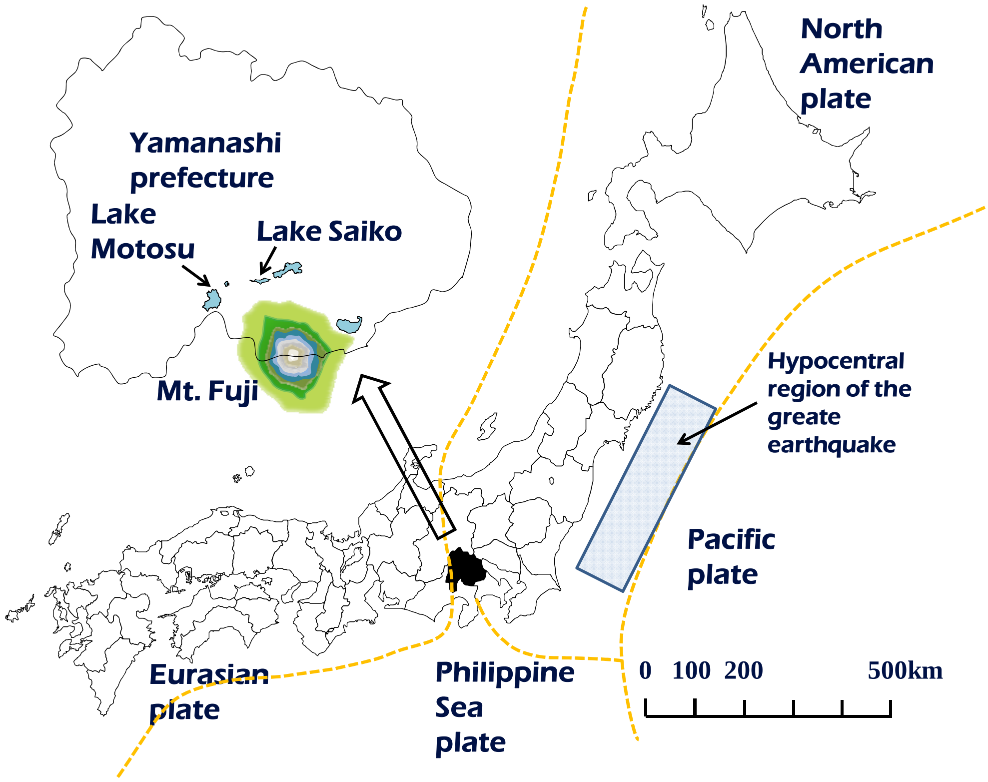


Figure 1.1. Location of Lake Saiko and its positional relation to the hypocentral region ofthe 2011 off the Pacific coast of Tohoku earthquake

2. SEISMIC SEICHE

A seismic seiche can be explained as standing waves set up in a closed water body with free water surface due to earthqaukes. When a propagated wave is completely reflected by the vertical wall, a complete superposed wave was formed and antinodes of water body appear the vertical wall. To satisfy this condition, it is necessary that wave lengths of water body L (m/s) coincide with multiples of half-wave length. Since a seiche is one of long waves, its propagation velocity C (m/s) is expressed as follows:

$$C = \sqrt{gh} \tag{2.1}$$

in which, g (cm/sec^2) denotes gravitational acceleration and h (m) denotes depth of water.
The predominant period of fundamental mode of seiche, T (s) can be given as:

$$T = \frac{L}{C} = \frac{L}{\sqrt{gh}} \tag{2.2}$$

where, a wave length L is given using the width of rectangular shape of water body l. When both sides of rectangular water body are bounded by vertical walls, L can be determined as:

$$L = 2l / N, N = 1,2,3,\cdots \quad (2.3)$$

In a case where only one side is vertical wall and the other side is free, L can be determined as:

$$L = 4l / N, N = 1,2,3,\cdots \quad (2.4)$$

3. SEISMIC SEICHES DUE TO 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE

3.1 Seismic seiche observed at Lake Saiko

A phenomenon similar to tsunami was observed at Lake Saiko right after the 2011 off the Pacific coast of Tohoku earthquake by anglers and inhabitants. Lake Saiko is one of the five lakes located on the foot of Mt. Fuji. The map at the upper left in Figure 1 illustrates the location of the five lakes. The distance from the fault rupture to the lakes ranges from 300 to 500 km. An angler, who had been fishing on a boat at Lake Saiko during the earthquake, told his experience that water level of the lake rose up gradually, then fell down gradually with an amplitude of 1 m (Sankei News, 2011).

