Probabilistic fault displacement hazard analysis of off-fault displacement in 2014 Nagano reverse-slip earthquake

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ABSTRACT

A hazard evaluation of off-fault displacements is important as well as on-fault displacements. On- and off-fault displacements caused by the 2016 Kumamoto are distributed along the main active faults. Probabilistic Fault Displacement Hazard Analysis (PFDHA) evaluates an annual rate of exceedance of off-fault displacement. We have developed off-fault PFDHA models in a reverse-slip earthquake. The PFDHA of the 2014 Nagano earthquake is performed based on PFDHA models constructed mainly by Japanese fault displacement data. We also examined differences between hanging wall and footwall in the PFDHA result of a reverse-slip earthquake. The improved off-fault displacements PFDHA models on hanging wall and on footwall were also used in PFDHA calculations. The estimated annual rates of exceedance show large differences between on the footwall and on the hanging wall with increasing distance from the main active fault. The investigation and improvement of off-fault models on footwall/hanging wall are important in the case of evaluating a reverse-slip earthquake.

Keywords: Probabilistic Fault Displacement Hazard Analysis (PFDHA); off-fault displacement; 2014 Nagano earthquake

1 INTRODUCTION

The 2016 Kumamoto earthquake occurred on the previously-known active faults. Many primary fault displacements distributed within a distance of a few tens of meters from the main active faults. Off-fault displacements were also reported by filed surveys and InSAR analysis (e.g., Ministry of Education, Culture, Sports, Science and Technology and Kyushu University, 2017). Evaluating a fault displacement hazard, off-fault displacements are considered as well as on-fault displacements. A probabilistic Fault Displacement Hazard Analysis (PFDHA) provides an evaluation of off-fault displacement as an annual rate of exceedance (e.g., Youngs et al., 2003). International Atomic Energy Agency (IAEA) recommends PFDHA in the case of an evaluation of fault displacement hazard for an existing nuclear site (international atomic energy agency, 2010).

PFDHA model of each fault mechanism has developed by several groups (e.g. Youngs et al., 2003 for normal-slip, Moss and Ross, 2011 for reverse-slip, and Petersen et al., 2011 for strike-slip). Moss and Ross (2011) provides only on-fault model because of sparse off-fault displacement data in reverse-slip earthquakes. In Japan, Takao et al. (2013) has developed the PFDHA model based on Japanese fault displacement data. The PFDHA model by Takao et al. (2013) consists of different fault mechanisms: strike-slip and reverse-slip. The off-fault displacement model was constructed by combined data with on hanging wall and footwall. In respect to off-fault displacement, fault displacement differences on footwall and hanging wall are expected. We focus on the off-fault displacement PFDHA model for footwall and hanging wall in strike-slip and reverse-slip mechanisms. We have developed the PFDHA models of on- and off-fault displacements for strike-slip and reverse-slip based on mainly Japanese earthquake data (Inoue et al., 2016). PFDHA of the 2016 Kumamoto earthquake have performed (Inoue et al., 2018). In this paper, we introduce developed PFDHA models of off-fault displacement in reverse-slip, and performed PFDHA of the 2014 Nagano earthquake, which was reverse-slip earthquake in Japan. We present the differences of annual rate of exceedance between hanging wall and footwall.

2 PFDHA EVALUATION OF THE 2014 NAGANO EARTHQUAKE

An annual rate of exceedance of off-fault displacement $v(d \geq d_0)$ is calculated by Eq. (1) (Chen and Petersen, 2011).

$$v(d \geq d_0) = \alpha P(sr \neq 0|m) \int_r P(d \neq 0|r) P(d \geq d_0|r, m, d \neq 0) f_R(r) dr \quad (1)$$

where, α: the annual rate of a earthquake m, $f_R(r)$: fault location uncertainty, $P(sr \neq 0|m)$: the probability of surface rupture given a magnitude

m earthquake on the fault, $P(d \neq 0|r)$: the probability of off-fault surface rupture, $P(d \geq d_0|r, m, d \neq 0)$: the conditional probability for non-zero displacement d greater than or equal to a given value d_0. r is a distance from a main surface rupture.

Fig.1 shows distribution of surface ruptures caused by the 2014 Nagano earthquake (Okada et al., 2015). We interpreted several surface ruptures as off-fault displacements, which were short, and less continuous (Youngs et al., 2003) as shown in Fig.1 (b). Most of the main surface ruptures (orange dotted lines in Fig.1 (b)) were distributed along the previously-known active faults (solid lines in Fig.1 (b)). We performed PFDHA of the off-fault displacement shown in Fig.1 (c), which located on hanging wall.

