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OBSERVED DYNAMIC PORE PRESSURE DURING EARTHQUAKE IN SATURATED ROCK

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SUMMARY

In this paper, earthquake induced dynamic pore pressure observed at the Kikuma oil storage base is discussed. During the 2000 Tottori-Ken Seibu earthquake, the 2001 Geiyo earthquake and its the largest aftershock, six pore pressure meters and one accelerometer recorded dynamic data significantly. Comparing the pore pressure and ground motion in time series, followings are pointed out. 1) Waveforms of pore pressure resemble each other. 2) Peak values of pore pressure appear during main part of horizontal ground motion. 3) Envelop of pore pressure resemble ground velocity closely and ground acceleration remotely. 4) Magnitude orders of peak pressure for three events are almost the same. 5) A ratio between peak pressure and peak velocity is stable.

INTRODUCTION

We have three oil storage rock cavern tank bases in Japan, namely, Kuji base, Kikuma base, and Kushikino base. Because these bases employ water sealing system, hydraulic behavior in rock plays key role. From this reason, several type instruments including dynamic pore pressure meter and accelerometer are installed in these bases. Study on hydraulic behavior in rock becomes active along with the use of the underground space. However, research on hydraulic behavior in saturated rock during an earthquake is very few. Shimizu et al.[1] discussed earthquake ground motion in Kamaishi Mine but they only focus on the peak acceleration. We reported dynamic pore pressure and earthquake ground motion in the Kushikino base during 1997 Kagoshima-Ken Hokuseibu earthquakes [2]. We pointed out following two things. 1) Dynamic pore pressure fluctuates after the S-wave arrival significantly. 2) Ratios of pore pressure and ground velocity are constant between two earthquake events.

We obtained seismic wave-induced pore pressure at the Kikuma base during the 2000 Tottori-Ken Seibu earthquake, the 2001 Geiyo earthquake and its largest aftershock successfully. In this paper, we compare the indicated fact with newly recorded ones. Hereafter, we call the largest aftershock of the 2001 Geiyo earthquake Aki-nada earthquake named after epicentral region.

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OUTLINE OF THE KIKUMA BASE

The Kikuma base is built as a part of National oil reserve project in Ehime prefecture in Shikoku region, Japan. The base is water sealed rock cavern tank of the storage capacity 1,360,000 kl. Operation has been started since May 1994.
Figure 1 shows layout of the Kikuma base. It has three rock cavern units namely, TK-101, TK-102, and TK-103. TK-101 and TK-102 has built in 1994. Sizes of these rock caverns are a width 20.5 meter, a height 30 meter. The top of the cavern is 35 meter below sea level. The TK-103 is diversion of the pilot plant built in 1981. It has 15 meter width and 20 meter height. The top of the cavern is 42 meter below sea level. As tanks are built in hilly area, depths of rock caverns from the ground surface are not constant but greater than 65 meters.

