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Core-to-Core Collaborative Research between Earthquake Research Institute, University of Tokyo and Disaster Prevention Research Institute, Kyoto University during FY2014 to FY2018

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The research program titled "Earthquake and Volcano Hazards Observation and Research Program" was started in fiscal year (FY) 2014 as a new five-year project authorized and funded by the Council for Science and Technology of the Ministry of Education, Culture, Sports, Science and Technology. It included a new format of collaborative research called, "Core-to-Core Collaborative Research between Earthquake Research Institute, University of Tokyo and Disaster Prevention Research Institute, Kyoto University". In this format, two types of research, "Participation Type Research" and "Subject Proposal Type Research" were conducted from FY2015. A preliminary study was performed in FY2015 for "Integrated Research" of "Participation Type Research," which developed a framework for seismic risk evaluation at prefectural offices of Osaka and Kochi for an earthquake occurring along the Nankai Trough, considering the epistemic uncertainty. The secondary study was performed from FY2016 through to FY2018, wherein the methodology for the seismic risk evaluation was improved on three aspects: i.e., revision in ground motion prediction models considering the saturation effect, revision in loss models in terms of the fatalities as well as the direct losses of buildings, and extension of target sites to the whole of Osaka and Kochi prefectures. The results suggest that the epistemic uncertainty in the ground motion prediction models is most sensitive to the overall uncertainty of seismic risk. Along with "Integrated Research", a total of 14 "Research on Specific Topics" related to time-dependent risk analysis, economical risk evaluation, source characterization, structural damage estimation models, ground motion estimation models, soil amplification models and disaster prevention planning considering the uncertainty of risk assessment, were studied during this period in order to improve the risk assessment studies for "Integrated Research". With respect to "Subject Proposal Type Research," a total of 27 individual research themes focused on research to understand hazards/risks by earthquakes and volcanic eruptions and to mitigate disasters by them.

Keywords: core-to-core collaborative research, disaster mitigation, earthquakes, volcanoes, hazard estimation, risk evaluation, Nankai Trough earthquake

1. Introduction

The research program "Observation and Research Program for Prediction of Earthquakes and Volcanic Eruptions", authorized and funded by the Council for Science and Technology of the Ministry of Education, Culture, Sports, Science and Technology (MEXT), was planned for FY2009 through to FY2013. It faced criticism after the 2011 off the Pacific coast of Tohoku Earthquake, as the outputs from the program were not effective in mitigating the disaster caused by the earthquake. At the end of this five-year program in FY2013, a new five-year research program was proposed that placed emphasis on the mitigation of disasters by earthquakes and volcanic eruptions in addition to conducting observation and research for understanding earthquakes and volcanic eruptions. In FY2014, a new five-year research program called "Earthquake and Volcano Hazards Observation and Research Program" was initiated, which included a new format of collaborative research called, "Core-to-Core Collaborative Research between Earthquake Research Institute, University of Tokyo (ERI) and Disaster Prevention Research Institute, Kyoto University (DPRI)" (Core-to-Core Research). It was clarified that the aim of the research program is not only for observation and research for earthquake and volcanic eruption prediction, but for conducting researches that are aimed at contributing to estimating and mitigating disasters caused by earthquakes and volcanic eruptions. ERI is the "Joint Usage/Research Center for Earthquake and Volcano Sciences" and DPRI is the "Joint Usage/Collaborative Research Center for Multi-disciplinary Disaster Prevention Study." The collaborative research between these two institutes (research centers) is expected to accelerate researches mitigating disaster caused by earthquakes and volcanic eruptions.

In this new format of collaborative research, two types of researches were conducted, namely "Participation Type Research" and "Subject Proposal Type Research". Groups of or individual researchers proposed ideas related to understanding the occurrence of disaster by earthquakes or volcanic eruptions and their consequence, as well as how to mitigate the damage for both research types. For "Participation Type Research", groups consisting of researchers from many institutions in Japan including ERI and DPRI, proposed research related to probabilistic seismic risk assessment associated with the occurrence of an earthquake along the Nankai Trough. "Subject Proposal Type Research" aimed to promote disaster mitigation research in a wider range of research areas. The proposals for both research types were evaluated by the "Coordinating Committee for Core-to-Core Research".

This article will outline the Core-to-Core Research from FY2014 and FY2018.

2. Structure of the Research Types

2.1. Participation Type Research

In "Participation Type Research", research related to probabilistic seismic risk assessment at Osaka and Kochi prefectures associated with the occurrence of an earthquake along the Nankai Trough was conducted.

This research had two objectives: conduct integrated research aimed at "Construction of a New Paradigm for Improving Uncertainty of Risk Evaluation for Large Magnitude Earthquakes" that combines research areas from source process to stakeholder involvement; and study specific research topics that were considered necessary to improve and update "Integrated Research."

2.1.1. Integrated Research

"Integrated 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 integrate the inputs from the aforementioned subgroups.

The collaborative research was initiated and required researches were appointed in the first year of the research project. As a preliminary study, the methodology of the entire research was constructed by the platform development group and models in related research fields were selected by corresponding research subgroups. Then, the process of seismic risk evaluation was revised and extended on the basis of a methodology determined in the preliminary study. The ground motion prediction equations (GMPEs) and risk models were revised and target sites were expanded to the whole prefecture.

2.1.2. Specific Research

Specific research topics were selected on the basis of discussions carried out in "Integrated Research." Table 1 shows the specific research conducted from FY2015 to FY2018.

Table. 1 Topics of the specific research for each fiscal year.

