ESTIMATION OF SEISMIC SOURCE FAULT LENGTH OF INLAND CRUSTAL EARTHQUAKE FROM SUBSURFACE DATA

N. Inoue¹, N. Kitada² and T. Kumamoto³

ABSTRACT

Strong ground motion evaluations have been based more and more on a finite-fault source rather than a point source. For inland crustal earthquakes with a long recurrence period, active fault surveys provide important information to develop an appropriate finite-fault source model (e.g. “Recipe” by Irikura and Miyake, 2015). After the 1995 Kobe earthquake, the headquarters for earthquake research promotion (HERP) has evaluated source faults from prioritized 110 major active faults among ca. 400 seismogenic active faults in Japan. As a result, the source fault length was almost equal to the active fault length. The active fault information is critical because the information is the most fundamental to construct source fault so far. The HERP has improved the method to incorporate subsurface structural datasets in order to evaluate the fault dimensions of the recent Japanese earthquakes. Based on integrated subsurface information, this paper presents the evaluation of source fault lengths of Japanese inland crustal earthquakes to examine improved HERP evaluation method. The fault length was estimated by visually superposing subsurface structural datasets on the active fault map around earthquake source regions using the GIS. The fault length of major active faults is largely consistent with the source fault length derived from the waveform inversion. While, the fault length of minor active faults is underestimated. The evaluated minor fault length from subsurface structural dataset is longer than the fault length derived from active faults. The result of this study is that the integration of subsurface dataset and active faults is effective to reduce a variability of the relation between evaluated fault length and inverted source fault length.

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Estimation of seismic source fault length of inland crustal earthquake from subsurface data

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ABSTRACT

Strong ground motion evaluations have been based more and more on a finite-fault source rather than a point source. For inland crustal earthquakes with a long recurrence period, active fault surveys provide important information to develop an appropriate finite-fault source model (e.g. “Recipe” by Irikura and Miyake, 2015). After the 1995 Kobe earthquake, the headquarters for earthquake research promotion (HERP) has evaluated source faults from prioritized 110 major active faults among ca. 400 seismogenic active faults in Japan. As a result, the source fault length was almost equal to the active fault length. The active fault information is critical because the information is the most fundamental to construct source fault so far. The HERP has improved the method to incorporate subsurface structural datasets in order to evaluate the fault dimensions of the recent Japanese earthquakes. Based on integrated subsurface information, this paper presents the evaluation of source fault lengths of Japanese inland crustal earthquakes to examine improved HERP evaluation method. The fault length was estimated by visually superposing subsurface structural datasets on the active fault map around earthquake source regions using the GIS. The fault length of major active faults is largely consistent with the source fault length derived from the waveform inversion. While, the fault length of minor active faults is underestimated. The evaluated minor fault length from subsurface structural dataset is longer than the fault length derived from active faults. The result of this study is that the integration of subsurface dataset and active faults is effective to reduce a variability of the relation between evaluated fault length and inverted source fault length.

Introduction

[1] provides a method to construct a characteristic finite-fault source model (hereafter RECIPE), which is on the basis of strong ground motions evaluations in Japan. The headquarters for earthquake research promotion (HERP) has applied the RECIPE for strong ground motion evaluations [2]. Finite-fault source models of inland crustal earthquakes have been defined on the basis of seismogenic faults (e.g. [3]), and are constructed based on the results of active fault surveys. Dimensions of seismogenic faults are related to the size of earthquake in a prediction problem. After the 1995 Kobe

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earthquake, the HERP started investigations and evaluations of ca. 110 prioritized active faults, which were selected from ca. 400 active faults. A length of a finite-fault source model was equal to that of a seismogenic fault. Recent several earthquakes occurred on minor active faults or in regions where no active faults had been recognized previously. The HERP revised the procedure to evaluate source faults for short or buried active faults by means of the subsurface information, such as geologic fault and geophysical information so on [4]. The HERP has re-evaluated seismogenic faults, and published revised evaluation results. Several seismogenic faults are longer length from the results of comparison with gravity anomaly, which suggested the possibility of extension of active faults.