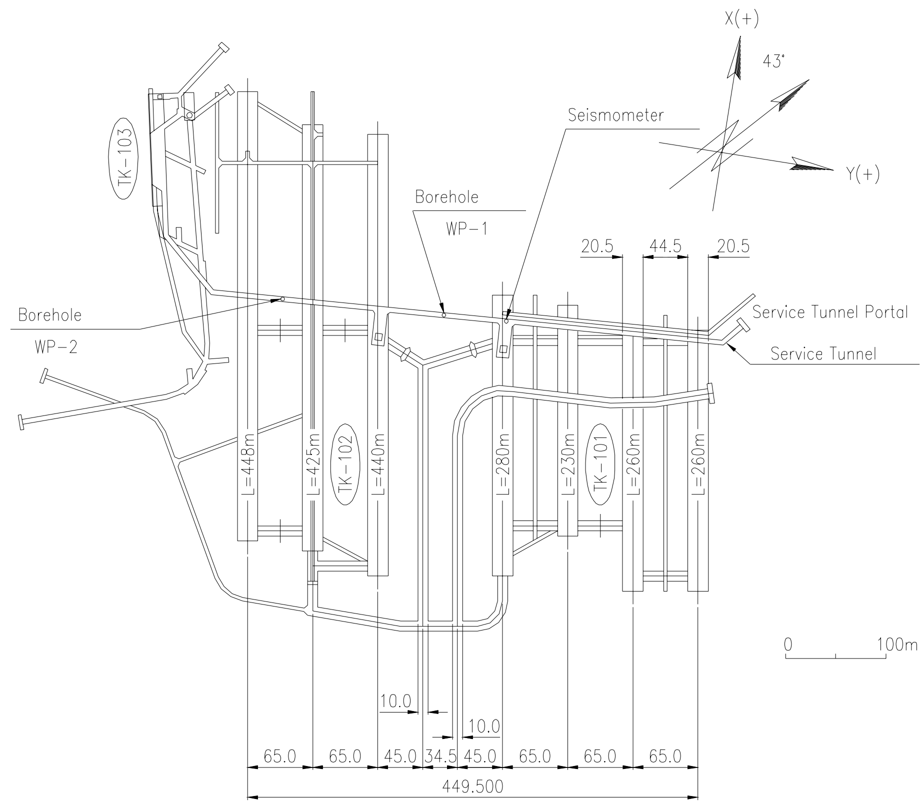

Fig.1 Layout of the Kikuma storage base. Location of pore pressure meter and seismometer also displayed.

The bedrock in the base area consists of partly metamorphosed Younger Ryoke granites of Late Cretaceous. Unconfined compressive strength of test piece is about 100 MPa on the average. The P-wave and S-wave velocity is about 5 km/s and 2.5 km/s by an ultra sonic wave test. The coefficient of permeability of fresh rock determined by several Lugeon tests is very low as 6.4×10^{-7} cm/s.

MEASURING SYSTEM

Pore pressure meters have been installed in bore hole, named WP-1 and WP-2 in Figure 1. To install pore pressure meter, bore holes are drilled from service tunnel floor. Three sensors are installed in three depths in each borehole as shown in Figure 2. Then packer seals each sensor.

Seismometer that records acceleration has been installed on the floor of service tunnel. Ground acceleration and pore pressure are recorded together when amplitude of acceleration exceeds 5 cm/s/s. Record length is 70 seconds with lead-time of 10 seconds. Direction of seismometer axis is shown in Figure 1 as X and Y. The Y direction is parallel to service tunnel axis.

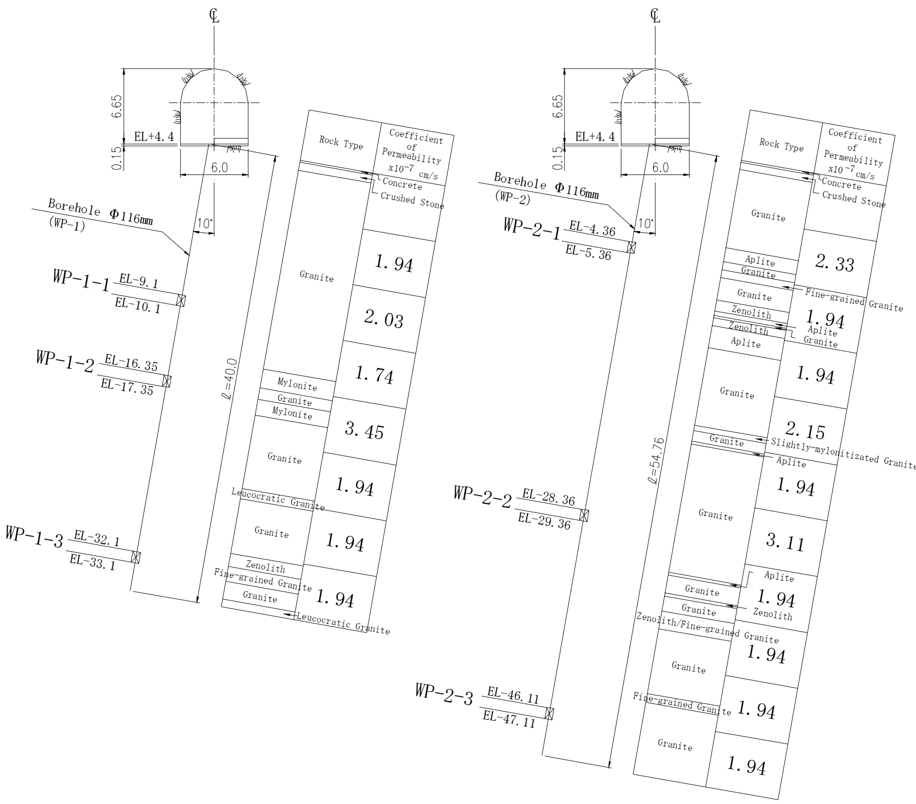

Fig.2 Section of boreholes for measuring pore pressure.

