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A Bending Fault Model of the 1964 Niigata Earthquake

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新潟地震の折れまがり断層モデル

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要 旨

新潟地震の断層モデルは安芸（1966）が地震表面波をもとにして出したものが最初であって、その後阿部勝征（1975）によって地震波の他に、日本海沿岸で観測された地震に伴う永久変位のデータを加えて再決定された。最近阿部邦昭（1977 a）は津波の数値実験をもとに観測にあらかじめ断層モデルとして、これまでの2つのモデルより転位量が大きく、面積の小さいモデルを提案した。その後阿部邦昭（1977 b）はこれまでの3つのモデルを比較した結果、前述の永久変位のデータを中心として、相似な転位量をもつ1枚の断層で近似することの困難な点を示し出した。その解決のかぎは断層の走向が震央の南北に並び、北では N 22° E、南では N 9° E の「く」の字形に折れまがった断層を仮定することに見い出される。

そこでこの点を考慮して阿部（1977 a）のモデルをさらに発展させたモデルを作る。方法は阿部（1977 a）のそれと全く同じで、ただしの程度は津波の観測記録と論理的に得られるそれとの比較でなかった。松ヶ崎（新潟市）と酒田の記録について2.5分間隔で転位を読み取り、前者は地震発生時刻より3時間、後者は1時間のサンプリングを行なう。この作業を5つの仮定されたモデルについて行い、最も合理的モデルについては前者は0.86、後者は0.82となった。これを一様な場合のそれと比較してみると、最大波に続く長周期成分の説明が可能になる点で異なっている。

このモデルのパラメータは北側の N 22° E の走向をもつ断層については長さ30 km、巾15 km、転位量6 m で傾斜方向はN 68° W で45°の逆断層である。又断層面の最も浅い点は0 kmで地表に達している。一方東側のN 9° E の走向をもつ断層については長さ30 km、巾15 km、転位量6 m で傾斜方向はN 82° W で45°の逆断層である。断層面の最も浅い点は地下5 kmであら。両者は断層平面上に北緯38°24'、東経139°16'に震央をもつ本震を共有する。従ってこの地震は1つは北東から N 22° E の方向に伝播し、
長さ30kmに及ぶ断層を生じさせ、他の1つはS9°Wの方向に伝播し長さ30kmに及ぶ断層を生じさせたと解釈することができる。これらが地震とともにほとんど同時に出来たと考えられる。

このような折れまがりモデルは茅野（1973）が指摘する余震分布図の折れまがりとも対応しており今のこところ矛盾がない。

なおこれらのパラメーターの評価には1. 理論誤差（たとえば断層が重なる震央付近では、変位はそれぞれの断層による変位の重ね合わせで表わされること（線型近似）の妥当性など）2. 計算誤差（計算の格子間隔を2.5kmとしたことによるもの）3. 実験誤差が関与している。長さ、巾に関しては計算誤差から±5km、転位量については最大波高のばらつきつまり実験誤差から±1km程度と評価される。これらの誤差を考慮して地震モーメントを求めると剛性率を3.6×10^{11} dyne/cm^{2}として(1-4)×10^{27} dyne-cmとなり地震波から求めたものと一致する。地震波によるモデルとくらべて狭い面積に大きな転位量が集中している事実はこれまでの結果と変わらない。
A Bending Fault Model of the 1964 Niigata Earthquake

Abstract

It is shown for the 1964 Niigata earthquake that the bending fault model is supported by time histories of tsunami, co-seismic crustal deformation and epicentral distribution of aftershocks. The model is consisted of two faults with a uniform dislocation whose planes link together at the hypocenter and the intercept angle is $13^\circ$. All the other parameters for these two faults were determined on the inverse refraction diagrams, time histories of tsunami and co-seismic deformation.

