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Fault model of the 1964 Off Oga Earthquake as a tsunami source

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Abstract
Source model of tsunami was derived based on correlation coefficients of peaks and troughs between observation and model. In the trial model parameters were systematically varied under constraints of seismic moment, central position and length of the fault. Thus other five parameters were determined from the maximum values of correlation coefficient. This method was applied to tsunami of the 1964 Off Oga Earthquake and a fault model was derived having sizes of 50 km (length), 20 km (width), 0.96 m (dislocation), angles of N20° E (strike), 30° E (dip), 90° (slip), and position of 40.32° N (latitude), 138.95° E (longitude), 5 km (depth). It is found that the fault plane almost coincides to south one of two fault planes of the 1983 Japan Sea Earthquake. From this coincidence it is concluded that this earthquake was a precursor of the 1983 Japan Sea Earthquake.

Key words: tsunami, fault model, 1964 Off Oga Earthquake, correlation coefficient, precursor.

1 Introduction
Tsunami is explained from long-wave theory of seawater. The long wave approximation holds good for wave longer than 25 times of sea depth. On the other hand an earthquake, generated in a shallow depth under the sea bottom, gives rise to a vertical displacement on the sea bottom. Since the rupture velocity is usually large in comparison with the long-wave velocity, a vertical displacement of sea surface is instantaneously completed in the whole displacement area. A linear size of the displaced area increases exponentially with the earthquake magnitude. Using a relation between seismic moment and moment magnitude (Kanamori, 1977), and assumptions of a typical aspect ratio 2, unit dislocation and rigidity of $4 \times 10^{10}$ Nm$^{-2}$ we obtain the fault length of 25, 45 and 81 km for the magnitude 6, 7 and 8, respectively. When assuming the sea depth of 2000 m, we obtain 50 km as a lower limit of the long wave. Thus we can assume the long wave for the tsunami generated from an earthquake having the magnitude larger than 6. This relation gives a theoretical base of long wave approximation to tsunami. In this article we deal the vertical displacement field at the ground surface derived from the static fault model because of the instantaneous generation. Aida (1974) applied the fault model to the observed tsunami in the first time and explained the marigrams observed at tide stations. In the application to a particular place three elements, these are location, dimension and mechanism, are needed. Thus, we must know nine parameters to reproduce the vertical displacement field on the ground surface. Recent development of seismic wave analysis brings us seismic moment, seismic source mechanism and aftershock distribution as the useful information to assume the model. Particularly, seismic source mechanism represented by CMT solution is important information to know the development of tsunami. It is correct that one source radiates seismic wave and tsunami in the same time but the estimated source mechanism depends on wave frequency used in the analysis. On this standing point it is important to reexamine the source model derived from seismic wave. In this article we will try to find a source model of tsunami independently on the seismic source mechanism and we apply this method to the 1964 Off Oga Earthquake Tsunami. In the application
This tsunami Hatori (1965) collected tide-gage data and obtained the inverse refraction diagram as shown in Figure 1. Members of Sendai Meteorological Observatory (1967) carried out the survey of the tsunami. Fukao and Furumoto (1975) clarified the seismic source mechanism and showed a pure dip slip model (Figure 2). Dimension of 50 km (length: $L$) $\times$ 20 km (width: $W$), mechanism of $50^\circ$ in dip angle $\delta$, $90^\circ$ in slip angle $\zeta$ and $31^\circ$ in azimuth angle $\theta$, was assumed for the model fault. Dislocation $D$ was assumed to be 1.2 m from the seismic moment $Mo$ of $4.3 \times 10^{19}$ Nm and the rigidity $\mu$ of $3.6 \times 10^{10}$ Nm$^{-2}$.

Fig. 1 Source area estimated from inverse-refraction diagram of the 1964 Off Oga Earthquake tsunami (Hatori, 1965).

Fig. 2 Seismic source mechanism and aftershock area of the 1964 Off Oga Earthquake (Fukao and Furumoto, 1975).

Aftershock observation group of Tohoku University (1965) observed the aftershocks and obtained an east down profile of the focal depth, which is shown in Figure 3.

2 Data and method

2.1 Tsunami observation data

The 1964 Off Oga Earthquake have a hypocenter of 40° 35' N, 139° 00' E and 0 km in the depth, and an origin time of 7h 58m(UT, 16h 58m in JST), May
7,1964 with magnitude of 6.9 (Chronological scientific table, 2000). The tsunami was observed at tide stations facing to the Japan Sea in Hokkaido and Honshu, Japan. The tide gage records for 1 hour from earthquake origin time, observed at Esashi, Fukushima, Iwasaki, Funakawa, Akita and Sakata (Figure 4), are used for comparison with computed waveforms after reducing tidal levels.

2.2 Numerical experiments

Linear long wave theory is used as the basic equation. Perfect reflection and perfect transmission are applied to the land–sea boundary and the open sea boundary, respectively. The equation of motion and the continuity equation are transformed into difference equations and they are solved step by step for 1 hour from the origin time using a computer. A rectangular region is covered with grid space of 1 km interval and on this region water level is computed at every three seconds on the initial water level given by the vertical displacement derived from the fault model (Mansinha and Smylie, 1971). The origin is taken at 38° N and 136° 45 ' E, and total grids count to 367×555 as shown in Figure 4. The sea depth is given from a digital map sampled with interval of 1 minute in the use of linear interpolation. The shallowest sea depth is limited to 5m because the linear wave equation The shallowest sea depth is was assumed. The time histories computed at tide stations are compared with the waveforms observed at the tide stations.