Fiscal year	Research topics: *Title*	*PI* [a]
2015	Study on disaster risk assessment considering the time line	Shinichi Matsushima (DPRI, KU)
	Integrated simulation for economical assessment of seismic damage	Muneo Hori (ERI, UT)
2016	Study on disaster risk assessment considering the time line	Shinichi Matsushima (DPRI, KU)
	Integrated simulation for economical assessment of seismic damage	Muneo Hori (ERI, UT)
	Construction of source models for evaluation of disaster risk for large earthquakes	Takashi Furumura (ERI, UT)
	Improvement of structural damage estimation methods	Hiroshi Kawase (DPRI, KU)
2017	Construction of source models for evaluation of disaster risk for large earthquakes	Takashi Furumura (ERI, UT)
	Improvement of structural damage estimation methods	Hiroshi Kawase (DPRI, KU)
	Increasing precision of estimation methods of soil amplification during large earthquakes	Kyohei Ueda (DPRI, KU)
	Improvement of strong motion estimation following large earthquakes focused on the source model	Masatoshi Miyazawa (DPRI, KU)
2018	Increasing precision of estimation methods of soil amplification during large earthquakes	Kyohei Ueda (DPRI, KU)
	Improvement of strong motion estimation following large earthquakes focused on the source model	Masatoshi Miyazawa (DPRI, KU)
	Study on disaster prevention planning based on damage risk assessment with uncertainty	Norio Maki (DPRI, KU)
	Data analysis and construction of modelling method for estimating exposure in the future	Kazuyoshi Nishijima (DPRI, KU)

a. Principal investigator

2.2. Subject Proposal Type Research

Earthquake and/or volcanic disasters are caused by the vulnerability of the human and social environment when hazards such as strong motions, tsunamis, volcanic ashes and/or lava flow from earthquakes and volcanic eruptions act on them. Disaster science concerning earthquakes and volcanic eruptions is geared toward to understanding the occurrence of events and the occurrence and transition of disasters caused by those events and in utilizing such knowledge to prevent/mitigate disaster. For this purpose, researchers in areas of physics, engineering, and cultural and social science are required to cooperate and conduct interdisciplinary and comprehensive research and pursue them to understand the cause of disasters.

"Subject Proposal Type Research" involved the following five categories: 1. study of cases of earthquake/volcanic disaster, 2. improvement of prior evaluation methods for earthquake/volcanic hazards, 3. improvement of real-time estimation methods for earthquake/volcanic hazards, 4. investigation of the mechanism of earthquake/volcanic disaster occurrence, and 5. improvement of information dissemination to mitigate earthquake/volcanic disasters.

Table 2 shows the number of research projects that were conducted for "Subject Proposal Type Research" from FY2014 to FY2018.

Table. 2 Number research projects of the Subject Proposal Type Research for each fiscal year.

Fiscal year	Research categories					
	1	*2*	*3*	*4*	*5*	*Total*
2014	3	3	3	1	2	12
2015	2	4	4	1	1	12
2016	2	1	3	1	5	12
2017	2	1	3	2	3	11
2018	2	2	1	1	1	7
Total	11	11	14	6	12	54

2.3. Reports of Research

A brief report of each research project conducted during the five years can be found at the web site maintained by the Coordinating Committee of Earthquake and Volcanic Eruption Prediction Researches [1].

3. Understanding Uncertainty of Seismic Risk Evaluation for Earthquakes along the Nankai Trough

In "Integrated Research" of "Participation Type Research," research by the eight subgroups mentioned in Section 2.1 was conducted to understand the uncertainty of seismic risk evaluation for earthquakes occurring along the Nankai Trough.

In this chapter, the output of "Integrated Research" of "Participation Type Research" is explained in detail, since this is the main feature of the Core-to-Core Research.

In the first year of the 5-year research project, a working group was formed to discuss the research objective, which was determined to be mitigation of disasters caused by large magnitude earthquakes along the Nankai Trough. A symposium was held at ERI, wherein researchers from related research areas gathered to discuss about the specific research plan for the Core-to-Core Research. In the symposium, it was agreed that seismic risk and its uncertainty would be evaluated using state-of-the-art methods.

In the initial phase of the research, a preliminary study for developing a methodology for evaluating seismic risk was conducted by the platform development subgroup. Models to be used for the related research fields were then selected by the corresponding subgroups. The target location was the prefectural offices of Kochi and Osaka prefectures. For the secondary study beginning in FY2016, the procedure of seismic risk evaluation was revised and extended on basis of the methodology developed in the preliminary study. The target location was expanded to the whole of Kochi and Osaka prefectures.

3.1. Preliminary Study

3.1.1. Scope of the study

The scope of the preliminary study was limited to evaluating the expected loss due to the damage of an arbitrary structure for the next Nankai Trough earthquake at arbitrary locations. The location of the assumed source region of an earthquake occurring along the Nankai Trough and the two target sites are shown in Fig. 1. The conditions of the research were set to evaluate seismic risk for direct economic loss due to damage of 2-storey wooden houses located at the prefectural offices of Osaka and Kochi prefectures.

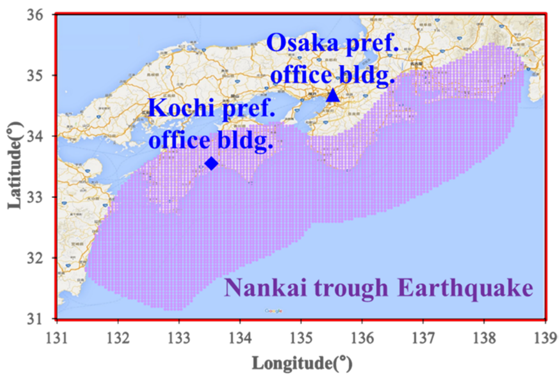
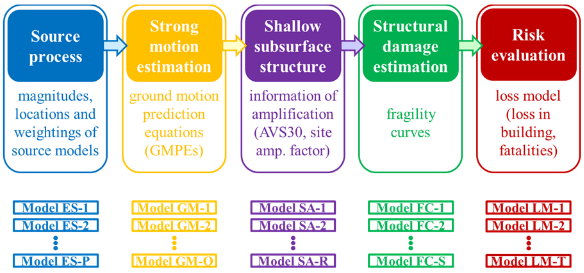


Fig. 1. Locations of the source area of the Nankai Trough earthquake and target sites.

3.1.2. Procedure of the study

In this study, probabilistic seismic risk evaluation is composed of five modules, i.e. source process modelling, strong motion estimation, shallow subsurface structure amplification, structural damage estimation and risk evaluation, which are sequentially connected as illustrated in Fig. 2. The output from the upstream module is used as the input for the following module. The magnitude and location of several earthquake source areas are defined and combined to construct source models. The source area is decided according to the magnitude. In order to consider the possibility of occurrence of the next event, the source models are weighted according to the judgement of the source model subgroup. Peak ground velocity (PGV) of ground motions at the target sites was predicted in the strong motion estimation module. Effects of site amplifications were estimated in the shallow subsurface structure module, while the vulnerability of the target structure was estimated using fragility curves in the structural damage estimation module. In the risk evaluation module, seismic risk was evaluated in terms of the expected value of loss.



