Tsunami hazard from submarine landslides: scenario-based assessment in the Ulleung Basin, East Sea (Japan Sea)

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ABSTRACT: In this study we use a scenario-based approach to highlight potential tsunami hazard from actual Late Pleistocene submarine landslides in the Ulleung Basin: two submarine landslides on the western slope of the Ulleung Basin, north and south of the Hupo Bank (2.53 and 1.12 km³ respectively) and a landslide (15.1 km³) on the continental slope south of the Ulleung Basin. The simulations attempt to highlight the consequences, should one of these events occur at Present. Results of the simulations indicate potential local hazard zones with very local waves <2m high in the Korean coast of the East Sea that could result from mid-sized landslides, not exceeding 3 km³ on the western slope of the basin. Time available for early warning since onset of these events is between 15-30 min. On the other hand, the continental margin south of the Ulleung Basin is an area where landslide tsunamis with significant hazard potential could originate. New landslides of similar size to those of the Late Pleistocene could produce tsunami waves >3 m in the stretch of coastline from Ulsan in the south to Uljin in the north. The timing available for early warning from landslide tsunamis originating in this area is 15-30 min along the affected section of the shoreline. We also suggest a Probabilistic Tsunami Hazard Assessment (PTHA) for comprehensive assessments of Korea's East Sea Coast. PTHA accounts for uncertainties in location, release mechanisms, evolution, and return periods of submarine landslides as well as epistemic uncertainty. However, to constrain these uncertainties detailed information on source areas, recurrence period and dynamics of submarine landslides is necessary and calls for additional data collection and further studies.

Key words: submarine landslides, tsunami hazard, Ulleung Basin, East Sea (Japan Sea)

1. INTRODUCTION

Tsunamis threaten coastal communities, infrastructure, and global economies (Morgan et al., 2009). The destructive power and damaging effects of tsunamis were shown by the catastrophic 2004 Sumatra (Mw 9.3) and 2011 Tohoku (Mw 9.0) earthquakes (e.g., Titov et al., 2005; Mori et al., 2011). Despite most tsunamis originate from subduction earthquakes (Satake and Atwater, 2007; Harbitz et al., 2014), submarine landslides may also generate tsunami (Papadopoulos et al., 2014; ten Brink et al., 2014). In the past, however, tsunamis generated by submarine landslides have been overlooked by the tsunami research community (Gusiakov, 2003; Tinti, 2003; Grilli et al., 2009; Harbitz et al., 2014).

Submarine landslide tsunamis differ from earthquake tsunamis in a number of ways (Fig. 1). Earthquakes make almost instantaneous energy input into the water column over the entire ruptures, but submarine landslides, which travel at tens to hundreds of meters a second, reduces their efficiency in tsunami generation (Tappin, 2017). The maximum wave height and energy of generated surface waves depend on various landslide parameters and factors, including landslide volume, type of landslide (viscous or rigid), landslide density, landslide position (relative height or depth), and slope angle (Fine et al., 2003). Submarine landslides are most of the times subcritical, which implies that the tsunami will run away from the wave-generating landslide (i.e., the tsunami travels faster than the landslide), limiting the build-up of the wave. However, for a landslide occurring in shallow water, effects of critical landslide motion (Froude number = 1) give large localized waves as illustrated by Ward (2001), resulting in more hazardous waves than if the same landslide occurred in deep water. There is also a strong directivity along the landslide axis of motion (Fryer et al., 2004; Enet and Grilli, 2007; Waythomas et al., 2009) that often

results in the focused local runup (e.g., Ruffman, 1997; Tappin et al., 2008), the magnitude of which is a function of tsunami source location, initial wave amplitude, and wavelength. The 1929 Grand Banks event (13 m) (Fine et al., 2005), the 1998 Papua New Guinea event (15 m) (Tappin et al., 2008) and the 1979 Nice event (3 m) (Assier-Rzadkiewicz et al., 2000) are just three examples of historical submarine landslide tsunamis that had large run-up heights locally. Earthquakes and tsunamis may also operate in combination to augment the damaging character of the resulting tsunamis. Hereof, it is to note that during the 2011 Tohoku earthquake and tsunami, the exceptionally high tsunami runups of up to 40 m recorded along the central Sanriku coast between 39.2° N and 40.2° N have been explained with an additional tsunami source, a submarine landslide located almost directly east of the central Sanriku coast (Tappin et al., 2014).

“Figure 1 is about here”

Tsunami risk assessment for the Korean coasts is based entirely on earthquake scenario simulations (Lim et al., 2008 and references therein), despite large submarine landslides are widely present on the western and southern slopes of the Ulleung Basin. As indicated above, tsunamis from submarine landslides have been largely ignored in the past, but estimates indicate that they could actually account for a significant portion of the tsunami record (Gusiakov, 2003; Tinti, 2003; Grilli et al., 2009; Harbitz et al., 2014). In Korea, many coastal communities, harbors and ports, as well as key industrial facilities are located along the eastern coast. Furthermore, 18 reactors at three nuclear power plants are now operating on the eastern coast, and several more plants are under construction (Choi et al., 2016). For nuclear applications, the annual design probability can be as low as 10^{-4} to 10^{-6} (Nicholson et al., 2013), corresponding to events with a mean return period in between 10 kyrs and 1 Myrs . Tsunami hazard assessment at those very low probabilities calls for inclusion of submarine landslides in the analysis (Geist and ten Brink, 2012),

particularly when large slope failures, such as those along the Korean side of the East Sea, have been extensively mapped. The US Nuclear Regulatory Commission considers submarine landslides as the most likely source of tsunami in the US Eastern coast (Nicholson et al., 2013). Recurrence information for submarine landslides is however uncertain or altogether lacking in Korea, resulting in high uncertainty in the source term for probabilistic analysis, compared to earthquake recurrence.

The aims of this study are therefore to (1) highlight potential tsunami hazard from submarine landslides on Korea's East Sea shore using scenario-based approaches and (2) assess the need for a Probabilistic Tsunami Hazard Assessment (PTHA) for the eastern coast of Korea focused on submarine landslides.

2. CHARACTERISTICS OF SUBMARINE LANDSLIDES IN THE ULLEUNG BASIN

Late Pleistocene slope failures on the western and southern continental slopes of the Ulleung Basin have disparate characteristics. Slope failures originating from the western margin have relatively small dimensions, while on the southern margin slope failures are at least one order of magnitude larger and may travel for several tens of kilometers along the slope and Ulleung Basin plain (Lee et al., 2014). The differences in failure volume are thought to result from variations in sediment supply, with the southern margin displaying much higher sedimentation rates, particularly during the glacial periods (Lee et al., 2014). Lee et al. (1999) identify at least 9 major Late Pleistocene debris flow events originating from slope failure of the southern margin with minimum volume estimates attaining up to 33.6 km³ and minimum run-out distances of up to 127 km (Table 1). To provide a scale of

these events, it is worth noting that the largest of these event covers an area of 1319 km², implying 1% of the territory of the Republic of Korea on-land.

Detailed side-scan sonar imaging and sediment coring of debris flow 8 (Table 1) have shown that these large debris flow lobes may actually result from multi-staged slope failure (Lee et al., 2013). Up to eight individual sedimentary bodies have been found to constitute debris flow 8 in the Ulleung Basin, suggesting that emplacement took place in a retrograding fashion in between 20.0 and 17.0 cal. ka B.P.

“Table 1 is about here”

Dating of turbidite successions in the Ulleung Basin shows variations in the frequency of slope failure from the southern margin throughout the last 30 kyrs and indicate a reduced rate of slope failure during the Holocene. Between 29.4 and 19.1 cal. ka B.P., various thin- to very thick-bedded turbidites accumulated at an average recurrence interval of ca. 605 years (Lee et al., 2010). After 19.1 cal. ka B.P., turbidites were deposited at a much larger average recurrence interval of 3,183 years at the same time that their thickness abruptly decreased. This depositional sequence suggests that slope failures of multiple sizes were frequent during sea level lowstands while the frequency and relative volume of these slope failures significantly decreased during the Holocene (Lee et al., 2010). An upward change from muddy to sandy turbidites around 21.4 cal. Ka B.P. suggests that the failing areas retrograded from the muddy upper-middle slope to the sandy uppermost slope when sea level was nearly at its lowest (Lee et al., 2010).

