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Review and rebuttal of the paper

Magnification of Tsunami Risks Due to Sea Level Rise Along the Eastern Coastline of Japan

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Editor handling the paper: Jeremy Bricker

The reviewers remain anonymous.

Round 1

Reviewer A

REVIEW

The topic of this paper is of high interest in the field of coastal disasters risk management in tsunami-prone areas. Given the scarcity of tsunami records in comparison to earthquake records, the estimation of tsunami heights by means of a probabilistic model that takes into account statistics of the tsunami generation mechanism can enrich datasets from past tsunamis and ultimately inform the design of coastal defences, urban planning and emergency management. Its distinct novel aspect is the consideration of the influence that sea level rise will have on water surface elevations in the future, which is a crucial element for the determination of inundation and run-up heights along the coast. Although the impact of sea level rise on tsunami risk has been addressed in previous studies, to the reviewer's knowledge, its incorporation in a PTHA is new.

Although the paper is conceptually strong, the reviewer has identified a number of questionable points in the methodology that can have a major impact on the results and conclusions, and should be further substantiated. Apart from this, the complexity of the followed methodology requires a more detailed and transparent presentation, otherwise it would be impossible for readers to follow its logic and apply it correctly in the future.

The reviewer's concerns and suggestions for improvement are summarized below:

The authors would like to thank the reviewer for the time taken to provide such constructive reviews about this manuscript. The authors have thus substantially revised and improved the manuscript, as shown in the detailed replies to each comment below. The authors welcome this discussion and remain open to make further changes to the manuscript, should the reviewer have any additional comments.

General comments

1.Methodology: The steps of the analysis seem to be followed in an unorthodox way. One would expect to see an analysis as follows: 1. Determination of annual exceedance probability of earthquake magnitude, 2. Determination of the probability of occurrence of a tsunami given an earthquake, 3. Determination of annual exceedance probability of tsunami heights, 4. Determination of exceedance probabilities of tsunami height on the coast after applying the SLR corrections and tsunami propagation model. It is unclear how exactly the authors incorporate the above crucial steps in this analysis. The reviewer suggests the addition of a sub-section in the beginning of section 2 with a logical diagram of the presented analysis and a summary of all assumptions that are made throughout the paper.

This was indeed poorly explained in the original version of the manuscript. Essentially, the methodology used in the present work is the logic-tree method, which differs from the "random phase method" that the reviewer is describing. In most types of probabilistic analysis, the sequence followed in the methodology is indeed that indicated by the reviewer. However, the logic-tree method used in the present research is slightly different. Both methods have their advantages and disadvantages, and this is mentioned in the text. Lines 96-105 have been changed to read:

"There are mainly two different methodologies that can be used to conduct a PTHA: the random phase method and the logic-tree method (see Annaka, 2007; Fukutani et al., 2018). The random phase method creates stochastic slip

distributions following the inversion modeling of fault slips that previously occurred to evaluate tsunami hazards. This method can clarify the correlation between the distribution of fault slips and tsunami heights, though other factors related with uncertainty of fault parameters and tsunami heights (such as interval occurrences) are difficult to consider using this method (see, Fukutani et al., 2018). The logic-tree method can classify uncertainties in tsunami models into aleatory and epistemic categories and evaluate the probability distribution of expected tsunami heights. Aleatory uncertainty is caused by randomness in the natural phenomena (i.e., the range of the potential magnitude), whereas the epistemic uncertainty originates from a lack of accurate data regarding the position of the epicenter, range and length of the faults. Comprehensive results can be estimated by averaging the results from each scenario based on the logic tree construction. "

The authors would like to note at this point that this method, despite it not being extensively used outside Japan, is the accepted way for conducting PTHA in the country. Many modelling studies conducted for the Tohoku region after 2011 use this approach, and there is a standardized methodology to conduct such studies. Hence, there is no originality at all in the present paper related to the use of this method (which is considered to be completely standard in Japan), and rather the originality relates to its application to SLR.