OBSERVATIONAL RESULTS

Source parameters of the 2000 Tottori-Ken Seibu earthquake, 2001 Geiyo earthquake and aftershock are listed in table 1. Characteristics of the records obtained by these events are discussed by each event.

Table 1 Source parameters of earthquakes used in this study. In the tables, h is focal depth, *M* is a magnitude and distance is epicentral distance.

Event (Epicentral region) name	Date	Epicenter		h [km]	*M*	Distance [km]
		Lat.	Long.			
2000 Tottori Ken Seibu EQ.	2000.10.06	35:16.51’	133:20.99’	11	7.3	143
2001 Geiyo EQ.	2001.03.24	34: 7.2’	132:42.5’	51	6.4	16
Aki nada	2001.03.26	34: 6.5’	132:43.2’	49	5.0	15

The 2000 Tottori Ken Seibu Earthquake

Recorded pore pressure and ground acceleration are displayed in Figure 3. Integrated ground velocity also displayed in the same Figure. Integration is performed in frequency domain with high-pass filter which cut-off frequency is 0.125 Hz. Ground motion both acceleration and velocity is rotated in to North-South direction and East-west direction.

Pore pressure obtained by the meter WP-1-1 shows the largest amplitude with peak value of 13 kPa. It seems that pore pressure meter WP-1-3 does not respond to earthquake. Other four pore pressure meters show same amplitude and same peak value. The waveform looks like each other well. Especially, the resemblance of the waveform in the same borehole is high.

Peak acceleration is 11 cm/s appeared in E-W component, while peak velocity is 1.3 cm/s appeared in N-S component. Remarkable point is that waveform of ground velocity resembles waveforms of pore pressure.

We can say that ground motion is composed of Rayleigh wave as following facts. First point is that U-D component and N-S component has large amplitude. N-S component is radial component from source to observation site. In the range of 18 second to 28 second in Figure 3, phase difference between U-D and N-S component is a quarter of the predominant period. This corresponds to the characteristics of Rayleigh wave. And Furumura shows remarkable Rayleigh and Love wave is observed in nation wide array named K-NET and KiK-net [3].

The 2001 Geiyo earthquake

In Figure 3, pore pressure, ground acceleration and ground velocity during the 2001 Geiyo earthquake are shown. Integration procedure and rotation of ground motion are same as former one. The WP-1-2 shows the largest amplitude with peak value of 34 kPa. It seems that WP-1-3 does not respond to earthquake. Though in the WP-2-1, pore pressure is accumulated slightly, others do not show such tendency. Nevertheless, envelop of dynamic pore pressure look like each other except WP-1-2. Especially, as former indicated, the resemblance of the waveform in the same borehole is high. An interval of each pore pressure meter is about 20 meter. On the other hand, seismic wave length is enough long to neglect such separation. If dynamic pore pressure is induced by seismic wave, it is natural that waveform look like each other.

In general, amplitude of ground motion is not small. Peak acceleration is 140 cm/s^2 in E-W component and peak velocity is 8.4 cm/s in N-S component. These values are never little values because those are recorded in the rock.

Comparing ground motion and pore pressure, we can see that fluctuation of pore pressure in P phase, but large fluctuation is seen in main part. This fact is also indicated former cases. Additionally we can point out that envelop of pore pressure resemble ground velocity closely than ground acceleration.

In Figure 5, Dynamic data obtained at Aki-nada earthquake are shown. A feature of data is the same as former cases. Waveform of pore pressure look like each other and good coincidence to the ground velocity is shown. As ground velocity is simple in this case, we can easily distinguish S-wave. During this earthquake, change of dynamic pore pressure is caused by with S-wave obviously.