3. METHODS

3.1. Input Bathymetric Information

The bathymetric information used for tsunami modeling and to support the interpretations is based mainly on an ASCII (text) grid file in longitude latitude coordinates at 0.0009° resolution both for the X and Y directions (Fig. 2). The 0.0009° resolution approximately corresponds to 100 m resolution in the Y direction and about 80 m in the X direction at the 37° latitude. The bathymetric data were acquired by the Korea Hydrographic and Oceanographic Agency (KHOA) during the multibeam bathymetric survey of the East Sea in 1996 to 1997 years for “Basic Maps of the Sea” of Korea.

Missing elevation information in the multibeam bathymetric data set were filled with Shuttle Radar Topography Mission (SRTM) and ETOPO1 Digital Elevation Model (DEM) data. All data was converted to GMT (Wessel et al., 2013) ‘netcdf’ format sampled to the resolution of the multibeam data set, merged in one single grid file (Fig. 2) and converted to UTM coordinates (zone 52N) using MIRONE (Luis, 2007).

“Figure 2 is about here”

3.2. Tsunami Wave Model

The tsunami wave model chosen for this study is Geowave (e.g., Watts, 1998; Watts et al., 2003). Geowave simulates tsunami generation, propagation, and inundation using a fourth order fully nonlinear, fully dispersive Boussinesq wave model with multiple wave dissipation mechanisms, wave breaking, and dry land overflow (Wei et al., 1999; Chen et al., 2000; Kennedy et al., 2000). Geowave provides a programming architecture to generate multiple tsunami sources with TOPICS and to insert those tsunami sources at the appropriate time into a simulation run in a modified version of FUNWAVE.

This study employed the source code made available to registered users of Geowave that was compiled under a Linux environment using ‘gfortran’. Simulation

results were visualized using a series of C-shell scripts and the Generic Mapping Tools (Wessel et al., 2013). The only modifications made to the source code relate to the dimensions of the input grid (800x800 in the original code versus 4000x4000 in the code used for this exercise), the number of time steps (8001 in the original code versus 15000 in the code used for this exercise) and the sponge layer thickness at the edges of the simulation domain (10 in the original code versus 25 in the code used for this exercise). Tide gage records have been computed at 4 stations along the Korean coast: from north to south these are Sokcho (11.8 meters water depth (mwd)), Donghae (0.8 mwd), Deokcheon-ri (1.5 mwd) and Pohang (15.8 mwd) for a simulation time of 65 min. (Stars in Fig. 2).

4. RESULTS

The work presented here concentrates on assessing tsunami hazard from submarine landslide sources in the western and southern shores of the Ulleung Basin based on three different scenarios (Table 2, Figs. 3, 4, and 5). Due to their proximity to the Korean coast, landslide tsunami sources originating in these areas are most likely to create damage to coastal settlements and infrastructures. These landslidetsunamis are likely to induce higher runup than landslide tsunamis originated elsewhere in the basin, while timing for early warning will be the shortest. The simulations carried out in this study produce tsunami scenarios based on actual submarine landslides identified in the basin from acoustic and geophysical data. These scenario-based simulations do not intend to assess exhaustively the landslide tsunami hazard to Korea's East shore, but just to present the significance of such events in determining hazard to coastal settlements and infrastructure. Nevertheless, the three scenarios, amongst multiple submarine landslides present in the data set, are

chosen to produce an overview of the consequences of potential landslide tsunamis for Korea's East shore. The three case-scenarios:

1. a Late Pleistocene submarine landslide north of the Hupo Bank on the continental slope west of the Ulleung Basin (Fig. 3).
2. a Late Pleistocene submarine landslide south of the Hupo Bank on the continental slope west of the Ulleung Basin (Fig. 4).
3. a Late Pleistocene submarine landslide on the continental slope south of the Ulleung Basin (debris flow lobe 8 of Lee et al. (1999); Fig. 5).

represent worst-case scenarios for each individual submarine landslide, as the slope failure is assumed to be triggered as a single stage slide (see Table 2 for geometric and geographic characteristics of the submarine landslides that made the different scenarios). The slide approximation used in Geowave is probably correct for the initial stages of slope failure, which have most influence in tsunami generation (Watts et al., 2005; Harbitz et al., 2006; Enet and Grilli, 2007; Løvholt et al., 2015). However, the initial slides most likely disintegrated to form a debris flow as observed in many instances in the Ulleung Basin (e.g., Lee et al., 1999, 2013).

“Table 2 is about here”

Tsunami simulations of maximum water wave elevation are made for each scenario and initial wave properties are given in Table 2. The tsunami simulations carried out for this exercise were performed with the Present-day sea level as free surface elevation datum. Nevertheless, at the time of occurrence of the various simulated submarine landslides, the sea level could differ from the Present one. Therefore, the simulations highlight the consequences should one of these failures occur at Present and not what actually happened at the timing of occurrence of these slope failures. On top of that, the

tidal stage during a tsunami cannot be predicted and is, therefore, a source of uncertainty (Mofjeld et al., 2007).

“Figures 3, 4 and 5 are about here”

4.1. Case 1: Submarine Landslide North of the Hupo Bank

The first tsunami scenario is the result of a slope failure on the continental slope west of the Ulleung Basin immediately north of the Hupo Bank. This landslide is similar in characteristics to the one identified by Cukur et al. (2016) with higher resolution bathymetric data and complete set of geophysical information. The slope failure occurs in water depths of 400 to 900 meters below sea level (mbsl) and results in an arcuate shaped embayment on the slope that is 7.6 km wide and 12.8 km long (Table 2). The landslide scar is relatively constant in height (~26 m) and the failure plane is parallel to the slope, which indicates that the failure most likely initiated as a slide (Fig. 3). The failure occurred on a very gentle slope of only 2° and no deposits can be observed on the bathymetric data associated to the landslide scar. This indicates that the initial slide likely disintegrated to form a debris flow that travelled all the way to the Ulleung Basin. The submarine landslide characteristics, modeled by Geowave indicate an initial acceleration (a_i) of 0.08 ms^{-2} , a terminal velocity (v_t) of 67.3 ms^{-1} , a characteristic time (t_c) of 794 s and a characteristic distance (d_c) of 23.2 km.

The terminal velocity of the landslide v_t is the maximum velocity that a submarine landslide can attain due to the drag force exerted by water, with thicker slides attaining a higher speed (Enet and Grilli, 2007; Xiao et al., 2015). Based on the equations of motion given by Watts (1998) and Watts et al., (2000) we estimate that the terminal velocity (v_t) of the center of the slide was reached at the base of the slope at ~1700 mbsl. The phase speed

of a tsunami (or its celerity) in water $H = 1700$ m deep, is $\bar{c} = 130$ m/s. The higher tsunami velocity compared to the landslide means that, the landslide was not ‘in phase’ with the tsunami it was generating, and therefore it was not efficient in building a large size tsunami (Tinti and Bortolucci, 2000; Fryer et al., 2004).

The characteristic time t_c designates the moment after failure when the wave build-up is finished and transformation of potential energy into kinetic energy takes place (Brune et al., 2010). It is defined as $t_c = v_t / a_i$. The characteristic time of motion t_c plays a special role as it designates the moment, when the initial tsunami shape is introduced as starting condition to the tsunami propagation model. The characteristic distance d_c roughly approximates the landslide runout distance, although part of the slide mass can travel farther as a turbidity current.

