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Natural Hazards and Earth System Sciences
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Discussions



# *Interactive comment on* "Tsunami risk assessment for multiple buildings by considering spatial correlation of wave height using copulas" *by* Yo Fukutani et al.

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Dear Anonymous Referee #1,

We have considered carefully the peer-reviewed comments from you and revised our manuscript. Authors' one-on-one comments are as follows. Also, we have attached the revised manuscript as a supplement material.

We declare that this work is original and has not been published elsewhere nor is it currently under consideration for publication elsewhere. Please address all correspondence concerning this manuscript to me. Thank you for your consideration of this



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manuscript.

Yo Fukutani

Authors comments to the Anonymous Referee #1

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Page 1-line 24: It would preferable if key concepts of probabilistic tsunami hazard assessment (PTHA) and probabilistic tsunami risk assessment are introduced here. The authors are simply referring to them without explaining what they are. Some more details on PTHA and PTRA would be preferable.

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Thank you for pointing this out. We have included additional details and references on PTHA and PTRA from Page 1 - line 25 to Page 2 - line 4 in the revised manuscript as follows:

Among them, a variety of probabilistic tsunami hazard assessment (PTHA) and probabilistic tsunami risk assessment (PTRA) methods for tsunami disasters were rapidly developed since the 2000s (e.g., Geist and Parsons, 2006; Annaka et al., 2007; González et al., 2009; Thio et al., 2010; Løvholt et al., 2012; Goda et al., 2014; Fukutani et al., 2015; Løvholt et al., 2015; Park and Cox, 2016; De Risi and Goda, 2017; Grezio et al., 2017; Davies et al., 2018). The main purpose of a PTHA is to assess the likelihood of a given measure of tsunami hazard metrics (e.g. maximum tsunami wave height) being exceeded at a particular location within a given time period. The most basic outcome of such an analysis is typically expressed as a hazard curve, which shows the exceedance level of the hazard metric with the probability. This is often expressed as a rate of exceedance per year. A PTHA can be expanded to a PTRA by combining hazard assessment with loss evaluation of a target. Several studies have proposed a method of PTRA for an individual site in a local area. Detailed risk assessment is undoubtedly important in terms of grasping the risk of exposing assets located in a local area.

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Page 1 – line 25: This study is very much on hazard as well as the risk. I suggest including hazard also in the title. Replace "the probabilistic risk. . ." with "a variety of probabilistic hazard and risk. . ."

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Thank you for the advice. Based on the advice, we have changed the title of our article slightly to “Tsunami hazard and risk assessment for multiple buildings by considering spatial correlation of wave height using copulas”. We also have replaced "the probabilistic risk. . ." with "a variety of probabilistic hazard and risk. . ." in Page 1 - line 25.

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Page 1 – line 28: Relevant overview that preferably should be added to these references would be those of Davies et al. (2018), Grezio et al. (2017), and Løvholt et al. (2015). BTW, what do you mean by "extant".

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Thank you for the comment. We have included these references in the Introduction, and we have deleted “extant” that you pointed out.

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Page 1 – line 29: Remove "for a local area". In the end of the sentence, replace "in the area" with "in a local area".

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Thank you for the advice. We have replaced "in the area" with "in a local area".

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Page 2 – line 3: Why are aggregates of buildings portfolios important in particular? Please elaborate.

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Thank you for pointing this out. We have added an explanation for the importance of evaluating the detailed risks posed by aggregates of building portfolios from Page 2 - line 5 to line 10 in the revised manuscript as follows:

However, probabilistic risk evaluation methods are also utilized in cases to evaluate risks for multiple buildings. With respect to businesses that own a building portfolio, including factories and offices over a wide area, it is extremely important in risk-based management decisions to evaluate the detailed risks posed by the building portfolio. A portfolio means a collection of assets held by an institution or a private individual. By quantitatively assessing the risks posed by the building portfolio, for example, it is possible to identify assets held that have a large impact on the overall risk, and to compare the amount of risk held over time, which leads to support for decision-makers.

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Page 2- line 5: Please clarify in more detail why this is important. For instance give an example, otherwise the reader is a bit lost.

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Thank you for pointing this out. We have added some examples from Page 2 - line 13 to line 20 in the revised manuscript to help readers understand, as follows:

For example, let us consider assessing the risk of two buildings located at two sites. When the positive correlation of hazards between two sites is strong, the hazard at one site tends to be large if the hazard at another site is large. In this case, the hazards at the two target sites both increase, and as a result, the aggregate risk for the two buildings increases. Conversely, when the positive correlation of hazards is small, the hazard at one site is not necessarily large, even if the hazard at another site is large.

In this case, the aggregate risk of the two buildings is smaller than when the positive correlation of hazards is strong. Therefore, analyses that do not consider the spatial correlation of hazards involves the risk of underestimating the risk over a wide area. It is clear that the difference of aggregate risk between two cases becomes more prominent as the number of target sites increases.

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Page 2 – line 17: I'm not sure "simultaneous" is the right word. Perhaps "dependent" or spatially correlated is a better term. In any case, reformulate.