DISCUSSION

As we find that magnitude orders of peak pressure are same for two earthquakes in the Kushikino base, we compare peak values in Figure 6. From the figure, magnitude orders are almost the same and independent to earthquake. That is WP-1-2 always shows the largest value among six sensors and WP-2-1 always shows the smallest value except WP-1-3. Although locations of each sensor are different in detail, we can assume that incident seismic wave is same. So that amplitude of dynamic pressure is determined by hydraulic characteristics around pore pressure meter. However, order of peak value does not correspond to an order of magnitude of coefficient of permeability strictly.

We also find a ratio between peak pore pressure and peak ground velocity is stable in each pore pressure meter for the case of the Kushikino base. Figure 7 shows such ratio. We use a peak value of U-D component ground velocity, to avoid SH-wave contamination. From the Figure 7, we can say that the ratio of each sensor is stable among three events. Especially for case of the 2001 Geiyo and Aki-nada earthquake, these ratios are very close. We check the ratio using horizontal peak ground velocity instead of

U-D component. The ratio of the 2001 Geiyo and Aki-nada is almost same but for the case of the Tottori Ken Seibu earthquake shows larger value than other two earthquakes.

Let consider the SV-wave incidence to the elastic half space. P-wave is excited at surface as a reflect wave. The SV-wave does not produce volumetric change but P-wave does. So that reflect P-wave have close connection to the pore pressure. If elastics half space is assumed, we can express a ration of volumetric change and amplitude of incident velocity. This ratio is function of elastic constant and incident angle.

As Aki-nada earthquake is aftershock of the 2001 Geiyo earthquake, focal mechanism is almost the same [4] and focal location is very close. Considering these fact, characteristics of incident waves might be same for these two cases. So that mechanism of dynamic pore pressure growth for these two events are same. This a reason why the ratio of pore pressure and ground velocity is stable. For the case of Kushikino base, situation is very close. We recorded two events in the Kushikino base, these event are occurred conjugate fault respectively. We conclude that in swarm earthquake or main shock aftershock sequence, the ratio of pore pressure and ground velocity is stable.

Dynamic pore pressure during the 2000 Tottori Ken Seibu earthquake is produced by Rayleigh wave. On the other hand, for the case of the 2001 Geiyo earthquake, pore pressure is produced by incident SV-wave. As SV-wave produced pore pressure is very sensitive to incident angle, this coincidence is made by chance.

CONCLUDING REMARKS

We study pore pressure and ground motion recorded in the Kikuma base. Followings are pointed out.

1) Waveforms of pore pressure resemble each other.

2) The peak values of pore pressure appear during a main part of ground motion.

3) Envelope of pre pressure time series resemble ground velocity closely.

4) Size order of peak pressure for the case of main shock and aftershock is the same.

5) A ratio between peak pressure and peal velocity is stable for the case of main shock and aftershocks.

As these observational facts are also pointed out in the Kushikino base, these facts are thought to be universal.

However, to perform a detail study concerning hydraulic in rock during an earthquake, characteristics of ground motion must be clarified. Array observation is needed to study an incident motion. In the Kikuma base, seismometer and pore pressure meter are separated as 60 meter for the WP-1 and 220 meter for the WP-2 in horizontally. This is not good condition for studying a wave induced pore pressure. These instruments are installed same place identically.