Figure 3.1 illustrates a topographic map of Lake Saiko. Another old angler felt strong vibrations due to this earthquake at point A in the figure. Then, he moved to point B at east shore by his car in order to see how his fishing boat at east shore was. It might take 5 minutes for him to move from point A to B after the termination of excitation. At point B at east shore, he saw high wave going back offward. His boat which had been placed on sand shore was washed away and small fishes and shellfishes were cast ashore due to high waves there. Then, he brought his cousin at the restaurant located at point C to east shore. It would take at least 2 minutes. The old angler and his cousin saw high wave going back offward again. Hearing investigation to these ocular witnesses revealed that high waves came repeatedly with a period longer than 2 minutes. They told that water had been turbid up to 50 meters offshore and the fluctuation of water surface had reached one meter at that time. They picked fishes and shellfishes up and threw them back to the water. Photogragh 3.1 is the fishes and shellfishes having been sent up at the shore taken by his cousin.

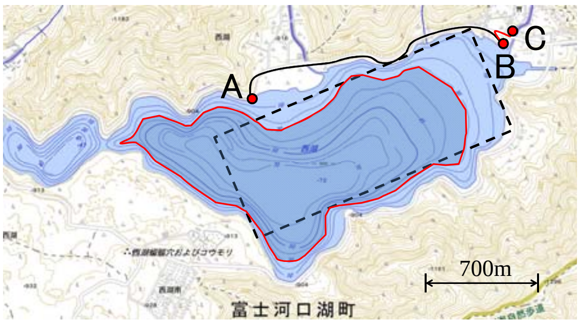


Figure 3.1. Topographical map of Lake Saiko

Phograph 3.1. Fishes and shellfishes set up at the shore

4. OBSERVED EARTHQUAKE GROUND MOTIONS NEAR SAIKO LAKE

Motosu K-NET observation station is located 1 km north-east of Lake Motosu. Horizontal distance from the observation station to Lake Saiko is approximately 6 km. Therefore, the long period component of the observation ground motions at the station can be regarded as identical with that at Lake Saiko. Thus, analyses are carried out on the acceleration data recorded there during the 2011 off the Pacific coast of Tohoku earthquake. Figure 3.1 shows the recorded accelerograms. The maximum values in acceleration are roughly 30 cm/sec^2 in the NS and EW directions and 20 cm/sec^2 in the UD direction, respectively. As shown in the figure, the time duration of primary motions in the three accelerograms is as long as 2 minutes.

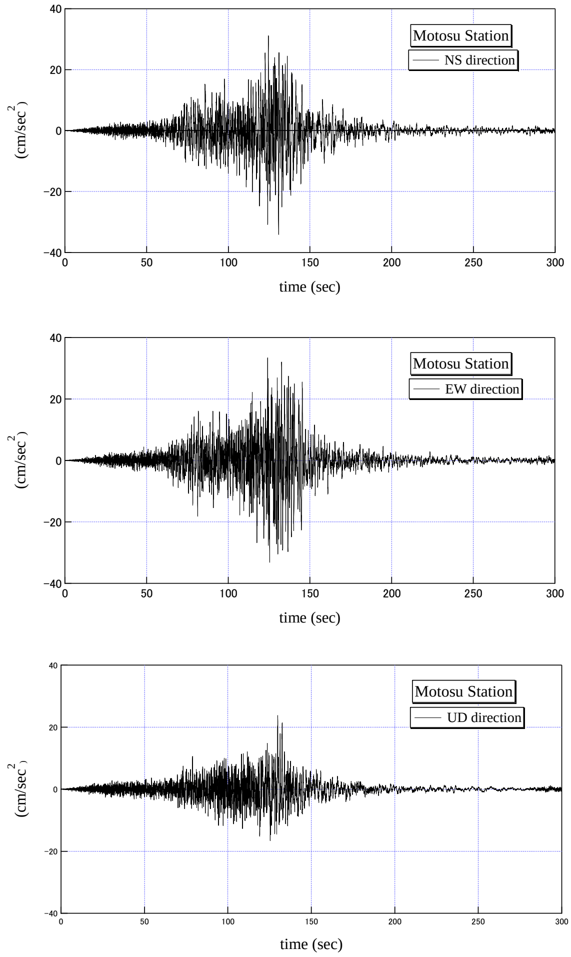


Figure 3.1. Accelerorams of recorded ground motions at Motosu K-NET observation station