2.3 Correlation coefficient

We notice peak and trough of waveforms, and calculate correlation coefficients between observation and computation. We define two kinds of correlation coefficient. Former one is defined for the heights of first peaks observed at all stations. On the other hand latter one is defined for the heights from first trough to third peak at Iwasaki and from first trough to second peak at Funakawa. The diagrams are shown in

Fig. 4 Grid space used in the numerical experiment. The epicenter and tide stations are indicated by a cross mark and solid circles, respectively.

Fig. 5 Diagram of space correlation coefficient and time correlation coefficient.

Figure 5. The correlation coefficient is calculated for
waveform obtained from each model fault. The first one is called as Corr1 and the second one is called as Corr2.

2.4 Model search

A fault model is perfectly described using 9 parameters as shown in Figure 6, those are 3 ones of the position (\(\phi, \lambda, d\)), 3 ones of the fault angle (\(\theta, \delta, \lambda\)) and 3 ones of the size (\(L, W, D\)). The position is defined at the center of upper margin of the fault plane. In the first approximation the central position and fault length are fixed at 40.32° N, 138.95° E and 50 km, respectively. It is based on the result of inverse refraction diagram obtained by Hatori (1965). In addition seismic moment is assumed as \(4.3 \times 10^{19}\) Nm obtained by Fukao and Furumoto (1975). As the rigidity the same value of \(3.6 \times 10^{10}\) Nm\(^{-2}\) is also used. The seismic moment gives a constraint for product \(DW\) through the formula of \(Mo = \mu DW\). These values are fixed through the model research. Thus residual five unknown parameters were examined for the intervals of 5 km and 10 degrees for linear distances and angles.

3 Result

A combination of parameters systematically explaining good correlation was found as the result. According to the result we can explain each parameter as the maximum value of correlation coefficient as shown in Figure 7 and 8. Thus we can explain each parameter as the maximum value of correlation coefficient. In the comparison other parameters are fixed as a combination of the best ones. The best ones correspond with the maximum correlation coefficients and it is a model of number 182. Among them most ones show similar variation between Corr1 and Corr2. One exceptional case is for the variation to fault width \(W\) shown in Figure 7. The average keeps the maximum at 25 km in width. Model No.182 consists of parameters of position (\(\phi, 40.32\degree N, \lambda, 138.95\degree E, d, 5\) km), angle (\(\theta, N20\degree E, \delta, 30\degree, \lambda, 90\degree\)) and size (\(L, 50\) km, \(W, 25\) km, \(D, 0.96\) m). Observation and computation, derived from the model No.182, is compared in Figure 9. This figure shows...
agreements in amplitude and phase between observation and model. Good correlation is not necessary to correspond coincidence between amplitude and phase. Therefore, it is important to verify the coincidence. Thus it is proved that the model is a good reproduction of observed tsunami

4 Discussion
The dip angle 30° is smaller than the value 50° obtained from the seismic wave (Fukao and Furumoto, 1975). The slip angle 90° shows a pure-dip slip, which is the same result as that derived from the seismic wave. The azimuth angle of 20° is smaller than 31°, which was derived from the seismic wave. The location is shown in Figure 10. The aspect ratio 2 is that of a standard model and the depth 5km suggests a very shallow earthquake. The shallow earthquake had been verified from the seismic wave, too. The fault plane was determined to be located under the sea bottom with the depth of 2000m-3000m. The deformed area covers the continental slope. As the low-dip angled model a small area of small subsidence appears at the surface over the lower margin. This area contributed to the negative phase of initial motion observed at Iwasaki and Funakawa. Particularly, the best model explains the arrival times of the first positive waves at Iwasaki, Funakawa, Akita and Sakata. The dip angle of 30° is harmonious with that of aftershock distribution
At the same area there was a large earthquake ($M=7.7$) called Japan Sea Earthquake on May 26, 1983. It is known as the large tsunami of the maximum inundation height of 13m (e.g. Abe and Ishii, 1987). The fault model to explain the observed tsunami was proposed by Aida (1984). The location is shown in Fig.10. It consists of two planes, one of which is the south one of $40 \times 30 \text{km}^2$ and another of which is the north one of $60 \times 30 \text{km}^2$. When we superpose the fault plane of the best model to that of the 1983 earthquake, we found an overlap to the south fault. They have the same dip angle of $30^\circ$ and almost the same azimuth angle. This fact suggests that the same fault plane recurrently ruptured in a short period of 29 years. It is concluded that the earthquake of 1964 was a foreshock of the 1983 Japan Sea Earthquake. Thus the 1964 Off Oga Earthquake was a precursor of the following 1983 Earthquake. It is remarkable in the short time interval that the recurrence interval of the two large earthquakes was 19 years.

5 Conclusion

A model fault was determined through the numerical experiments of tsunami, generated off Oga in the Japan Sea on May 7, 1964. The solution corresponds with the maximum of correlation coefficient in the wave height between observation and computation. Each fault parameter was examined independently. The obtained fault has a plane of $50 \times 25 \text{km}^2$ with dislocation of 0.96m, mechanism of $30^\circ$ in dip, $90^\circ$ in slip and $20^\circ$ in azimuth angles. The location occupied the same area as the south fault of the 1983 Japan Sea Earthquake, previously obtained. The overlapping shows a recurrent rupturing of the area in a short period of 19 years.

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