The authors also added a logical diagram and some extra sentences to explain the steps that can be used to produce fractile curves:

"Fig. 2 presents a logical diagram that illustrates the steps to compute the fractile curves of tsunami heights by using the PTHA method. Firstly, the earthquake fault source model and its characteristics are defined to create a logic tree construction, which determines the various displacement parameters. Subsequently, a tsunami source model is created and various SLR scenarios are formulated, which are then computed using a numerical simulation model based on the non-linear long wave equations. Consequently, the relationship between annual exceedance probability curves of tsunami heights and the cumulative weights of the branches can be obtained"

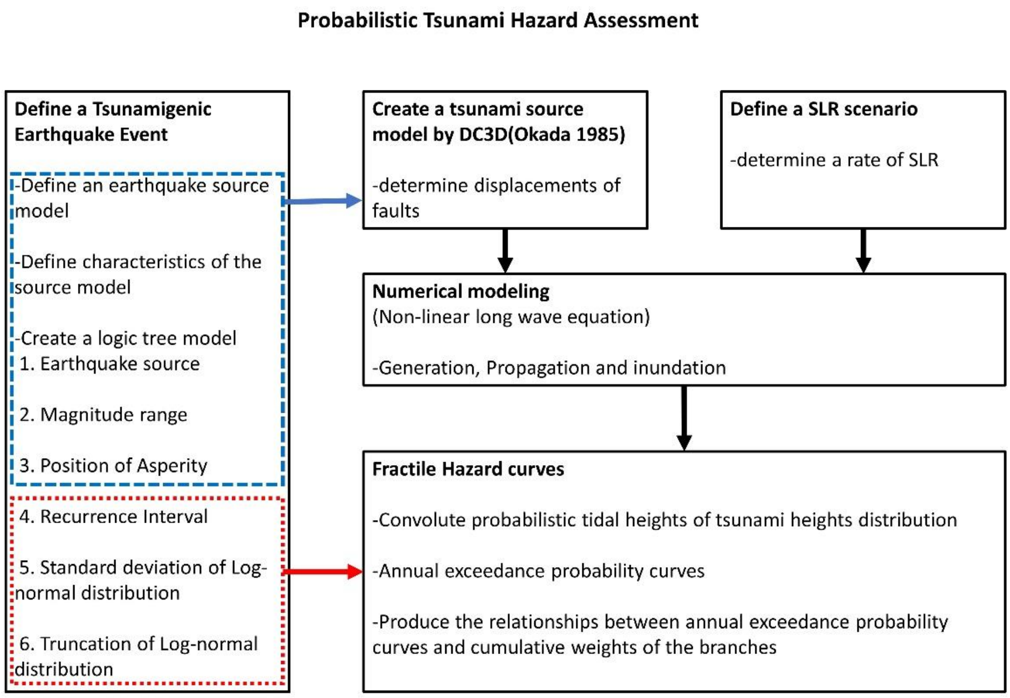


Fig.2 Logical diagram of the present study.

2.Methodology: A logic tree is presented that illustrates uncertainties in a number of key parameters in relation to the 2011 Tohoku tsunami. This is a nice tool to use in order to determine the possible variation of water surface elevation on the coast of Kujukuri due to a tsunami comparable to the one of 2011. However, it is unclear to the reviewer why this is the starting point of the analysis, as it seems more like a sensitivity analysis that can be performed after tsunami heights are determined in different SLR scenarios. The rationale behind the methodology needs to be better explained.

This comment ties in with the previous comment. Essentially, the logic tree is the methodology used, which is a standard methodology used in Japan to conduct a PTHA.

3.Results & Conclusions: These parts of the paper are difficult to assess as long as there are question marks on the methodology. The authors are encouraged to revise this part once the detailed comments on the methodology have been addressed.

The authors hope that with the revisions made it is now easier to interpret the results and conclusion but remain open to further constructive discussion with the reviewer.

4.Discussion: The 2011 Tohoku earthquake caused significant subsidence in various locations along the coast of Tohoku. One would expect that such phenomenon may also extend to the bottom of the ocean during a strong earthquake. Subsidence could possibly influence the degree of water surface elevation during a tsunami and perhaps even more severely than sea level rise. It would be good for the authors to reflect on this issue and provide insight into the effect that this may have on the result of their analysis.

This is obviously an important consideration, particularly when analyzing parts of the Tohoku coastline that were severely affected by land subsidence. However, it should also be noted that land subsidence along the targeted coastline was limited (i.e. -7cm at Kujukuri Beach, -31cm at Sendai New-Port), and hence not so important for the results and conclusions outlined in the present manuscript. Nevertheless, such considerations can be important, and hence the following sentences were added to the conclusions.

"It is important to also note that as a consequence of a major earthquake land subsidence can take place, and the *2011 Tohoku Earthquake* and *Tsunami* caused such a phenomenon along a wide stretch of the Tohoku coastline. Land subsidence of up to - 1.14m was recorded at Ishinomaki city (Imakiire & Koarai, 2012), which lead to widespread problems for coastal infrastructure (Cao et al. 2020) and required extensive land elevation of coastal settlements (Esteban et al. 2015). Such effects should also be taken into account in simulations, though the *2011 Tohoku Earthquake* and *Tsunami* only caused modest subsidence in the case study area of the present research (-7 cm at Kujukuri Beach and -31 cm at Sendai New-Port), and hence was excluded from the present simulations".