The output of the simulation of this landslide-generated tsunami north of the Hupo Bank allows to measure free water surface changes at any point along time (Fig. 6). The height wave plots show that the landslide produces a dipole wave with a trough (blue for elevations lower than -0.1 m in Fig. 6) located over the sediment failure area in the upper slope and an adjacent high (red for elevations higher than 0.1 m in Fig. 6) to the northeast. Water elevations in between -0.1 and 0.1 m are shown in white to highlight the highest amplitudes, but the shading in the images shows actual tsunami activity within this elevation interval. This initial wave radially spreads and progressively deforms, acquiring a more circular shape. The Ursell number ($Ur = C_i \lambda^2 / d^3$), where C_i is the maximum wave amplitude and λ is the characteristic wavelength (Murty, 1977), allows to assess the relative importance of nonlinear and dispersive effects during water wave propagation. For typical amplitudes and wavelength of the tsunami as well as water depths in that area of the basin, it can be seen that dispersion played a role in tsunami propagation.

“Figure 6 is about here”

To the southwest the tsunami wave train advances toward the Korean Peninsula at a significantly slower speed, greater amplitude and smaller wavelength than the outgoing wave, directed toward the center of the basin (Fig. 6). Such outgoing wave impacts the Ulleung Island ~20 min after landslide initiation (Fig. 6). The slower back-going tsunami reaches the Korean Peninsula ~30 min after onset of the landslide, first reporting a negative amplitude as shown by the Donghae and, 5 minutes later, by the Sokcho synthetic wave gage (Fig. 7). At these two locations the first wave was the highest and arrived with relatively small amplitudes of 20-25 cm. The tidal gage plots show that subsequent waves arrived periodically at 5-8 min intervals with slightly lower amplitude (Fig. 7). The maximum elevations plot (Fig. 8) shows the maximum free surface elevation reached at each cell during the entire simulation. Most values range from 0 to 0.4 m, with a mean elevation of 0.2 m. Wave elevation peaks close to 2 m are observed near the coastline, particularly for the stretch of coastline 20 km south of Uljin to 20 km north of Gangneung. The maximum elevation reached by the first tsunami wave arrival is found ~5 km north of Donghae, where records indicate a 1.6 m wave. However the highest free surface elevation is reached near Wondeok-eup, Samcheok-si, Gangwon-do near the border with the Gyeongsangbuk-do region with 1.9 m (Fig. 8). In this case the wave does not result from the direct tsunami arrival, but from subsequent tsunami reflections, refractions and diffractions.

“Figures 7 and 8 are about here”

This work does not provide a detailed analysis of the runup and inundation effects of the tsunami waves on shore, but based on the average 0.2 m wave height over the shelf, a generalized tsunami runup of up to 2.5 m can be expected for beach profiles with a gentle slope of 1° (Synolakis, 1987), which reduces to 1.6 m for a beach with a slope profile of 3°.

In the central stretch of coastline in between Uljin and Donghae, it takes about 25 minutes for the tsunami waves to reach the coastline. In about 1 hour the tsunami has reached most of South Korea's East Sea shore. With regard to the timing of arrival of the highest tsunami wave, Fig. 9 shows that, in the same central stretch of coastline in between Uljin and Donghae, the highest tsunami waves arrived with the first tsunami arrival, ~25 minutes after tsunami initiation. However the time of highest tsunami arrival for locations along the coastline to the south and north of the first impact zone is significantly later than the initial tsunami arrival time (Fig. 9). This indicates that reflected and refracted tsunami waves arrived in these areas of the coast with higher amplitude than the first tsunami arrival.

“Figure 9 is about here”

4.2. Case 2: Submarine Landslide South of the Hupo Bank

This tsunami scenario results again from a slope failure on the continental slope west of the Ulleung Basin, but in this case to the south of the Hupo Bank, where the continental slope defines a reentrant characterized by multiple slope failures (Fig. 4). A distinctive feature of landslides in this reentrant to the south of the Hupo Bank is an arcuate depression near the shelf edge. The origin of this feature is not clear with bathymetric data alone, but could be linked to fluid expulsion to the seafloor. A potential cause-effect relationship may exist between the fluid expulsion and the landslides, suggesting that new submarine landslides could be expected in the area in the future (Fig. 4). The slope failure of this case occurred immediately north of this reentrant in water depths between 1000 to 1600 mbsl and resulted in a horseshoe scarp on the slope that is 3.5 km wide and 4 km long (Table 2), i.e. a significantly smaller landslide in deeper water depths. The landslide scar affects however a significantly larger package of sediments involving a total thickness of

~80 m. The failure plane seems also parallel to the slope indicating an initial failure style as a slide (Fig. 4). The slope occurred on a comparatively steeper slope averaging 6° and a body of sediment seems visible on the bathymetric data at the foot of the landslide scar, indicating that the initial slide again disintegrated to form a debris flow that came to rest at the foot of the scar (Fig. 4).

The submarine landslide characteristics modeled by Geowave indicate an initial acceleration (a_i) of 0.25 ms^{-2} , which is in agreement with the steeper slopes along that failure, a terminal velocity (v_t) of 65.1 ms^{-1} , a comparatively shorter characteristic time (t_c) and characteristic distance (d_c) of 256 s and 16.7 km respectively. The phase speed of the tsunami in water $H=1500 \text{ m}$ deep, is $\overline{c} = 121 \text{ ms}^{-1}$, which given the landslide terminal velocity implies a Froude number of 0.54 and a relatively low tsunami generating efficiency, which is typical for deep-water submarine landslides (Fine et al., 2003; de Blasio, 2011;).

The output of the simulation for this landslide-generated tsunami is shown in Fig. 10. The height wave plots show the characteristic initial dipole of landslide generated tsunamis with a wave trough at the location of the landslide scar on the slope and an adjacent high at the location where the landslide deposited the sediment involved in the slope failure (Fig. 10) to the northeast. The trough initially produced by the landslide is just 1.07 m deep, while the adjacent high is 45 cm in elevation. The tsunami's characteristic initial wavelength is 29 km. Both trough and high are initially elongated in the WNW-ESE direction and this initial wave radially spreads and progressively deforms, acquiring a more circular shape. The Ursell number for typical amplitudes (0.1-0.3 m) and wavelengths (10-25 km) of this tsunami in water depths exceeding 500 m is found to be small (<1). This means that frequency dispersion effect dominates over nonlinear effect (or amplitude

dispersion effect) at the source although, as the tsunami approaches the shore, the nonlinear effect must become increasingly important due to shoaling.

“Figure 10 is about here”

Due to the bathymetric configuration, the tsunami wave train advances over the shelf toward the Korean Peninsula at a significantly slower speed, greater amplitude and smaller wavelength than the outgoing wave, directed to the ESE (Fig. 10). The back-going tsunami reaches the Korean Peninsula near the Changgi Cape just ~15 min after onset of the landslide. The synthetic wave gages located in Deokcheon-ri and Pohang in 1.5 and 15.8 mwd (see Fig. 2 for location) both report initial negative amplitude 26 minutes in Deokcheon-ri and 33 min in Pohang after onset of the landslide (Fig. 11). At Deokcheon-ri the first arrival wave was the highest and arrived with an amplitude of 1.1 m. The tidal gage plots show that subsequent waves arrived periodically at 3 min intervals with a wave amplitude of ~0.5 m (Fig. 11). However, at Pohang the wave amplitude was rather insignificant as the Yongil Bay was largely sheltered from the tsunami by the Changgi Cape (Fig. 11).

“Figure 11 is about here”

The maximum elevations plot for this tsunami (Fig. 12) shows most values not higher than 0.4 m. However, near the coastline, elevations appear to exceed 1 m and reach up to 3.5 m. Here the bathymetric lows along the Hupo Bank have a significant effect in concentrating the tsunami energy at certain locations along the coastline, particularly in between Yongdok and Pyonghae. In a similar way diffraction of tsunami energy at the Changgi Cape concentrated the highest tsunami energy on the opposite side of the Yongil Bay (Fig. 12).