[5] applied the revised HERP procedure for active faults around nuclear power plants in Japan. They compared active faults, which were identified by detailed geomorphological analysis, and subsurface information, such as geologic fault, gravity anomaly and distribution of seismicity. The results indicate the possible occurrence of large earthquakes, because the lengths of the subsurface earthquake faults are estimated to be longer than the length of the surface faults if subsurface structures are included. This paper examined the revised HERP method to evaluate the length of source fault of inland earthquake in Japan, and compared the evaluated length with that of source faults, which were estimated from inversions of strong ground motions.

**Data and Method**

Fig. 2 indicates the outline of the revised HERP procedure. The following subsurface datasets were used in this study in accordance with [5]:

1. Geological map published from the Geological Survey of Japan (GSJ, [18]).
2. Seismicity data provided by the Japan Meteorological Agency (JMA).
3. Gridded aeromagnetic anomaly database compiled by GSJ [19].
4. Gridded gravity anomaly database compiled by GSJ [20].

Fig. 3 denotes the schematic diagrams of the procedure in this study. A source fault was estimated by considering evaluations of HERP and the concept of seismogenic fault ([21], Fig. 3a) based on the active fault map published by [22]. The result revealed by [23] was used as the active fault information of the 2008 Iwate Miyagi inland earthquake. The evaluated source fault

![Figure 1. Schematic diagram of seismogenic fault [3]](image)
was compared with geological fault, magnetic anomaly, seismicity and gravity anomaly. The shallow (<20km) distributions of hypocenters were used to evaluate the seismicity. The magnetic anomaly data were reduced to the pole magnetic anomaly. The long wavelength component was extracted from the Bouguer anomaly by a power spectral analysis [24]. The components of wavelength of gravity anomaly are different in each epicentral region. Fig. 4 shows the examples of the power spectral analyses. The evaluated source fault length was estimated by visually superposing subsurface structural datasets on the active fault map around earthquake source regions using the GIS. The following general conceptual criteria were applied:

1. If subsurface structure, such as geological fault, gravity steep gradient, seismicity and so on, corresponds to the location and strike of the active fault, the source fault length was extended along the subsurface structure (Fig. 3b and left side of 3c).
2. If active faults indicate weak relation with gravity anomaly, the source fault length was extended until intersecting other subsurface structure considering the source fault lengths of several tens of kilometers with short active faults, which has been suggested by [25] (right side of Fig. 3c).

Previous researches suggest the gradient of larger than 3-4 mgal/km correspond to the area of active fault or active seismicity (e.g. [26], [27]). 3 mgal/km was adopted in order to evaluate the gravity anomaly. In the case of weak or no relation between fault structures and gravity anomaly, the length of the fault was extended to another gravity structure as a conservative judge (right side of Fig. 3c). In this case, the 1 mgal/km was adopted. This threshold is tentative evaluation. Further work is needed to evaluate this threshold of the gradient quantitatively.

Table 1 shows the earthquakes examined by this study. Most of source faults were evaluated by [28] with the trimming procedure of source fault proposed by [29]. The 2016 Kumamoto and 2014 Nagano earthquakes are important because these earthquakes occurred on the active faults, which the HERP has evaluated.

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Year</th>
<th>Mech.</th>
<th>SL(km)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kumamoto</td>
<td>2016</td>
<td>S</td>
<td>42</td>
<td>[6]</td>
</tr>
<tr>
<td>Nagano</td>
<td>2014</td>
<td>R</td>
<td>22</td>
<td>[7]</td>
</tr>
<tr>
<td>Fukushima HamaDori</td>
<td>2011</td>
<td>N</td>
<td>40</td>
<td>[8]</td>
</tr>
<tr>
<td>Iwate Miyagi inland</td>
<td>2008</td>
<td>R</td>
<td>39</td>
<td>[9]</td>
</tr>
<tr>
<td>Noto</td>
<td>2007</td>
<td>R</td>
<td>28</td>
<td>[10]</td>
</tr>
<tr>
<td>Tottori Seibu</td>
<td>2000</td>
<td>S</td>
<td>34</td>
<td>[12]</td>
</tr>
<tr>
<td>Iwate inland</td>
<td>1998</td>
<td>R</td>
<td>10</td>
<td>[13]</td>
</tr>
<tr>
<td>Kobe</td>
<td>1995</td>
<td>S</td>
<td>64</td>
<td>[14]</td>
</tr>
<tr>
<td>Izu Oshima kinkai</td>
<td>1978</td>
<td>S</td>
<td>35</td>
<td>[15]</td>
</tr>
<tr>
<td>Mikawa</td>
<td>1945</td>
<td>R</td>
<td>25</td>
<td>[16]</td>
</tr>
<tr>
<td>Nobi</td>
<td>1891</td>
<td>S</td>
<td>122</td>
<td>[17]</td>
</tr>
</tbody>
</table>

* Mechanism: S:Strike-slip, R:Reverse, N:Normal
** Length of Source Fault
Figure 2. Concept of revised HERP procedure.

