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Issues and Challenges in Seismic Risk Evaluation and its Uncertainty Reduction for the Nankai Trough Earthquake

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Synopsis

The research project titled "Promotion of observation and research plan of earthquakes and volcanos for contributing to mitigation of disasters" was initiated in 2014, and the preliminary study was performed in FY2015. As a preliminary study, a framework for seismic risk evaluation with the consideration of epistemic uncertainty was developed. The secondary study was performed in FY2016, and the methodology for the seismic risk evaluation is improved in 3 parts: i.e., the revision in GMPE models considering the saturation effect, the revision in loss model in terms of the fatalities as well as the direct losses in buildings, and the extension of target sites to entire Kochi and Osaka prefectures. The results of preliminary and secondary studies suggest that the epistemic uncertainty in GMPEs is most sensitive to the overall uncertainty of seismic risk.

Keywords: Seismic risk evaluation, Uncertainty reduction, Nankai trough earthquake

1. Introduction

After the 2011 Tohoku earthquake, the research program for earthquakes by Ministry of Education, Culture, Sports, Science and Technology (MEXT) had put emphasis on the mitigation of earthquake disasters, in addition to the prediction of earthquake occurrences. Correspondingly, a five-year plan of the research project was proposed in 2013 and started in April, 2014 including a new format of a collaborative research called, "Core-to-Core collaborative research between Earthquake Research Institute, University of Tokyo and Disaster Prevention Research Institute, Kyoto University". The title of the research project is "Promotion of observation and research plan of earthquakes and volcanos for contributing to mitigation of disasters", and it was clarified that the aim of this research project is not only for observation and research for earthquake prediction but for estimation and reduction of disaster risks. For these purposes, this collaborative research was formulated with 7 research subgroups related to seismic risk evaluation, i.e. source process, wave propagation and deep subsurface structure, strong motion estimation, shallow subsurface structure, structural damage estimation, risk evaluation, and stakeholder involvement. Another subgroup was formed to develop the platform for seismic risk evaluation and to integrate the inputs from the aforementioned subgroups.

The collaborative research was initiated and required researches were extracted in the first fiscal year (FY2014) of the research project, and the preliminary study was performed in the second fiscal year (FY2015). As the preliminary study, the methodology of entire research was constructed by platform development group, and models in related research fields were selected by corresponding research subgroups. In the third year (FY2016) of the 5-year plan of the research project, the process of seismic risk evaluation was revised and extended based on a methodology constructed in the preliminary study of the collaborative research. The ground motion prediction equations (GMPEs) and risk models were revised and target sites were extended to units of prefectures.

2. Preliminary study

2.1 Scope of the study

As the initial phase of the research project, preliminary study was performed in FY2015. The scope of the research was limited to evaluate the expected loss to an arbitrary structure at an arbitrary location due to a certain earthquake. 2-storey wooden house was determined as the target structure, and locations of prefectural buildings for Kochi and Osaka prefectures were selected as target sites. The Nankai trough earthquake was considered as the target earthquake. Locations of the source area of the Nankai trough earthquake and two target sites are shown in Fig. 1. The problem in the preliminary study was defined as the evaluation of seismic risk of direct (i.e. economic) loss for a 2-storey wooden house at locations of prefectural office buildings in Kochi and Osaka prefecture.

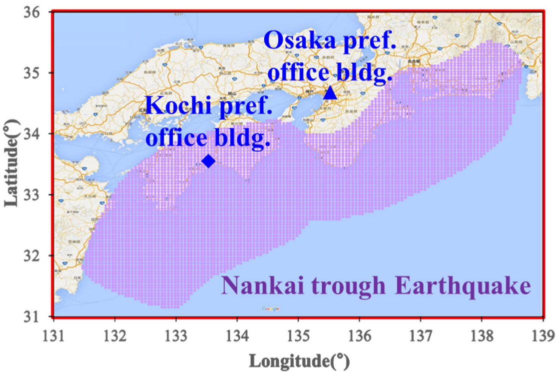


Fig. 1 Locations of the source area of the Nankai trough earthquake and target sites

2.2 Procedure of the study

In this study, the seismic risk evaluation process is idealized to be a simplified sequential process with five stages: i.e., source process, strong motion estimation, shallow subsurface structure, structural damage estimation, and risk evaluation. The idealized process of the five stages is illustrated in Fig. 2. The output from a former stage is utilized as the input to the following stage. We define the magnitude and location of each earthquake source, and combine them to construct source models. The source models are proposed with their weightings of occurrence. Ground motions at the sites were predicted in the strong motion estimation stage with the format of peak ground velocity (PGV). Effects of site amplifications were estimated in the shallow subsurface structure stage, and the vulnerability of target structure was estimated using fragility curves in the structural damage estimation stage. In the risk evaluation stage, the seismic risk was evaluated in terms of the expected value of loss.

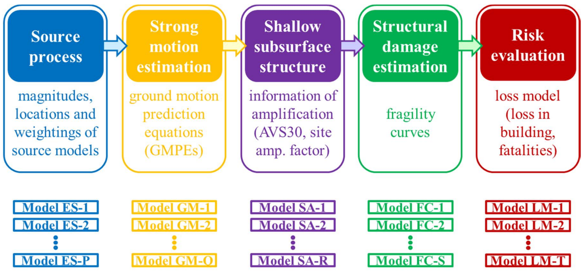


Fig. 2 Simplified sequential process for the evaluation of seismic risk and its uncertainty (Lee et al., 2016)

In this study, the misfits of the models to the data and/or the presence of competing models are considered as the epistemic uncertainty and the overall uncertainty of the calculated seismic risk is affected by each epistemic uncertainty. Each epistemic uncertainty is estimated by each research subgroup and the overall uncertainty is evaluated considering those epistemic uncertainties. The great number of risks are able to be calculated using Monte-Carlo Simulation (MCS), and the probabilistic distribution of risk is able to be estimated based on the result of MCS. The overall uncertainty inherited in the calculated risk is able to be defined based on the probabilistic distribution.