Esteban, M., Onuki, M., Ikeda, I and Akiyama, T. (2015) *"Reconstruction Following the 2011 Tohoku Earthquake Tsunami: Case Study of Otsuchi Town in Iwate Prefecture, Japan"* in Handbook of Coastal Disaster Mitigation for Engineers and Planners. Esteban, M., Takagi, H. and Shibayama, T. (eds.). pp 615-630. Butterworth-Heinemann (Elsevier), Oxford, UK

Cao, V. Q. A., Esteban, M. and Mino, T. (2020) *"Adapting wastewater treatment plants to sea level rise: Learning from land subsidence in Tohoku, Japan",* Natural Hazards, 103, 885-902.

Comments in the text

127-132: A Brownian Passage Time distribution is used to determine the return period of the 2011 Tohoku earthquake. It is unclear here which seismic parameter this return period represents. Is it the Mw or anything else? How can we deduce from this the exceedance probability of earthquake parameters that relate with tsunami generation (e.g. variables that appear in the tsunami source model of next page)? Another point that needs clarification here is how the return period of this seismic parameter relates to the return period of a tsunami. Have you assumed here that once an earthquake of this magnitude occurs, a tsunami occurs with 100% certainty? This has to be specified.

A BPT curve in itself is not related to any specific seismic parameter, although this curve can be created by using the average occurrence of an earthquake and the parameter of dispersion. These parameters were based on previous studies (NIED, 2013; Fujiwara et. al., 2013). A BPT is used to determine the return periods in this study, which is not related to determination of the various tsunami source models. The variety of tsunami source models was determined by a source type of earthquakes, a range of magnitudes and asperity of earthquake.

In this study, the range of the magnitude is so large that all cases could generate tsunamis.

133: Here you have assumed that the tsunami height follows a log-normal distribution. How have you come up with this probability distribution type? It is unclear if this is a probability distribution function that refers to one event, i.e. the 2011 tsunami, or the probability distribution function of tsunami height throughout the period for which we have historical records. Whether we are talking about a probability per event or a probability per historical tsunami dataset plays a very significant role for the determination of annual exceedance probabilities and your hazard curves in section 2.6.

The distribution of tsunami heights around the median value is assumed to be log-normal distribution based on the previous research on the distribution of the ratios between observed and calculated tsunami heights (AIDA, 1978). While a standard deviation of log-normal distribution β is related with an error factor κ which often referred to as Aida's κ in Japan, as $\kappa = \exp(\beta)$ (AIDA, 1978). While β is introduced for taking account of the aleatory uncertainty of tsunami heights the value of this parameter is treated as epistemic uncertainty. In this logic, the branches for β picked up the four values. The three branches were based on the κ data determined from a numerical simulation for the optimal fault models of tsunamigenetic earthquakes with many historical run-up data based on ergodic hypothesis. The other branch is introduced by considering the possibility that ergodic hypothesis is not true. According to the truncation of the log-normal distribution, $\pm 2.3\beta$ and $\pm 10\beta$ are selected as extremes.

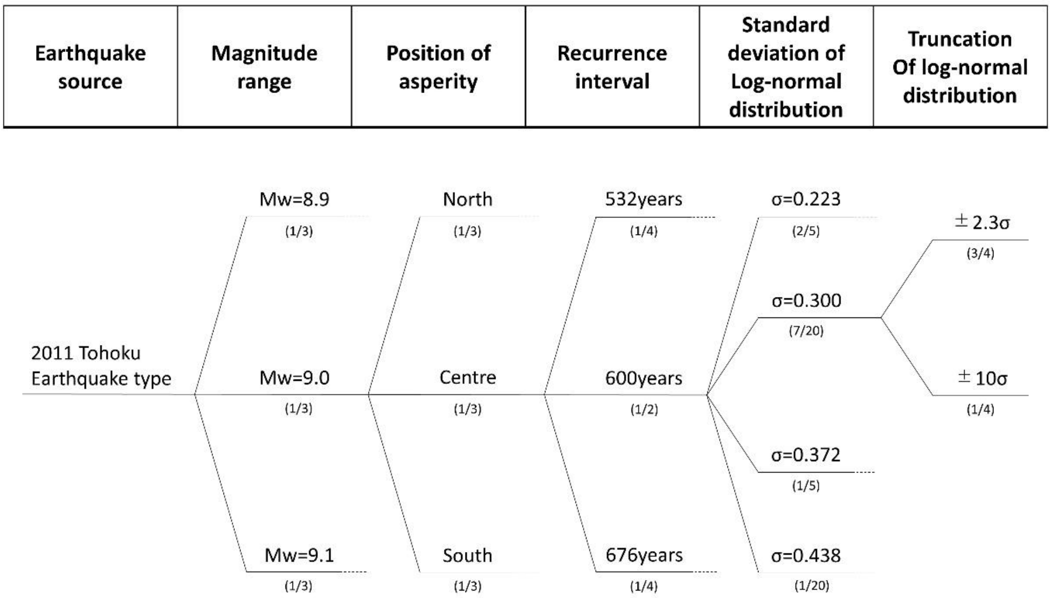
134: In this paragraph you make reference to tsunami heights for the first time. An exact definition of the term is missing throughout the paper. It would be important to have it defined as early as possible.