Source: 5th IASPEI / IAEE international Symposium: Effects of Surface Geology on Seismic Motion [2]

Fig. 2. Sequential process of modules for the evaluation of seismic risk and its uncertainty.

In this study, the misfits of the models to the data and/or the presence of competing models are considered as epistemic uncertainty; the overall uncertainty of the calculated seismic risk is influenced by each epistemic uncertainty. Each epistemic uncertainty is estimated by each research subgroup and the overall uncertainty is evaluated considering those epistemic uncertainties. A great number of combinations of models and modelling uncertainties are assumed to calculate risk on the basis of Monte-Carlo Simulation (MCS); the probabilistic distribution of risk is obtained from the results of the MCS. The overall uncertainty in the calculated risk is defined on the basis of the probabilistic distribution. The degree of uncertainty is defined as the length of the interval between the 5% quantile value and the 95% quantile value of the expected losses obtained from the MCS results, as shown as a schematic figure in Fig. 3.

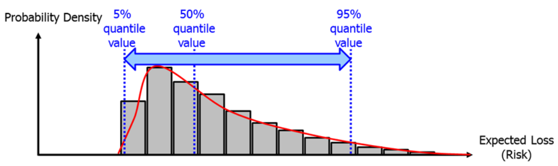


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Fig. 3. The definition of the degree of uncertainty.

The ultimate goal of this research is to investigate possibilities to reduce the overall uncertainty of seismic risk. A sensitivity analysis with quantified values of risks and their uncertainties was performed to investigate which part's uncertainty has the largest effect on the overall uncertainty. First, the reference value of overall uncertainty is evaluated in case uncertainties of all parts exist. This uncertainty is called "original uncertainty" in this paper. Second, overall uncertainty is calculated when we do not consider uncertainty of the source model and uncertainties of all the other parts exist. The same process is performed with respect to GMPEs, site amplification, fragility curve and loss model parts. Third, the most important part is defined by comparing the variation in the overall uncertainty for each case. If the overall uncertainty is significantly affected by the uncertainty of a certain part, the uncertainty of that part should be considered as an important factor 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.

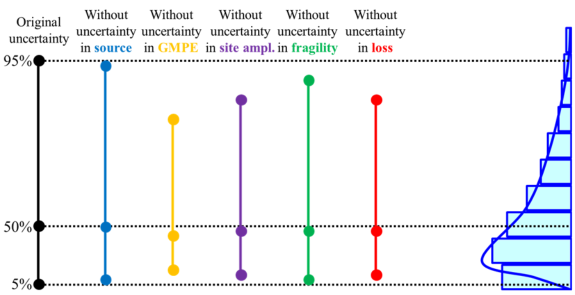


Fig. 4. Image of sensitivity analysis.

3.1.3. Models applied in the source process study

Source process

Six source areas were selected for the Nankai Trough earthquake based on the Japan Seismic Hazard Information System (J-SHIS) [3]. The moment magnitude (M_w) values of six source areas are assumed as 9.1, 8.7, 8.3, 8.5, 8.2, and 8.4. The shortest distance from six sources to the Kochi prefectural office site are 25.7, 25.6, 227, 25.6, 227, and 25.6 km, respectively. Those to the Osaka prefectural office site are 70.9, 107, 107, 114, 107, and 114 km, respectively. Six source models were proposed by combining six source areas as shown in Fig. 5. While the former two source models consist of a single source area, the other four source models consist of two source areas. When there are two source areas in a source model, it is considered that the two source areas will rupture at a certain time interval, but not concurrently. Weights of source models were assumed as 10, 30, 15, 15, 15, and 15%, for source models (SM) 1 to 6, respectively. The probability of occurrence of the earthquake is not considered, so the conditional risk is considered under the conditions of the occurrence of an earthquake.

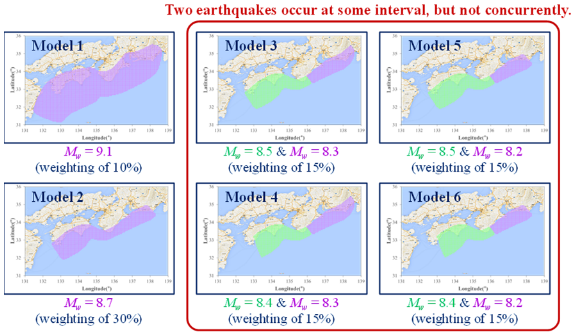


Fig. 5. Six source models for the Nankai Trough earthquake proposed in this study.

Strong motion estimation

GMPEs are empirical attenuation relation derived from regression analysis. In this study, GMPEs that have been developed based on Japanese data and are capable of estimating PGVs are used for the seismic risk evaluation. They are defined as follows;

$$\log PGV_{\mathrm{EB}} = f(M_{\mathrm{w}}, X, \Lambda) + \varepsilon_{\mathrm{GMPE}} \quad (1)$$

where, PGV_{EB} is PGV at the engineering bedrock of the target site. M_{w} is the moment magnitude of the source area, and X is the shortest distance to the source from the site. Each GMPE model has an error term considering modelling uncertainty, $\varepsilon_{\mathrm{GMPE}}$. The value of $\varepsilon_{\mathrm{GMPE}}$ is randomly selected using normal distribution with standard deviation (σ) values of corresponding GMPEs. Since $\varepsilon_{\mathrm{GMPE}}$ is assumed as being normally distributed, the predicted PGVs will be lognormally distributed.

Five GMPE models were selected for strong motion estimation module; Si and Midorikawa [4] (GMPE1), Kanno and others [5] (GMPE2), Satoh [6] (GMPE3), and Morikawa and Fujiwara [7] (GMPE4 and GMPE5). In this study, only GMPE4 and GMPE5 are applicable for SM1 whose moment magnitude is over 9, while all five GMPEs can be applied in the other five source models whose M_{w} is under 9. The reason is that the saturation effect for an earthquake with of a large magnitude is considered only in GMPE4 and GMPE5, but not in the other three GMPEs.

