Response to reviewers

Title: An Interdisciplinary Agent-based Evacuation Model: Integrating Natural Environment, Built environment, and Social System for Community Preparedness and Resilience

No.: NHESS-2021-370

Dear Reviewers and Editors,

Thank you very much for your comments. We are presenting our responses to the comments from each reviewer. Changes are highlighted as YELLOW in the manuscript revision.

Reviewer 1:

1. This is a well-written and easy-to-understand paper, however, with limited novelty and contribution, at least from the way it is presented.

   Response: *We agree with the reviewer that there are previous studies (Mas et al., 2011, 2012; Wang et al 2016; Chen et al. 2022) that have used agent-based models to analyze tsunami evacuation. While ABM has been a popular tool for many disciplines and topics of studies, there are two major reasons why our study differs from others:*

   1. *This study compares simulation results with the Beat-the-Wave model for the U.S. The BtW model defines clearance time solely in terms of travel speed (and thus, evacuation travel time) rather than as a function of authorities' decision time, warning dissemination time, evacuation preparation time, and evacuation travel time (see Lindell et al., 2019). The BtW model is a reasonable first step for communities or authorities who don't have the capability to conduct ABM analyses. However, the analyses in this article show how our ABM incorporates more realistic assumptions into evacuation time calculations and is a further step to comprehensive evacuation analysis.*
   2. *Compared with previous ABM studies, we include more comprehensive behaviors, disaster, and infrastructure components in our model. New components included in this study: liquefaction and landslide impact as compound disasters, terrain type and slope, travel speed based on drill data, and the integration of evacuation decision and evacuation logistics, using PADM, to inform our ABM.*

2. The main contribution flagged by the authors is the use of 'empirical data' to feed agent behaviors in the model. I found that using local evacuation expectations surveys is not a new approach, so I consider the gap is not being filled here.

   Response: *Local survey data can be useful when we want to adjust a simulation model to a community. For example, people's decisions and intentions, which are different between communities in Japan and the U.S., will impact the evacuation results. Data in Japan suggest more people recognize earthquake shaking as an environmental cue to evacuate, thus evacuating sooner and more on foot than in the U.S., but we didn't know that until we collected data from U.S. communities. Although the integration of evacuation expectations survey data with an ABM is not new, it is the first time a study has used the PADM to guide the collection of evacuation expectations data to inform agents' decisions and behaviors in an ABM for tsunami evacuation on the U.S. West Coast.*

3. In contrast, evacuation drill data can be an essential source to elucidate evacuee behavior, however in some cases also inaccurate compared to the actual behavior in an emergency. It is not clear how the evacuation drill data is leveraged in the study. Only travel speed is adjusted based on the data gathered from the drill, and a modified hiking function is proposed. Changing the hiking function with empirical data from the drill is understandable. Still, the applicability of such a function holds the same uncertainty as the original function since both come from physical experiments and not from a real tsunami situation. I think the authors should not stress the use of evacuation drill data (empirical data) as a novelty since this is another non-emergency-related behavior, and its superiority compared to standard physical experiments cannot be proved.

   Response: *We agree that there are differences between an actual evacuation and a drill evacuation. However, we are unclear whether the reviewer is arguing that the average travel speed is faster or slower in an emergency. Specifically,*

   A. If the argument is that drills underestimate travel speed because people will run rather than walk during an actual evacuation, then using drill data will yield an overestimate of the mortality rate.

   B. If the argument is that drills overestimate travel speed because the drill participants under-represent older and disabled coastal residents, then using drill data will yield an underestimate of the mortality rate.