In this study, all digital buoys were set at 10 m depths to measure tsunami heights. The authors added a sentence to clarify this in L2w3.

In computational domains A3 and B3, digital buoys at Sendai New-Port and Offshore of Asahi City were set at 10 m depths to compare the characteristics of near-field and mid-field (see Fig.5).

Figure 2: It's difficult to read this figure, because the descriptions on the top of every block are vague. Please rephrase the titles to make them more specific. E.g. The recurrence interval should become 'recurrence interval of tsunami height'. Also the brunches that connect one block with the next are misleading because they connect specific values of consecutive blocks.

The authors created a new figure, following the reviewer's advice.



153: It is unclear what you mean here. Please specify how the logic tree helps you determine displacement.

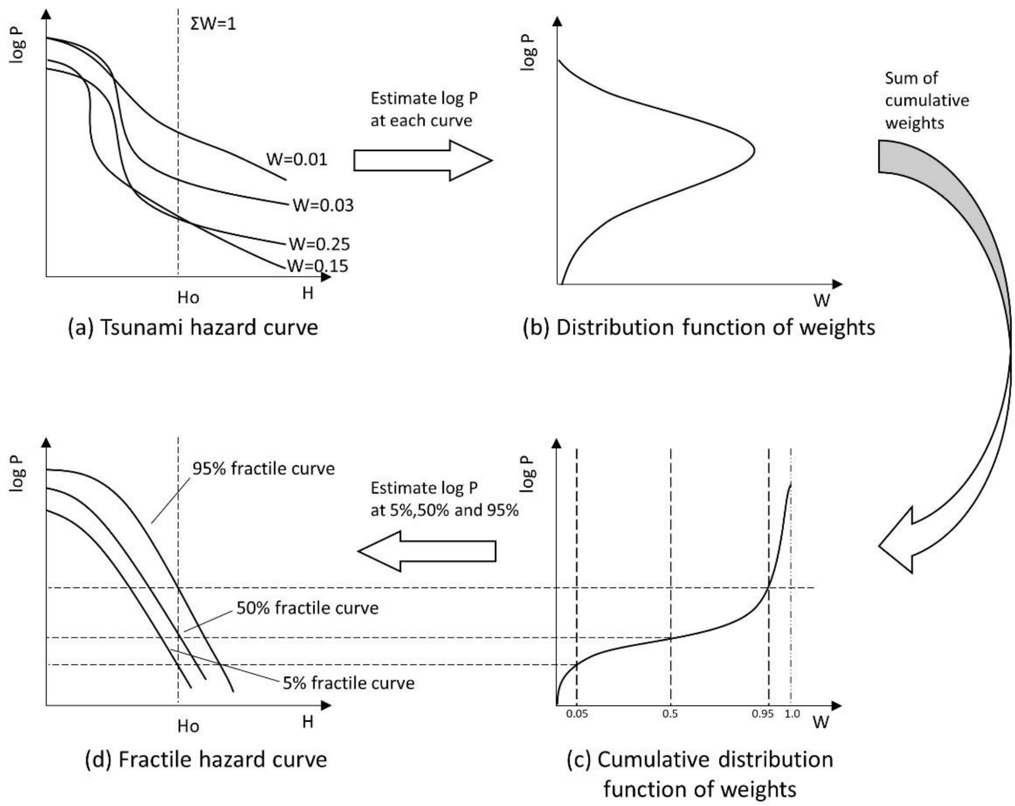
The branches from the logic tree (except the part of the recurrence interval, standard deviation of a log normal distribution and truncation of a log normal distribution) determined displacements. In this way, the tsunami source model was created by using the parameter of moment magnitudes and asperity. In this study, magnitude moments determined the how much the fault slips moved, and asperity determined the distribution/location of the fault (following methods of the previous study from Sugino et. al. (2014)). The other parameters were not used to create the tsunami source model, although they are used to determine to create fractile curves.