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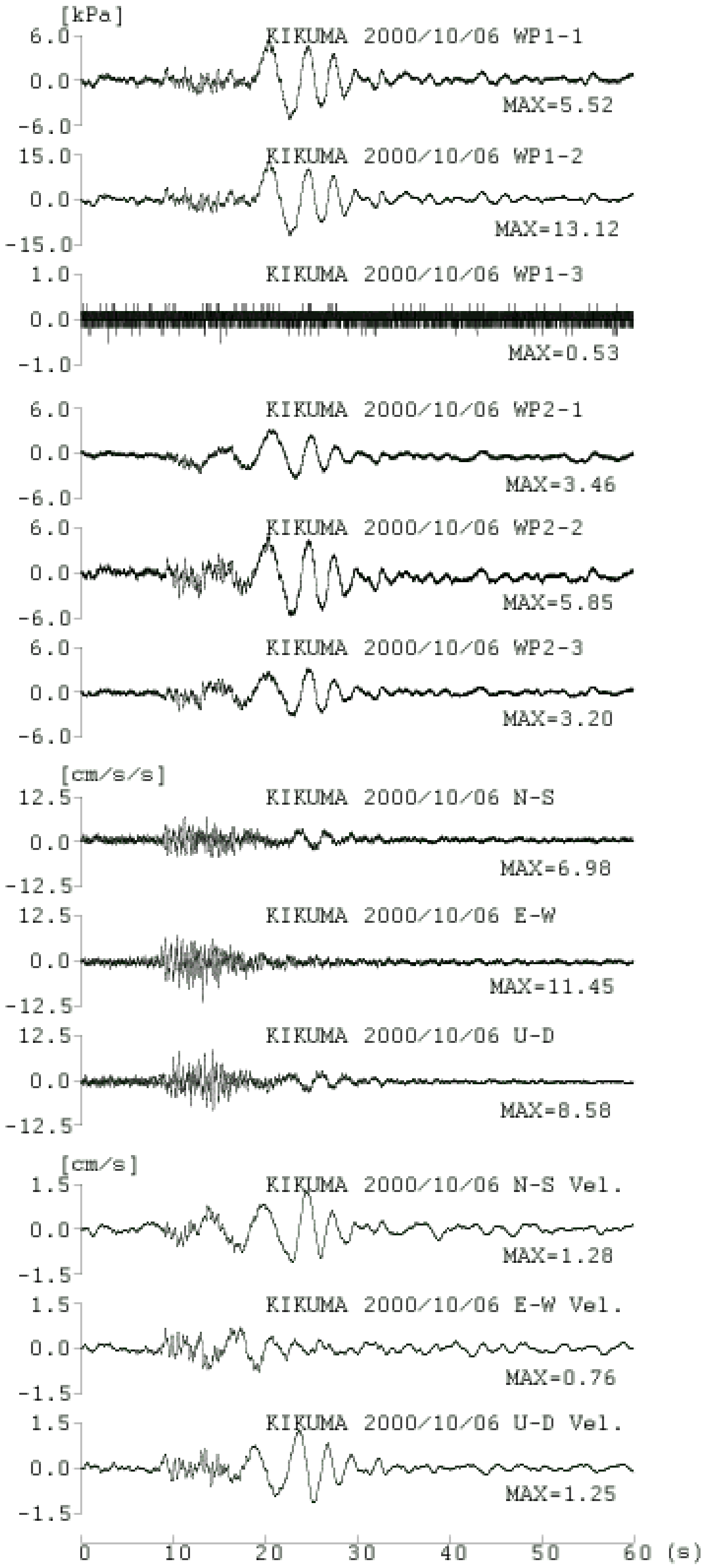

Figure 3 Observed dynamic pore pressure (top six traces). ground acceleration (middle three traces) and integrated ground velocity (bottom three traces) during the 2000 Tottoti-Ken Seibu earthquake