Introduction

As the numerical experiment Aida (1969) dealt the tsunami of the 1964 Niigata earthquake and it was based on the results of an echo-sounding observed by Mogi et al. (1964). Mansinha and Smylie (1971) obtained the analytical expressions of the displacement field for an inclined fault. Since then co-seismic deformation has been understood from the fault model. The fault models for this earthquake were independently discussed by Hirasawa (1965) and Aki (1966). They made their models on seismic waves. Katsuyuki Abe (1975) re-examined the fault model using not only seismic waves but also co-seismic deformation.

It is recognized that a fault model of an earthquake is useful for the source model of a tsunami (e.g. Aida (1974)). It has also been shown that each parameter of the fault model determined for an earthquake is not always consistent with the observed tsunamis. For example Kuniaki Abe (1975) showed that a dip angle is smaller than $45^\circ$ for the 1933 Sanriku earthquake model. Recently Kuniaki Abe (1977 a) investigated this earthquake on the standpoint described above and proposed another fault model. At the same time it was found that it is difficult to explain co-seismic deformations along the inland coast as far as one-sheet models, which is represented with only one fault plane of a uniform dislocation, is concerned.
as Kuniaki Abe (1977 b) described. It is necessary to refine the models ever proposed.

**Bending fault model**

According to Abe (1977 b) the result of leveling along the inland coast is harmonious with Abe's (1977 a) model for the north half and is harmonious with Abe's (1975) model for the south half. A strike direction is one of the differences between these two models. It is N 22° E for the former and N 9° E for the latter. This discrepancy in leveling data is eliminated by the use of a bending fault model which consists of two faults, linking together at the hypocenter with different strike angles. Strike angles are succeeded to those of the two models. Namely it is N 22° E for the north fault and N 9° E for the south one.

Fault parameters were determined on time histories of tsunami as Abe (1977 b) did for the non-bending fault model. In the determination the epicentral location of the main shock is fixed to be 38.40° N and 139.26° E according to Abe (1975) and a pure dip slip is assumed for the slip motion according to Hirasawa (1965). There are too many parameters to be uniquely determined in comparison with the number of data. But the effect of each parameter is reflected in time histories. Abe (1977 b) discussed this effect for the non-bending fault model. He determined a dip angle to be 45° and a dislocation to be 6 m. These values are also received for a bending fault model because of the smallness of an intercept angle. It is considered that a total length and width for a bending model are comparable to the length and width of the non-bending model. Mutual position of the two faults for the bending model is varied in the restriction of owning a hypocenter jointly. A displacement field is represented by the use of the formulation by Mansinha and Smylie (1971). Numerical experiments were tried in the determination of the mutual position and fault area as parameters. The same method as Abe (1977 b) used is succeeded to this experiment. An addition is assumed for the displacement field in the epicentral region in which two faults overlap.

**Result**

Time histories of tsunami were computed for 5 reverse fault models from the origin time till 3 hour later at Matsugasaki (Niigata city) and Sakata. Correlation coefficients of wave forms were obtained between computation and observation with a sampling time of 2.5 min. Fault parameters and correlation coefficients obtained for 3 hours at Matsugasaki and for 1 hour at Sakata are shown in Table 1. A
Table 1. Models and correlation coefficients

<table>
<thead>
<tr>
<th>Models</th>
<th>Bending Models</th>
<th>Non-bending Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>Length (km)</td>
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<td>30</td>
</tr>
<tr>
<td>Width (km)</td>
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<td>15</td>
</tr>
<tr>
<td>Depth (km)</td>
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<td>7</td>
</tr>
<tr>
<td>Dislocation (m)</td>
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<td>6</td>
</tr>
<tr>
<td>Strike</td>
<td>N22°E</td>
<td>N33°E</td>
</tr>
<tr>
<td>Dip angle</td>
<td>45°</td>
<td>45°</td>
</tr>
<tr>
<td>Center Latitude N 38°</td>
<td>20°</td>
<td>20°</td>
</tr>
<tr>
<td>Longitude E 139°</td>
<td>24°</td>
<td>18°</td>
</tr>
</tbody>
</table>

Correlation Coefficient

- Sakata: 0.82 0.48 0.58 0.82 0.80 0.85 0.85 0.78
- Masunagasaki: 0.79 0.79 0.84 0.86 0.85 0.78