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Thank you for pointing this out. We have deleted "simultaneous" throughout the manuscript and used "joint" instead, which is commonly used in the statistics field.

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Page 3 – The simplification done by using response surfaces suppresses the uncertainty in the tsunami height (the authors uses the term wave height). This needs to be illuminated better. For instances, they could should error norms obtained using this fitting mechanism. Moreover, it needs to be clarified that tsunami heights can vary quite a bit in a local area. This property of a tsunami is concealed here, but the authors should actually quantify how large this variability is for one or more of the inundation simulations. This is important, as the authors method only operates on the fitted response function, which does not represent the full truth.

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Thank you for pointing this out. We have added details on the uncertainty of tsunami hazard assessment and additional references from Page 3 - line 23 to Page 4 - line 15 in the revised manuscript as follows:

Tsunami hazard assessment has many uncertainties in each process of tsunami generation, propagation, and run-up. Even considering only the earthquake source parameters that are the basis for calculating the initial displaced water level of the tsunami, there are fault length, fault width, fault depth, slip amount, rake, strike, and dip. The temporal and spatial changes of all these parameters more or less affect the tsunami hazard assessment. Numerous studies on the effect of earthquake source parameters on the initial displaced water level of tsunamis have been conducted (e.g., Hwang and Divoky 1970; Ward 1982; Ng et al. 1991; Pelayo and Wiens 1992; Whitmore 1993; Geist and Yoshioka 1996; Geist 1999; Song et al. 2005). These studies reported that fault slip was an important factor governing tsunami intensity. In addition, the Sagami Trough, which is the target earthquake of this study, has a complex crustal structure in the area where the Pacific Plate, the Philippine Sea Plate, and the North American Plate meet. Therefore, the depth where the Sagami Trough earthquake occurs is considered uncertain. Therefore, in this study, we decided to consider only the tsunami hazard uncertainty caused by the changes of slip amount and fault depth as an example. The heterogeneity of fault slip is an equally important factor, but we did not consider non-uniform slip distribution for purposes of simplicity. It is an important issue in the future to evaluate the heterogeneity of fault slip by response surface methodology. This is true for both slip heterogeneity and other fault parameters. For the above reasons, we model maximum tsunami wave height considering tsunami wave uncertainty with Eq. (2) after conducting tsunami numerical simulation with a nonlinear long wave equation. This formula is following the tsunami hazard evaluation method proposed by Kotani et al. (2016) that applied a reliability analysis framework using the response surface method proposed in Honjo (2011). The expression is as follows:

h(S,D)=aS+bD+cSD+dSˆ2+e

where h (S, D) denotes the tsunami wave height, S denotes the slip, D denotes the fault depth, and a, b, c, d, and e denote the undetermined coefficients. It should be noted that an error term is not included in Eq. (2). An example of the error term is to consider an error due to modeling. For example, Kotani et al. (2016) quantified the modeling error as the difference between the observed tsunami height and the numerically simulated tsunami height. The modeling error of the numerical analysis was also considered as one of the tsunami hazard uncertainties. However, the main purpose of this study is to propose a tsunami damage assessment method for multiple buildings using copula considering wave height correlation. Therefore, the modeling error is also ignored for simplification in this study.

Also, we have added results of the tsunami inundation simulations in Fig. 5 with explanations for the figure from Page 7 - line 14 to line 19 in the revised manuscript as follows:

As an example, Fig. 5 shows the numerical simulation results of 9 cases around Oiso and Miura in which the Mw of the source 8 is changed to $\pm$ 0.1, the fault depth is changed to + 2.0 km, and - 1.0 km. As shown in the figure, the distributions of the maximum tsunami wave height vary locally by changing the slip amount and the fault depth, and the effect of the slip amount on the maximum tsunami wave height is more dominant than the fault depth. In addition, while there is a clear positive correlation between the maximum tsunami wave height and slip amount of the earthquake, there is no clear correlation between the maximum tsunami wave height and the fault depth.

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Page 3 – line 13: Is "slip ratio" the slip?

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Thank you for pointing this out. We have modified as you noted.

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Page 3 – line 17: Statement starting with "Although tsunami numerical simulations. . ." is misleading. As said, fitting response functions will remove a lot of the actual variability. This needs to be explained better, otherwise it will seem that the method is better than it actually is. . .

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Thank you for the advice. We have added detailed explanations about the variability of tsunami hazard assessment in the second chapter to avoid appearing to mislead.

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Page 3- line 20: As a non-expert in copula theory, this is hard to follow. Is the copula producing a unitary distribution C, mapping x to a new random variable u (with equal probability) over ui=[0,1]? Please clarified better, give more details, perhaps even a simple synthetic example. Moreover, the varible u is not even formally defined.