   Regardless of which argument the reviewer is making (both might be true), we disagree with the reviewer's assertion that an evacuation drill is just "another non-emergency-related behavior". The logical extension of that argument would be that evacuation intentions studies are also just "another non-emergency-related *behavior" that cannot tell us anything about how people would respond in an actual emergency. In fact, predictors of intended evacuation in evacuation intentions studies are the same as the predictors of actual evacuation in post-disaster surveys.*

More fundamentally, we think the reviewer's comment misinterprets our position, which is to determine if our evacuation drill data are ***different from*** *previous results, not* ***superior to*** *them, as the reviewer asserts). Specifically, we know that previous studies have analyzed walking speed but, when we began our study, we didn't know whether the conditions in those studies differed significantly from a tsunami evacuation. That is why we conducted the drill study (Chen et al., 2022). If travel speed in an evacuation drill is the same as the previous (non-evacuation drill) studies, then our simulation model will yield results that are similar to those of previous simulations. However, if travel speed in a drill is different from previous studies, the drill may be better at representing the real situation* ***or we need to find why, and under what conditions, the difference will be generated****. The reason could be: slope, surface, psychological stress, etc. To understand those conditions, a drill is a useful proxy for an actual emergency–which we obviously cannot impose upon a community. Therefore, our use of evacuation drill data is a useful innovation that assesses the generalizability of previously published data walking speed to tsunami evacuations.*

4. On the other hand, site-specific analysis becomes helpful in a particular area. The authors have made an excellent effort to explore the effect of walking speeds on mortality rate.

   Response: *Thank you for the positive comments and we also emphasize the site-specific analysis in the response to comment 2.*

5. Overall the manuscript can be considered a valuable resource for Coos Bay authorities, though very limited in scientific advancement in the field.

   Response: *We agree that this study is a valuable resource for the Coos Bay and Crescent City communities, but disagree that it is "very limited in scientific advancement in the field". In addition to the scientific contributions mentioned in response to this reviewer's comment 1, this study will advances evacuation simulation methods in three ways:*
   1) *The method/framework of integrating expectation survey and drills to simulation in this study can be generalized and used in other communities;*
   2) *The method of integrating inherent relationships (e.g., slope vs. speed in drill; speed vs. terrain surface type) advances the procedures for evacuation simulation; and*

    3) *The method of integrating liquefaction and landslide components as a compound disaster impacting evacuation makes the evacuation simulation more realistic.*

6. Authors can find further comments in the attached document.

   Response: *We have already responded to the majority of the important comments in the .pdf, but there are two additional important comments that we will address:*

7. (from additional comments in the .pdf document) I do not see the 'interdisciplinary' aspect of the paper being presented in the manuscript. In what way this model is interdisciplinary? Weren't previous models also interdisciplinary ABMs?

   Response: *The "interdisciplinary" refers to two aspects: 1. Completing our study involved collaboration among social scientists (decision and behavior layer), coastal and geotechnical engineers (tsunami inundation layer and other disaster layers), transportation engineers (simulation), practitioners, and agencies. 2. This simulation includes three systems - the natural environment, built environment, and social system - to comprehensively represent the tsunami evacuation process.*

8. (from additional comments in the .pdf document) How are the differences in resolution from tsunami layer and topographical layer handled with respect to the resolution of the ABM model? Can you explain if the agent moves along a network, in a continuous space or a grid space?

   Response: *Due to the nature of the data, the tsunami inundation layer and elevation layer have resolutions of 15m and 10m, respectively. We use the highest resolution data we have access to. The agents move along the network in a continuous space. Even though the 15m and 10m data layers create a "puzzle" that may impact agents' behavior (for example, moving from one 10 meter square with a slope of 0.5 to the next adjacent 10 meter square with a slope of 0.6, the speed changes discreetly), the impact from that transition is small enough and is likely to be averaged out, so we believe it can be neglected.*

Reviewer 2:

This is an interesting study that explored evacuation efficiencies of a coastal community in face of tsunami threats. It considered the natural environment, built environment, and social systems that have an impact on the emergency evacuations. Though I have some concerns on specific contents of the model, I suggest to consider it for publication after major revisions. Please see my detailed comments below.