In this study, PGV at the engineering bedrock where the average shear-wave velocity (V_s) for top 30 m depth (AVS30) is 600 m/s, is first estimated. PGVs predicted by GMPE2 to GMPE5 are targeted for engineering bedrock with AVS30 of 311, 500, 350 and 350 m/s, respectively. The predicted PGVs for these five GMPEs include the effect of site amplification: thus the predicted PGVs needs to be adjusted to PGVs at engineering bedrock with AVS30 of 600m/s. The conversion procedure of PGVs predicted by five GMPEs is illustrated in Fig. 6. In case of GMPE2, PGV is converted by its own converting relation [5], but the converting relation by Fujimoto and Midorikawa [8], shown in Eq. (4), is applied for PGVs by other GMPEs. The comparison of the predicted and converted PGVs of five GMPEs are shown in Fig. 7, in case of the source model 2 whose M_{w} is 8.7 and focal depth is 19.2 km.

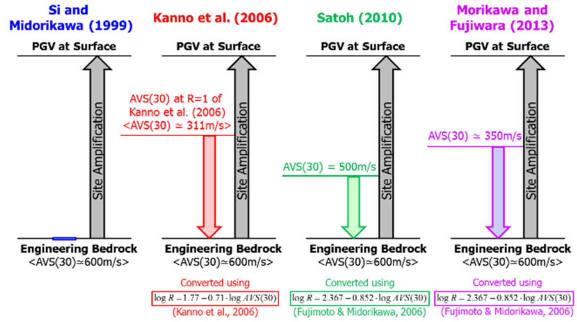


Fig. 6. Conversion of PGVs by five GMPEs.

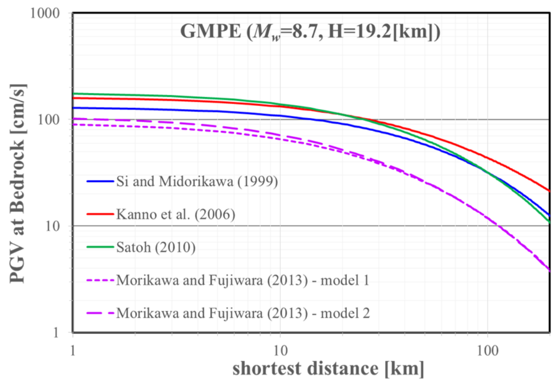


Fig. 7. Comparison of PGVs by five GMPEs.

Shallow subsurface structure

The site amplification from engineering bedrock with AVS30 of 600m/s to the surface is defined by the site amplification model. In this study, the site amplification model was proposed for the shallow subsurface structure module as a simplified format as follows;

$$PGV_{\mathrm{GS}} = AF \cdot PGV_{\mathrm{EB}} \quad (2)$$

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

In this study, the site amplification factor of PGV is estimated through two steps. The first step is the estimation of AVS30 from the soil profile based on the study by Matsuoka and others [9] as shown in Eq. (3). AVS30 is defined as the function of conditions of the site for each geomorphologic classification, such as elevation (Ev), slope (Sp), and distance from mountain or hill (Dm). Information of geomorphologic classification of J-SHIS [3] is applied. $\varepsilon_{\mathrm{SA1}}$ is modelling uncertainty in the first step. The second step is the estimation of amplification factor from estimated AVS30 as shown in Eq. (4) [8]. $\varepsilon_{\mathrm{SA2}}$ is modelling uncertainty in the second step. The methods of applying modelling uncertainties are the same as those in GMPEs. The standard deviation of previous studies [9, 8] is applied as $\varepsilon_{\mathrm{SA1}}$ and $\varepsilon_{\mathrm{SA2}}$. Epsilons are also assumed to be normally distributed;

therefore, the predicted PGV at the ground surface will likewise follow a log-normal distribution.

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

$$\log AF = 2.367 - 0.852 \log AVS30 + \varepsilon_{SA2} \quad (4)$$

Structural damage estimation

The fragility curve model for 2-storey wooden houses defined by Murao and Yamazaki [10] was selected for the structure damage estimation module. The exceedance probability P_R, which is the probability that damage of rank R or worse will occur for a ground motion of PGV_{GS}, is defined using a cumulative probability distribution function Φ. Φis a standard normal distribution and P_R is assumed to be lognormally distributed as follows;

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

where, μ_D is the modelling uncertainty term assumed in this study. $\ln \mu_D$ is assumed as 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 is assumed as 20% in this study. λ and ζ_D are parameters of the fragility curve, corresponding to the mean and standard deviation of $\ln PGV_{GS}$, respectively.

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

Table. 3 Parameters of the fragility curve for wooden house [10].

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

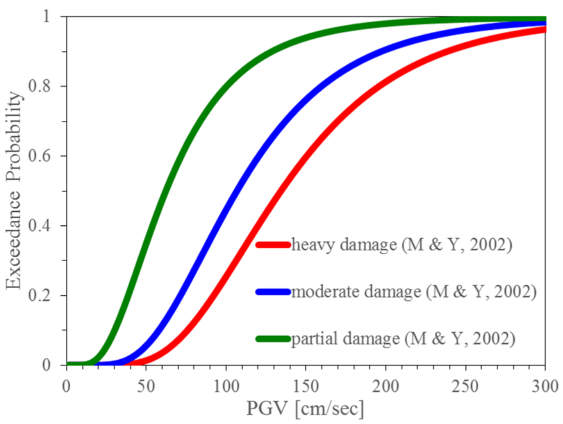


Fig. 8. Fragility curves for wooden houses [10].

Risk evaluation

Risk is defined as the expected value of loss. A simplified loss model is proposed for the risk evaluation module. Quantified values for direct (economic) losses [10] shown in Table 4, are applied as a loss model. The lower bound of values of loss for each damage degree are applied for loss model 1 (LM1) and the upper bound values are applied for loss model 2 (LM2). In case of the partial damage in LM1, 5% loss is used for the lowest value.

Table. 4 Quantified values for direct (economic) loss [10].