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Thank you for pointing this out. We have added a simple synthetic example and explanation of copulas in Fig. 2 and from Page 4 - line 23 to line 26 in the revised manuscript as follows:

There exists a n-dimensional copula C such that for all x in the domain of F, the following expression holds (Sklar, 1959):

$$H(x_1, \ldots, x_n)=C\{F_1(x_1),\ldots,F_n(x_n)\}=C(u_1,\ldots,u_n)$$

where $u_i=F_i(x_i)$âĹĹ[0,1], $i=1,\ldots,n$. Figure 3 shows a simple synthetic example of a copula in a bivariate case. Fig. 3 (a) is a joint distribution function, Figs. 3 (b) and (c) are distribution functions of each variable (marginal distributions) and Fig. 3 (c) is a copula distributed over [0, 1].

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Page 4 – line 11: You have not introduced regions before, it is not clear what you mean. Please introduce the concept of regions. It may seem from the paper that regions refer to sources, which is quite confusing. More elaboration and clarification is needed.

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Thank you for pointing this out. We have decided to use the term “sources” instead of the term “regions” throughout the manuscript to clarify and avoid confusion. Please check the manuscript.

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Page 5 – line 15: Again essential details in the modelling is needed. The source parameters describing the focal mechanisms (slip, width, shear modulus, geometry etc) is missing. Please elaborate.

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Thank you for pointing this out. We have added detailed explanations of the source parameters used in this study from Page 6 - line 19 to line 27 in the revised manuscript as follows:

Each small fault corresponded to a 2.5 km square, and the slip amount of the fault was set to a uniform value based on the moment magnitude (Mw) of each earthquake by using the following scaling laws of earthquakes according to Kanamori (1977):

Mo=$\mu$SA

Mw=(log10 Mo-9.1)/1.5

where Mo denotes moment magnitude (Nm), $\mu$ denotes shear modulus (Pa), S denotes slip amount (m) and A denotes earthquake source area (m2). $\mu$ was set to 3.4 $\times$ 1010 (Pa). In this study, we did not consider non-uniform slip distribution for purposes of simplicity. We set other fault parameters (i.e., fault depth, dip, rake, and strike) to the sources based on information published by the Cabinet Office (2013) in Japan, which were created from the crustal structure of data of the plates.

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Page 5 – last paragraph: I would say that the uncertainty treatment is rather rudimentary, although some sensitivity is presented. The authors should clarify additional factors not covered by their study, such as variable (heterogeneous) slip, different possible fault configurations etc. Page 5 – Line 9: The response surface method collapses all spatial variability into a, rather crude, single equation. In this way the uncertainty gets lost. This needs to be illuminated better. The variability from the simulations needs to be quantified.

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Thank you for pointing this out. We have described the possible uncertainty of tsunami hazard assessment in the second chapter. In addition, we have added the following sentence in the last paragraph that you pointed out. As detailed in the second chapter, this study focused on the slip amount and the fault depth among many uncertain factors.

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Page 7 – line 9: "normality of the frequency distribution of the tsunami height is not secured" "distribution of the tsunami heights do not necessarily follow a normal distribution".

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Thank you for the comment. We have modified as you mentioned.

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Page 7 – line 18: What is [0,1] space. Be more specific. Moreover, define and introduce the AIC and BIC methods.

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Thank you for pointing this out. We have changed the description to “over [0, 1]” throughout the manuscript. We also have added explanations of [0, 1] and copulas in Fig. 2 and from Page 4 - line 26 to line 29 in the revised manuscript.





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Page 7 – lines 24-29: Elaborate on how the different sampling technical (both with and without copulas) are carried out. For instance, you do not explain how the uncorrelated sampling is carried out.

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Thank you for pointing this out. We have added an explanation of how the uncorrelated sampling is carried out on Page 9 - line 13 to line 15 in the revised manuscript as follows:

To compare with this result, Fig. 11 (b) shows the results without considering the wave height correlation. We independently generated the tsunami wave height by using a uniform random number and the cumulative frequency distribution of the tsunami wave height at each site without using a copula.

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Page 9 – line 7: I suggest that the authors explain in more detail how their findings can be used, for instance in PTHA and tsunami risk assessment. Possible use might be of value beyond the present study, but is a little bit concealed.

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Thank you for the advice. We have added details on how the findings in this study can be used to Page 10 - line 21 to line 31 in the revised manuscript as follows:

In addition, the response surface method used in this study significantly reduces the numerical simulation costs for probabilistic tsunami hazard assessment considering uncertainty. In this study, we only focused on the slip amount and fault depth among many tsunami hazard uncertainties, and evaluated them using the response surface method. It has been reported that the heterogeneity of the slip distribution of the fault has a great influence on tsunami intensity. It is a future issue to evaluate these effects with a response surface method. The evaluation result was shown for only two buildings, but when an entity evaluates the risk of assets it owns it is assumed that there will be more target sites. It is clear that as the number of target assets increases, the percentile value and maximum value of aggregate damage of assets becomes more prominent. Risk assessment that does not consider the spatial correlation of wave heights will lead to underestimation of the risks held. The basic method shown in this study can be applied even when the number of target assets increases. It is also important to avoid underestimating the assessed risk by considering the wave height correlation using a copula.

Please also note the supplement to this comment:
https://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2019-139/nhess-2019-139-AC1-supplement.pdf

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Interactive comment on Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2019-139, 2019.



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