“Figure 12 is about here”

Estimating the runup using the empirical formulation of Synolakis (1987) does not seem to provide additional insight into the effects of the tsunami and the expected runups are well below the maximum wave amplitudes recorded by Geowave near the coastline. Similarly to the previous case, using an average 0.2 m wave height over the shelf a generalized tsunami runup of up to 2.5 m can be expected for beach profiles with a gentle slope of 1°, which reduces to 1.6 m for a beach with a slope profile of 3°.

The tsunami arrival time was significantly faster (15 min) compared to the first landslide tsunami, north of the Hupo Bank (25 min). This shorter arrival time is largely due to the narrower shelf in this area of the East Sea (Fig. 2). The arrival time is particularly short on the east side of the Changgi Cape. However, in between Ulsan and Donghae the first tsunami arrival most often took in between 25 to 35 min. With regard to the timing of arrival of the highest tsunami wave, Fig. 13 shows that in the eastern side of the Changgi Cape these maximum waves coincided with the first tsunami arrival, ~15 minutes after tsunami initiation. However the time of highest tsunami arrival time for some locations along the coastline to the south and north of the first impact zone and within the Yongil bay is significantly slower than the initial tsunami arrival time (Fig. 13). This indicates again that reflected and refracted tsunami waves arrived at the coast with higher amplitude than the first tsunami arrival.

“Figure 13 is about here”

4.3. Case 3: Worst Case Scenario. A Landslide in the Southern Margin of the Ulleung Basin

This last tsunami simulation presents a worst case scenario based on results from Lee et al. (1999). These results show the presence of large MTDs on the floor of the

Ulleung Basin that originated from the southern slope of the basin (Table 1). Later investigations by Lee et al. (2013, 2014) have however pointed out that the MTD identified as Lobe 8 in Lee et al. (1999) could actually result from failure in various stages between 20 and 17 kyrs BP. The deposition of the various lobes in multiple stages has obvious implications for the size of the subsequent tsunami wave. Nevertheless, we choose here to model this scenario as the result of one single event to highlight the consequences of an extreme event. The occurrence of slope failures from the southern slope in multiple stages has been proven for lobe 8 of Lee et al. (1999), but nothing is known on the multi-staged nature of lobes 1 to 7 (Lee et al., 1999), which might have even larger volumes than lobe 8 (see Table 1).

Fig. 5 presents the MR1 side-scan sonar mosaic of Lee et al. (2013) geographically registered onto the bathymetric information. Upslope from the debris flow body (highlighted in orange in the interpretation of Fig. 5) a series of lineations on the bathymetric data seem to trace the debris flow to a series of not well-defined scarps near the shelf edge of the southern Ulleung Basin continental slope. We hypothesize that this area is the source of the MTD and therefore simulate the tsunami as originating from it. To this purpose we have taken into account the sediment volume involved in the MTD (15.1 km³ according to Lee et al. (1999)) and have used such volume for simulation of the slide. The simulated slope failure occurs in water depths between 300 to 1000 mbsl, it is 14.4 km wide and 12.6 km long (Table 2) and involves a sediment thickness of ~83 m, i.e. a landslide one order of magnitude larger than the previous ones. Notice that landslides of such size are not infrequent in the marine environment (e.g., see catalogues in ten Brink et al. (2006), Chaytor et al. (2009), Urgeles and Camerlenghi (2013)) and may attain volumes up to several thousands of km³ (e.g. the Storegga slide (Solheim et al., 2005), which

tsunami deposits have been identified all over northern Europe (Bondevik et al., 2005)).

The slope at the source area of the landslide is 2.2 ° on average.

At the initial position of the center of mass of the landslide (water depth $H = 930$ m), the tsunami phase speed is $\bar{c} = 95 \text{ ms}^{-1}$, which implies a Froude number of 0.74 (Fine et al., 2003; de Blasio, 2011). This Froude number is slightly closer to the resonance value of 1 implying that the landslide was also a bit more efficient in building a tsunami wave compared to the previous cases.

The tsunami simulation for this Late Pleistocene landslide shows a much larger dipole than for the previous ones (Fig. 14). The wave trough centered on the landslide scar area is 3.5 m deep while the adjacent high is 1.3 m, which makes an initial tsunami amplitude 3 times larger than that of previous scenarios. Both trough and high are oriented NE-SW in the initial direction of landslide motion. The tsunami has a characteristic initial wavelength of 70 km. Both trough and high are initially elongated in the WNW-ESE direction. This initial wave radially spreads and progressively deforms, acquiring a more circular shape. Large tsunami amplitudes and wavelengths imply that large Ursell numbers are obtained throughout the basin and therefore the nonlinear effect (or amplitude dispersion effect) predominates.

“Figure 14 is about here”

Because the direction of landslide motion is subparallel to the Korean coast, the leading wave upon arrival to the coastline may be characterized by a trough or a high. The divide between the areas where such a leading wave was a trough or a high is ~10 km north of Yongdok (Fig. 14). The tsunami attained the Changgi Cape ~21 minutes after initiation of the landslide, although the ensuing crest of the tsunami did not reach the coastline until ~5 minutes later (Fig. 15). The outgoing tsunami high did not reach the Korean peninsula until ~32 min after onset of the landslide (Fig. 15). The synthetic wave

gages located in Deokcheon-ri and Pohang (see Fig. 2 for location) respectively record the outgoing tsunami wave high and the back-going tsunami trough as a first arrival, with significantly higher amplitude than in the previous case. The leading tsunami wave arrives 35 minutes after onset of the landslide at Deokcheon-ri and 38.5 min after onset of the landslide in Pohang (Fig. 16). At Deokcheon-ri the first arrival wave was the highest with an elevation of 2 m and characterized by an initial high. Subsequent waves arrived periodically at 6 min intervals with a wave amplitude of ~ 0.5 m at this location (Fig. 16). At Pohang the wave amplitude was half that at Deokcheon-ri showing again that Yongil Bay was largely sheltered from the tsunami by the Changgi Cape (Fig. 16). In this case the leading wave was the back-going tsunami trough.

“Figures 15 and 16 are about here”

The maximum tsunami elevation shows values exceeding 1 m in most of the simulation domain (Fig. 17; notice the artefacts on the NE side of the image corresponding to tsunami reflections at the edge of the simulation domain), while approaching the Korean Peninsula tsunami elevation values exceed 2 m. The color palette on Fig. 17 is saturated on 3 m, so nearshore tsunami elevations are better depicted in Fig. 18. Notice that tsunami elevations on the East coast of the Changgi Cape, may reach more than 9 m. It is also clear from Figs. 17 and 18 that the Hupo Bank acted to focus tsunami energy on the stretch of coast from 10 km north of Yongdok to Pyonghae. Again Pohang and the Yongil Bay in general were sheltered from the tsunami by the Changgi Cape (Figs. 17 and 18). Notice that tsunami runups on land estimated using the empirical formulation of Synolakis (1987) may reach values up to 20 m for a beach sloping 1° , which reduce to 11 m for a beach sloping 3° .

“Figures 17 and 18 are about here”

The tsunami arrival time of Fig. 15 shows that the tsunami impacted most of the Korean peninsula within the simulation domain ~30 min after onset of the landslide. These times almost doubled within the Yongil Bay. The tsunami arrival time also shows that the Hupo Bank slowed down tsunami propagation by about 2 min. With regard to the timing of arrival of the highest tsunami wave, Fig. 19 shows that the highest waves in the stretch between Pohang and Pyonghae and also south of Kampo where reached due to reflection, refraction and diffraction from the tsunami wave at the Changgi Cape. At these locations the arrival times of the highest tsunami wave double those of the first tsunami wave (i.e. more than 50 min latter after onset of the landslide).

“Figure 19 is about here”

5. DISCUSSION

5.1. An Outlook at Landslide Tsunami Hazard to Korea’s East Sea Coast

It is often the case that data is not sufficiently available to establish a reliable distribution of submarine landslides for a basin or particular continental margin, which is a major obstacle for a Probabilistic Tsunami Hazard Assessment (PTHA). Therefore, in these instances a deterministic, data-driven approach based on the worst-case credible scenario without the benefit from the underlying statistical distributions is the only feasible alternative (Harbitz et al., 2014).