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

3.1.4. Result of the sensitivity analysis

Sensitivity analyses are performed for two target sites. The results are shown in Fig. 9. Quantile values of 5, 50 and 95% are shown by the dot for loss estimate line for each case. Very large uncertainties in the calculated risks are observed in all cases, especially in case of Kochi prefectural office site. For the comparison of uncertainty, the rate of reduction in uncertainty with respect to original uncertainty is defined as a criterion. The reduction rates are presented in Table 5. 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, where those of source process and fragility curve were relatively insensitive.

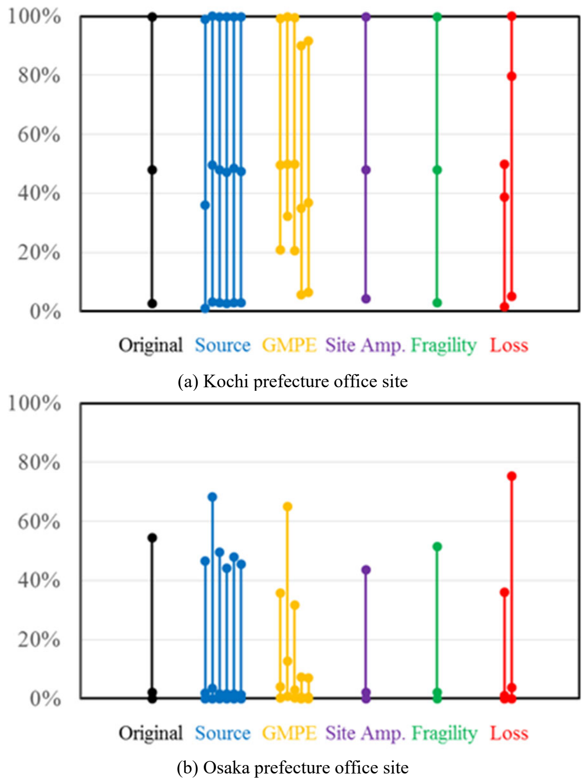


Fig. 9. Results of sensitivity analysis.

Table. 5 Rate of reduction of uncertainty.

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

3.1.5. Issues of preliminary analysis and challenges for the next step

From the preliminary study, some research agendas were found necessary to be investigated. First, the validity of suggested GMPEs needed to be verified because great differences were observed not only in the expected losses but also in the predicted PGVs as shown in Fig. 7. Second, the loss model needs to be defined more sophisticatedly since it was too simple and distinctive, and had more assumptions compared with other models.

3.2. Seismic risk evaluation

The secondary study was performed to conduct actual seismic risk evaluation for the whole area of the Kochi and Osaka prefectures, along with research to solve the aforementioned research agendas.

3.2.1. Revision of GMPEs

According to a recent paper [11], the effect of saturation of ground motions needs to be considered for megathrust earthquakes at the subduction zone. Based on the study, in case the shortest distance from source to site is applied for GMPEs, saturation of M_w needs to be considered for M_w over 8.3. This idea is adapted for GMPE1 to GMPE3, since the saturation effect is considered in GMPE4 and GMPE5 [7]. Except for two source areas whose M_w are 8.3 and 8.2. M_w is larger than 8.3, and therefore the saturation effect is considered for every source model. The comparison of the predicted PGVs of revised five GMPEs is illustrated in Fig. 10.

Compared with Fig. 7, the variability in the predicted PGVs decreased. The results of sensitivity analyses including the effect of saturation of magnitude for GMPEs are shown in Fig. 11. The decrease in expected risk values lead to a decrease of their uncertainties. Based on the reduction rate of each case, the relative relation of influence to the results does not change

As shown in Fig. 9(a), the expected loss at the Kochi prefectural office site by SM1 is smaller than others despite its M_w being much larger than the others. This was improved as shown in Fig. 11(a), mainly because not only GMPE4 and GMPE5 but also GMPE1 to GMPE3, which predicts larger PGVs, were applied to SM1.

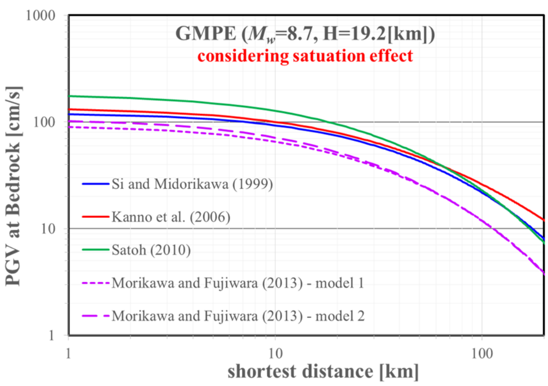


Fig. 10. Comparison of PGVs by 5 GMPEs considering saturation.

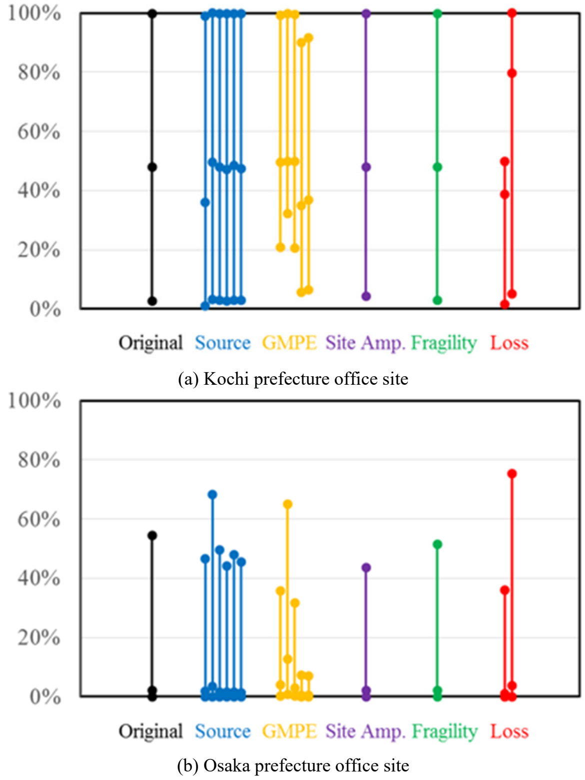


Fig. 11. Sensitivity analysis results for direct loss of houses considering the revision in GMPEs.