The degree of uncertainty is defined as the length of interval from 5% quantile value to 95% quantile value of expected losses in the MCS result, as shown in Fig. 3.

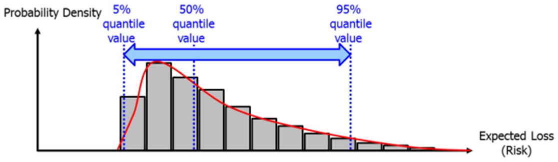


Fig. 3 The definition of the degree of uncertainty (Lee et al., 2016)

The ultimate goal of this research is to investigate possibilities to reduce the overall uncertainty of seismic risk. Sensitivity analysis with quantified values of risks and their uncertainties was performed to investigate which part's uncertainty mostly affects the overall uncertainty. Firstly, reference value of overall uncertainty is evaluated in case of that uncertainties of all parts exists. This uncertainty is called as "original uncertainty" in this paper. Secondly, overall uncertainty is calculated for case when we do not consider uncertainty of the source model and uncertainties of all the other parts exist. Same process is performed with respect to GMPEs, site amplification, fragility curve and loss model parts. Thirdly, the most important part is defined by the comparison of the variation of the overall uncertainty for each case. If the overall uncertainty significantly is affected by the uncertainty of a certain part, the uncertainty of that part should be considered as an important part to reduce the overall uncertainty. An image of sensitivity analysis is illustrated in Fig. 4. In Fig. 4, the uncertainty of GMPE is most sensitive to the overall uncertainty.

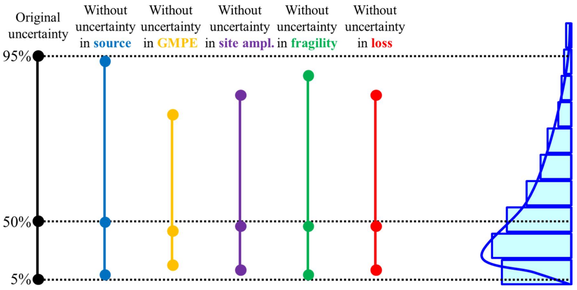


Fig. 4 Image of sensitivity analysis

2.3 Applied models in the study

(1) Source process

Six earthquake sources were selected for the Nankai trough earthquake for source process stage based on the Japan Seismic Hazard Information System (J-SHIS) (NIED, 2016). The moment magnitudes of six earthquake sources are 9.1, 8.7, 8.3, 8.5, 8.2, and 8.4. The shortest distances from six sources to Kochi prefectural building site are 25.7 km, 25.6 km, 227 km, 25.6 km, 227 km, and 25.6 km, and those to Osaka prefectural building are 70.9 km, 107 km, 107 km, 114 km, 107 km, and 114 km. Six source models were proposed for source process stage using selected six earthquake sources as shown in Fig. 5. While the former two source models consists of a single source, the other four source models consists of two sources. The meaning of two sources in a source model is that two earthquakes occur at a certain time interval, but not concurrently. Weights, were also suggested as 10%, 30%, 15%, 15%, 15%, and 15%, for source model 1 to 6, respectively. The probability of occurrence for the six source models is not considered, so the conditional risk given the occurrence of the earthquake, is considered.

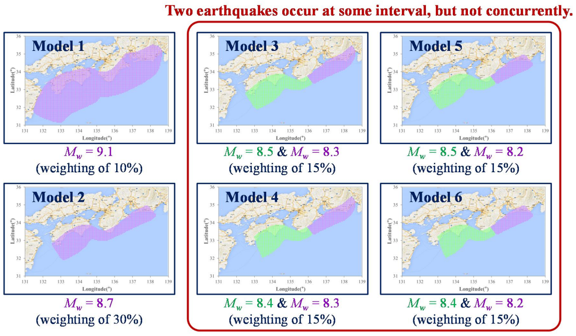


Fig. 5 Proposed six source models for the Nankai trough earthquake

(2) Strong motion estimation

GMPEs are defined empirically to predict the attenuation relation from earthquake source to site. In this study, GMPEs developed based on Japanese data, and are able to estimate PGVs are applied for the seismic risk evaluation. They are defined as follows:

$$\log PGV_{EB} = f(M_w, X, \cdots) + \varepsilon_{GMPE} \qquad (1)$$

where, PGV_{EB} is PGV on the engineering bedrock of site. M_w is the moment magnitude of earthquake source, and X is the source-to-site distance. Each GMPE model has an error term considering modelling uncertainty, $\varepsilon_{\text{GMPE}}$. $\varepsilon_{\text{GMPE}}$ is modelling uncertainty of GMPE, whose values are randomly selected using normal distribution with σ values of corresponding GMPEs. The σ values are values of the standard errors calculated in the process of empirical estimation for GMPEs. Because $\varepsilon_{\text{GMPE}}$ is assumed as normally distributed, the predicted PGVs will be lognormally distributed.

Five GMPE models were selected for strong motion estimation stage, which are GMPE-1 by Si and Midorikawa (1999), GMPE-2 by Kanno et al. (2006), GMPE-3 by Satoh (2010), and GMPE-4 and GMPE-5 by Morikawa and Fujiwara (2013). In this study, only GMPE-4 and GMPE-5 are applicable for source model 1 whose moment magnitude is over 9, while all 5 GMPEs can be applied for the other 5 source models whose moment magnitudes are under 9. The reason why is that the saturation effect for the earthquake with large magnitude is considered only in GMPE-4 and GMPE-5, while it is not considered in the other 3 GMPEs.

