Seismic and displacement hazard assessments on active faults in Japan

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Abstract

Here I briefly review 20-yr progress in active fault study in Japan and raise several new issues. In terms of seismic hazard assessment, the Headquarters of Earthquake Research Promotion successfully published the first probabilistic national seismic hazard map in 2005 based on the recent intensive surveys on the major active faults. The hazard map is roughly consistent with the historical intensity distribution affected by the shortly repeated subduction earthquakes. However, underestimates and unpredictability occurred inland areas due to unmapped blind faults. In contrast, overestimates for a large fault system might be another issue (e.g., 2014 Nagano-ken-hokubu earthquake of M6.7 on the Itoigawa-Shizuoka Tectonic Line). Surface displacement is the other aspect of hazard on active faulting. Recent development of remote sensing techniques demonstrates that the surface ruptures not only occurred along the pre-existing mapped scarps but also involved numerous distributed faults away from the main rupture zone. It requires further study of probabilistic fault displacement hazard analysis for strict assessment such as nuclear safety.

Keywords: seismic hazard map, fault segmentation, blind fault, rupture complexity

1. Introduction

It has been 20 years since the January 17, 1995 Kobe (Hyogo-ken-nambu) earthquake of M 7.3. Because the Nojima fault (Photo 1), one of the mapped active faults (Mizuno et al., 1990), caused the Kobe earthquake, not only scientists but also the general public have become aware of the importance of active fault as a potential source of a destructive inland earthquake. Under such a background, the Headquarters for Earthquake Research Promotion (HERP) has been established in 1995 and leading a huge amount of surveys including drilling, trench excavation, seismic reflection, and other geophysical explorations have been deployed across more than 100 major active faults. The accumulated data have been effectively contributed to making seismic hazard map.

During the recent 20 years, several destructive earthquakes including the March 2011 great Tohoku earthquake occurred and have affected our studies. Here I review the recent progress and several issues associated with seismic and displacement hazard assessments on active faults in Japan.

2. Seismic hazard

2.1 First national seismic hazard map

The first national seismic hazard map for Japan was published in 2005 based on probabilities of large earthquakes along subduction zones, onshore active faults, and background seismicity (HERP, 2005). The probabilities and expected magnitudes are calculated from historical, paleoseismological and geological data as well as instrumental seismicity data. A vast amount of paleoseismological data, mostly obtained after the Kobe earthquake, is newly incorporated into the detailed calculations taking the conditional probability into account. Time-dependent seismic hazard considering conditional probabilities on most major active faults provide us with more realistic estimates (Fujiwara et al. 2009). These outputs are available to the general public and researchers on the portal web named as 'J-SHIS', a browser-based GIS (http://www.j-shis.bosai.go.jp/map/?lang=en) to enhance utilization of the seismic hazard maps, as well as giving the fundamental information of fault locations, subsurface and surface geologic conditions (site amplifications), exposed population, and other models. Active fault database is also accessible from the Geological Survey of Japan, AIST (https://gbank.gsj.jp/activefault/index_e_gmap.html).

Photo 1. Fresh rupture scarp emerged along the Nojima fault on Awaji Island at the 1995 Kobe earthquake.