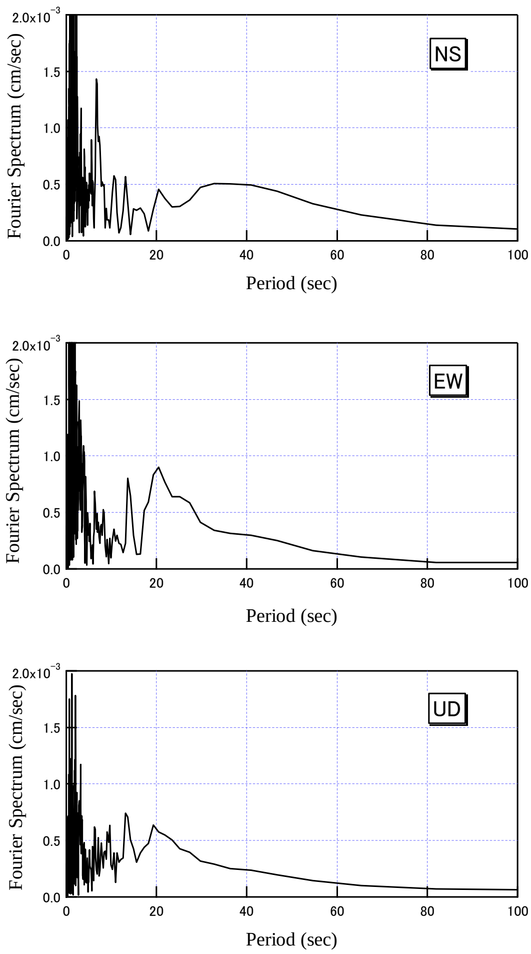


Figure 3.2. Fourier spectra of recorded ground motions at Motosu K-NET observation station

Figure 3.2 illustrates Fourier spectra for the recorded accelerations. In the NS component, three peaks can be seen in the period ranging from 10 to 20 seconds and a peak at the period a little longer than 20 seconds. In a wide range of period from 25 to 80 seconds, furthermore, Fourier spectrum sets high values. In the EW and UD components, however, the value of Fourier spectrum is not as large as that in the NS direction, in the period longer than 25 seconds.

5. SURFACE WAVE AND OCCURRENCE OF SEICHE

Figure 5.1 illustrates accelerograms of the observed ground motions processed by low-pass filter with a period longer than 50 seconds. As shown in the figure, they display harmonic oscillation with a predominant period around 60 seconds, although the amplitude is smaller than 0.2 cm/sec^2 in the NS direction and is smaller than 0.1 cm/sec^2 in the EW and UD direction, respectively. Figure 5.2 illustrates a superposition of displacement time histories of NS and UD component of the observed ground motions processed by a low-pass filter longer than 50 seconds. As shown in the figure, the maximum displacement reaches 45 cm in double-sideband amplitude, 30 cm in single-sideband amplitude, respectively in the NS direction. Figure 5.3 illustrates, on the contrary, a superposition of acceleration time histories of EW and UD components.　There is a little phase difference between the two acceleration time histories.　However, the phase difference remains constant with the passage of time.