While PGV on engineering bedrock is predicted by GMPE-1, in which the average Vs for top 30 m (AVS30) is 600 m/s, PGVs predicted by GMPE-2, GMPE-3, GMPE-4, and GMPE-5 are targeted for sites with AVS30s of 311 m/s, 500 m/s, 350 m/s and 350 m/s, respectively. In other words, predicted PGVs are affected not only by the attenuation relation but also by the site amplification effect excepting the case of GMPE-1. Therefore, predicted PGVs needs to be converted into PGVs on engineering bedrock so the effect of attenuation and that of site amplification can be considered separately. Conversion procedure of PGVs predicted by five GMPEs is illustrated in Fig. 6. In case of GMPE-2, PGV is converted by its own converting relation (Kanno et al., 2006), but the converting relation by Fujimoto and Midorikawa (2006), shown in Eq. (4), is applied for PGVs by other GMPEs. The comparison of the predicted and converted PGVs of 5 GMPEs are shown in Fig. 7 in case of the earthquake source 2 whose the moment magnitude and focal depth are 8.7 and 19.2 km, respectively.

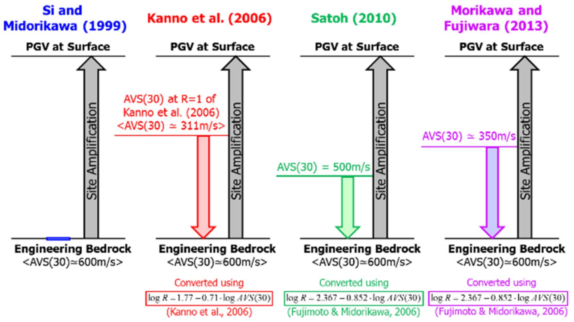


Fig. 6 Conversion of PGVs by 5 GMPEs

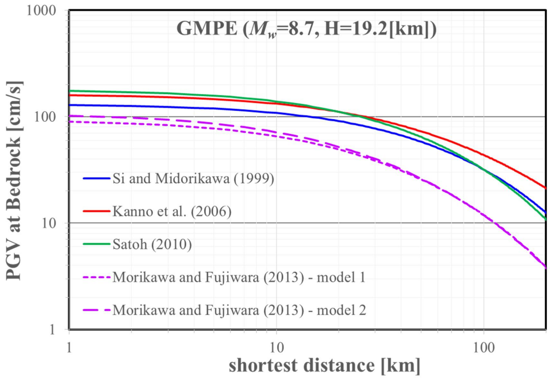


Fig. 7 Comparison of PGVs by 5 GMPEs

(3) Shallow subsurface structure

From an engineering bedrock to a ground surface, the seismic ground motion is amplified. The relation between ground motion parameter on the engineering bedrock and that on the ground surface is defined by the site amplification model. In this study, the site amplification model was proposed for shallow subsurface structure stage as a simplified format as follows:

$$(PGV)_{GS} = AF \cdot (PGV)_{EB} \qquad (2)$$

where, PGV_{GS} and AF are PGV on the ground surface and the amplification factor of site.

In this study, the meaning of the prediction of site amplification is the estimation of the site amplification factor, and it is estimated by two steps. First step is the estimation of AVS30 from the soil profile based on the study by Matsuoka et al. (2005) as shown in Eq. (3). AVS30 is defined as the function of soil profile of site, such as elevation (Ev), slope (Sp), and distance from mountain or hill (Dm). Information on soil profile in J-SHIS is applied. ε_{SA1} is modelling uncertainty in the first step. Second step is the estimation of amplification factor from estimated AVS30 based on the study by Fujimoto and Midorikawa (2006) as shown in Eq. (4). ε_{SA2} is modelling uncertainty in the second step. The methods of applying modelling uncertainties are as same as that in GMPEs, and the sigma values in Matsuoka et al. (2005) and that Fujimoto and Midorikawa (2006) are applied. Epsilons are also assumed as normal distribution, so the predicted PGV on the ground surface will still follow the lognormal distribution.

$$\log AVS30 = f(Ev, Sp, Dm, \cdots) + \varepsilon_{SA1} \tag{3}$$

$$\log AF = 2.367 - 0.852 \cdot \log AVS30 + \varepsilon_{SA2} \tag{4}$$

(4) Structural damage estimation

Fragility curve model for 2-storey wooden houses defined by Murao and Yamazaki (2002) was selected for structure damage estimation stage. In these fragility curves, exceedance probabilities are defined as with respect to PGV as follows:

$$P(PGV_{GS}) = \Phi\left(\frac{\ln PGV_{GS} - \ln\mu_D}{\zeta_D}\right) \tag{5}$$

where, μ_D is the modelling uncertainty term assumed in this study. $\ln\mu_D$ is assumed lognormally distributed with distribution parameters of λ and ζ_λ. ζ_λ is the coefficient of variation (c.o.v.) of $\ln\mu_D$ and it is assume as 20% in this study. λ and ζ_D are parameters of the fragility curve and the meaning of them are the mean and standard deviation of ln PGV_{GS}, respectively.

Damage degree for wooden houses is classified as heavy damage, moderated damage, and partial damage. Same fragility curve model is applied to different damage degree, but the parameters, λ and ζ_D, are applied separately. Parameters of fragility curves for 3 damage degrees are presented in Table 1, and fragility curves corresponding to 3 damage degrees are shown in Fig. 8.

Table 1 Parameters of the fragility curve for wooden house (Murao and Yamazaki, 2002)

Structure	Damage	λ	ζ_D
Wooden house	partial	4.13	0.566
	moderate	4.67	0.478
	heavy	4.90	0.447

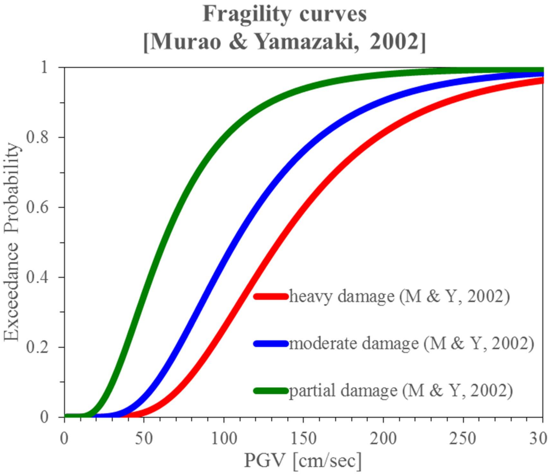


Fig. 8 Fragility curves for wooden houses (Murao and Yamazaki, 2002)