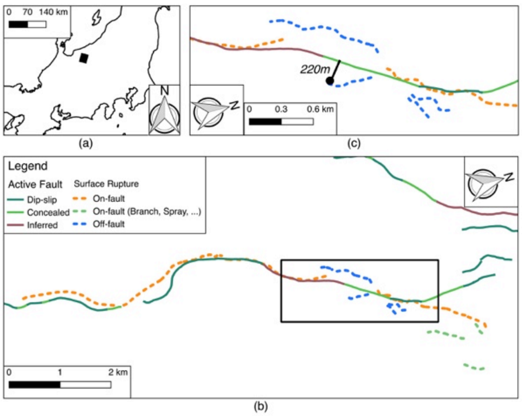


Fig. 1. Evaluation location and distribution of active faults (Nakata and Imaizumi, 2002) and surface ruptures (Okada et al., 2015). (a) Index map of (b). (b) Distribution of surface ruptures of the 2014 Nagano earthquake (Okada et al., 2015) and active faults (Nakata and Imaizumi, 2002). (c) Location of PFDHA evaluation (black circle). This point locates on hanging wall.

The components of Eq. (1) were mainly applied from Takao et al. (2013). In the following sections, the detailed parameters and equations were described.

2.1 Annual rate and probability of surface rupture

A value of 1000 year was used as the α, and m was 7.7, which are determined by the long-term active fault evaluation by the Headquarters for Earthquake Research Promotion (2013). The Mw of the 2014 Nagano earthquake, 6.2 was also used. The probability of surface rupture was given by:

$$P(sr \neq 0|m) = e^{(a+bm)}/1 + e^{(a+bm)} \qquad (2)$$

where m is magnitude, for Takao et al. (2013), a and b are -32.03 and 4.90.

2.2 Conditional probability of off-fault surface rupture

From Takao et al. (2013):

$$P(d \neq 0|r, m) = e^z/1 + e^z \qquad (3)$$

where $z = -3.839 + (-3.866 + 0.350m)\ln(r + 0.200)$. r is distance from the main active fault in kilometers.

2.3 Attenuation relation

From Takao et al. (2013):

$$d/MD = 0.55\exp(-0.17r) \qquad (4)$$

where MD is maximum displacement of the main active fault, r is distance from the main active fault in kilometers. The off-fault displacement attenuation relation by Eq. (4) was constructed from off-fault displacement data, which were not distinguished footwall/hanging wall blocks. MD is calculated from:

$$\log(MD) = -5.16 + 0.82m \qquad (5)$$

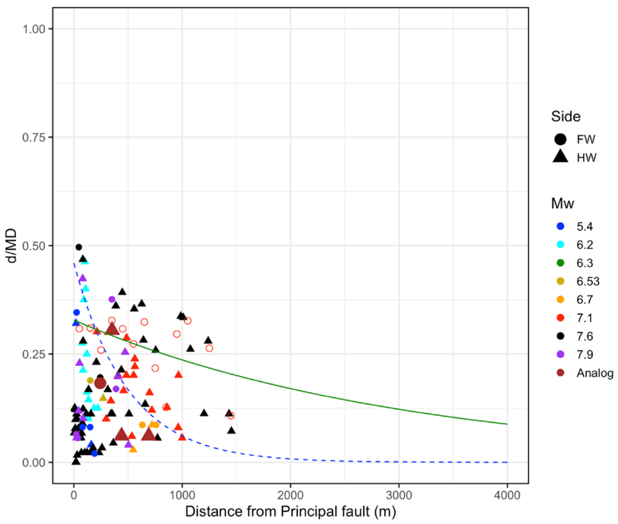


Fig. 2. Off-fault displacement attenuation relation. Solid and dotted lines represent attenuation relation on the hanging wall and footwall, respectively. Red open circles show the 90th-percentile of data.

We have developed attenuation relation of off-fault displacement in reverse-slip on the basis of adding Boncio et al. (2018) to previously compiled our data set (Inoue et al., 2016). Inoue et al. (2016) compiled off-fault displacement of Japanese and global reveres-slip earthquakes, and constructed off-fault displacement attenuation relations on hanging wall and footwall. The range of r in their data is limited to about 1km in a distance from the main surface rupture. Boncio et al. (2018) compiled off-fault ruptures of global reverse-slip earthquakes, and discussed a width from main fault on hanging wall and on footwall. Their results show asymmetry width on hanging wall and footwall.

We carried out analogue experiments of reverse-slip with fine grade wheat flour, and collected off-fault displacement data. A new attenuation relation is estimated by compile above-mentioned data set as follows:

$$d_{HW}/MD = 0.3187\exp(-0.0003r) \quad (6)$$
$$d_{FW}/MD = 0.5074\exp(-0.0020r) \quad (7)$$

where d_{HW} and d_{FW} are off-fault displacement on the hanging wall and on the footwall, respectively. r is distance from the main active fault in meters. Fig.2 shows compiled off-fault data, Eq. (6) and Eq. (7).