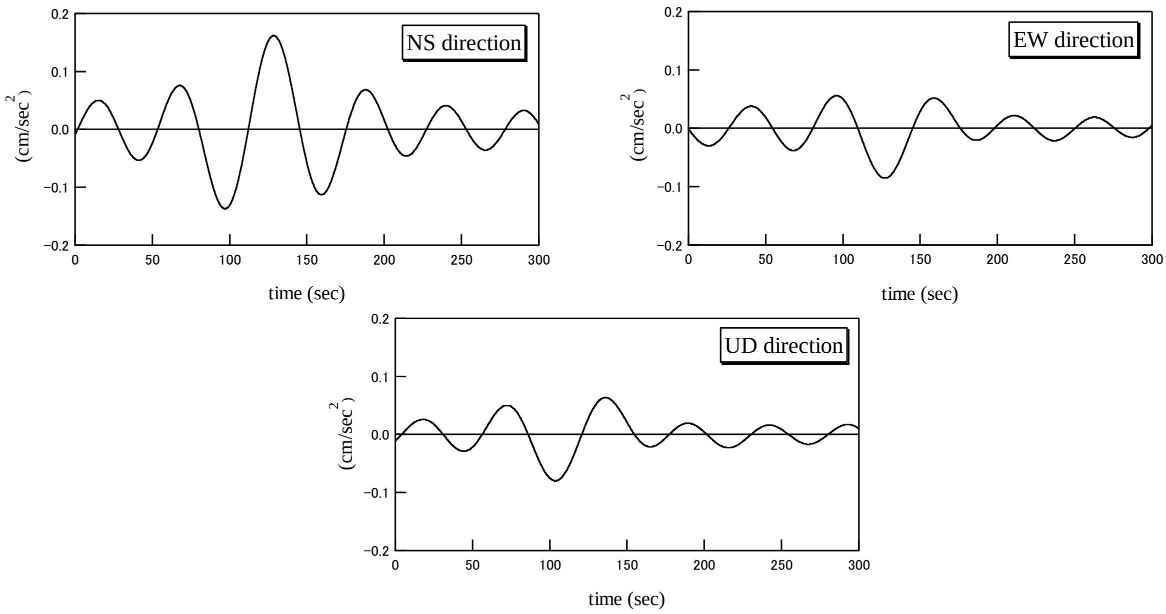


Figure 5.1. Accelerograms of the observed ground motions processed by low-pass filter with a period, 50 seconds.

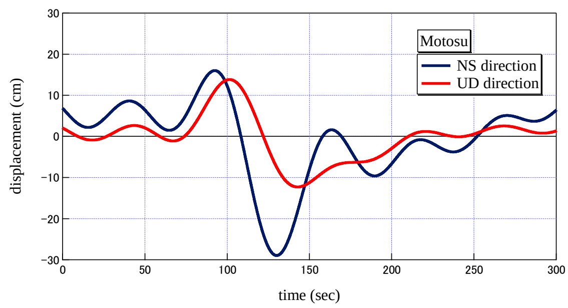


Figure 5.2. Superposition of displacement time histories of NS and UD components of the observed ground motions processed by a low-pass filter with a period, 50 seconds

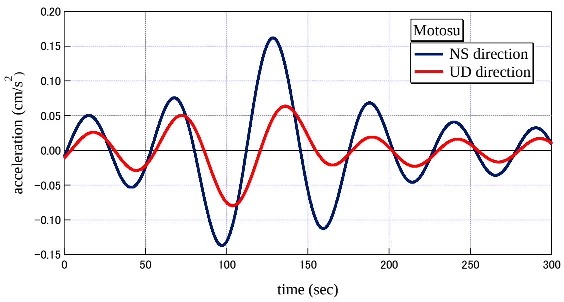
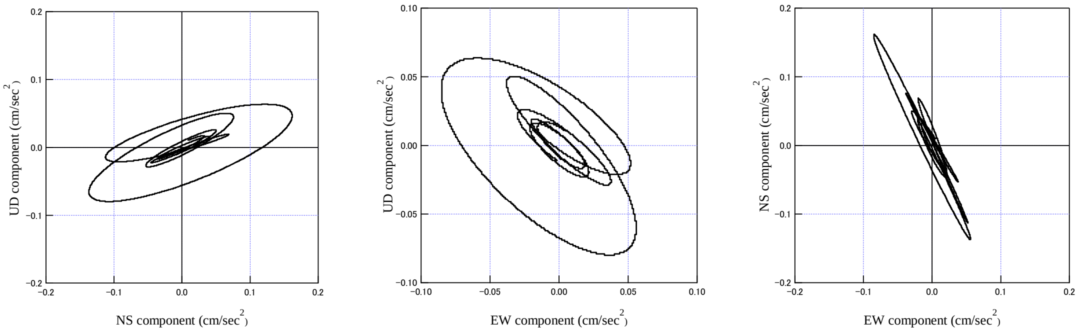


Figure 5.3. Superposition of acceleration time histories of NS and UD components of the observed ground motions processed by a low-pass filter with a period, 50 seconds

Using the acceleration time histories shown in Figure 5.3, traces of acceleration particle orbit were drawn as shown in Figure 5.4.　Both traces drawn on the NS-UD coordinate and that on the EW-UD coordinate exhibit unidirectional elliptical orbit.　The trace on the NS-EW coordinate, on the contrary, can be approximated by a straight line in the direction from the north-northwest to the south-southeast direction.　Thus, the surface wave with a predominant period around 60 seconds has a feature of

Rayleigh wave.