Figure 3 (a). Interpretation of Active Fault by means of seismogenic fault.
(b) Schematic diagram of interpretation of Geological Fault and Epicenter [5].

(c) Schematic diagram of interpretation of Gravity Anomaly

Figure 3. Flow of this study.

(a) 2004 Chuetsu earthquake
(b) 2016 Kumamoto earthquake

Figure 4. Results of power spectral analysis. Red solid lines indicate the range of frequency of each component.
Result and Discussion

Figs. 5 and 6 show the examples of the evaluation based on the revised HERP procedure. Fig. 5a shows the evaluation result of the 1995 Kobe earthquake. The large gradient zones correspond to the distributions of active faults. The active faults are located around the Osaka basin, which is filled with the soft sediments. There is large density contrast around the active faults. The gravity anomaly is useful to detect buried fault structure beneath unconsolidated deposits. Fig. 5b shows the evaluation of the 2016 Kumamoto earthquake. The geological fault is suggested by [30]. The northeastern part of the Futagawa fault extended about 10km as compared to the magnetic and gravity anomaly. The evaluated length of the 2016 Kumamoto earthquake included the Hinagu fault because the source fault also consists of the Futagawa and Hinagu faults [6]. In this study, the length of the northern part of the Hinagu fault was adopted.

Fig. 6a indicates the evaluation result of the 1891 Nobi earthquake. The gravity anomaly shows less relation with active fault. The gifu-ichinomiya, which is the southwest branch of the source fault, also shows no relation with other subsurface information. [31] concludes the gifu-ichinomiya fault is not active fault. However, [32] points out the survey was not enough. The evaluation result of the 2000 Tottori earthquake is shown in Fig. 6b. The locations differ between the evaluated source fault and inverted source fault.

![Legend](image)

(a) 1995 Kobe earthquake

![Legend](image)

(b) 2016 Kumamoto earthquake

Figure 5. Examples of the evaluation. Contour lines show the band passed gravity anomaly with 2 mgal. Red, black and purple broken lines denote the fault inferred by active fault, geologic fault and potential data, respectively.
Figure 6. Examples of the evaluation. Contour lines show the band passed gravity anomaly with 2 mgal. Red, black and purple broken lines denote the fault inferred by active fault, geologic fault and potential data, respectively.

Table 2. Evaluation results of length of the source faults.

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Year</th>
<th>Mech.</th>
<th>LEst(km)</th>
<th>SRL(km)</th>
<th>LAF(km)</th>
<th>LSB(km)</th>
<th>Kind</th>
</tr>
</thead>
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<tr>
<td>Kumamoto</td>
<td>2016</td>
<td>S</td>
<td>46</td>
<td>31</td>
<td>35</td>
<td>42</td>
<td>Major</td>
</tr>
<tr>
<td>Nagano</td>
<td>2014</td>
<td>R</td>
<td>70</td>
<td>9</td>
<td>58</td>
<td>22</td>
<td>Major</td>
</tr>
<tr>
<td>Fukushima Hamadori</td>
<td>2011</td>
<td>N</td>
<td>42</td>
<td>30</td>
<td>16</td>
<td>40</td>
<td>Minor</td>
</tr>
<tr>
<td>Iwate Miyagi inland</td>
<td>2008</td>
<td>R</td>
<td>40</td>
<td>20</td>
<td>3</td>
<td>39</td>
<td>Minor</td>
</tr>
<tr>
<td>Noto</td>
<td>2007</td>
<td>R</td>
<td>29</td>
<td>0</td>
<td>34</td>
<td>26</td>
<td>Minor</td>
</tr>
<tr>
<td>Chuetsu</td>
<td>2004</td>
<td>R</td>
<td>47</td>
<td>0</td>
<td>22</td>
<td>28</td>
<td>Major</td>
</tr>
<tr>
<td>Tottori</td>
<td>2000</td>
<td>S</td>
<td>41</td>
<td>6</td>
<td>0</td>
<td>34</td>
<td>Minor</td>
</tr>
<tr>
<td>Iwate inland</td>
<td>1998</td>
<td>R</td>
<td>30</td>
<td>0</td>
<td>12</td>
<td>10</td>
<td>Minor</td>
</tr>
<tr>
<td>Kobe</td>
<td>1995</td>
<td>S</td>
<td>67</td>
<td>10</td>
<td>60</td>
<td>64</td>
<td>Major</td>
</tr>
<tr>
<td>Izu Oshima Kinkai</td>
<td>1978</td>
<td>S</td>
<td>10</td>
<td>0</td>
<td>4</td>
<td>35</td>
<td>Minor</td>
</tr>
<tr>
<td>Mikawa</td>
<td>1945</td>
<td>R</td>
<td>18</td>
<td>30</td>
<td>11</td>
<td>25</td>
<td>Minor</td>
</tr>
<tr>
<td>Nobi</td>
<td>1891</td>
<td>S</td>
<td>81</td>
<td>80</td>
<td>80</td>
<td>122</td>
<td>Major</td>
</tr>
</tbody>
</table>