161-162: Please provide units for each variable that appears in equations 1 and 2. At this point it seems that you do not consider any uncertainty in variables M0, ω and S. It would be helpful to have in the beginning of your methodology section a table that indicates all variables in your analysis, whether you consider them certain or uncertain, and how you incorporate uncertainty of every uncertain variable in your analysis.

Thanks for your comment. The authors have added units to all the variables. Also, a new diagram (see the new Fig. 2) has been added to further clarify how the model works.

221: Please provide a definition of a fractile hazard curve and how this links to annual exceedance probability of tsunami height.

Fractile hazard curves show the relationship between annual exceedance probability of tsunami heights and cumulative weights. An ergodic hypothesis is assumed to define the variation in tsunami heights (an ergodic hypothesis is a hypothesis where the variation of time and spatial domain are equivalent). In this study, Aida's κ and the standard deviation of log-normal distribution β represent the variation in the spatial and time domain, respectively. Consequently, a tsunami hazard curve (an annual probability of exceedance) should be created. The weight on the branches of the logic tree determine the probable rate of occurrence of the scenarios based on the questionnaire survey of earthquake and tsunami experts and error evaluations,, and each value is linked to different tsunami hazard curves as shown in the figure a) below. At each tsunami height, different annual probabilities can be estimated and the distribution function of weights at each tsunami height can be reproduced (as shown in the figure b)). According to the distribution function of weights, the cumulative distribution function of weights can be obtained, as shown in figure (c. Fractile hazard curve could be computed by estimating annual exceedance probability at different cumulative distribution function of weights.



223-227: Here you come back to the log-normal distribution of the tsunami height. As mentioned in an earlier comment, it is unclear what this log-normal distribution represents in your PTHA. Once this has been further explained, the reviewer will be in a position to assess the logic of the choices that have made here.

This comment was addressed with the earlier comment and figure.

228: Please describe what an ergodic hypothesis entails and how it serves you in this point. Is there any difference between your approach and the standard approach of determining an exceedance probability as (1-cumulative probability)?

This comment was addressed in an earlier comment, together with the figure above.

233: Please specify what the percentages 5%, 16%... represent.

This sentence is superfluous and was deleted.

Reviewer B:

This manuscript presents a new finding on applying PTHA to east Japan region with sea level rise impact using classical PTHA method. The manuscript is straight forward and easy to follow. Although there is no new scientific technique applied in this study but their results will be benefit for tsunami countermeasures in the future. One thing I noticed is that the authors use the word "risk" but they only present and discuss about "hazard" (tsunami amplitude) without discussion on vulnerability and exposure, I would suggest the author to use "hazard" instead. Please find below for my suggestions for further improvements.

The authors would like to thank the reviewer for the time taken to provide such constructive reviews about this manuscript. Indeed, the word "risk" is not appropriate in many instances in this paper. The authors reviewed the entire paper and changed many instances of the word "risk" to that of "hazard" (where appropriate).

•Some recently published papers that study about SLR impact on tsunamis coupling sea-level rise with tsunamis: Projected adverse impact of future tsunamis on Banda Aceh city, Indonesia. How Would the Potential Collapse of the Cumbre Vieja Volcano in La Palma Canary Islands Impact the Guadeloupe Islands? Insights into the Consequences of Climate Change.

The authors would like to thank the reviewer for these additional references. The authors have added the following sentences to the text:

"However, to the authors' best knowledge, when performing such exercises, very little research has considered the influence that sea-level rise (SLR) will have on the overall risk (some exceptions to this being the work of Arnoud et al. (2021) on how tsunamis originating from La Palma volcano could affect Guadeloupe, and Tursina et al. (2021) on the impact of SLR on future tsunamis in Banda Aceh)."

•L69-85 and 238-254: I understand that two study areas in Tohoku and Kanto regions were selected as their similar topography. Is it possible to discuss more (i.e. section 3.1) on how non-linear effect is different for these two areas (i.e. why increase in Sendai but why decrease in Asahi?)?

In general, the nonlinear effects of inundations and bottom friction are important for near-shore areas where the water depth is very shallow. As this simulation is based on non-linear long wave equation and digital buoys were installed at 10 m depths, the results from these digital buoys would have a nonlinear effect. However, the authors believed that further future study should aim to clarify how non-linear effects result in different damage patterns in each area (i.e. using different governing equations with or without non-linear effects).

•L152-172: Am I correct that you only construct PTHA based on the 2011 earthquake-type (M9 class) only (no other smaller earthquakes)?