(5) Risk evaluation

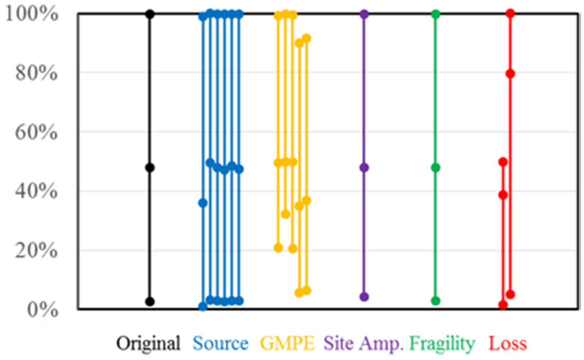
In this study, risk is defined as the expected value of loss. Simplified loss model is are proposed for risk evaluation stage. Quantified values for direct (economic) losses in the study by Murao and Yamazaki (2002), shown in Table 2, are applied to loss model. The lower bound values of losses for each damage degree are applied for loss model-1 and the upper bound values of them are applied for loss model-2. In case of the partial damage in loss model-1, 0% of loss is replaced to 5% of that.

Table 2 Quantified values for direct (economic) losses (Murao and Yamazaki, 2002)

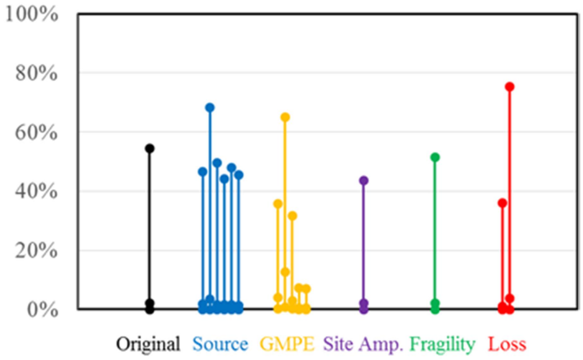
Structure	Damage	losses
Wooden house	partial	0% ~ 20% of loss
	moderate	20% ~ 50% of loss
	heavy	50% ~ 100% of loss

2.3 Result of the sensitivity analysis

Sensitivity analyses are performed for two target sites and results are shown in Fig. 9. 5%, 50% and 95% quantile value is shown by the dot for each loss estimate line. Very large uncertainties in the calculated risks are observed in all cases, especially in case of Kochi prefectural building. For the comparison of uncertainty, the rate of reduction in uncertainty with respect to original uncertainty is defined as a criteria. The reduction rates are presented in Table 3. Based on the reduction rate of each case, uncertainty of GMPEs are most influential to overall uncertainty. Those of site amplification and loss model were less sensitive, and those of source process and fragility curve were relatively insensitive.



(a) Kochi prefectural building site



(b) Osaka prefectural building site

Fig. 9 Results of sensitivity analysis

Table 3 Reduction rate in uncertainty

	Kochi pref. bldg.	Osaka pref. bldg.
Source process	0%	2%
GMPEs	19%	46%
Site amplification	2%	20%
Fragility curve	1%	5%
Loss	26%	-2%

2.4 Issues of preliminary analysis and challenges for the next step

From the preliminary study, research agendas were suggested considering the order of the uncertainty reduction rate in the result of sensitivity analysis. First, the validity of suggested GMPEs needed to be verified because great differences were observed not only in the expected losses but in the predicted PGVs as shown in Fig. 7. Second, loss model needed to be defined more sophisticatedly because it was too much simple and had more assumptions compared with other models.

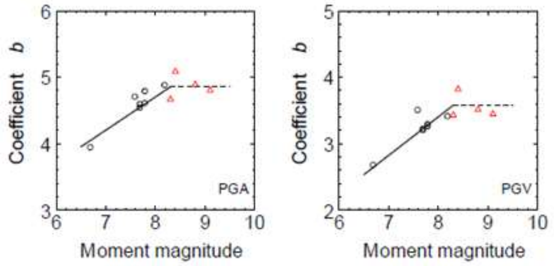
3. Seismic risk evaluation study

The secondary study has been performed in the research in FY2016 to solve some aforementioned research agendas. The issue of applying the path effects considering the saturation has been discussed to relieve the great differences in the suggested GMPEs based on the study by Si et al. (2016). Loss model has revised based on the study by Tabata and Okada (2006), in which the risk is defined in terms of fatality as well as the direct (economic) losses of buildings. In addition, target sites are extended from two points in Kochi and Osaka prefectures to entire two prefectures.

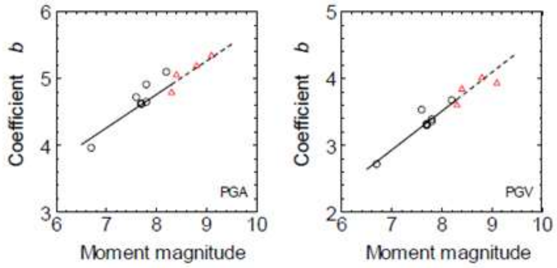
3.1 Revision in GMPEs

According to the recent paper by Si et al (2016), the path effects considering the saturation needs to be considered for megathrust earthquakes of the subduction zone. Based on their study, in case the shortest distance from source to site is applied for GMPEs, saturation of the magnitude needs to be considered for the earthquake source whose moment magnitude is over 8.3, as shown in Fig. 10. This result is adapted in this study. It is applied to GMPE-1, GMPE-2 and GMPE-3, because the saturation have been already considered in GMPE-4 and GMPE-5 (Morikawa and Fujiwara, 2013). Except two earthquake sources whose the moment magnitudes are 8.3 and 8.2, the moment magnitudes in this study are larger than 8.3, and at least one of them is used in every source model. The comparison of the predicted PGVs of revised 5 GMPEs are illustrated in Fig. 11. Compared with Fig. 7, the variability in the predicted PGVs is decreased.