1. The BtW model in abstract shall be spelled out. So is the LCD in introduction.

   Response: *Thank you for this comment. We spelled out BtW in the revised Abstract but LCD was spelled out when it was first used in line 117.*

2. I see there is a Tsunami inundation layer in the model but no simulation of tsunami process. Is the tsunami inundation considered stable from the beginning to the end of the model? I mean do you consider the tsunami process from the start of the tsunami from the coast, the rising of water depth, the extension of inundation areas to inland and the decline of tsunami water? It can make big difference if the tsunami inundation is dynamic or stable.

   Response: *We agree that it makes a substantial difference whether the tsunami inundation is dynamic or stable. That is why the model is dynamic from the beginning of the simulation with the water depth updated every 30 seconds in 15-meter resolution grid cells (see section 2.3.3)*.

3. The authors always stress the unique use of empirical data and evacuation drilling data in this study. But using different data only is not sufficient to be an innovative study. Could you clarify other innovative aspects of the study, e.g. in terms of methodology, evacuation theory or others?

   Response: *Please see our responses to reviewer 1's comments 1, 2, 3 and 5*.

4. Tsunami is not as flood water that may rise over a time period (e.g. in several hours), but likely occurs and threats people in minutes or seconds. Every second matters in such a tsunami triggered by earthquake. So it is important to know what kind of tsunami is simulated in the study, better with more details of the tsunami scenario.

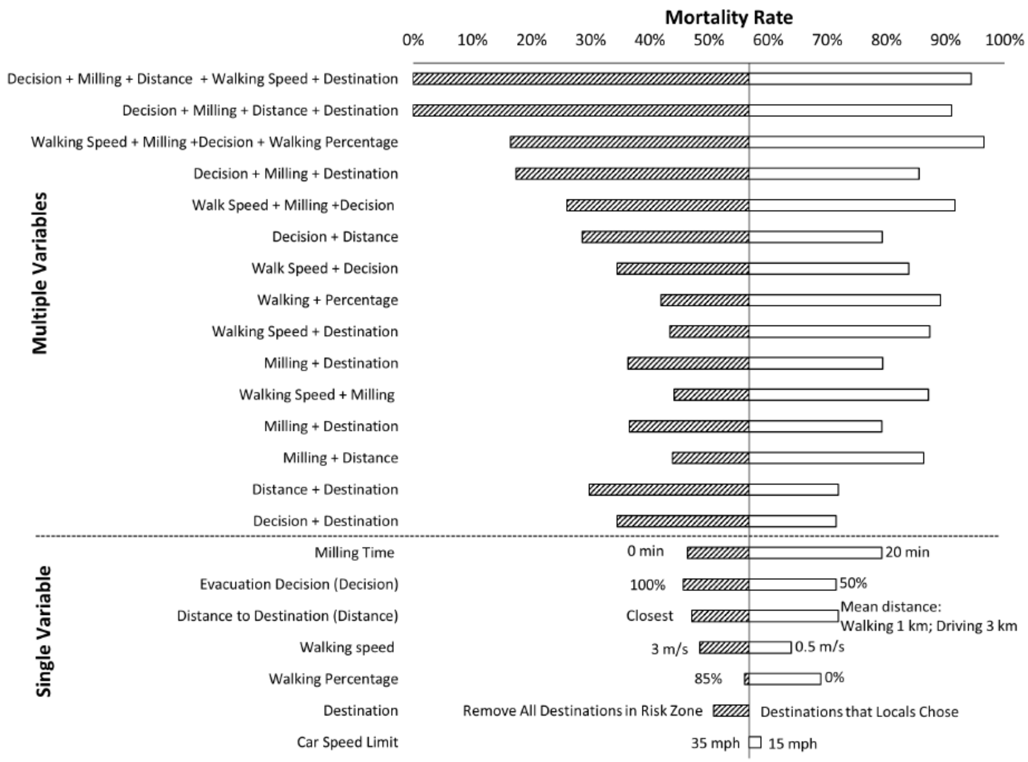
   Response: *As we mentioned in section 2.3.3, our study simulates an M9 CSZ earthquake and tsunami using the XXL tsunami inundation model, which normally refers to a rapid-onset tsunami that will strike U.S. West Coast communities within 20 - 40 minutes. More details can be found in Chen et al. (2021), Witter et al. (1992), and Goldfinger et al. (2012).*

5. Figure 1, please enlarge the map, while the curve plots can be smaller. The pedestrians and cars can not be seen. And, what do the colors in the map mean?