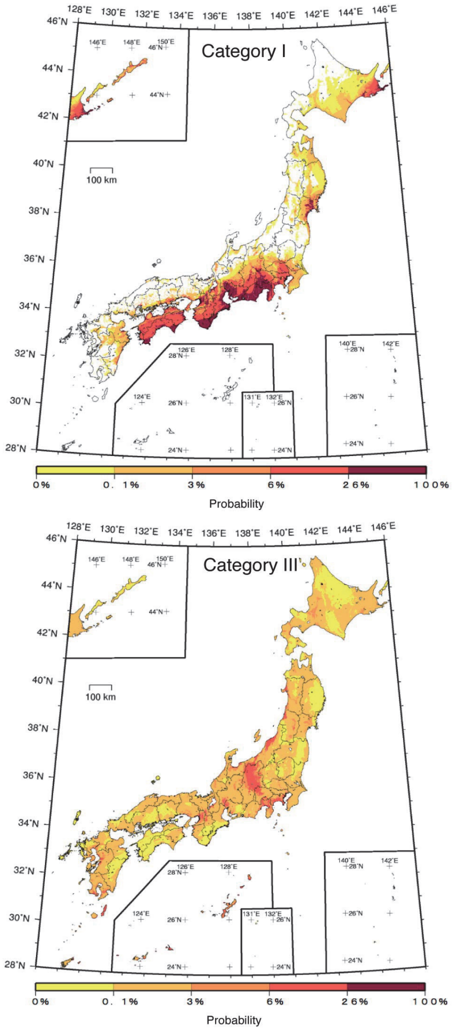

Fig. 1. 30-yr probabilities of strong ground motion of JMA intensity ≥ 6 lower caused by seismic sources of Category I (subduction-zone earthquakes with specified seismic source faults) and Category III (shallow earthquakes inland area and in sea area). (HERP, 2010).

The map, a result of a probabilistic seismic hazard analysis (PSHA), shows the probability of exceedance of the Japan Meteorological Agency (JMA) intensity 6- (roughly equal to MMI IX-X) in Japan for a 30-year period (Fig. 1). Since the high-probability regions are highly affected by the subduction zone earthquakes, regional differences for inland earthquakes are invisible. In other words, tremendous efforts and data from active faults are not effectively utilized in the map. Thus, the HERP has started to make three versions of the hazard map, categorizing all the sources into repeated subduction megathrust earthquakes (category I, Fig. 1a), unknown sources of subduction earthquakes (category II), and inland active faults (category III, Fig. 1b). Now if one wants to see the hazard of the M~7 class inland shocks, a PSHA for category III is appropriate and avoids confusing regional differences of the hazard with the extreme high probabilities due to the subduction earthquakes.

Validation of the hazard map is a new issue. A simple spatial comparison with the epicenters of large shocks superimposed on the hazard map, falsifying the hazard map (e.g., Geller, 2011), is inappropriate. Miyazawa and Mori (2009) compared the HERP's national seismic hazard map with maximum seismic intensity maps during the past 500 years, and then concluded that both are very similar except the case for onshore crustal earthquakes. Ishikawa et al. (2011) reached the similar conclusion with their more rigorous tests for the recent 120-year data. Both tests point out that there may be still a deficiency of data for the inland active faults that have recurrence times of thousands of years.

2.2 Blind fault and class C fault issue

During the recent 20 years since the Kobe earthquake, several large inland earthquakes have struck the regions off the major active faults chosen by the HERP. As already mentioned, however, palaeoseismic trenching studies and other approaches to extract active fault parameters largely rely on surface-rupturing processes. In other words, if no surface rupture had taken place, no large earthquake would have been identified. From that viewpoint, Toda (2013) re-examined the surface-rupturing earthquakes since 1923 when the Japan Meteorological Agency (JMA) officially started their catalog recording. Only 20% of M≥6.5 and 44% of M≥7.0 shallow earthquakes left the surface breaks that correspond to their source fault dimension (Fig. 2). He thus speculates that the number of potential destructive earthquakes of M6-7 estimated from the major active faults would be significantly underestimated. He also performed numerical calculations with active fault data and their assigned probabilities in the report also largely underestimate the number of observed earthquakes. Both independent analyses suggest that there would be far more minor active faults hidden beneath Japanese islands.

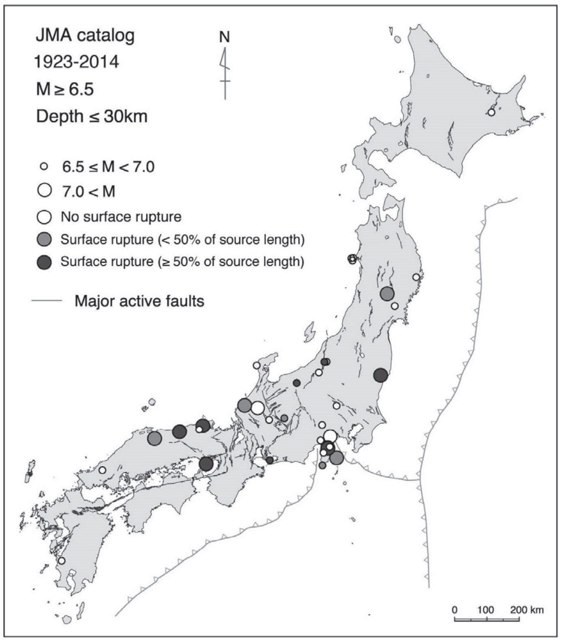

Fig. 2. Distribution of inland earthquakes which have occurred in Japan since 1923.