The results of sensitivity analyses including the effect of saturation of magnitude for GMPEs are shown in Fig. 12. Expected values of risks are slightly decreased because magnitudes over 8.3 are neglected. Affected by decrease in expected values, their uncertainties are also decreased. Based on the reduction rate of each case, the conclusion does not change. Uncertainty in GMPEs are still most influential to the overall uncertainty, and those in site amplification and loss model are less sensitive, and those of source process and fragility curve are relatively insensitive.



(a) fault shortest distance



(b) equivalent earthquake distance

Fig. 10 Relation between coefficient *b* in the GMPE and magnitude (Si et al., 2016)

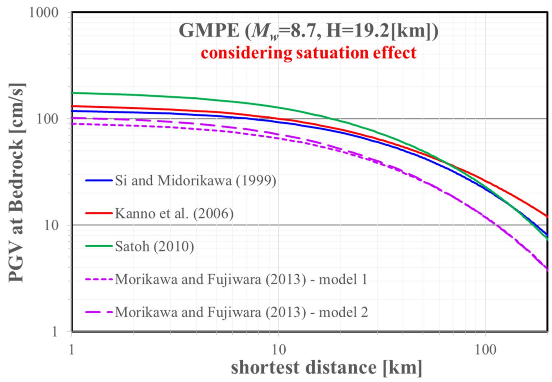
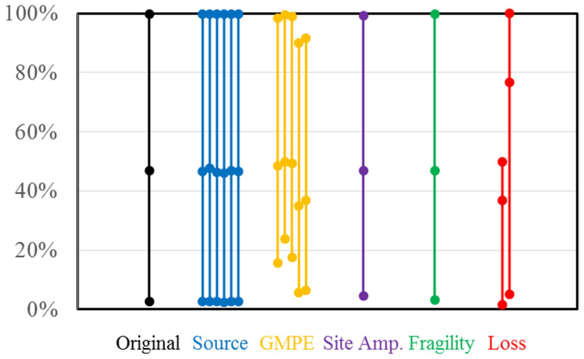
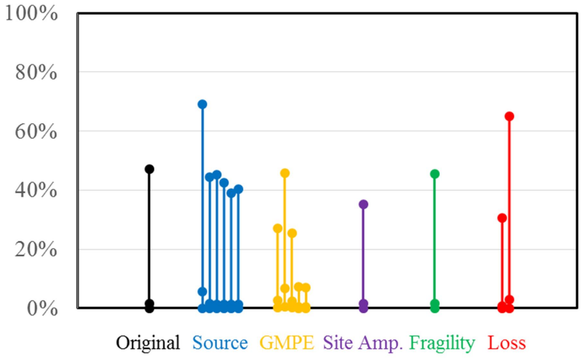


Fig. 11 Comparison of PGVs by 5 GMPEs the path effects considering the saturation



(a) Kochi prefectural building site



(b) Osaka prefectural building site

Fig. 12 Sensitivity analysis results considering the revision in GMPEs

Several issues that were brought up in the preliminary study were improved in the research of FY2016. As shown in Fig. 9(a), the expected loss at Kochi prefectural building site by source model 1 is smaller than others despite its moment magnitude is much larger than the others. But this was improved as shown in Fig. 12(a), mainly because not only GMPE-4 and GMPE-5 but also GMPE-1, GMPE-2 and GMPE-3, which predict larger PGVs, were also applied to source model 1. The reason why the expected loss by source model 1 is still not larger than others in Fig. 12(a), is because of the effect of magnitude saturation and the shortest distance from each source to Kochi prefectural building site is not much different from source to source. However, the expected loss at Osaka prefectural building site by source model 1 is larger than those of the others despite the effects of magnitude saturation. That is mainly because the earthquake source can affect the ground motion at the site not by their magnitude but by the shortest distance.

3.2 Revision in loss model

In the loss model of the preliminary study, the risk was defined as the expected value of the rate of direct losses. The main improvement of the loss model in FY2016 is that the risk is defined as the expected values of the rates of losses in terms of the fatalities as well as the direct losses in buildings. The seismic death risk function for casualties per house defined by Tabata and Okada (2006) is applied to link the damages in buildings to the fatalities, in which the death rate is defined as the function of the damage index of the building and the rate of surrounding buildings as follows:

$$Dr(x,y) = ae^{bx} + cxy^2 \qquad (6)$$

where, $Dr(x,y)$ is the rate of casualties [%] per wooden house. x is the damage index (D. Index) of the building, and y is the surrounding collapse rate. Parameters of a, b, and c are obtained empirically by regression as 0.0104, 6.68, and 11.0 for single wooden house, respectively.

Because the data for the surrounding collapse rate is not always easily accessible, it is assumed as the function of damage index and applied in this study, which is estimated using the data of Kobe city used in Tabata and Okada (2006) as shown in Fig. 13. The estimated function is as $y = x^2/2$, and the death rate per wooden house is defined by the function of damage index as Eq. (7) marked by red line in Fig. 13.

$$Dr(x) = ae^{bx} + cx(x^2/2)^2 \qquad (7)$$

Damage indices need to be quantified to be applied to the death rate function for casualties per wooden house. Quantified damage indices applied in the study by Tabata & Okada (2006) are marked by dot lines in Fig. 14. These values are based on the fragility curves defined in Okada & Takai (2004) as marked by dot and dash lines in Fig. 15. Because not the fragility curves by Okada and Takai (2004) but those by Murao and Yamazaki (2002), marked by solid lines in Fig. 15, are applied in this study, however, the damage indices for the death rate function need to be revised. As shown in