* Mechanism: S:Strike-slip, R:Reverse, N:Normal
** Evaluated length of fault
*** Length of Surface rupture
+ Length of seismogenic fault
++ Length of source fault
+++ Fault type: major is the faults, which the HERP selected for detail investigation. Minor is not selected by the HERP as 110 prioritized active faults.
Figure 7. Relationship among various fault lengths evaluated in this study. Solid line shows the 1:1 line. Fault type denotes as follows: major is the faults, which the HERP selected for detail investigation. Minor is not selected by the HERP as 110 prioritized active faults. (a) Relationship between seismogenic fault length and source fault length, (b) Relationship between fault length derived from revised HERP method and source fault length. Solid and broken arrows indicate estimated fault length based on overlaying the subsurface information and conservative judge.

Fig. 7 indicates the relationship between the evaluated fault length and that estimated from the results of seismological inversion (Table 2). Several earthquakes are plotted above the 1:1 line in Fig. 7a. These earthquakes (the 1998 Iwate inland, 2004 Chuetsu, 2014 Nagano earthquakes) are considered as non-characteristic earthquakes ([33], [34], [35]). The 2014 Nagano earthquake occurred at the northern part of the Itoigawa Shizuoka Tectonic Line (ISTL) (e.g. [36]), which has been evaluated by detail active fault surveys. However, the size of the 2014 earthquake was lower than the expected size [33]. The source region of the source is the northern extend of the ISTL, which was corresponds to the re-evaluated by revised HERP procedure [38].

The earthquake, whose source length was shorter than 40-50km, indicated large variability. [25] and [37] discuss the size of the earthquake of short active fault length. On the other hand, most earthquakes on major faults show good relationship with the inversion models except the non-characteristic earthquakes.

The evaluation results by the revised HERP method shown in Fig. 7b, the length of the shorter active fault were much longer, and depicted small variability with the length of the source faults. These results consistent to [5], and indicated effectiveness of the methodology.

The source fault of the 1891 Nobi earthquake indicates the complex fault geometry. In the complex fault zone, some source fault geometry shows complex form, for example, the Landers earthquake [39]. The source fault on the sea was estimated by the distribution of aftershocks of the 1978 Izu Oshima Kinkai earthquake. The re-analysis of the seismic survey around the focal region did not show the evidence of the active fault.
For the prediction, the size of the earthquake is estimated from the length of the fault or dimension of the fault (i.e. length and width of the fault). Further researches are needed to evaluate the size of the earthquake from evaluated dimensions, including the width of the fault, with the revised HERP procedure.

Conclusions

The source fault length evaluated with various subsurface information by means of the revised HERP procedure was examined in this study. The estimated fault lengths in the minor fault zone are shorter than that of seismological investigated result. In major fault except the 1891 Nobi earthquake, the fault length estimated from active fault and subsurface information is consistent with that of source fault inferred from strong ground motion inversion. The result of this study is that the integration of subsurface dataset and active faults is effective for the evaluation of the source fault. The evaluations of earthquake size with estimation of width and the threshold of the gravity gradient require further investigation.

Acknowledgments

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References