Harbitz et al. (2014) point out that the probability of a tsunami exceeding a certain value is often dominated by one (risk-driving) event. Hence, in many instances it may still be efficient to use a scenario-based tsunami hazard assessment (SBTHA) such as the one proposed in this study. Where high-quality information on the spatial, size, age and other relevant characteristics of submarine landslides is not available, the simpler SBTHA

approach is likely to give at least equally good results when proper scientific judgement is applied.

To understand the hazard from tsunamis it is useful to establish a tsunami wave height threshold for potential damage. Wave height or amplitude differs from runup height, which determines inundation extent. In this work no runups have been determined through modeling and just an approximation is given based on empirical formulas from Synolakis (1987). Abe (1995) indicates that the runup is approximately double the wave height or equivalent to the peak-to-trough amplitude. Based on historical Pacific tsunamis, damage to boats, docks, and swimmers may occur due to strong currents for a 0.5 m minimum tsunami amplitude or runup; more severe damage and inundation is likely at a 1.5–2 m minimum (Whitmore et al., 2008). Leonard et al. (2014) choose a tsunami runup threshold of 1.5 m (equivalent to 1.5 m peak-to-trough amplitude or *0.75 m wave height) for potential coastal damage and a 3 m runup threshold as having significant damage potential, i.e. major damage expected that may be geographically extensive.

The simulation carried out in Case 1 indicates potential coastal damage hazard zones with very local waves <2 m high in the East Sea Korean coast between Sokcho and Yongdok (Figs. 3 and 8). These local waves could result from mid-sized landslides, not exceeding 3 km³ in relatively gentle slopes. South of the Changgi Cape there are also potential coastal hazard zones resulting from landslides not exceeding 2 km³ in steeper slopes of up to 6°. These landslides would induce waves that can locally attain 3 m (Figs. 4 12). Locations facing the Hupo Bank are at increased risk from these tsunamis as the bank seems to focus tsunami energy at certain spots along the coastline. These two sources of local landslide tsunamis (we have just investigated a couple, but there seem to be multiple past sources and there is a risk for future ones) may represent potential coastal damage along 2-3 coastal sectors that individually do not exceed 10-15 km during a particular

event (Figs. 8 and 12). Time available for early warning since onset of the event is between 15-30 min for events originating north and along the Hupo Bank (Figs. 6 and 9) and 15 min maximum for events originating south of it (Figs. 10 and 13), given the narrow continental shelf and the short distance between the sources and the impact areas.

The continental margin south of the Ulleung Basin is perhaps an area where landslide tsunamis of a more regional nature, bearing more significant hazard potential, could originate. New landslides of size similar to those that have occurred in the Late Pleistocene-Holocene, which are at least one order of magnitude larger than those occurring on the continental margin to the west of the Ulleung Basin, could produce tsunami waves >3 m in the stretch of coastline from Ulsan in the south to Uljin in the north (Figs. 17 and 18). The timing available for early warning from landslide tsunamis originating in this area is 15-30 min along the affected section of the shoreline. Such a short time (despite distance) to the north of the Changgi Cape results from the particular configuration of the tsunami with respect to the coastline, which makes that the first wave to arrive in this sector is the outgoing tsunami high, not the trough (Figs. 15 and 19). The Yongil Bay seems to be a particularly well-sheltered area with respect to all tsunami sources investigated (Figs. 8, 12, 17 and 18).

5.2. Tsunami Hazard for Korea's East Sea Coast: Directions Forward

A major advantage of PTHA is that such analysis provides a probabilistic representation of the hazard with large epistemic (knowledge based) uncertainties related to location, release mechanisms, evolution, and return periods of the scenarios (Harbitz et al., 2014). However, for such analysis high-quality information on the spatial, size, age and other relevant characteristics of submarine landslides is needed. The risk in the PTHA

analysis is to underestimate the aleatory (random) uncertainties, which would cause either underestimated PTHA results due to unrealistic assessment of uncertainties, or very high hazard levels driven essentially by large uncertainties (Harbitz et al., 2014).

Probabilistic tsunami hazard assessments (PTHAs) has largely focused on tsunamis generated by earthquakes (e.g., Choi et al., 2005; Annaka et al., 2007; Burbidge et al., 2009; Grezio et al., 2010; Sørensen et al., 2012). It is only recently that other sources, such as landslides, have started to be seriously considered (Grilli et al., 2009; Geist and Lynett, 2014; ten Brink et al., 2014). This omission has often resulted from lack of knowledge: Subduction faults are generally well known and mapped and there are a limited number of scenarios that cover the majority of the earthquake based sources (Lane et al., 2016). By comparison, there are many more landslide sources that may affect a region because landslide-generated tsunamis are by nature local features.

A conscious tsunami hazard assessment based on geological evidence would be desirable for Korea's East Sea Coast, given the widespread evidence of large pre-historical submarine slope failures. As remembered by Geist and ten Brink (2012), although probability is key to assess tsunami hazard, a probabilistic assessment is only as good as the underlying data and assumptions. Therefore, it is critical to address the state of knowledge and the kinds of new data that would need to be collected to improve our ability to estimate probability of occurrence and tsunami hazard.

Despite submarine landslides and mass-wasting phenomena have been the subject of several studies in the Ulleung Basin of the East Sea (e.g., Lee and Chough, 2001; Lee et al., 2010,2013; Cukur et al., 2016; Horozal et al., 2016), no systematic mapping and dating of such features has been performed. Undertaking such a task is necessary if one wants to understand the source areas, recurrence periods and approximate to some extent the dynamics of submarine landslides. The USGS has done research to identify and date

significant submarine landslides along the eastern Atlantic margin of the U.S. and the Gulf of Mexico (ten Brink et al., 2006, 2009; Geist and Parsons, 2010; Geist et al., 2013) and similar approaches are being carried out in other areas such as the Mediterranean Sea (Urgeles and Camerlenghi, 2013). Recent efforts have focused on how submarine landslide probability might be determined using available geological and geophysical information and identifying the challenges of incorporating this information into PTHA (Grilli et al., 2009; Geist and Lynett, 2014; Lane et al., 2016; Pampell-Manis et al., 2016; Løvholt and Urgeles, 2017). The task calls for the acquisition of multibeam bathymetry (with collocated backscatter) to define the geometry and areal extent of submarine landslide failure areas and deposits as well as coring and chirp high resolution seismic profiling to assess the age of these events from sediment samples and correlating these ages through seismic sections. Support to drilling and coring initiatives in the East Sea should be beneficial to this end.

6. CONCLUSIONS

Submarine landslides of the western and southern margin of the Ulleung Basin have disparate characteristics, with those on the western margin having volumes of a few km³ and limited runout. On the southern slope submarine landslides are one order of magnitude larger and may travel distances of several tens of kms. Some of these failures occur on relatively steep slopes (western margin) while others display a retrogressive behavior. All of these characteristics modify the resulting tsunamigenic potential.

Tsunami simulations from past landslides along the western and southern slopes of the Ulleung Basin provide a crude estimate of the consequences if one of these events should have occurred at Present. The simulations show that small landslides with volumes up to 3 km³, such as the ones present on the western slope of the Ulleung Basin may

involve limited coastal damage (runup rarely exceeding 3 m) along stretches of coastline not exceeding 15 km. Where the continental shelf is relatively narrow (south of the Changgi Cape) the time available to produce early warning for such events is very limited. The larger landslides that have been mapped along the southern slopes of the Ulleung Basin involve potentially larger tsunami hazard with tsunami waves producing significant damage (runup > 3 m) along large stretches of coastline (> 50 km). Morphologic features such as the Hupo Bank help focus tsunami energy on particular coastal areas, while the Yongil bay seems largely sheltered from such events.