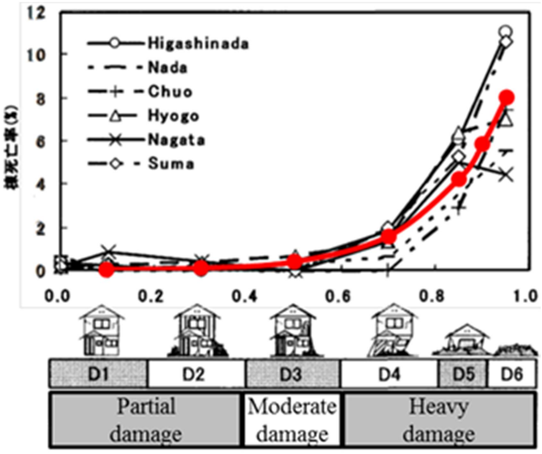


Fig. 13 Data of Kobe city and the approximated seismic death risk function for casualties per wooden house (Tabata and Okada, 2006)

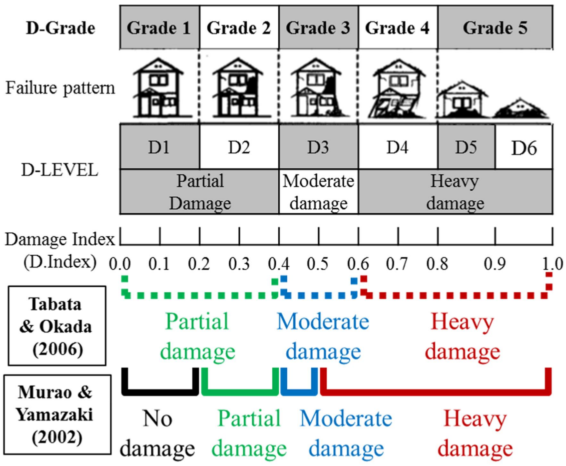


Fig. 14 Data of Kobe city for death rate per house (Tabata and Okada, 2006)

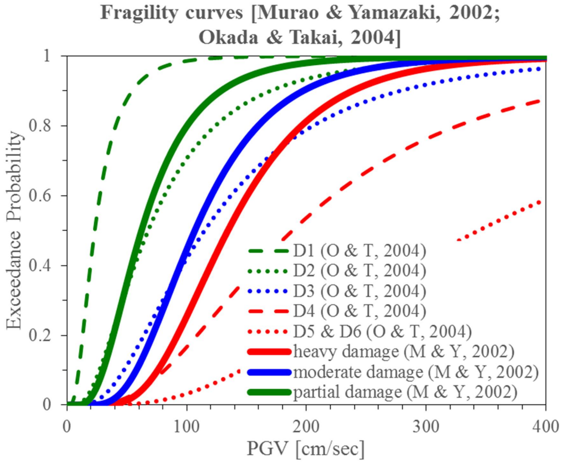


Fig. 15 Comparison of fragility curves (Murao and Yamazaki, 2002; Okada and Takai, 2004)

Fig. 15, the comparison between fragility curves corresponds to 3 damage degrees in Murao and Yamazaki (2002) and those corresponds to 5 damage indices in Okada & Takai (2004) is performed, which are indicated as 'M & Y, 2002' and 'O & T, 2004' in the figure, respectively. The damage indices for death rate function are revised based on the comparison. and marked by solid lines in Fig. 14.

The quantified values for the rate of direct losses in building are improved based on the strict meaning of the rate of losses in study by Murao and Yamazaki (2002). As shown in Fig. 16, degree of loss rate depends on the judgement of investigator. In the preliminary study, the values for the rate of direct losses based on the survey by local government were directly applied for loss model. However, because the fragility curves applied in this study is not based on the survey by local government but based on that by the special committee for earthquake, quantified values need to be changed. The quantified values are revised as shown in Fig. 16 based on the comparisons of proportions for damage degrees and fragility curves as illustrated in Fig. 16 and Fig. 17, respectively.

One more improvement in loss model is performed by the application method. One more loss model with median value is added. And the way of considering uncertainty in loss model is revised from the random selection of model in the proposed models to the random selection of values in each section using distribution of it, which is assumed as uniformly distributed.

The final loss model revised in FY2016 is briefly illustrated in Fig. 18. First, the classification of damage is revised from 3 classes to 4 classes. Second, the quantified damage indexes are defined. Finally, the loss model is defined in terms of rates of fatalities and direct losses in building with respect to damage indexes.

The results of sensitivity analyses including revision in loss model are presented in Fig. 19. Expected values of risks are decreased because of the revisions in quantified values for the rate of losses in building. Several differences in results of uncertainties are exist. Uncertainties are decreased at Kochi prefectural building site but increased at Osaka prefectural building site. While the effect of decrease in variability is larger than that of increase in expected risks at Kochi, the effect of increase in expected risks is larger than that of decrease in variability at Osaka. Based on the reduction rate of each case, the conclusion does not change.

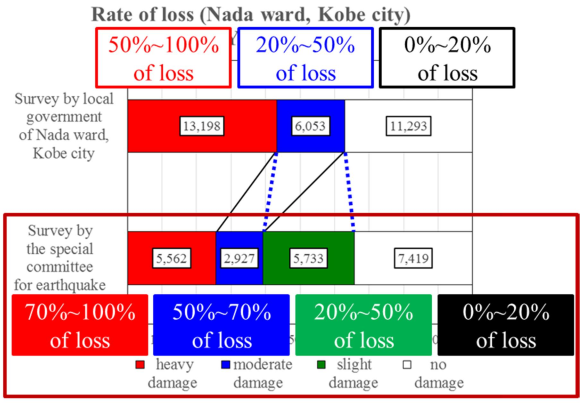


Fig. 16 Differences in quantified values of rates of losses in building affected by the judgements of investigators (Murao and Yamazaki, 2002)