The best fit model was selected from those based on the largest value of the coefficient. It is a forth model and thus a fault system consisting of two uniform faults is obtained. North one has an area of 30 km (length) × 20 km (width), a dip angle of 45° toward N 68° W, a dislocation of 6 m and a depth of the top position of the fault plane to be 0 km. Location of the center, which is the top position of the fault plane on the center line for the total length, is 38°29′N (latitude) and 139°24′E (longitude). On the other hand south one has an area of 30 km (length) × 15 km (width), a dip angle of 45° toward N 81° W, a dislocation of 6 m, a depth of the top position of the fault plane to be 5 km. Location of the center is 28°20′N (latitude) and 139°18′E (longitude). It is noticed that south one represents itself in a deeper place and has a smaller width in comparison with north one. It is found from the result shown in Table 1 that it improves the correlation relation to make a small overlapping area of the two faults.

A displacement field was computed on the sea bottom for the best fit model and it was shown in Figure 1 with the inverse refraction diagram. It shows the vertical component of the displacement and horizontal components were neglected to be ineffective to a tsunami generation. The result is harmonious with that on the echo-sounding by Mogi et al. (1964) and the co-seismic deformation observed by Nakamura et al. (1964) in the Awashima Island. Particularly the facts that a large displacement was obtained on the north fault and the equi-displacement line of 0 m is parallel to the coastal line agree with the result by Mogi et al. (1964). A comparison with the co-seismic deformation in the Awashima Island was discussed by Abe (1977 b) for the non-bending model. In the bending model the north fault corresponds with the non-bending model proposed by Abe (1977 b) for the north part from the hypocenter. Accordingly the same displacement field was obtained on the island and his discussion is available for this model.
Figure 1. Displacement field of the vertical component derived from the bending fault model and locations of bench marks. Inverse refraction diagram is reproduced from the paper by Abe (1977 a) with a small modification. Observation points and travel times are shown in the corner. This figure covers most of the area used in the computation.
This model makes it possible to explain the leveling data observed by Geographical Survey Institute (1966, 1970) along the coast of the Honshu Island on an average. This is shown with the results of non-bending models in Figure 2. The observed co-seismic subsidence is too large to be explained on the model by Abe (1975) for the north part and too large to be explained on the model by Abe (1977 b) for the south part. The present model is shown to be better than the two in respect to explaining the co-seismic subsidence for both the north and south.

Time histories on this model are shown in Figure 3a, 3b with the result on one of the non-bending models (Abe, 1977 b). A main difference between the two models is found in the period of the wave following the maximum phase observed at Matsugasaki. It is impossible to explain the period of 30 min. on the non-bending model but it is possible to explain it on the present model. It is considered that the origin of this wave is due to the bending of the fault strike. This long-period component wave was also observed at Sakata one hour later from the origin time and it is possible to explain it on the present model too.

Inundation heights of the tsunami were measured by Aida et al. (1964), Nakamura and Suzuki (1966) along the coastal line. The values were corrected on the mean sea level at Naetsu in the origin time and shown with the maximum height computed from the present model as a function of the distance from Niigata.
Figure 3. a, b Data and models of time histories at Matsugasaki (a) and Sakata (b). Lapse time from the origin time is shown in hour and the height above the mean sea level is shown in m. Data at Matsugasaki is used correcting the ebb motion and decrease in the river.

Figure 4. Inundation heights measured along the coast by Aida et al. (1964), Nakamura and Suzuki (1966) and the maximum heights computed are shown as a function of the distance from Niigata along a line with the direction of N 22°E. An arrow line indicates a length of the synthetic fault projected on an abscissa.
city along a line of N 22° E. It is shown in Figure 4. It is possible to explain the observed distribution along the coastal line like a Gaussian distribution from this model. The peak value and the half width of the distribution computed depend on a dislocation and a synthetic length of the fault respectively. Particularly the computed height is proportional to the dislocation because of a linearity in the wave equation of the tsunami. The dislocation error is estimated to be

Figure 5. Location map of aftershocks after Kayano (1973), which is reproduced to the exclusion of them having focal depths beyond 24 km. Main shock, fault planes and uplifted region are shown with the marks ◊, solid line and dotted line respectively.
±1 m from the deviation of the observed values. Splitting of the distribution observed at the epicentral region is due to the curve of the coastal line and the effect is amplified by the bending of the fault strike. Accordingly the observed deviation is concluded to be partly due to the splitting and partly due to an observation error.