$P(d \geq d_0 | r, m, d \neq 0)$ is estimated by convolution of probability density of Eq. (5) and Eq. (6) or Eq. (7). A log normal distribution is used for Eq. (5). The gamma distribution is applied for Eq. (6) and Eq. (7), which are 90_{th}-percentile curve of distributed fault displacement data. Following Youngs et al. (2003), a and b are 2.5 and Eq. (6) or Eq. (7) divided by 4.617, respectively.

3 DISCUSSION: ANNUAL RATE OF EXCEEDANCE

Fig.3 denotes annual rate of exceedance of the evaluation location as shown in Fig. 1 (c), and on footwall with a same distance from the main active fault to the evaluation location as shown in Fig.1(c). The annual rate of exceedance of Mw6.2 is smaller and decays rapidly compared to the result of Mw7.7. The annual rate of exceedance on hanging wall is larger than that on footwall.

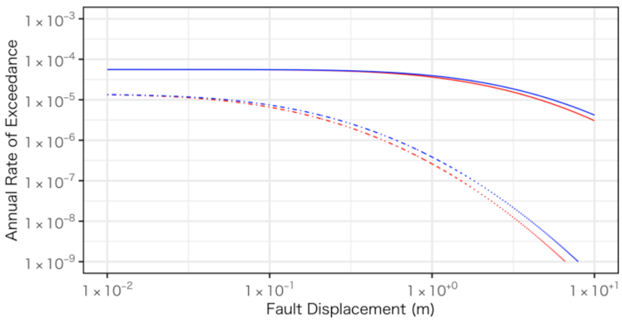
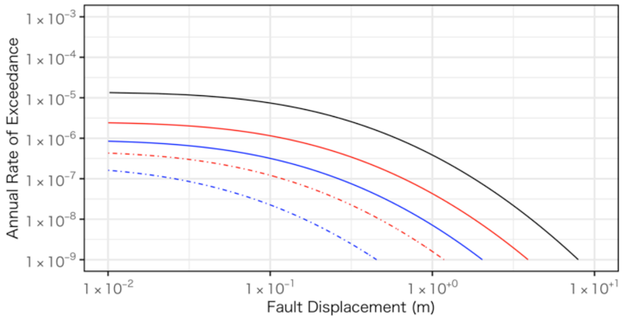
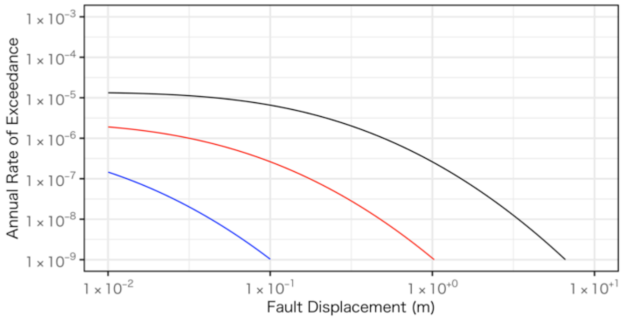


Fig. 3. PFDHA result at the evaluation location shown in Fig. 1 (c), and on footwall with a same distance from the main active fault to the evaluation location as shown in Fig.1(c). Solid and dotted lines denote PFDHA results of Mw7.7 and Mw 6.2, respectively. Blue and red lines denote PFDHA results on hanging wall and footwall, respectively.

Fig.4 denotes annual rate of exceedance at various distances from the main active fault. Fig. 4 (a) and (b) are results on hanging wall and footwall, respectively. The comparison between same color lines in Fig. 4 (a) and (b) shows the annual rate of exceedance on the footwall decays rapidly. The exceedance differences between on the footwall and on the hanging wall are larger with increasing distance. This suggests that off-fault PFDHA models on footwall and on hanging wall affects calculated annual rate of exceedance in the case of evaluation of a reverse-slip earthquake.



(a) PFDHA results on hanging wall. Black solid, blue solid, red solid, blue dotted and red dotted lines denote results at different distances, the evaluation site as shown in Fig. 1 (c), 1km, 2km, 3km and 5km from the main active fault. Mw is 6.2.



(b) PFDHA results on Footwall. Black solid, blue solid, red solid lines denote results at different distances, footwall with a same distance to the evaluation site as shown in Fig. 1 (c), 1km and 2kmfrom the main active fault. Mw is 6.2.

Fig. 4. PFDHA result at different distances from the main fault.

4 CONLCUSION

The improved off-fault PFDHA models are introduced in this paper. The PFDHA of the 2014 Nagano earthquake is performed based on PFDHA models constructed mainly by Japanese fault displacement data. The improved off-fault displacements PFDHA models on hanging wall and on footwall were also used to perform PFDHA. We also examined differences between hanging wall and footwall in the PFDHA result of a reverse-slip earthquake. The estimated annual rates of exceedance show large differences between on the footwall and on the hanging wall with increasing distance from the main active fault. The investigation and improvement of off-fault models on footwall/hanging wall are important in the case of evaluating a reverse-slip earthquake.

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