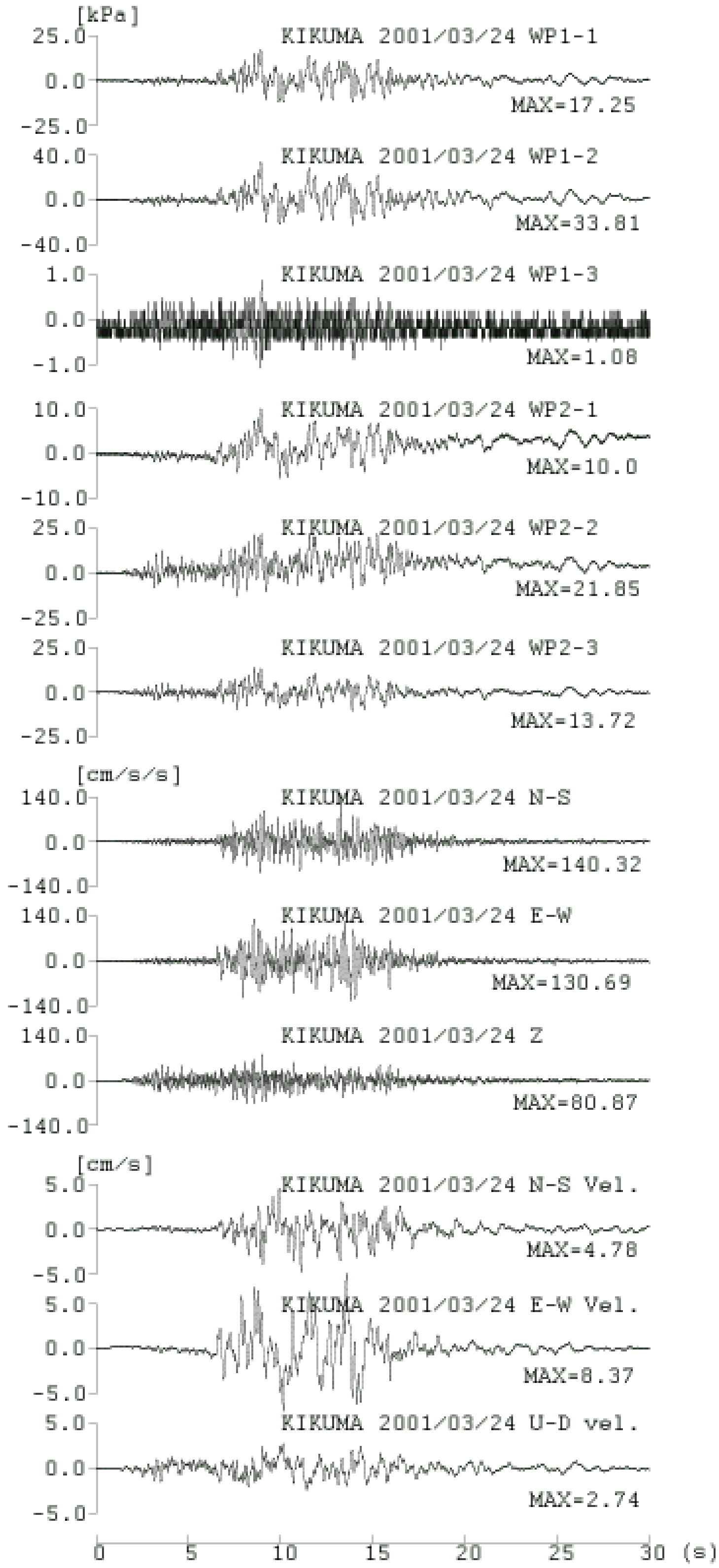

Figure 4 Observed dynamic pore pressure (top six traces). ground acceleration (middle three traces) and integrated ground velocity (bottom three traces) during the 2001 Geiyo earthquake