The bending is also supported from the result of the aftershock distribution. Kayano (1973) revised the focal determination of the aftershocks and obtained a location map. Since he used aftershocks occurred within the time interval from June 23 to July 6, a location of the aftershocks occurred for a week from the origin time of the main shock to June 23 is excluded from his map. Nevertheless he could determine the locations of many aftershocks. The aftershocks with the focal depth shallower than 24 km were picked up from his location map and shown in Figure 5. This operation is useful to obtain a concentrated location map and a loss of the data number is small through this operation. The present model is superposed on the figure. It is concluded that the bending of the aftershock location pointed out by Kayano (1973) is equivalent to that of the fault strike. It is also found that most of the aftershocks are included in the uplift region derived from the present model.

Discussion

Seismic moment is represented by Aki (1966) as

\[ M = \mu DS \]

where \( \mu \) is the rigidity, \( D \) is the average dislocation over the area \( S \) of the fault plane. For the bending model this formula is modified as

\[ M = \mu D_1 S_1 + \mu D_2 S_2 \]

where a suffix corresponds with a non-bending fault. In this case the seismic moment is obtained to be \( 2.3 \times 10^{27} \) dyne-cm assuming the rigidity of \( 3.6 \times 10^{11} \) dyne/cm².

Some kinds of the error are included in the fault parameters estimated. They are a theoretical error, a computational error and an observational error. Computational one is due to the space interval of the numerical computation. It is 2.5 km for this case. Accordingly the errors of a length and width are estimated to be ±5 km in common. The error of a dislocation is estimated to be ±1 m as described above. Seismic moment is obtained to be \( (1.1-4.0) \times 10^{27} \) dyne-cm on these values and it is comparable to those estimated from seismic waves by Aki (1966) and Abe (1975). Abe (1977 a) indicated a compactness of the fault model consistent with the tsunami generation in comparison with the seismic model. His
discussion is also available for this case.

This fault model is a static model. But a tsunami generation is a dynamic motion in the same manner for the fault generation. In spite of the dynamic motion the observed time history was explained by the use of the static model. This fact is due to a largeness of the velocity ratio of the fault propagation to the tsunami propagation, that is a long wave velocity. It does not prevent from imagination the fault generation process. The north and south faults were generated in the hypocenter at the same time and propagated toward N 22° E and S 9° W respectively. Hirasawa (1965) proposed a bilateral fault model for this earthquake. He was also based on a non-bending model. The bending model shows that the main shock triggered the two faults and the direction of a fault propagation deviates from 180° by 13°. The dynamical process does not conflict with this static model since the two fault planes own the hypocenter jointly in this static model.

Conclusion

1. A bending fault model for the 1964 Niigata earthquake is supported by time histories of tsunami, co-seismic deformation and epicentral distribution of aftershocks. It consists of two uniform faults with the different strikes which own the hypocenter of the main shock jointly.

2. All the parameters for the two faults were determined on the data of tsunami and co-seismic deformation assuming a pure dip slip. For the north fault a reverse fault was obtained having an area of 30 km (length) × 20 km (width), a dislocation of 6 m, a dip of 45° toward N 68° W and a depth of top side of 0 km. For the south one a reverse fault was obtained having an area of 30 km (length) × 15 km (width), a dislocation of 6 m, a dip angle of 45° toward N 81° W and a depth of the top side of 5 km. The strikes are N 22° E and N 9° E for the north fault and south fault respectively. The difference is 13°.

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