Several approaches to assess tsunami hazard of different methodological complexity are possible. The detailed extent, characteristics and recurrence information for submarine landslides is however uncertain or altogether lacking in Korea resulting in high uncertainty in the source term for probabilistic analysis. As a result, the risk from tsunamis is not well characterized and calls for additional data collection and further studies.

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REFERENCES

- Abe, K., 1995, Estimate of Tsunami Run-up Heights from Earthquake Magnitudes, in: Tsuchiya, Y., Shuto, N. (Eds.), *Tsunami: Progress in Prediction, Disaster Prevention and Warning, Advances in Natural and Technological Hazards Research*, Springer Netherlands, pp. 21–35.
- Annaka, T., Satake, K., Sakakiyama, T., Yanagisawa, K., and Shuto, N., 2007, Logic-tree Approach for Probabilistic Tsunami Hazard Analysis and its Applications to the Japanese Coasts, in: Satake, K., Okal, E.A., Borrero, J.C. (Eds.), *Tsunami and Its Hazards in the Indian and Pacific Oceans, Pageoph Topical Volumes*, Birkhäuser Basel, pp. 577–592.
- Assier-Rzadkiewicz, S., Heinrich, P., Sabatier, P.C., Savoye, B., and Bourillet, J.F., 2000, Numerical Modelling of a Landslide-generated Tsunami: The 1979 Nice Event. *Pure and Applied Geophysics*, 157, 1707–1727.
- Bondevik, S., Løvholt, F., Harbitz, C., Mangerud, J., Dawson, A., and Inge Svendsen, J., 2005, The Storegga Slide tsunami—comparing field observations with numerical simulations. *Marine and Petroleum Geology*, 22, 195–208.
- Brune, S., Ladage, S., Babeyko, A.Y., Müller, C., Kopp, H., and Sobolev, S.V., 2010, Submarine landslides at the eastern Sunda margin: observations and tsunami impact assessment. *Natural Hazards*, 54, 547–562.
- Burbidge, D., Cummins, P.R., Mleczko, R., and Thio, H.K., 2009, A Probabilistic Tsunami Hazard Assessment for Western Australia, in: Cummins, P.R., Satake, K., Kong, L.S.L. (Eds.), *Tsunami Science Four Years after the 2004 Indian Ocean Tsunami, Pageoph Topical Volumes*, Birkhäuser Basel, pp. 2059–2088.

- 643 Chaytor, J.D., ten Brink, U.S., Solow, A.R., and Andrews, B.D., 2009, Size distribution of
644 submarine landslides along the U.S. Atlantic margin. *Marine Geology*, 264, 16–27.
- 645 Chen, Q., Kirby, J.T., Dalrymple, R.A., Kennedy, A.B., and Chawla, A., 2000, Boussinesq
646 Modeling of Wave Transformation, Breaking, and Runup II: 2D. *Journal of*
647 *Waterway, Port, Coastal, and Ocean Engineering*, 126, 48–56.
- 648 Choi, B.-H., Cho, Y.-S., and Yoon, S.B., 2016, Tsunami research in Korea. *Natural*
649 *Hazards*, 84, 437–454.
- 650 Choi, B.H., Pelinovsky, E., Lee, H.J., and Woo, S.B., 2005, Estimates of Tsunami Risk
651 Zones on the Coasts Adjacent to the East (Japan) Sea based on the Synthetic
652 Catalogue. *Natural Hazards*, 36, 355–381.
- 653 Cukur, D., Kim, S.-P., Kong, G.-S., Bahk, J.-J., Horozal, S., Um, I.-K., Lee, G.-S., Chang,
654 T.-S., Ha, H.-J., Völker, D., and Kim, J.-K., 2016, Geophysical evidence and
655 inferred triggering factors of submarine landslides on the western continental
656 margin of the Ulleung Basin, East Sea. *Geo-Marine Letters*, 36, 425–444.
- 657 de Blasio, F.V., 2011, *Introduction to the Physics of Landslides*. Springer Netherlands,
658 Dordrecht. doi:10.1007/978-94-007-1122-8
- 659 Enet, F. and Grilli, S.T., 2007, Experimental Study of Tsunami Generation by Three-
660 Dimensional Rigid Underwater Landslides. *Journal of Waterway, Port, Coastal,*
661 *and Ocean Engineering*, 133, 442–454.
- 662 Fine, I.V., Rabinovich, A.B., Bornhold, B.D., Thomson, R.E., and Kulikov, E.A., 2005,
663 The Grand Banks landslide-generated tsunami of November 18, 1929: preliminary
664 analysis and numerical modeling. *Marine Geology*, 215, 45–57.
- 665 Fine, I.V., Rabinovich, A.B., Thomson, R.E., and Kulikov, E.A., 2003, Numerical
666 modeling of tsunami generation by submarine and subaerial landslides, in:
667 Yalçiner, A.C., Pelinovsky, E., Okal, E.A., Synolakis, C.E. (Eds.), *Submarine*

- 668 Landslides and Tsunamis, NATO Science Series. Kluwer Academic Publishers,
669 Dordrecht ; Boston, pp. 69–88.
- 670 Fryer, G.J., Watts, P., and Pratson, L.F., 2004, Source of the great tsunami of 1 April 1946:
671 a landslide in the upper Aleutian forearc. *Marine Geology*, 203, 201–218.
- 672 Geist, E. and Lynett, P., 2014, Source Processes for the Probabilistic Assessment of
673 Tsunami Hazards. *Oceanography*, 27, 86–93.
- 674 Geist, E.L., Chaytor, J.D., Parsons, T., and Brink, U. ten, 2013, Estimation of submarine
675 mass failure probability from a sequence of deposits with age dates. *Geosphere*, 9,
676 287–298.
- 677 Geist, E.L. and Parsons, T., 2010, Estimating the Empirical Probability of Submarine
678 Landslide Occurrence, in: Mosher, D.C., Shipp, R.C., Moscardelli, L., Chaytor,
679 J.D., Baxter, C.D.P., Lee, H.J., Urgeles, R. (Eds.), *Submarine Mass Movements
680 and Their Consequences, Advances in Natural and Technological Hazards
681 Research*. Springer Netherlands, pp. 377–386.
- 682 Geist, E.L. and ten Brink, U.S., 2012, NRC/ USGS Workshop Report: Landslide Tsunami
683 Probability. USGS administrative report to the US Nuclear Regulatory
684 Commission, 43 p.
- 685 Grezio, A., Marzocchi, W., Sandri, L., and Gasparini, P., 2010, A Bayesian procedure for
686 Probabilistic Tsunami Hazard Assessment. *Natural Hazards*, 53, 159–174.
- 687 Grilli, S.T., Taylor, O.-D.S., Baxter, C.D.P., and Marezki, S., 2009, A probabilistic
688 approach for determining submarine landslide tsunami hazard along the upper east
689 coast of the United States. *Marine Geology*, 264, 74–97.
- 690 Gusiakov, V.K., 2003. Identification of slide-generated tsunamis in the historical
691 catalogues, in: Yalçiner, A.C., Pelinovsky, E., Okal, E.A., Synolakis, C.E. (Eds.),