Asada (1991) has already pointed out the so called ‘class C fault issue’ which raises a question about hidden active faults with slip rates of slower than 0.01 mm/yr. He claimed that “since the recent destructive inland earthquakes are occupied equally by all the classes (1 mm/yr ≤ class A < 10 mm/yr, 0.1 mm/yr ≤ class B < 1 mm/yr, 0.01 mm/yr ≤ class C < 0.1 mm/yr), the number of class C faults must be 100 times of the class A faults.” But in the catalogue of the Research Group for Active Faults in Japan (1991), the estimated numbers of class A, B and C faults are 103, 884, and 660 respectively, which suggests that majority of the slowly moving class C faults are hidden, possibly due to fast rates of erosion and sedimentation associated with Japan’s climate and surface processes.

2.3 Fault segmentation and site-based evaluation

The size and rupture dimension of the 11 March 2011 Tohoku earthquake surprised many earthquake scientists in Japan. The Tohoku earthquake broke five pre-defined segments, yielding a magnitude 9.0 earthquake involving ~50 m coseismic slip. Such segmentation along the Japan Trench is based on the ‘characteristic earthquake model’ (Schwartz & Coppersmith 1984) in which each segment has repeatedly produced a characteristic size of rupture length, displacement and thus magnitude within a certain interval. The characteristic earthquake does not consider any significant change in size of the repeating earthquakes. Thus the HERP’s estimates was that the largest future earthquakes along the different segments of the Japan trench were expected to have magnitudes between 7 and 8 with different inter-event times. The Tohoku earthquake thus forced us to reconsider the conventional segmentation based on the characteristic earthquake model.

Proper assessment of multiple segment rupture for inland earthquakes, which determines the size of the earthquake, is also a serious issue for design-and-construction decisions. As already noted, the HERP basically follows the definition of “seismogenic active fault” provided by Matsuda (1991) in which the seismogenic faults are chosen and connected within a gap smaller than 5 km (Wesnousky 1988; 2006). However, the strategy only calculates the maximum size of large earthquakes and their frequency, ignoring the more frequent segment-based smaller ruptures. As well as the advanced palaeoseismic studies along the San Andreas fault in California (e.g., Scharer et al. 2014), numerous palaeoseismic excavations across the ISTL (Fig. 3) already show that it is more likely that frequent M~7 shocks have occurred, along with complex combinations of multiple segment ruptures.

The 22 November 2014 Nagano-ken-hokubu earthquake (M=6.7, Mw=6.2) also demonstrated a clear difficulty in estimating size of an earthquake. More than 9 km of complex surface faulting occurred on the previously mapped N-NW trending Kamishiro fault, one of the segments of the 150-km-long Itoigawa-Shizuoka Tectonic Line (ISTL) active fault system (Figs 3 and 4). The surface rupture lies ~5 km west of the epicentre, juxtaposing a basin with a NNW-trending mountain range. Surface rupture mostly observed as warped and buckled the ground surface, corresponds to vertical and contractional deformation associated with a shallow east-dipping thrust fault (east side up), accommodating NW-SE compression. The maximum vertical displacement and contraction measured were 80 cm and 50 cm respectively (Fig. 4). The 2014 earthquake is the first surface-rupturing earthquake to strike on one of the 110 major active faults evaluated by the HERP since 1995. Numerous palaeoseismic data, in particular on the most active central ISTL, allowed the HERP to forecast a 14% 30-yr probability of an M=8.3 earthquake if the entire ISTL ruptured. One of the other rupture scenarios was an Mw =7.4 event on the northern half of the ISTL, involving the Kamishiro fault, which was also largely overestimated. In addition, the observed 80-cm-vertical displacement is much smaller than the expected 3-4-m slip from a 1,000-1,500 yr elapsed time and a vertical slip rate of 3 mm/yr of the Kamishiro fault. Thus, given the evidence so far available, it can be concluded that either the 2014 earthquake was not a characteristic event, or the palaeoseismic data are extremely incomplete.

