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Natural Hazards and Earth System Sciences
Discussions

Interactive comment on "Detectability of seismic waves from the submarine landslide that caused the 1998 Papua New Guinea tsunami" *by* Akio Katsumata et al.

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Dear Editor and the reviewers of NHESS,

We summarize the responses to the comments from reviewers and other researchers, and show tentative revised manuscript as the supplement. The comments are categorized in several kinds below.

1 Signals of high-frequency

There were comments that the 1998 PNG landslide had been detected with hydrophones and high-frequency seismic data.

Reviewer #1 (Prof. Fryer) Fourth, Katsumata, et al. ignore hydrophones in their discussion of potential detection systems and instead suggest direct detection of the tsunami via pressure gauges like S-net. But direct detection is intrinsically slow because you have to wait for the tsunami to reach your sensor. Since sound waves in the ocean travel faster than the tsunami, hydrophones potentially provide more warning time and would therefore be superior. Again, the Caplan-Auerbach paper is relevant here.

Prof. Tappin Fryer identifies missing references and the potential for T-phase warning which could provide an alternative approach.

Reviewer #2 First, Katsumata et al are trying to find the signature of the submarine slide in the seismic record, without mentioning and describing in the figures that 4 aftershocks were identified during the 22 Minutes following the main shock (Synolakis 2002). In Figure 3 JAY record shows that waves of the two largest aftershocks are arriving at 09:09.30 and 09:10:30 (not mentioned by the authors). Synolakis specified that one of the aftershocks at 09:02 mb 4.4 could correspond to the submarine landslide. In Figure 1 an additional record filtered 0.1- 1 s would probably help to show the high frequency waves of this aftershock, in fact the slide. Long duration of main shock ($>$ 2-5 min) and aftershocks occurring in the tens of minutes after the main shock could definitively masked the waves generated by the submarine landslide generated in the 10-20 minutes following the quake. But as this event was identified and located by seismic waves picking and measurement, signal should be visible on the JAY record at higher frequency (> 1 Hz).

Reviewer #2 Conclusion : Katsumata et al finally demonstrate that the synthetic record obtained for JAY seismic station doesn't match with the observed record in the specific band (50-100s). JAY record shows that no signal is visible in the bandwidth of 0.5s to 100s, 13 minutes after the quake, when the slide waves are expected. The conclusion of the authors is not relevant : other type and parameters of the slide could be modeled to compute synthetic records and compare with JAY record in higher frequency band (0.1 - 1s). Detect, identify and warn a tsunami due to submarine or aerial slide following large earthquake is definitively a complex challenge, essentially because of the duration of the quake and also the number and magnitude of aftershocks. As mentioned by Katsumata et al., S-net and DONET equipped with accelerometers, seismometers and pressure sensors are the most likely candidates to detect and warn submarine landslide. Nevertheless seismic arrays and seismic stations located closer to the slide (< 100 km) could be able to detect slide waves. In addition, hydroacoustic arrays (Synolakis) and coastal seismic station located on islands close to the epicenter could also help to detect T phase generated by the quakes and those generated by the slide. This paper needs major revision.

Prof. Tappin The anonymous reviewer (RC2) undoubtedly identifies a fundamental flaw in the analysis. The PNG 09.02 'seismic' event is unique and was identified by Synolakis et al. as reflecting the slump movement, not a seismic event. The modelled and observed signals do not match. The authors have to go back and revisit the frequency signal at this time, and address this before the paper can be published – it is fundamental to the papers conclusions and the possibilities for tsunami warning from submarine landslides.

Prof. Okal The main argument of the paper is that there is no detectable seismic signature to the landslide which generated the catastrophic PNG tsunami of 17 July 1998. This statement directly contradicts the work of Okal [2003], in which I presented (on Figure 3) and discussed in detail the record of the landslide at the

same station JAY allegedly studied by the authors. It is clear that they used the wrong (very low-frequency) filters, and thus missed the signal. They do not justify working in such inadequate frequency bands, and completely ignore the detailed analysis of seismic and hydroacoustic phases which went into my 2003 paper.

(Response)

- We added descriptions about detections of the landslide and aftershocks by hydrophones and high-frequency seismic wave. However, We considered that size estimation is indispensable for tsunami warning purpose. Size of landslide is an indispensable factor to estimate tsunami height. Passband of instruments should cover the process duration to estimate the size of the event properly. Frequency ranges of hydrophones and high-frequency seismic records do not cover the frequency related to the duration of the landslide. We missed to describe importance of landslide size estimation for tsunami warning purpose in the previous manuscript. We added description in "Introduction" to claim that hydrophone is not useful for estimation of landslide size. The duration of the waves would reflect the duration of the landslide. However it is not directly connected to the mass.