This is correct.

•L238-254: I can also confirm that the maximum amplitude for each area is directly related to location of asperity. In Fig. 6(b), I noticed quite large amplitude at the beginning (blue line, south asperity during 30-45 min), is this directly because the asperity is just located very close to the waveform input point in Asahi city? I would also suggest to add more sub figures in Fig. 3 to show other scenario of slip distributions (including north and south too).

This is correct. The first large amplitude arrived comparably earlier because the asperity of the earthquake is closer to Asahi City.

•L261-292: (1) What about reproduce the 2011 tsunami to examine the maximum tsunami amplitude in Sendai port (which is > 6.6 m?) Then you will know the exact maximum amplitude and can estimate the return period for each fractile percentage, may be shall be something like 1,000 years. (2) Please give short explanations of tsunami level 1 and 2 somewhere before this section. (3) You may also discuss about the Off-Miyagi earthquake tsunami that regularly occur in Tohoku region and compare its return period with your results. (4) You may also discuss about seawall height in Sendai (level 1, 100 years recurrence) such as how your results will affect to the already newly reconstructed seawall (although impact from SLR is very less but may be can discuss using PTHA results of current sea leve?) (5) Kujukuri beach is far from the Tohoku source can be locally affected by other local sources (i.e. Off-Boso earthquake) so you may also mention about your thought on how tsunami from this earthquake may affect your present results

The author would like to thank for your comments and answer (1)-(4) below.

(1) According to reports from Sendai City, 7.2 m tsunami heights were measured at Sendai New-Port. The corresponding return periods for this measurement were found to be 2071 years, 852 years and 613 years (from 5%, 50% and 95% fractile curves). In addition, the return period of the average fractile curves was 987 years (i.e around 1000 years, as the reviewer indicates).

(2) The authors explained the definitions of tsunami level 1 and 2 in the sentences 25-29.

As a consequence of this, the Japanese coastal engineering community established two levels of tsunami design, and the idea that hard measures along the coastline can always protect human society against tsunamis has been abandoned (Shibayama et al., 2013). Level 1 tsunamis are events with a return period of several decades up to around 100 years, with coastal structures being designed to protect people and their property against such events. Level 2 tsunamis have a return period of the order of 1000 years, and evacuation measures should be designed to ensure that all residents can safely escape even in the case that such inundation takes place.

The authors now added some extra information about tsunami level 2 in line 283:

However, the authors would like to state that the maximum heights of actual tsunamis could be higher. Using the obtained fractile curves, the tsunami heights with a return periods of 1,000 years (i.e., a Level 2 tsunami, against which ev*acuation countermeasures are presently being designed in Japan) were compared for present day and future conditions.*

(3) In the present research the authors would prefer not to discuss the case of the Off-Miyagi earthquake, and restrict matters to the 2011 Tohoku earthquake.

(4) The authors would like to discuss how tsunami level 1 affect to new seawalls, though the return periods of the earthquakes described in the present study are much higher, and it was felt that such low level events would be better discussed in a separate article (probably together with the occurrence of Off-Miyagi earthquake).

(5) As the reviewer correctly mentioned, many historical tsunamis have caused damage along the coastline surrounding Asahi City. In addition, the paper from Koyano et. al (2020) showed that earthquake tsunamis located north part of Japan trench generated edge waves and tsunami resonances, which caused local high tsunami height. These facts could indicate the importance of further study about tsunami characteristics along the coastline around Asahi City, though these would be better dealt with in a separate study.

•L326-349: You may also discuss impact of uncertainties from PTHA (same returen period but can be diffeent by many meters) which is much larger than SLR (mostly equal to the added sea level), how we can interprete these impacts based on your results, etc.

Basically, the authors interpreted uncertainties by using a logic tree branches and weights on them. As uncertainty from SLR was not contained in a logic tree, SLR just contributed to shorten the return period.

Round 2

Reviewer A

The reviewer appreciated that the authors have suitably responsed to all qustions and comments. However, the reviewer still wonder how the authors can explain about tsunami with smaller amplitude as the authors only used M9 class type earthquaukes in their PTHA. Please clarify a bit more this point before getting this manuscript published.

The authors would like to thank the reviewer for the time taken to continue to provide constructive comment on this manuscript. Also, the authors agree that it is necessary to address this point better. As a result, the last paragraph of the discussion section in the manuscript has been changed as follows: *"In fact, earthquakes having smaller magnitudes (such as the 1896 Sanriku Earthquake Tsunami, with an estimated magnitude of 8.2) are also known to have generated tsunamis along the Tohoku coast. Including such smaller earthquake-induced events would improve the accuracy of the estimated return periods for smaller tsunami heights".*

Reviewer B

All responses that the authors gave to my comments were satisfactory. However I noticed that most responses were poorly addressed in the text of the manuscript. Although I am conviced about the quality of this study, I strongly recommend that all comments are addressed with clarifications in the text of the manuscript. This will ensure reproducibility of the results. In the reviewer's files you can find more specific comments in blue colour.