3.2.2. Revision of loss model

The risk is defined as the expected values of the rates of losses in terms of the fatalities as well as the direct losses of wooden houses. The death rate (casualties per house) defined by Tabata and Okada [12] is applied to link the damage of wooden houses to the fatalities, from the relation between the damage index and the rate collapse of surrounding houses as follows;

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

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

Since data for the surrounding collapse rate is not always easily accessible, it is assumed as the function of damage index, which is estimated from the data of

Kobe city [12], as shown in Fig. 12. The estimated function is $y = x^2/2$, and the death rate per wooden house is defined by the function of damage index as Eq. (7) marked by red line in Fig. 12.

$$D_r(x, y) = ae^{bx} + cx(x^2/2)^2 \quad (7)$$

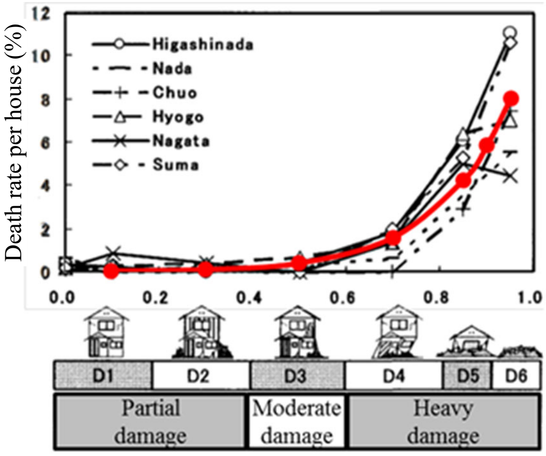


Fig. 12. Data of Kobe city and the approximated seismic death rate function for casualties per wooden house (after [12]).

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 [12] are marked by dotted lines in Fig. 13. These values are based on the fragility curves defined in Okada and Takai [13] as marked by dotted and dashed lines in Fig. 14. Since the fragility curves by Murao and Yamazaki [10], marked by solid lines in Fig. 14, are applied in this study instead of those by Okada and Takai [13], the damage indices for the death rate function needs to be revised. From the comparison of fragility curves of Murao and Yamazaki [10] and Okada and Takai [13], the damage indices for death rate function are revised to those marked by solid lines in Fig. 13.

The quantified values for the rate of direct loss of houses are improved based on the strict meaning of the

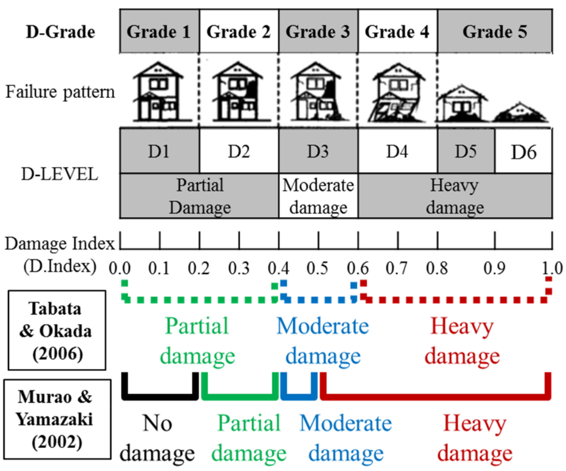


Fig. 13. Data of Kobe city and the approximated seismic death rate function for casualties per wooden house (after [12]).

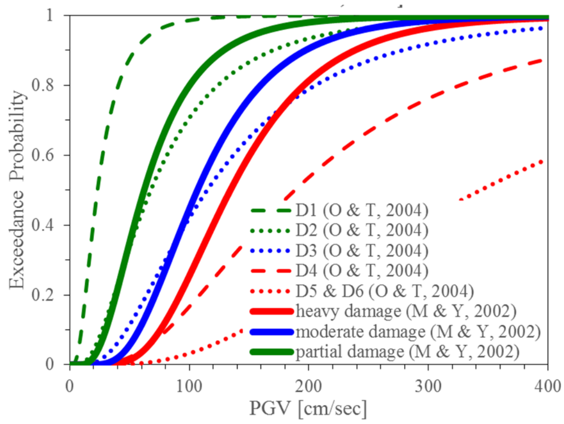


Fig. 14. Comparison of fragility curves [10, 13].

rate of loss [10]. As shown in Fig. 15, the degree of loss rate depends on the judgement of investigator. In the preliminary study, the values for the rate of direct loss based on the survey conducted by the local government were directly applied in the loss model. However, since the fragility curves applied in this study are not based on the survey by the local government, but rather on that by the "Special Committee for Earthquake Disaster Recovery and Urban Reconstruction," the quantified values need to be changed. The quantified values are revised as shown in Fig. 16 based on the comparisons of

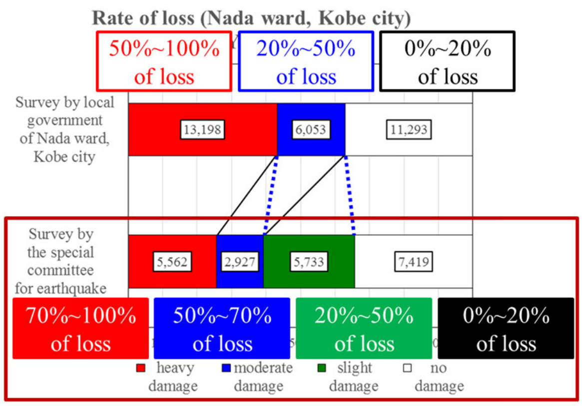


Fig. 15. Differences in quantified values of rates of losses in building affected by the judgements of investigators [10].

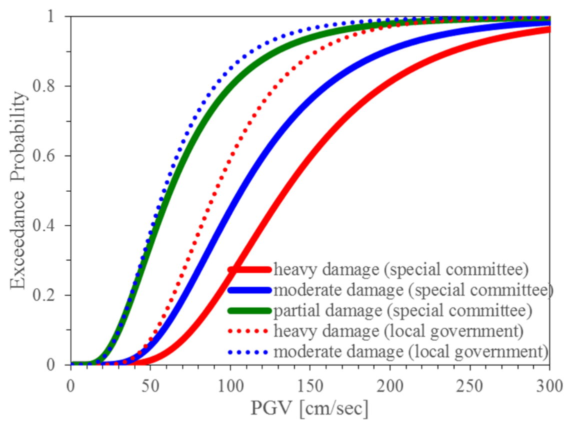


Fig. 16. Comparison of fragility curves affected by the judgements of investigators [10].

proportions for damage degrees and fragility curves as illustrated in Fig. 15 and Fig. 16, respectively.