Response: *We have enlarged the map in the revision. If the reviewer is referring to the blue/light blue color, it means the tsunami wave and the colors roughly represent the depth of the tsunami wave. We have added a legend to explain the colors. It is worthy to note that the Figure 1 is visualization of the model GUI of one time moment of one scenario.*

6. It is still hard to understand the process of people evacuation from receiving warnings to being evacuated. How do people make decisions and how much time do each activity take? I suppose a flow chart would be helpful to illustrate the decision behaviors, process and their time needs. The authors may want to refer to the daily routine chart in the study: An agent-based modeling framework for simulating human exposure to environmental stresses in urban areas. Urban Science 2 (2), 36. https://doi.org/10.3390/urbansci2020036

   Response: *The decision-making and milling process has been well documented in the PADM (Lindell, 2018; Lindell and Perry, 2012), which we used as a guide to collect survey data on people's expectations about their activities and the time they would take in the milling process. As noted in Section 2.3.1, the ETE model defines the time to clear the risk area as a function of authorities' decision time, warning dissemination time, evacuation preparation time, and evacuation travel time (Lindell et al., 2019). Since environmental cues are the principal source of information about the threat of a local tsunami, the components for authorities' decision time and warning dissemination time are zero, so the only relevant ETE components are evacuation preparation time, which is estimated from the survey data, and evacuation travel time, which is computed in the ABMS. When we designed this study, we decided that a detailed analysis of the milling process was beyond its scope, so we included a sensitivity analysis to test the impact of milling time on evacuation results. As the "Single Variable" panel in Figure 8 indicates, milling time has the most significant impact on mortality rate of all the variables. This means that emergency managers should tell coastal residents that they need to leave as soon as possible after earthquake shaking stops.*



We examined the article that the reviewer suggested and we agree that time of day can make a difference in the activities in which people are engaged when threatened by a disaster. Indeed, we have previously published a figure that provides time budget data that can be used to adjust estimates of warning dissemination and evacuation preparation times (Lindell & Perry, 1992, Figure 4.3). Although we would have liked to collect data on respondents' estimates of their milling times at different times of day/days of the week, limitations on questionnaire length precluded inclusion of those items. Accordingly, this issue should be examined in future research.

7. what does the equation 1 mean? What is x and f(x), and why is it this equation but not others?

   Response: *x means the milling time and f(x) means the probability of having that milling time for an individual. We have edited the paragraph to explain it more clearly. Regarding why we chose the gamma distribution, Section 2.3.1 stated that we used maximum likelihood estimation to test three different distributions that are suitable for this type of data. The results in Figure 2 show that the gamma function yields the best goodness-of-fit statistics.*

8. In figure 3b, why is it more percentage of people evacuating by foot when the distance is longer?

__Response:__ The original submission might have been confusing because the y-axis scale was for Proportions (i.e., it ranges 0-1) but was labeled Percent. Consequently, we have relabeled the y-axis in Figures 3b and 3d "Proportion". In addition, we have revised the text to make it clear that Figures 3b and 3d are cumulative distribution functions, which indicate the proportion of the respondents who would evacuate a given distance __or less__. For example, Figure 3b indicates that the proportion of the respondents who would evacuate 500m or less is p = 0.20, whereas the proportion of the respondents who would evacuate 1000m or less is p = 0.60. Also, the range of the x-axis is different for 3b and 3d to accommodate for the size and visualization of the figure.

9. Section 2.3.2. Built Environment shall better be introduced as traffic environment. There is only roads and bridges considered but no buildings at all.