2 Analysis method

Reviewer #2 Second, the synthetic records obtained by modeling by Katsumata et al, for the closest station JAY, are of much bigger than the waves on records, in the 50-100s band. As mentioned by Fryer, the slide could be a slump type, or debris avalanche type, and in addition, the rheology parameters could vary extremely. The conclusion is, because no signal is visible in the bandwidth 50-100 s on the JAY station record, the hypothesis of the synthetic source and propagation performed by the authors is probably not correct. Katsumata et al should performed other synthetic records, knowing that in the Figure 2 shows that, at JAY station, in the bandwidth 0.5s to 100s, no clear signal is visible at the theoretical arrival time of the waves of the slide.

- Analatical solution for a homogeneous unbounded media shows that far field displacement is proportional to the force amplitude (e.g., Aki and Richards, 2002). Whereas complex process may affect the seismic records and total energy may be changed extremely according to travel distance, the peak force acting on the ground should be constrained by the total mass and its acceleration.

  The calculation procedure was checked with the result of Takeo (1990, JGR). It is true that the synthetic amplitude in Fig. 5 is too large compared with the observed records. Seismic phases are not recognized either at GUMO, CTAO, WRAB, and DAV. A simple explanation for those would be that the assumed force might be too large. We do not insist on the correctness of the assumption. Rather our conclusion is that detection of landslide with long-period seismic wave is difficult after a big earthquakes.

Reviewer #2 Third, other processing methods exist to help to identify waves visually or by signal processing : computation of spectrograms is one of the efficient method, and computation of polarization parameters of waves.

- We added spectrograms in Figure 2.

3 Landslide type

Reviewer #1 (Prof. Fryer) First, the paper treats all submarine landslides as if they are the same, but landslides have a broad range of characteristics which should at

least be mentioned. The landslide types most important in generating tsunamis are slumps and debris avalanches. A slump is a landslide in which a coherent block of material slides downslope on a rotational slip surface. The event is of relatively short duration (a few tens of seconds) and downslope motion is relatively small, so remote detection of the slope failure is going to be a challenge. The PNG tsunami came from such a source. A debris avalanche, by contrast, involves complete disintegration of the sliding body, motion lasts for a long time (conceivably several minutes), and both downslope motion and runout at the base of the slope are large. The St. Helens landslide the authors refer to was a debris avalanche. Even if we cannot warn of slump-generated tsunamis, the larger signals from debris avalanches should allow us to warn of those events.

Prof. Tappin To confirm, the PNG landslide was a slump. I mapped it.

- We added description about various types of submarine mass failure referring to Schwab et al. (1993), and mentioned that the 1998 PNG event had a relatively short travel distance.

  It is considered that the amplitudes of seismic waves are proportional to the peak force. Even if the duration of mass motion is long, the amplitude of the seismic waves would not be different for the same size of forces. We added this description in the section of synthetic seismogram.

4 References

Reviewer #1 (Prof. Fryer) Second, no mention is made of those landslides which have been detected remotely. Ekström and Stark (Science, March 2013), have identified large subaerial landslides from broadband seismology, while Caplan-Auerbach, et al. (GRL, May 2001) have detected submarine landslides from hydrophone data (note that in both these cases the landslides identified were debris avalanches rather than slumps). No mention of either of these is made in the paper.

- Landslides detected remotely by seismic waves are mention in the section of "Discussion". However, Ekström and Stark (2013) was not referred to. We added descriptions about Ekström and Stark (2013) in sections of "Synthetic seismograph" and "Discussion" with other references about seismic waves from landslides. We also referred to Ekström and Stark (2013) as "acceleration and deceleration stages" and "scaling relationship of surface wave magnitude".
- As to detection of landslides with hydrophones, Synolakis et al. (2002) and Okal (2003) showed a hydrophone record from the 1998 PNG landslide. We added Caplan-Auerbach, et al. (2001) as a reference. It is considered that the detection of waves from landslides are possible with hydrophones. However, we consider that identification of landslide and estimation of size of landslides are difficult with hydrophone data. We added such description in "Introduction".

Reviewer #1 (Prof. Fryer) Third, Katsumata, et al., credit Kodaira, et al. for the suggestion that a landslide supplemented the 2011 Tohoku tsunami, but make no mention of the more detailed analysis and modeling by Tappin, et al. (Marine Geology, 2014), which pretty much confirms that there was a landslide. There should at least be a reference to the paper of Tappin, et al.

- We changed the manuscript with adding Tappin, et al. (2014) as a reference.