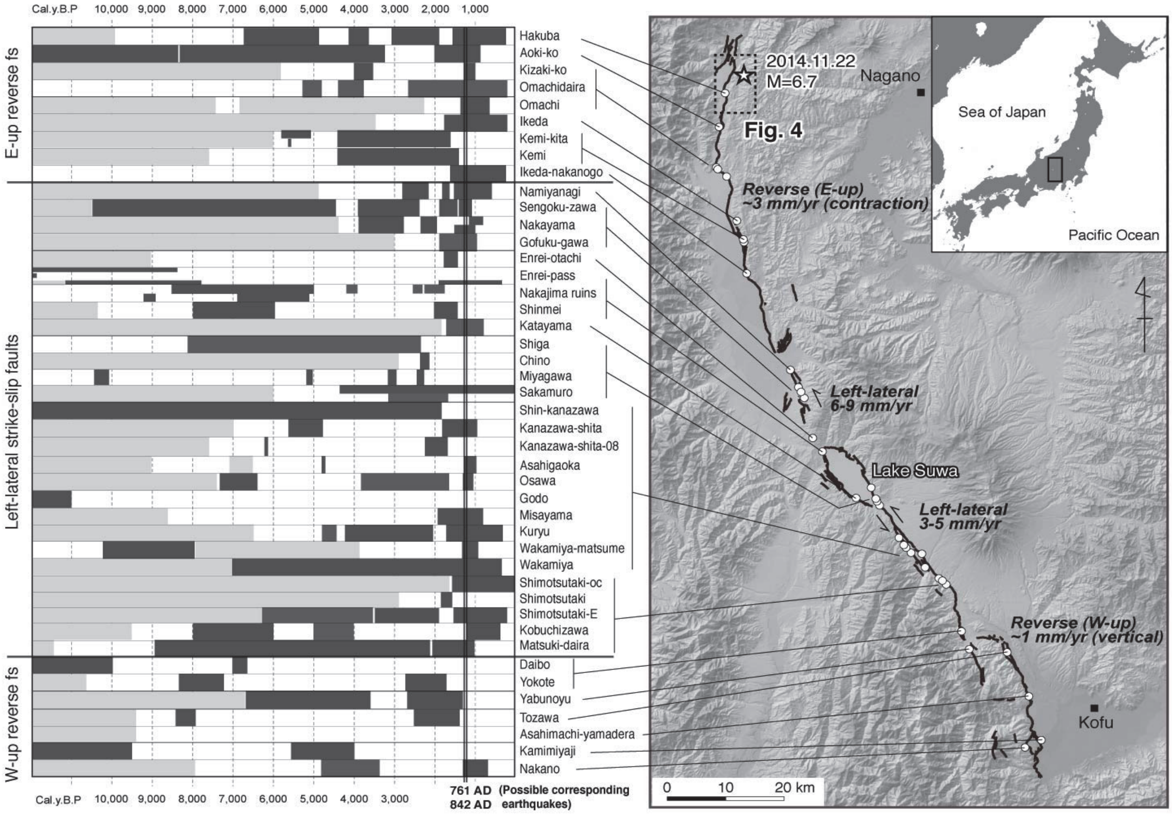

Fig. 3. Space-time diagram for large magnitude surface-rupturing earthquakes on the ISTL during the past 12,000 years (Maruyama et al. 2010). Horizontal dark gray bar indicates a range of palaeo-earthquake occurrence. Horizontal light gray bar denotes a time range across which no datable strata were recovered.