   __Response:__ "Traffic environment" is not better than "built environment"; the reviewer's preferred term is just more specific than the term we are using. We use the term "built environment" in this study because we expect future studies to examine the effects of evacuation delays due to building collapses from earthquake shaking, liquefaction, and landslides–cases in which the term "built environment" would unquestionably be appropriate. More generally, we have adopted the interdisciplinary three system graph advocated by others (Melit, 1999; Murray-Tuite et al., 2021).

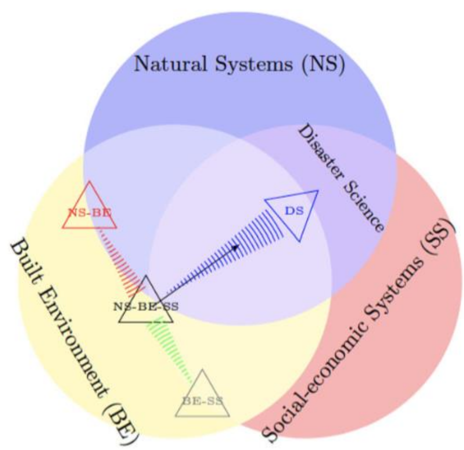


Fig. 1. Definition of disaster science (adapted from Mileti, 1999).

In our study, the built environment system includes transportation facilities, the non-retrofitted bridges, and the impact from landslides and soil liquefaction on the road network. Even though our study does not examine 100% of the built environment system, it critically affects the evacuation. We discussed this limitation and the need for further research in the conclusion section:

“Future research should investigate 1) the impact of more complex agent-agent interactions, such as leader-follower behaviors and grouping behaviors (Chen et al., 2020), as well as car abandonment (Wang et al., 2016); 2) the impact of building damage from earthquake before tsunami (Gomez-Zapata et al., 2021); 3) authorities’ decision and warning dissemination processes for distant tsunamis; and 4) validation of the model using data from actual tsunami evacuations.”

10. Figure 6, when milling time is 50 minutes, mortality rate is 100%, which means all people died. This is not realistic unless you assume all people in all areas of the study region will all be in the tsunami water. This requires a sound explanation or major update.

    Response: *The maximum mortality rate is 100% because the analysis only included people living in the inundation zone. If our analysis had also included people outside the inundation zone, then a tsunami that killed 100% of the people in the inundation zone might only show a misleadingly low mortality rate–for example, only 10% of the population of the entire city. We ignored the possibility that people living outside the inundation zone would enter it so they could see the tsunami wave [there is a very small percentage that actually do so (Lindell et al., 2015)]. However, the behavior of others outside the inundation zone who also try to evacuate could impede the evacuation of those inside the inundation zone because this shadow evacuation would create traffic jams that prevent people in the inundation zone from reaching safety before first wave arrival (see Lindell et al., 2019, for a discussion of shadow evacuation). The revision contains a sentence in the caption explaining that the reference population is the population of the inundation zone.*

11. I assume the very important factors shall include warning time in advance and the location of shelter destinations that could more significantly affect the mortality rate. It would be great if the authors can run the model with some longer warning time and more or less shelter destinations, and to compare the mortality rates. I suppose the result would be more significant than walk speed or travel mode. Destination is uphill and inland

    Response: *As noted in the revised introduction, a local tsunami caused by a CSZ earthquake will only provide 20-40 min warning time. Thus, increasing the “warning time in advance” is not technologically feasible for local tsunamis in the CSZ because it would unrealistically presume that the U.S. Geological Survey is able to forecast an earthquake before it occurs.*

    CSZ residents have been informed that they should evacuate as high as they can and as far inland as they can after the earthquake strikes but before the tsunami arrives. Accordingly, we asked the respondents to identify the accommodations/

destinations to which they expect to evacuate. These may not be actual buildings (i.e., a structure and supplies), but all destinations are based on community and destination survey data we collected (Chen et al., 2021). As Figure 8 indicates, distance to destination has less influence on mortality rate than milling time but about the same as the evacuation decision rate.

12. In conclusion, you wrote "Three distinct contributions of this study …" but you actually listed four contributions.

    Response: *We changed "three" to "four"; thank you for calling our attention to this oversight.*

References:

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