The authors would like to thank the reviewer for the time taken to continue to provide constructive comment on this manuscript. The authors have thus substantially revised and improved the manuscript, as shown in the detailed replies to each comment below. The authors welcome this discussion and remain open to make further changes to the manuscript, should the reviewer have any additional comments.

The response by the authors provides a satisfactory answer to the reviewer's doubts. The addition of the logical diagram provides clarity and transparency that was missing from the previous version. However there is no substantive revision of the text in the article. The text that is presented in quotation marks and italics appears to be the same with the text in the previous version with only exception a minor addition in the first sentence. The author believes that it will be beneficial for the readers and it was level up the quality of the article if the authors provide more context for the logic-tree approach. For example, it can be mentioned here that this is a mainstream method in Japan with more references to studies that have used it. The advantages and disadvantages of using this method in comparison to the rival ‘random phase method’ can also be stressed out.

Apologies for not having improved the manuscript enough. Following the comments from the reviewer, the authors have added the following sentences: *„In Japan, a subcommittee of the Japan Society of Civil Engineers (JSCE) has been established in order to upgrade and propose safety assessment techniques for nuclear power plants against tsunamis. The logic tree method has been introduced as an example of PTHA methods in the technical reference books on tsunamis published by this committee (JSCE, 2006, 2011, 2016). The logic-tree method was also adopted in the PTHA for future Nankai-Tonankai Earthquake Tsunamis, conducted by the Headquarters for Earthquake Research Promotion in Japan (2020). As the logic-tree method has advantages in terms of its simplicity to determine source parameters, it has also been widely used in academic research (e.g., Fukutani et al. 2014, 2015; Sugino et al., 2015; Park and Cox, 2016; Nobuoka and Nogami, 2017). As the framework of the logic-tree method has been formulated based on that of the PSHA, it is relatively easy to combine these two methods and conduct a multi-hazard risk assessment, which is another advantage of the logic-tree method. For instance, Park et al. (2019) conducted a probabilistic seismic and tsunami damage analysis of buildings in their study area by extending the logic-tree model proposed in Park and Cox (2016).“* Also the following sentences were added to clarify the disadvantage of the logic-tree method (and advantage of the random phase method): *“It is worth mentioning that the necessity of assigning a weight to each of the branches is one of the disadvantages of the logic-tree method, as this requires considerable effort in practice and might be influenced by the subjectivity of each expert. In contrast, the random phase method can randomly generate the asperity distribution and* M_w *of a target earthquake, which can appear to be more scientifically justified. However, as mentioned earlier, it is not easy for the random phase method to account for uncertainties in earthquakes other than the distribution of the asperity and the variations in* M_w*.“*

The response to all comments is satisfactory to the reviewer, but relevant clarifications haven’t been included in the article. The reviewer’s opinion is that the responses to all comments below are addressed with additions in text or in the form of supporting information that will have to be published together with this article. This will allow reproducibility of the results of this study

The authors agree that it would be better for future authors to have access to all the information that was provided privately in the response to the reviewer. The following changes were made to the manuscript:

-The clarification of the BPT curve was added as a footnote in line 140: *"BPT curve in itself is not related to any specific seismic parameter, although this curve can be created by using the average occurrence of an earthquake and the parameter of dispersion. These parameters were based on previous studies (NIED, 2013; Fujiwara et. al., 2013). A BPT is used to determine the return periods in this study, which is not related to the determination of the various tsunami source models. The variety of tsunami source models was determined according to the earthquake source type, range of magnitudes and asperity. Note also that in the present study the range of the magnitude is so large that all cases could generate tsunamis."*

-The notes on the distribution of tsunami heights were also added as a footnote: *"Following Annaka et al. (2007), the present study assumed that the distribution of tsunami heights around the median value would follow a log-normal distribution. The standard deviation of the log-normal distribution σ, which is related to an error factor κ (often referred to as Aida's κ in Japan), given as $\kappa = \exp(\sigma)$ (Aida, 1978), was changed to account for different shapes of a log-normal distribution. In the present study, four values were adopted for σ (the same values adopted in Annaka [2007]), meaning that four branches were made in the logic-tree (see Figure 3). "*

-The following sentences were added to section 2.3. *"Essentially, the branches from the logic-tree (except the part relating to the recurrence interval, standard deviation of a log normal distribution and truncation of a log normal distribution) determined the displacement through the parameters of moment magnitudes and asperity. The moment magnitude is used to determine how much the fault area slips (average displacement), and the asperity is used to determine the distribution of the slip amount over the entire fault area (following Sugino et. al., 2014).*

"

-The calculation process of the fractile hazard curves was added as an Appendix, and is mentioned in the text.