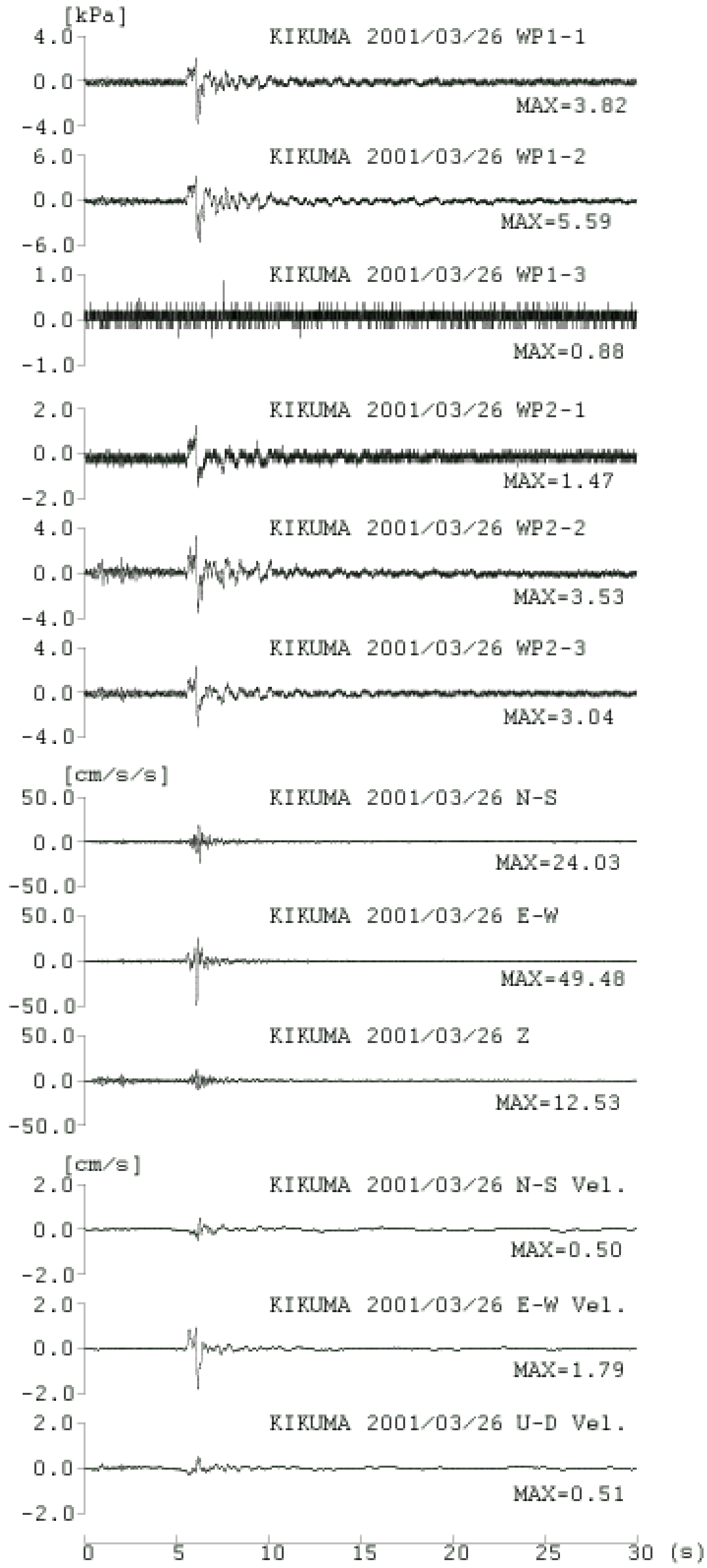

Figure 5 Observed dynamic pore pressure (top six traces). ground acceleration (middle three traces) and integrated ground velocity (bottom three traces) during Aki-nada earthquake

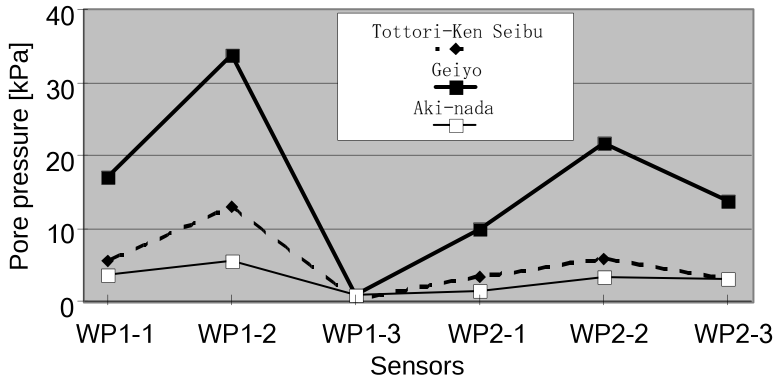

Figure 6 Peak value of dynamic pore pressure for three events.

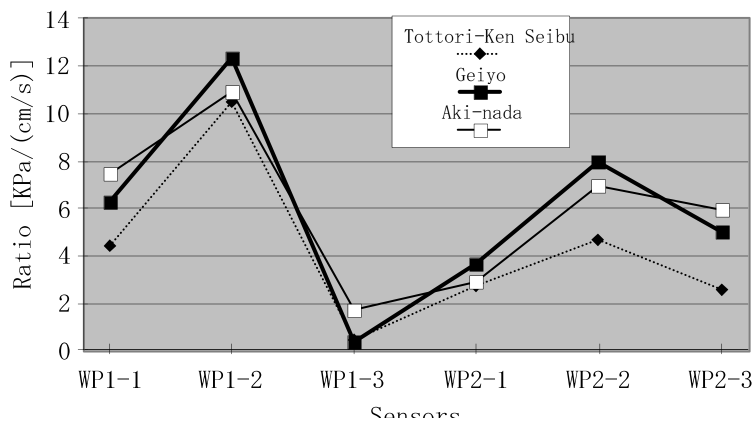

Figure 7 Ratio between peak value of pore pressure and ground velocity.