- 692 Submarine Landslides and Tsunamis, NATO Science Series, Kluwer Academic
 693 Publishers, Dordrecht ; Boston, pp. 17–24.
- 694 Harbitz, C.B., Løvholt, F., and Bungum, H., 2014, Submarine landslide tsunamis: how
 695 extreme and how likely? *Natural Hazards*, 72, 1341–1374.
- 696 Harbitz, C.B., Lovholt, F., Pedersen, G., and Masson, D.G., 2006, Mechanisms of tsunami
 697 generation by submarine landslides: a short review. *Norsk Geologisk Tidsskrift*, 86,
 698 255.
- 699 Horozal, S., Bahk, J.J., Lee, S.H., Urgeles, R., Kim, S.P., Kim, G.Y., Cukur, D., Lee, G.H.,
 700 Ryu, B.J., and Kim, J.H., 2016, Late Neogene–Quaternary submarine mass wasting
 701 along the margins of the Ulleung Basin, East Sea: Geomorphologic controls and
 702 geohazard potential. *Quaternary International*, 392, 69–98.
- 703 Kennedy, A.B., Chen, Q., Kirby, J.T., and Dalrymple, R.A., 2000, Boussinesq Modeling of
 704 Wave Transformation, Breaking, and Runup I: 1D. *Journal of Waterway, Port,
 705 Coastal, and Ocean Engineering*, 126, 39–47.
- 706 Lane, E.M., Mountjoy, J.J., Power, W.L., and Popinet, S., 2016, Initialising landslide-
 707 generated tsunamis for probabilistic tsunami hazard assessment in Cook Strait.
 708 *International Journal of Ocean and Climate Systems*, 7, 4–13.
- 709 Lee, S. H., Jung, W.-Y., Bahk, J.J., Gardner, J.M., Kim, J.K., and Lee, Su Hwan, 2013,
 710 Depositional features of co-genetic turbidite–debrite beds and possible mechanisms
 711 for their formation in distal lobated bodies beyond the base-of-slope, Ulleung
 712 Basin, East Sea (Japan Sea). *Marine Geology*, 346, 124–140.
- 713 Lee, S.H., Bahk, J.-J., Kim, H.J., Kim, G.-Y., Kim, S.-P., Jeong, S.-W., and Park, S.-S.,
 714 2014, Contrasting Development of the Latest Quaternary Slope Failures and Mass-
 715 Transport Deposits in the Ulleung Basin, East Sea (Japan Sea), in: Krastel, S.,
 716 Behrmann, J.-H., Völker, D., Stipp, M., Berndt, C., Urgeles, R., Chaytor, J., Huhn,

- 717 K., Strasser, M., Harbitz, C.B. (Eds.), Submarine Mass Movements and Their
 718 Consequences, Advances in Natural and Technological Hazards Research, Springer
 719 International Publishing, pp. 403–412.
- 720 Lee, S.H., Bahk, J.J., Kim, H.J., Lee, K.E., Jou, H.T., and Suk, B.C., 2010, Changes in the
 721 frequency, scale, and failing areas of latest Quaternary (<29.4 cal. ka B.P.) slope
 722 failures along the SW Ulleung Basin, East Sea (Japan Sea), inferred from
 723 depositional characters of densely dated turbidite successions. *Geo-Marine Letters*,
 724 30, 133–142.
- 725 Lee, S.H. and Chough, S.K., 2001, High-resolution (2–7 kHz) acoustic and geometric
 726 characters of submarine creep deposits in the South Korea Plateau, East Sea.
 727 *Sedimentology*, 48, 629–644.
- 728 Lee, S.H., Chough, S.K., Back, G.G., Kim, Y.B., and Sung, B.S., 1999, Gradual
 729 downslope change in high-resolution acoustic characters and geometry of large-
 730 scale submarine debris lobes in Ulleung Basin, East Sea (Sea of Japan), Korea.
 731 *Geo-Marine Letters*, 19, 254–261.
- 732 Leonard, L.J., Rogers, G.C., and Mazzotti, S., 2014, Tsunami hazard assessment of
 733 Canada. *Natural Hazards*, 70, 237–274.
- 734 Lim, C.H., Bae, J.S., Lee, J.I., and Yoon, S.B., 2008, Propagation characteristics of
 735 historical tsunamis that attacked the east coast of Korea. *Natural Hazards*, 47, 95–
 736 118.
- 737 Løvholt, F., Pedersen, G., Harbitz, C.B., Glimsdal, S., and Kim, J., 2015, On the
 738 characteristics of landslide tsunamis. *Philosophical Transactions of the Royal
 739 Society A*, 373, 20140376. doi:10.1098/rsta.2014.0376
- 740 Løvholt, F. and Urgeles, R., 2017, Towards a probabilistic tsunami hazard analysis for the
 741 Gulf of Cadiz, in: *Geophysical Research Abstracts*. Presented at the European

- 742 Geosciences Union General Assembly 2017, Vienna (Austria), pp. EGU2017-
743 3657–1.
- 744 Luis, J.F., 2007, Mirone: A multi-purpose tool for exploring grid data. *Computers and*
745 *Geosciences*, 33, 31–41.
- 746 Mofjeld, H.O., González, F.I., Titov, V.V., Venturato, A.J., and Newman, J.C., 2007,
747 Effects of Tides on Maximum Tsunami Wave Heights: Probability Distributions.
748 *Journal of Atmospheric and Oceanic Technology*, 24, 117–123.
- 749 Morgan, J.K., Silver, E., Camerlenghi, A., Dugan, B., Kirby, S., Shipp, C., and Suyehiro,
750 K., 2009, Addressing geohazards through ocean drilling. *Scientific Drilling*, 7, 15–
751 30.
- 752 Mori, N., Takahashi, T., Yasuda, T., and Yanagisawa, H., 2011, Survey of 2011 Tohoku
753 earthquake tsunami inundation and run-up. *Geophysical Research Letters*, 38,
754 L00G14. doi:10.1029/2011GL049210
- 755 Murty, T.S., 1977, Seismic sea waves: Tsunamis. *Bulletin of the Fisheries Research Board*
756 *of Canada*, No. 198, 337 p.
- 757 Nicholson, T.J., Reed, W., and Cook, C., 2013, Summary of Significant Observations,
758 Insights, and Identified Opportunities for Collaboration on PFHA, in: *Proceedings*
759 *of the Workshop on Probabilistic Flood Hazard Assessment (PFHA)*, pp. 10-2–10-
760 14, <https://www.nrc.gov/docs/ML1327/ML13277A074.pdf>.
- 761 Pampell-Manis, A., Horrillo, J., Shigihara, Y., and Parambath, L., 2016, Probabilistic
762 assessment of landslide tsunami hazard for the northern Gulf of Mexico. *Journal of*
763 *Geophysical Research Oceans*, 121, 1009–1027.
- 764 Papadopoulos, G.A., Gràcia, E., Urgeles, R., Sallares, V., De Martini, P.M., Pantosti, D.,
765 González, M., Yalciner, A.C., Mascle, J., Sakellariou, D., Salamon, A., Tinti, S.,
766 Karastathis, V., Fokaefs, A., Camerlenghi, A., Novikova, T., and 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.
- Ruffman, A., 1997, Tsunami runup mapping as an emergency preparedness planning tool: the 1929 tsunami in St. Lawrence, Newfoundland – volume 1. Government of Canada Publications, 111 p.
- Satake, K. and Tanioka, Y., 2003, The July 1998 Papua New Guinea Earthquake: Mechanism and Quantification of Unusual Tsunami Generation. *Pure and Applied Geophysics*, 160, 2087–2118.
- Satake, K. and Atwater, B.F., 2007, Long-Term Perspectives on Giant Earthquakes and Tsunamis at Subduction Zones. *Annual Review of Earth and Planetary Sciences*, 35, 349–374.
- Solheim, A., Berg, K., Forsberg, C.F., and Bryn, P., 2005, The Storegga Slide complex: repetitive large scale sliding with similar cause and development. *Marine and Petroleum Geology*, 22, 97–107.
- Sørensen, M.B., Spada, M., Babeyko, A., Wiemer, S., and Grünthal, G., 2012, Probabilistic tsunami hazard in the Mediterranean Sea. *Journal of Geophysical Research Solid Earth*, 117, B01305. doi:10.1029/2010JB008169
- Synolakis, C.E., 1987. The runup of solitary waves. *Journal of Fluid Mechanics*, 185, 523–545.
- Tappin, D.R., Grilli, S.T., Harris, J.C., Geller, R.J., Masterlark, T., Kirby, J.T., Shi, F., Ma, G., Thingbaijam, K.K.S., and Mai, P.M., 2014, Did a submarine landslide contribute to the 2011 Tohoku tsunami? *Marine Geology*, 357, 344–361.