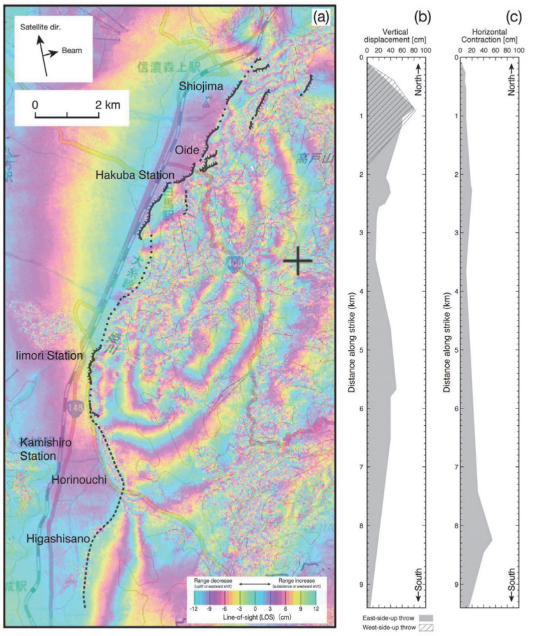

Fig. 4. (a) Map of the 2014 surface ruptures along the Kamishiro fault (Okada et al., 2015) superimposed on an interferogram computed from ALOS-2/PALSAR-2 (Geospatial Information Authority of Japan, 2015). Solid line and dashed line indicate confirmed and inferred rupture traces respectively. Distribution of (b) vertical slip and (c) fault normal contraction of the surface rupture zones along the Kamishiro fault (simplified from Okada et al., 2015).

3. Displacement hazard

The other hazard associated with active faulting is ground displacement that brings damage any manmade structures. There are numerous cases the significant fault slip destroyed major roads, railways, private houses, school buildings, dam reservoirs and others. To prevent such disaster in advance, for example, the Aliquist-Priolo Earthquake Fault Zoning Act, which forces people not to construct new structure along fault zone 500 feet away from most mapped faults and 200 feet away from less significant faults, has been enforced since 1972 in California. No potential active faulting is definitely required for the crucial constriction such as nuclear power plant.

Although mapping fault traces is not easy task in Japan unlike San Andreas fault system in California, majorities of rupture locations at future earthquakes are believed to occur along the mapped fault traces based on the surface rupture maps during the past a few hundred years. These surface rupturing earthquakes also lead to the empirical relations between magnitude and displacement, and between fault length and displacement (e.g., Matsuda, 1975; Wells and Coppersmith, 1994), allowing us to predict amount of slip at a specific site along a fault. Up to the present, except a local ordinate of Tokushima Prefecture along the Median Tectonic Line in Shikoku, we have not had any regulation associated with the predicted surface displacement along an active fault. However, concerning about the proximity of nuclear power plants (NPP) to active faults (e.g., Chapman et al., 2014), re-evaluation of minor but suspect faults have become a main issue with respect to fault displacement hazard.

3.1 Probabilistic analysis and rupture complexity

Takao et al. (2013) proposed an evaluation formula of the probabilistic fault displacement hazard analysis (PFDHA) based on 19 surface-rupturing earthquakes since 1891 Nobi earthquake in Japan. Despite limited number of distributed fault data, they concluded that significant displacement associated with engineering concerns mostly occurs on principal fault traces and the effect of the distributed faults is extremely small.

However, recent development of remote sensing techniques, in particular SAR interferometry and airborne LiDAR, enables us to map accurate and complex features of surface ruptures associated with the inland earthquakes. Several significant cases were observed in the 2007 Niigata-ken-Chuetsu earthquake, 2008 Iwate-Miyagi-nairiku earthquake, 2011 Fukushima-ken-Hamadori earthquake (Fig. 5), and 2014 Nagano-ken-hokubu earthquake (Fig. 4) in Japan, and the 2014 South Napa earthquake in California, and the 2010 El Mayor-Cucapah earthquake in Mexico. These earthquakes demonstrate that the surface ruptures not only occurred along the pre-existing mapped scarps but also involved numerous distributed faults a few kilometers away from the main rupture zone. A few cases also show remotely triggered aseismic surface slips. However, the amounts of slip on these distributed subsidiary faults are generally small as Takao et al. (2013) pointed out, and might be handled engineering elaborations. In addition, since some of these distributed faults are proved to have moved during the late Quaternary period, one could map such subsidiary faults by intensive geological survey in advance.