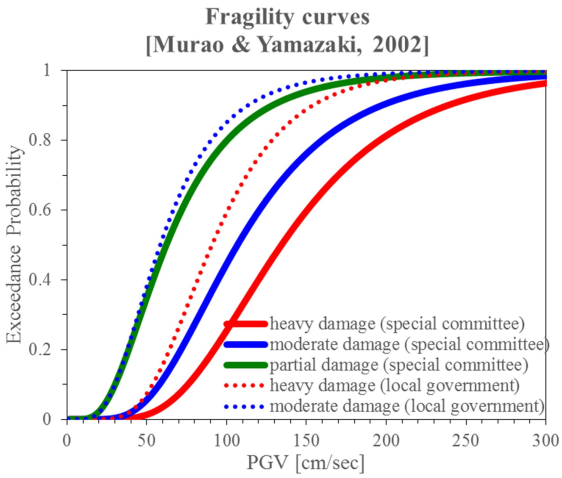


Fig. 17 Comparison of fragility curves affected by the judgements of investigators (Murao and Yamazaki, 2002)

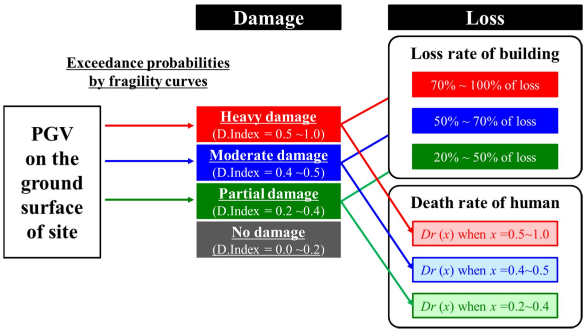
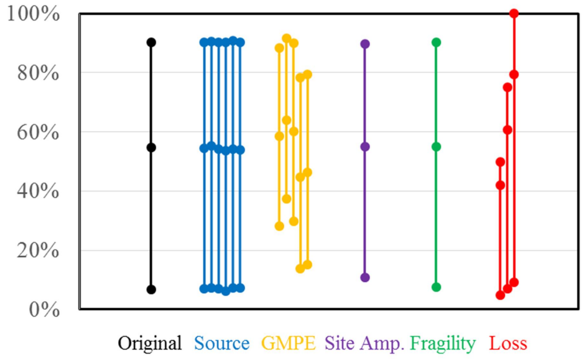
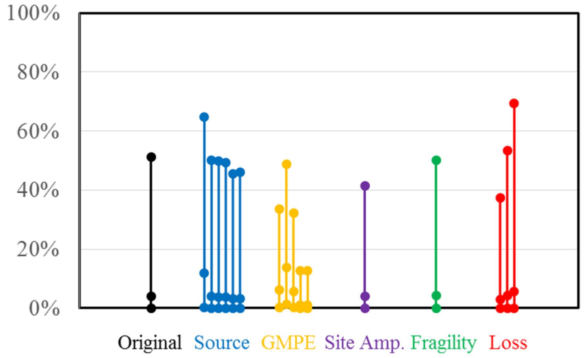


Fig. 18 Illustration of the loss model in FY2016

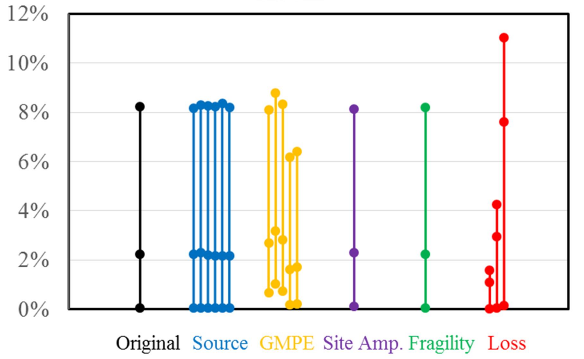


(a) Kochi prefectural building site

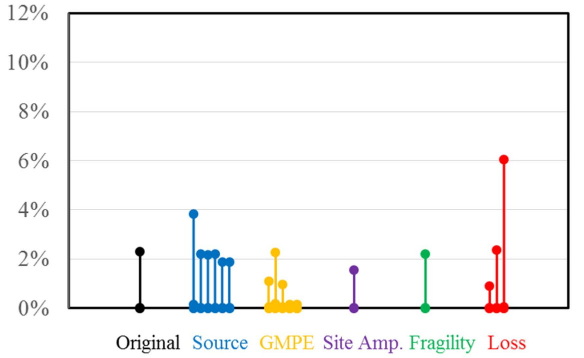


(b) Osaka prefectural building site

Fig. 19 Sensitivity analysis results of direct losses in building considering the revision in loss model



(a) Result of Kochi prefectural building



(b) Result of Osaka prefectural building

Fig. 20 Sensitivity analysis results of fatalities considering the revision in loss model

Uncertainty in GMPEs are still most influential to the overall uncertainty, and those in site amplification and loss model are less sensitive, and those of source process and fragility curve are relatively insensitive.

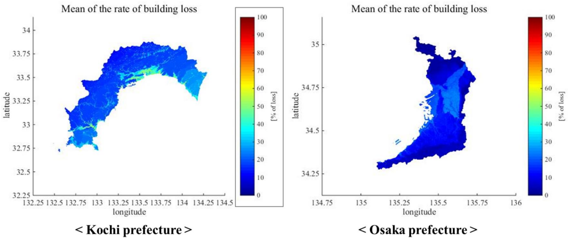
The results of sensitivity analyses considering fatalities are shown in Fig. 20. For human loss rate, the effect by loss model is relatively larger than that in building loss. This is because the death rate function has higher order term. Based on the reduction rate of each case in the rate of human loss, the conclusion does not change.

3.3 Extension of target sites

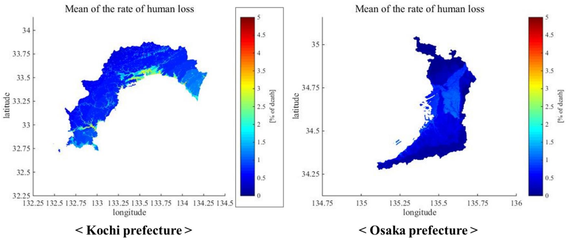
The evaluation of the seismic risk and its uncertainty has been extended to entire Kochi and Osaka prefectures using revised methodology. The number of meshes of Kochi and Osaka prefectures are 103,465 and 27,640, and the size of a mesh is 100m×100m.