One more improvement to the loss model is carried out by adding a model with a median value and considering uncertainty in the loss model by assuming a uniform distribution instead of random selection of values in each category.

The final loss model revised is briefly illustrated in Fig. 17. First, the classification of damage is revised from three classes to four classes. Second, the quantified damage indexes are defined. Finally, the loss model is defined in terms of rates of fatalities and direct loss of houses with respect to damage indices.

The results of sensitivity analyses including the revision in the loss model are presented in Fig. 18. Expected values of risks are decreased because of the revisions in quantified values for the rate of loss of houses. Uncertainties are decreased at the Kochi prefectural office site but increased at the Osaka prefectural office site.

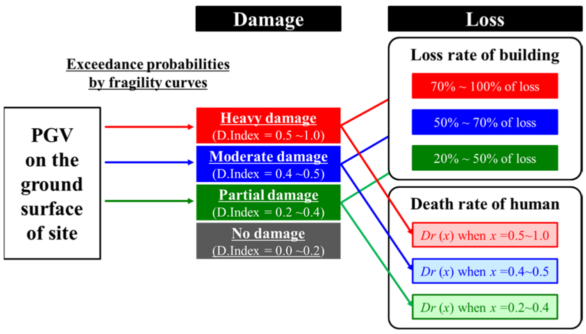


Fig. 17. Illustration of the loss model.

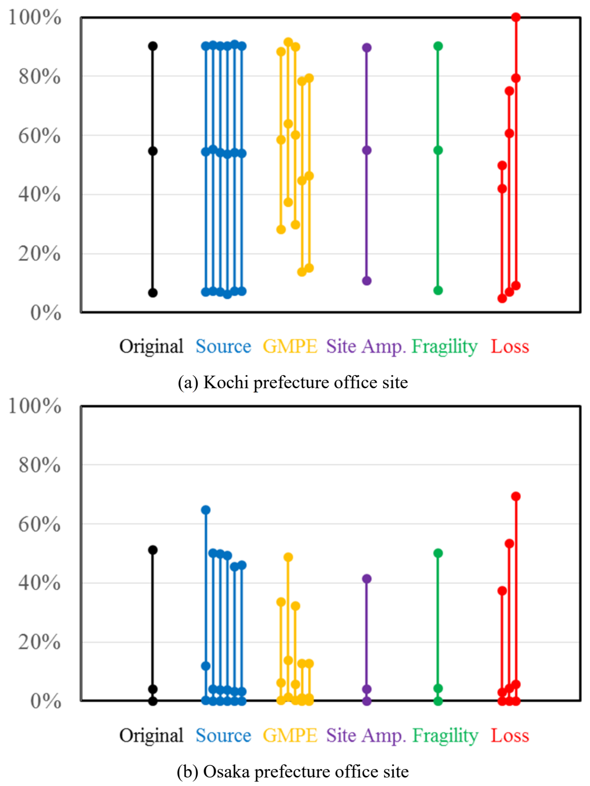


Fig. 18. Sensitivity analysis results of direct losses of houses considering the revision in loss model.

3.2.3. Expansion of target sites

The evaluation of seismic risk and its uncertainty has been extended to entire the 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.

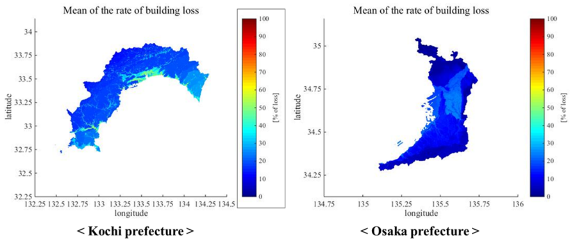
The expected rates of building losses for a wooden house and those of the corresponding human losses are illustrated in Fig. 19(a) and Fig. 19(b), respectively. The expected values were very high, around 50% of losses in buildings and around 3% of fatalities are predicted, in certain places of Kochi 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. 20(a) and Fig. 20(b), respectively. Overall uncertainties are large in the Kochi prefecture and those of the Osaka prefecture are relatively small. The spatial distribution of the uncertainty reduction rates in building losses in Kochi and Osaka prefectures is illustrated in Fig. 21. Based on the results of a sensitivity analysis, the conclusion is slightly different. The effect of the 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 is illustrated in Fig. 22. Based on the results of a sensitivity analysis, the conclusion is the 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 overall uncertainty, while that in site amplification is less sensitive, and those of source process, fragility curve and loss model are relatively insensitive.

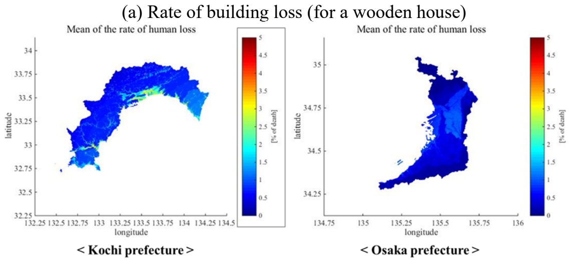
3.3. Summary of risk evaluation for the Nankai Trough earthquake

"Integrated Research" was aimed at evaluating seismic risk and its uncertainty for an earthquake occurring along the Nankai Trough, by utilizing state-of-the-art methods. In the preliminary study, very large uncertainties in the calculated risks were observed, especially for the Kochi prefectural office site. For comparison of uncertainty, the rate of reduction in uncertainty with respect to the original uncertainty is defined as a criterion. Based on the reduction rate of each case, the uncertainty of strong motion simulation module is most influential to overall uncertainty. Those of site amplification and loss model modules were less sensitive, and those of source process and structure damage estimation modules were relatively insensitive.