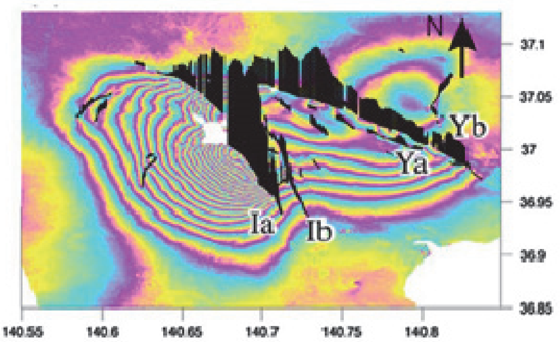

Fig. 5. Surface fault offsets across discontinuity traces identified in the interferogram from a perspective view in the 2011 Fukushima-ken-hamadori (Iwaki) earthquake of M=7.0 (Fukushima et al., 2013). The maximum offset of 1.5 m was found along the western trace of the Itozawa fault (Ia). Note that there are many secondary faults away from the two main rupture traces of Ia and Yb (Yunodake fault).

3.2 Site-based fault identification

Relicensing process for existing NPPs in Japan after the Fukushima-Daiichi NPP disaster at the 2011 Tohoku earthquake raised an issue to identify active faults, most of which are small faults, near and/or beneath their facilities. The definition of “active fault” given by the Japan’s new Nuclear Regulatory Authority (NRA) is based on paleoseismological evidence of faulting during the late Pleistocene (120-130 ka). If no young overlying sediments that can be examined to determine the last fault movement, NRA requires investigators to seek evidence over the past 400,000 years. As mentioned, the problem is not a principle fault strand but small faults or distributed fault traces.

Such suspect minor faults exposed at their constructions and new investigation sites are often originated from non-tectonic processes. A suspect fault at the Ohi NNP operated by the Kansai Electric Power Co. Inc. had been intensively investigated and then evaluated as inactive by NRA. Several minor faults exposed on their trench walls, claimed as active faults by two NRA’s expert geoscientists, were also indeed non-tectonic faults associated with a massive paleo-landslide. Another non-tectonic faults would be generated from differentially heaving bedrock due to expansive weathered clay-rich Tertiary units at the Higashidori NNP, the Tohoku Electric Power Co. Inc. A similar non-tectonic faulting case is already reported from Noe et al. (2007) near the Denver metropolitan area in Colorado. Numerous small faults displaced the late Quaternary strata and claimed as a group of active faults by the NRA's expert geoscientists, were exposed in and around the facility. However, most of the faults are only observable shallower than several meters from the surface. Furthermore, their strikes, dips and locations are rather random, and nothing to do with current stress regime and locations of suspect geomorphological scarps the expert scientists claim.

However, recent cases of the surface rupturing earthquakes and large local stress perturbations (e.g., Oskin et al., 2012) suggest that displacement hazard is not easily evaluated. Thus it might be important to explore "what-if" scenarios in case, incorporating expert, evidence-based judgments on the likelihood of movement and possible magnitudes of displacement, and suggest a probabilistic fault displacement hazard analysis (PFDHA) (Chapman et al., 2014).

4. Conclusions

Here I briefly reviewed 20-yr progress in active fault study in Japan and raised several issues. In terms of seismic hazard assessment, the HERP successfully published the first national seismic hazard map in 2005 based on the recent intensive surveys of the major active faults, which is roughly consistent with the historical intensity data associated with the subduction earthquakes. However, underestimates occurred in inland areas due to unmapped hidden faults and so called class C faults. In contrast, overestimates might be an issue for a large fault system (e.g., 2014 Nagano-ken-hokubu earthquake along the Kamishiro fault, a part of the Itoigawa Shizuoka Tectonic Line). Regarding to the displacement hazard, recent development of remote sensing techniques demonstrates that the surface ruptures not only occurred along the pre-existing mapped scarps but also involved numerous distributed faults away from the principal fault strand. It requires further study of probabilistic fault displacement hazard analysis.

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