Fractile hazard curves are created based on the tsunami hazard curves obtained from the numerical simulations and cumulative weights. An ergodic hypothesis is assumed to define the variation in tsunami heights (an ergodic hypothesis is a hypothesis where the variation of time and spatial domain are equivalent). In this study, Aida's κ and the standard deviation of log-normal distribution σ represent the variation in the spatial and time domain, respectively. Consequently, a tsunami hazard curve (an annual probability of exceedance) can be created. The weight on each of the branches of the logic-tree determines the probable rate of occurrence of the scenarios based on the questionnaire survey of earthquake and tsunami experts and error evaluations, and each value is linked to different tsunami hazard curves as shown in the Figure A1a. At each *tsunami height, different annual probabilities can be estimated and the distribution function of weights for each tsunami height can be obtained (as shown in Figure A1b). According to the distribution function of weights, the cumulative distribution function of weights can be obtained, as shown in Figure A1c. Fractile hazard curves can then be obtained by estimating the annual exceedance probability of different cumulative distribution function of weights.*

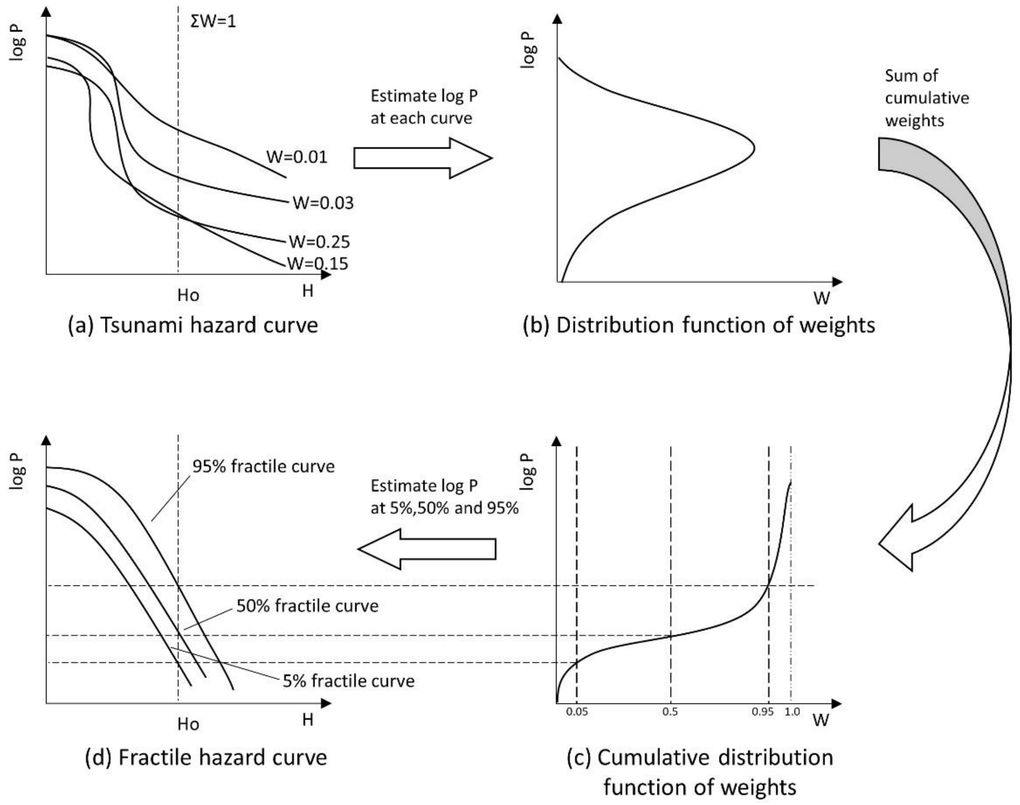


Figure A1. Calculation process of fractile hazard curves (created in reference to Figure 5.3.6-1 in JSCE [2016]).

Reference

Japan Society of Civil Engineers (JSCE). (2016). Tsunami Assessment Method for Nuclear Power Plants in Japan 2016. Retrieved from https://committees.jsce.or.jp/ceofnp04/system/files/TAM2016_main_202010.pdf