Prof. Tappin I question some of the interpretations of the different tsunami mechanisms in the Mediterranean. There are major seismic hazards here, such as Messina, 1908 and the EBTP of 365 AD. There are other earthquake tsunamis

in the Ionian Sea. The work of Salamon et al., is questionable as it is based on the interpretation of ancient texts in earthquake identification (intensities) and not on modern methodologies of marine mapping and seismological identification of earthquakes and their magnitudes. A more appropriate reference is: Papadopoulos, G.A., Gárcia, E., Urgeles, R., Sallares, V., De Martini, P.M., Pantosti, D., González, M., Yalciner, A.C., Mascle, J., Sakellariou, D., Salamon, A., Tinti, S., Karastathis, V., Fokaefs, A., Camerlenghi, A., Novikova, T., Papageorgiou, A., 2014. Historical and pre-historical tsunamis in the Mediterranean and its connected seas: Geological signatures, generation mechanisms and coastal impacts. Marine Geology 354, 81-109.

- We added this suggested paper. However sources of many tsunamis were not identified in this paper. We did not change the context of "Discussion" so much.

Prof. Tappin The Salamon reference is missing. I don't think there is a peer reviewed paper from 2011. 2007 maybe from the eastern Med?

- We received this paper PDF directly from the author. However, we could not reach the journal page, either. So we replaced this reference with BSSA, 2007.

Prof. Okal It is wrong to use the reference to Tappin et al. [2008] to suggest that the slide underwent a "deceleration stage affected by interaction of the sliding mass with sea water". All submarine slides will feature such interaction. What was unique in the PNG slide was that it was stopped abruptly when it abutted against the opposite wall of the amphitheater in which it took place. All of this was explained in detail by Synolakis et al. [2002] and Okal [2003]; as mentioned above, the authors seem to ignore the latter paper, as they ignore the fundamental paper by Sweet and Silver [2003], who conducted the in situ discovery and study of the slide.

- We did not refer to Tappin et al. [2008] to explain the acceleration and deceleration stages. We referred to Tappin et al. [2008] as the estimation of the landslide duration. We added Ekström and Stark (2013) as the reference for acceleration and deceleration stages. We also added Synolakis et al. [2002], Okal [2003], and Sweet and Silver [2003] to mention the stopping of the landslide.

5 Expression

Reviewer #1 (Prof. Fryer) I have only one specific comment on the writing. On page 4, lines 9-14, in a rather awkward passage, the Mediterranean is described as "seismically inactive." I understand the point that the authors are trying to make, but most readers will not. I recommend instead that they write something like "The Mediterranean is a region where seismic activity is low enough that most of the known tsunamis have been caused by landslides (Salamon, et al., 2011). Because of the greater seismicity, such conditions do not exist in southeast Asia. It is plausible there that heavy rainfall and rapid deposition of terrigenous sediment offshore might contribute to the occurrence of submarine landslides, including the PNG landslide, despite their location in a seismically active region."

- We followed this kind suggestion.

Prof. Okal I note on Page 4, Line 9 the statement "The Mediterranean is a seismically inactive region"! This is completely false. The USGS catalog contains 1132 events with at least one magnitude reaching 5 or greater for the period 1963–2015, between latitudes 30 and 45°N, longitudes -5 and 35°E, and depths 0 and

100 km... This factually wrong scientific statement takes an insulting societal tone when confronted to the memory of the thousands of victims of earthquakes in the Mediterranean Basin, documented since historic times.

- We must admit that the expression of "inactive" was improper. We changed expression following a comment from Prof. Fryer.

Prof. Okal The dynamics of the underwater PNG landslide and of the Mt. St. Helens one are totally different, given that the latter was caused by an atmospheric explosion, and reached velocities of 70 m/s (as documented from films) which cannot be sustained by underwater landslides.

- We referred to Kanamori and Given (1982) just to compare the force values. We do not discuss the difference in the sliding process.

6 Effectiveness

Prof. Okal The proposal to densely instrument the seafloor in order to detect and identify in real time a landslide and issue a warning is naive in the context of the PNG tsunami, given that the whole process would have to be realized in a few minutes. Most of the casualties at Sissano resulted from the lack of an escape route: the residents were trapped on a narrow spit of land between the Bismarck Sea and Sissano Lagoon. The only survivors had managed to climb the few trees which were not uprooted. As such distances, the only reliable means of tsunami mitigation is proper planning (the village should not have been built on the spit), and in real-time, self-evacuation. References Okal, E.A., T waves from the 1998 Papua New Guinea earthquake and its Fryer identifies missing references and the potential for T-phase warning which could provide an alternative approach.

- Evacuation method is a very important factor for mitigation of tsunami disaster. We consider that awareness of coming tsunami is also an important one at the same time. Only when all factors are controlled properly, the victims would be reduced. So we think that we should pay attention to awareness of coming tsunami. When T phase from a landslide is detected, we consider that tsunami height can not be estimated only from T phase.

Please also note the supplement to this comment:
https://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2018-317/nhess-2018-317-AC4-supplement.pdf

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