After the preliminary study, the methodology for seismic risk evaluation was improved in three parts. First, the models for GMPEs were improved considering the saturation effect. Second, the loss model was improved by adding a human loss model that is related to the direct loss of houses. The

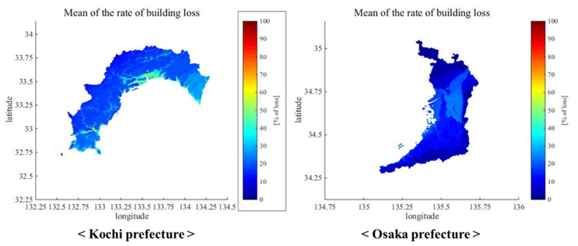


(a) Rate of building loss (for a wooden house)

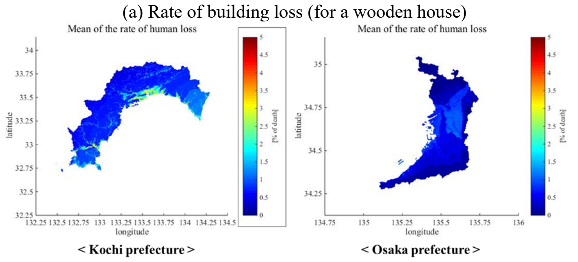


(b) Rate of human loss (per wooden house)

Fig. 19. Expected values of the seismic risk.



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

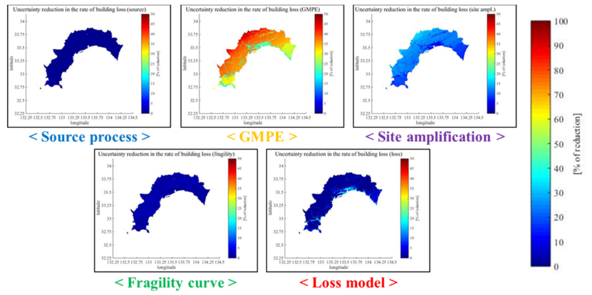


(b) Rate of human loss (per wooden house)

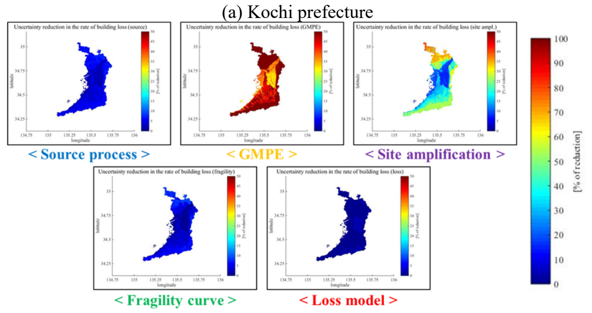
Fig. 20. Uncertainty of the seismic risk.

classification of damage degree and the quantified value for the corresponding damage degree were revised, and the application method of the loss model was also revised. Third, target sites were extended to the whole of Kochi and Osaka prefectures. The conclusion did not change drastically after these three parts were improved.

The expected rates of direct loss for a wooden house and the corresponding human loss were found to be very high, around 50% of losses in houses and around 3% of fatalities per house were predicted, in certain places in the Kochi prefecture. Compared with the Kochi prefecture, those of the Osaka prefecture were relatively small. The uncertainties of loss of wooden houses and human loss were also found to be large in the Kochi prefecture and those of the Osaka prefecture were relatively small. Uncertainty in strong motion estimation module is still most influential to the overall uncertainty, while that in site amplification module is less sensitive, and those of source process, fragility curve and loss model modules are relatively insensitive.

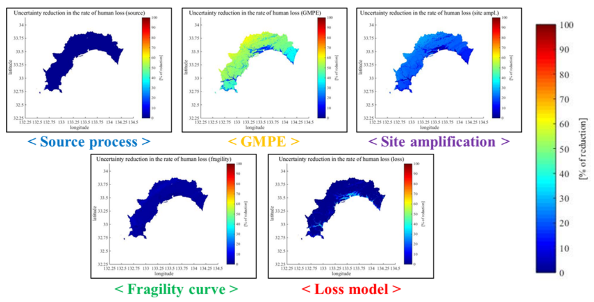


(a) Kochi prefecture

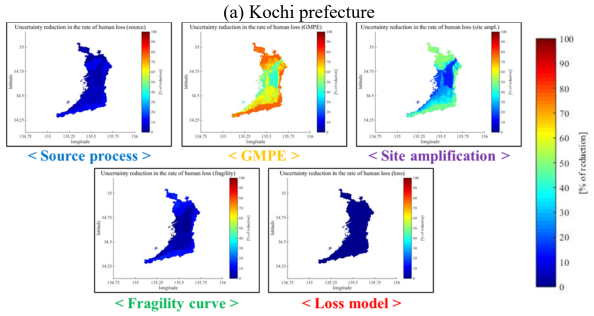


(b) Osaka prefecture

Fig. 21. Results of sensitivity analysis - Uncertainty reduction rate of loss of houses.



(a) Kochi prefecture



(b) Osaka prefecture

Fig. 22. Results of sensitivity analysis - Uncertainty reduction rate of human loss.

4. Summary of the Core-to-Core Research

The Core-to-Core Collaborative Research between Earthquake Research Institute, University of Tokyo (ERI) and Disaster Prevention Research Institute, Kyoto University (DPRI) started in FY2014 as a new format of a collaborative research within the research project Earthquake and Volcano Hazards Observation and Research Program. During the period between FY2014 and FY2018, Participation Type Research and Subject Proposal Type Research were conducted.

In “Subject Proposal Type Research”, a total of 54 research proposals were accepted for researchers in areas such as physics, engineering, and cultural and social science to cooperate and conduct interdisciplinary and comprehensive research and pursue research to understand the cause of disasters and utilize the knowledge to prevent/mitigate disaster.

In "Participation Type Research", "Integrated Research" and "Specific Research" was conducted for "Construction of a New Paradigm for Improving Uncertainty of Risk Evaluation for Large Magnitude Earthquakes." In "Integrated Research", probabilistic seismic risk assessment at Osaka and Kochi prefectures associated with the occurrence of an earthquake along the Nankai Trough was conducted by combining research areas from source process to stakeholder involvement. As a result, the uncertainty of probabilistic seismic risk was explicitly expressed quantitatively.

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