- 790 Tappin, D.R., Watts, P., and Grilli, S.T., 2008, The Papua New Guinea tsunami of 17 July
791 1998: anatomy of a catastrophic event. *Natural Hazards and Earth System Sciences*,
792 8, 243–266.
- 793 Tappin, D.R., 2017, Tsunamis from submarine landslides. *Geology Today*, 33, 190–200.
- 794 ten Brink, U.S., Barkan, R., Andrews, B.D., and Chaytor, J.D., 2009, Size distributions and
795 failure initiation of submarine and subaerial landslides. *Earth and Planetary Science*
796 *Letters*, 287, 31–42.
- 797 ten Brink, U.S., Chaytor, J.D., Geist, E.L., Brothers, D.S., and Andrews, B.D., 2014,
798 Assessment of tsunami hazard to the U.S. Atlantic margin. *Marine Geology*, 353,
799 31–54.
- 800 ten Brink, U.S., Geist, E.L., and Andrews, B.D., 2006, Size distribution of submarine
801 landslides and its implication to tsunami hazard in Puerto Rico. *Geophysical*
802 *Research Letters*, 33, doi:10.1029/2006GL026125.
- 803 Tinti, S., 2003, Needs and perspectives of tsunami research in Europe, in: Yalçiner, A.C.,
804 Pelinovsky, E., Okal, E.A., Synolakis, C.E. (Eds.), *Submarine Landslides and*
805 *Tsunamis*, NATO Science Series. Kluwer Academic Publishers, Dordrecht ;
806 Boston, pp. 9–16.
- 807 Tinti, S. and Bortolucci, E., 2000, Energy of Water Waves Induced by Submarine
808 Landslides. *Pure and Applied Geophysics*, 157, 281–318.
- 809 Titov, V., Rabinovich, A.B., Mofjeld, H.O., Thomson, R.E., and González, F.I., 2005, The
810 Global Reach of the 26 December 2004 Sumatra Tsunami. *Science*, 309, 2045–
811 2048.
- 812 Urgeles, R. and Camerlenghi, A., 2013, Submarine landslides of the Mediterranean Sea:
813 Trigger mechanisms, dynamics, and frequency-magnitude distribution. *Journal of*

- 814 Geophysical Research Earth Surface, 118, 2013JF002720.
815 doi:10.1002/2013JF002720.
- 816 Ward, S.N., 2001, Landslide tsunami. *Journal of Geophysical Research Solid Earth*, 106,
817 11201, doi:10.1029/2000JB900450.
- 818 Watts, P., 1998, Wavemaker Curves for Tsunamis Generated by Underwater Landslides.
819 *Journal of Waterway Port Coastal and Ocean Engineering*, 124, 127–137.
- 820 Watts, P., Grilli, S.T., Kirby, J.T., Fryer, G.J., and Tappin, D.R., 2003, Landslide tsunami
821 case studies using a Boussinesq model and a fully nonlinear tsunami generation
822 model. *Natural Hazards and Earth System Sciences*, 3, 391–402.
- 823 Watts, P., Grilli, S.T., Tappin, D.R., and Fryer, G.J., 2005, Tsunami Generation by
824 Submarine Mass Failure. II: Predictive Equations and Case Studies. *Journal of*
825 *Waterway, Port, Coastal, and Ocean Engineering*, 131, 298–310.
- 826 Watts, P., Imamura, F., and Grilli, S., 2000, Comparing model simulations of three
827 benchmark tsunami generation cases. *Science of Tsunami Hazards*, 18, 107–124.
- 828 Waythomas, C.F., Watts, P., Shi, F., and Kirby, J.T., 2009, Pacific Basin tsunami hazards
829 associated with mass flows in the Aleutian arc of Alaska. *Quaternary Science*
830 *Reviews*, 28, 1006–1019.
- 831 Wei, G., Kirby, J.T., and Sinha, A., 1999, Generation of waves in Boussinesq models using
832 a source function method. *Coastal Engineering*, 36, 271–299.
- 833 Wessel, P., Smith, W.H.F., Scharroo, R., Luis, J., and Wobbe, F., 2013, Generic Mapping
834 Tools: Improved Version Released. *Eos Transactions American Geophysical*
835 *Union*, 94, 409–410.
- 836 Whitmore, P., Benz, H., Bolton, M., Crawford, G., Dengler, L., Fryer, G., Goltz, J.,
837 Hansen, R., Kryzanowski, K., Malone, S., Oppenheimer, D., Petty, E., Rogers, G.,

838 and Wilson, J., 2008, NOAA/West Coast and Alaska Tsunami Warning Center
839 Pacific Ocean response criteria. *Science of Tsunami Hazards*, 27, 19.
840 Xiao, L., Ward, S.N., and Wang, J., 2015, Tsunami Squares Approach to Landslide-
841 Generated Waves: Application to Gongjiafang Landslide, Three Gorges Reservoir,
842 China. *Pure and Applied Geophysics*, 172, 3639–3654.

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Table 1. Main geometric parameters of mass transport deposits derived from submarine landslides in the Ulleung Basin (from Lee et al., 1999).

	Av.					Runout	
	Length	Width	Thickness	Thickness	Area	Volume	distance
Lobe	(km)	(km)	(m)	(m)	(km ²)	(km ³)	(km)
1	>22.2	13.5-28.5	22.6	10.7-39.3	>523.5	>11.8	88.7
2	>38.3	3.8-24	26.9	15-45	>686.5	>18.5	66.6
4	>42.5	9-25.5	25.2	8.9-52.5	>1319.2	>33.6	105.4
5	>33.3	3.1-15	20.5	17.5-25.2	>447.1	>12.1	55.5
6	>42.5	9-10.5	19.7	20-38.3	>443.2	>8.6	77.6
8	>51.8	12.2-18	19.3	8.9-39.3	>777.6	>15.1	127.6
9	25.9	3.2-6.8	5.3	3.6-10.7	116.6	0.6	120.1

Table 2. TOPICS input and output data

Landslide			Case 1	Case 2	Case 3
Landslide geometry	V	(km ³)	2.53	1.12	15.1
	x _o	(m E)	548508.9	586145.7	586525.9
	y _o	(m N)	4157191.6	4010600.9	3954703.3
	d	(m)	700	1290	934
	L	(km)	12.8	4	12.6
	l	(km)	7.6	3.5	14.4
	w	(m)	26	80	83
	φ	(°)	322.5	238.6	332
	θ	(°)	2	6	2.2
Landslide dynamics	a _i	(ms ⁻²)	0.08	0.25	0.09
	v _t	(ms ⁻¹)	67.3	65.1	70.0
	t _c	(s)	794	256	751
	d _c	(km)	23.2	16.7	53
Initial tsunami	λ _c	(km)	78.6	28.8	71.9
	C _i	(m)	0.31	0.48	1.33
	T _i	(m)	-0.88	-1.07	-3.56

Notes: The longitude and latitude of the submarine landslide centroid (x_o , y_o) are the supposed center of mass; The centroid initial depth d (before the slide) corresponds to the depth of the scar center minus half of the maximum thickness w ; The length L (Long axis) and width l (small axis) of the submarine landslide supposed-parallaloid; The mean azimuth (direction of landslide) ϕ defined counter-clockwise and the mean slope ϑ along slide. TOPICS outputs are: the slide initial acceleration a_i , terminal velocity v_t and its characteristic duration t_c (the wave period relative to the wave celerity at the centroid depth), the characteristic distance d_c and the characteristic initial tsunami wavelength λ_c . C_i and T_i represent the initial crest and trough amplitudes, respectively.

Fig. 1.

(a)

(b)

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.

Fig. 6.

Fig. 7.

Fig. 8.

Fig. 9.

Fig. 10.

Fig. 11.

Fig. 12.

Fig. 13.

Fig. 14.

Fig. 15.

Fig. 16.

Fig. 17.

Fig. 18.

Fig. 19.