The expected values of rates of building losses for a wooden house and those of human losses are illustrated in Fig. 21(a) and Fig. 21(b), respectively. The expected values very high, around 50% of losses in building and around 3% of fatalities are predicted, in certain places in Kochi prefecture, which is around Kochi city. Compared with Kochi prefecture, those of Osaka prefecture are relatively small.

The uncertainties of rates of building losses for a wooden house and those of human losses are illustrated in Fig. 22(a) and Fig. 22(b), respectively. Overall uncertainties are large in Kochi prefecture and those of Osaka prefecture are relatively small. The spatial distribution of the uncertainty reduction rates in the building losses in Kochi and Osaka prefectures are illustrated in Fig. 23. Based on the results of sensitivity analysis, the conclusion is slightly changed. The effect of loss model is less important than previous results of sensitivity analysis. The spatial distribution of the uncertainty reduction rates of the human losses in Kochi and Osaka prefectures are illustrated in Fig. 24. Based on the results of sensitivity analysis, the conclusion is as same as that for the building losses. After the extension of sites, the conclusion is almost similar but slightly changed. Uncertainty in GMPEs is still most influential to the overall uncertainty, and that in site amplification is less sensitive, and those of source process, fragility curve and loss model are relatively insensitive.

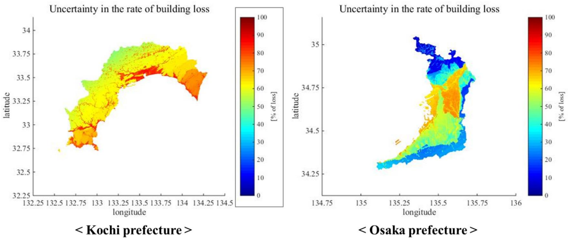


(a) Rate of building loss (for a wooden house)

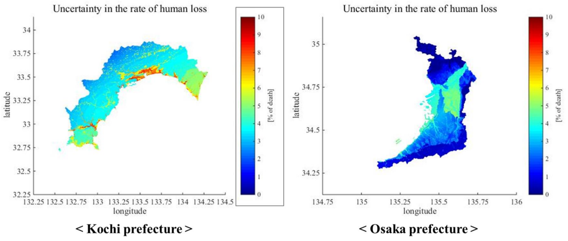


(b) Rate of human loss (per wooden house)

Fig. 21 Expected values of the seismic risks (MCS = 10,000 times)

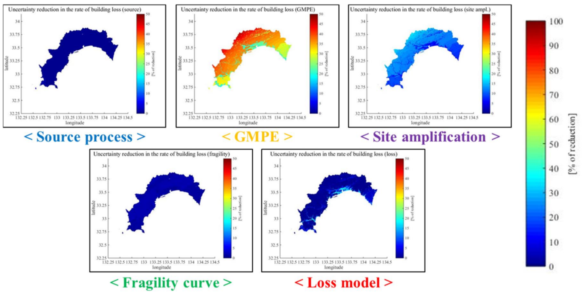


(a) Rate of building loss (for a wooden house)

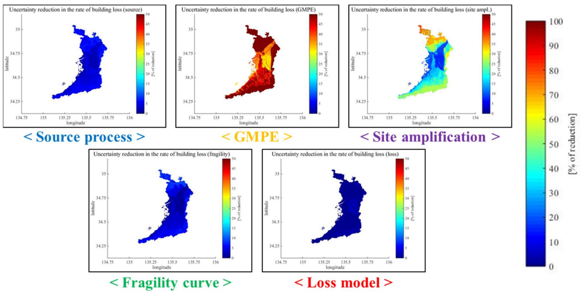


(b) Rate of human loss (per wooden house)

Fig. 22 Uncertainty of the seismic risks (MCS = 10,000 times)

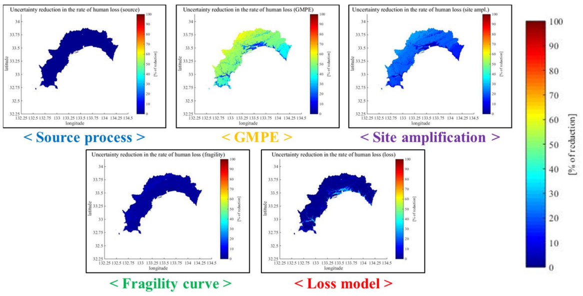


(a) Kochi prefecture

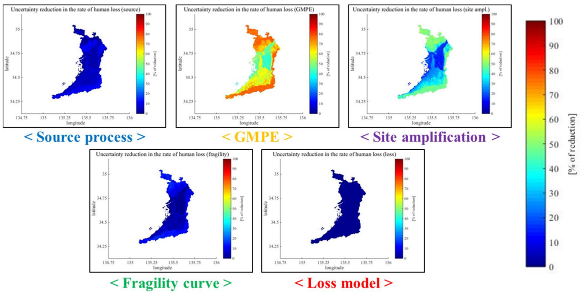


(b) Osaka prefecture

Fig. 23 Results of sensitivity analysis - Uncertainty reduction rate of building losses



(a) Kochi prefecture



(b) Osaka prefecture

Fig. 24 Results of sensitivity analysis - Uncertainty reduction rate of human losses

4. Summary

The methodology for the seismic risk evaluation is improvements in 3 parts. First, the models for GMPEs were improved considering the path effect (saturation effect). Second, the loss model was improved. The loss model in terms of human losses is added to that in terms of direct losses of buildings. The classification of damage degree, and quantified value for corresponding damage degree was revised, and the application method of loss model were also revised. Third, target sites are extended to entire Kochi and Osaka prefectures. The conclusion does not change drastically after improvements in 3 parts. The reduction of uncertainty in ground motion prediction has to be focused on the reduction of the overall uncertainty of seismic risk.

Acknowledgements

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