(a) UD-NS component (b) UD-EW component (c) NS-EW component

Figure 5.4. Traces of acceleration particle orbit

The Geospatial Information Authority of Japan (2011) reported continuous crustal movements per second having been monitored using the GPS-based control points due to the earthquake. According to the movie clip released by the authority, large crustal movements propagated toward Kanto and Koshinetsu regions as fault ruptures advanced southward, and then fault ruptures shift to off Fukushima prefecture and then off Ibaraki prefecture. The maximum displacement was measured as 5.3 m at Ojika peninsula near the epicenter. In Yamanashi prefecture, the principal axis of crustal movements sifted from the east-west direction to the north-south direction. Even in Yamanashi prefecture more than 350 km away from the fault ruptures, maximum displacement over 30 cm was measured and 10 cm of residual displacement remained after the earthquake. The behaviour and degree of crustal movement obtained by monitoring the GPS-based control points coincides with displacement time histories and particle orbits of the strong motion data as shown in figures 5.1 to 5.4.

6. VERIFICATION USING A MODEL EXPERIMENT

6.1 Lake Saiko model and its predominant period

As described above, the author estimated that the surface wave in the north-northwest to the south-southeast direction with a predominant period around 60 seconds would cause a seismic seiche at Lake Saiko. Model vibration test was carried out, therefore, in order to validate the estimated mechanism. Assuming that the shape of the lake bed in the north-northwest to the south-southeast direction is rectangle and L and D in equation (2) is 650 m and 45 m, respectively. Predominant period of fundamental mode of seiche is approximately 62 seconds as shown in equation (6.1).

$$T = \frac{2 \times 650}{\sqrt{9.8 \times 45}} = 62 \tag{6.1}$$

The lakebed model of Lake Saiko was formed by putting sheets made of Styrofoam having been cut in the form of depth contour of the lake. The scale of the model to the actual lake is 1/1780 in the horizontal direction and 1/000 in the vertical direction, respectively. The maximum depth of water of the model lake is 7 cm. Thus, the predominant period of fundamental mode of seiche is approximately 1.1 seconds in the model lake as shown in equation (6.2).

$$T = \frac{\frac{2 \times 650}{1780}}{\sqrt{\frac{9.8 \times 45}{1000}}} = 1.1 \tag{6.2}$$

6.2 Model experiment

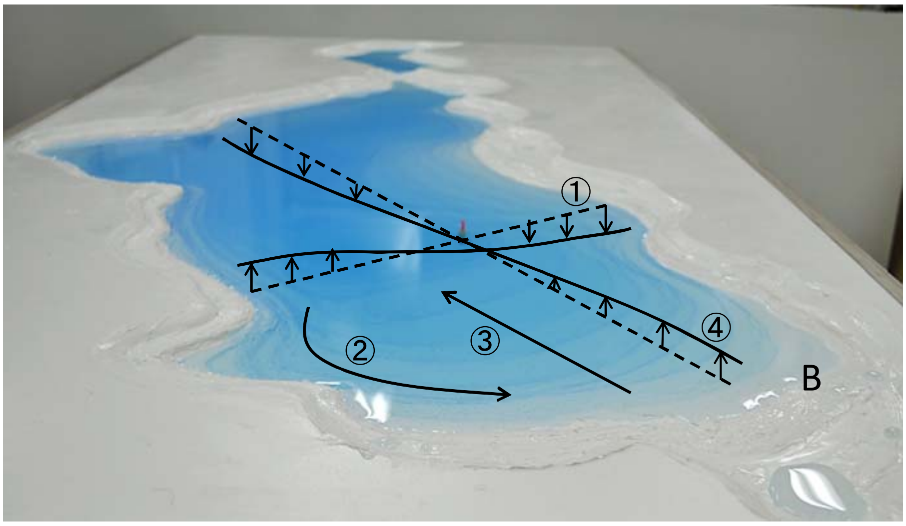
Pouring coloured water into the lakebed model, the Saiko model was formed. The model was fixed on a table with wheels attached. The table was shook once in the north-northwest to the south-southeast direction with a period of approximately 1 second. As a result, fluctuations of water surface in the north-northwest to the south-southeast direction with a period of 1.2 seconds appeared clearly twice. Then, distinguished fluctuations of water surface in the east-northeast to west-southwest direction with a period of 3.6 seconds came up three times (Suzuki, 2012).

Photograph 2 explains the mechanism of a seismic seiche came up at Lake Saiko. As shown in the photograph, earthquake motions in the north-northwest to the south-southeast direction excited the seiche in this direction first (1). Waters at southeast shore moved toward shallow body of water at east shore (2). This water body at east shore also moved westward (3). This removal of water excited a seiche in the east-northeast to west-southwest direction (4). Thus, a seismic seiche excited by earthquake motions in the short side of water body shifted to that in the long side of water body at Lake Saiko. High waves observed at point B in photographs 1 can be explained by such a shifting of principal axes of fluctuation of water surface.

Since the predominant period of seiche in the long side of water body at the model lake was 3.6 seconds, L and D was assumed to be 2000 m and 40 m, respectively as shown in equation (6.3). The predominant period of a seiche at actual lake can be calculated as 202 second, more than 3 minutes as shown in equation (6.4).

$$T = \frac{\frac{2\times 2000}{1780}}{\sqrt{\frac{9.8\times 40}{1000}}} = 3.6 \tag{6.3}$$

$$T = \frac{2\times 2000}{\sqrt{9.8\times 40}} = 202 \tag{6.4}$$



Photograph 6.1. Saiko model and description of mechanism on seismic seiche came up in Lake Saiko (Point B in the photograph is correspondent with the location of Point B in Figure 1.1)

6. CONCLUDING REMARKS

A phenomenon similar to tsunami was observed right after 2011 off the Pacific coast of Tohoku earthquake by anglers and inhabitants at Lake Saiko, which is one of the five lakes located on the foot of Mt. Fuji in Japan. In this paper, the author tried to verify that the phenomenon was caused by a seismic seiche from an engineering point of view, by examining earthquake ground motions observed near the lake and conducting vibration experiment using the Saiko model. The results obtained in this paper are summarized in the following.

(1) Interviews with ocular witnesses revealed that high waves came repeatedly with a period longer than 2 minutes.

(2) The maximum displacement of long-period component of earthquake ground motions near the lake reaches 45 cm in double-sideband amplitude in the horizontal direction.

(3) The long-period component of earthquake ground motion has distinct predominant direction of north-northwest to south-southeast and it has a feature of Rayleigh wave.

(4) It was found in the model excitation experiment that fluctuations of water surface in the north-northwest to the south-southeast direction with a period of 1.2 seconds appeared clearly twice and then, distinguished fluctuations of water surface in the east-northeast to west-southwest direction with a period of 3.6 seconds came up three times.

(5) Based on the experimental results, the seismic seiche which came up in Lake Sako can be explained in the following:

Earthquake motions in the north-northwest to south-southeast direction excited the seiche in this direction (short side of water body of the lake) first. Waters at southeast shore moved toward shallow body of water at east shore. This water body at east shore also moved westward. This removal of water excited the seiche in the east-northeast to west-southwest direction (long side of water body of the lake). Thus, a seismic seiche excited by earthquake motions in the short side of water body shifted to that in the long side of water body at Lake Saiko.

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REFERENCES

Mcgarr, A. and Vorhis, R. C. (1965). Seismic Seiches. *U. S. Geological Survey Professional Paper*: **544-E**, pp.196-236.

Sankei News (2011). http://sankei.jp.msn.com/affairs/news/110419/dst11041914210030-n1.htm (access date: 2012.4.17)

Giographical Information Agency of Japan. (2011). Continuous observation of at the GPS-based control stations during the 2011 off the Pacific coast of Tohoku earthquake. http://www.gsi.go.jp/cais/chikakuhendo40010.html. (access date: 2012.4.17)

Suzuki, T. (2012). Seismic seiche occurred at Saiko Lake due to the 2011 off the Pacific coast of Tohoku earthquake. *Proceedings of Japan Society of Civil Engineer.* **A1, No.68, No.2** (to be appeared).