Understanding and Reducing the Disaster Risk of Landslide-induced Tsunamis: Outcome of the Panel Discussion and the World Tsunami Awareness Day Special Event of the Fifth World Landslide Forum

Shinji Sassa, Stephan T. Grilli, David R. Tappin, Kyoji Sassa, Dwikorita Karnawati, Viacheslav K. Gusiakov, Finn Løvholt

Abstract

Landslide-induced tsunamis are one of the most important multi-hazard risks in light of landslide disasters. During the Fifth World Landslide Forum, a World Tsunami Awareness Day Special Event was held in hybrid mode on 5 November 2021. This article presents the outcome of the panel discussion organized across America, Europe, and Asia, as well as a review of the special event for understanding and reducing the disaster risk of landslide-induced tsunamis.

Shinji Sassa (✉)
Port and Airport Research Institute, National Institute of Maritime, Port and Aviation Technology, Japan
e-mail: sassa@p.mpat.go.jp

Stephan T. Grilli
University of Rhode Island, Department of Ocean Engineering, Narragansett, RI, USA
e-mail: grilli@uri.edu

David R. Tappin
British Geological Survey, Keyworth, Nottingham, UK
e-mail: drta@bgs.ac.uk

Kyoji Sassa
International Consortium on Landsides, Kyoto, Japan
e-mail: kyoji.sassa@gmail.com

Dwikorita Karnawati
Agency for Meteorology, Climatology and Geophysics of the Republic of Indonesia, Jakarta, Indonesia
e-mail: dwiko@bmkg.go.id

Viacheslav K. Gusiakov
Institute of Computational Mathematics and Mathematical Geophysics, Russian Academy of Sciences, Novosibirsk, Russia
e-mail: gvk@sscc.ru

Finn Løvholt
Norwegian Geotechnical Institute, Oslo, Norway
e-mail: Finn.Lovholt@ngi.no

Keywords

Landslide-induced tsunami, Hazard mapping, Early warning, Multi-phased physics, Multiple mechanisms

Introduction

During the Fifth World Landslide Forum (WLF5), in Kyoto, Japan, a World Tsunami Awareness Day Special Event was organized on November 5th, 2021, following a Landslide-induced Tsunami session held on November 4th, 2021. A total of twenty-three relevant papers from thirteen countries/regions were presented and included in the four types of publications for WLF5: Thematic Issue of Journal Landslides (3; 2020), Full Color Book (11; Sassa et al. 2020), Electronic Proceedings (3; 2020) and One-Page Abstract Volume (6; 2021). The key topics ranged from numerical modelling and analysis of landslide-generated waves in rivers, to tsunami uncertainty due to landslide dynamics, using statistics to understand submarine landslide processes and hazard, tsunamis from submarine landslides triggered on islands, simulations of tsunami waves induced by coastal and submarine landslides, tsunami generation by volcanic flank collapse, underestimated tsunami hazard from submarine landslides, landslide-induced icy tsunamis in a reservoir, tsunami early warning system, and tsunami disaster caused by earthquake-induced submarine landslides.

In the World Tsunami Awareness Day Special Event of WLF5, a panel discussion was held across America, Europe, and Asia, for better understanding and reducing the disaster risk of landslide-induced tsunamis, consistent with the Kyoto Landslide Commitment 2020 (KLC2020). Shinji Sassa (S.S.) served as the coordinator of the World Tsunami Awareness Day Special Event during WLF5, and organized the Panel Discussion. The panelists were Stephan T. Grilli (USA), David R. Tappin (UK), Kyoji Sassa (Japan), Dwikorita Karnawati (Indonesia), Viacheslav K. Gusiakov (Russia), and Finn Løvholt (Norway) (S.G., D.T., K.S., D.K., V.G., F.L., respectively). This article presents the outcome of the panel discussion as well as a review of the World Tsunami Awareness Day Special Event of WLF5.

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Review of the World Tsunami Awareness Day Special Event

The World Tsunami Awareness Day Special Event of WLF5 featured a total of eleven relevant presentations concerning landslide-induced tsunamis, which will be reviewed as below.

F. Løvholt addressed landslide tsunami uncertainty and presented a probabilistic tsunami hazard analysis (LPTHA) framework for analysing uncertainties emerging from the landslide source processes. An example is presented for the Lyngen fjord in Norway. The statistics of the fall height (H) to run-out length (L) ratio as a function of the volume for large rockslides in Norway is shown in Fig. 1. Comparing tsunami inundation maps using different magnitude frequency distributions (MFDs, Fig. 2) indicates that the results are sensitive to the choice of MFD to which the uncertainty is directly linked concerning landslide dynamics.

D. Minh Duc analysed a landslide-induced tsunami-like wave in the Truong river in Vietnam. A heavy rainfall induced a landslide along bedrock of weathered granite that caused an impulsive wave across the river, affecting houses in a residential area (Fig. 3). The results of the numerical analysis combined with the observations of the landslide

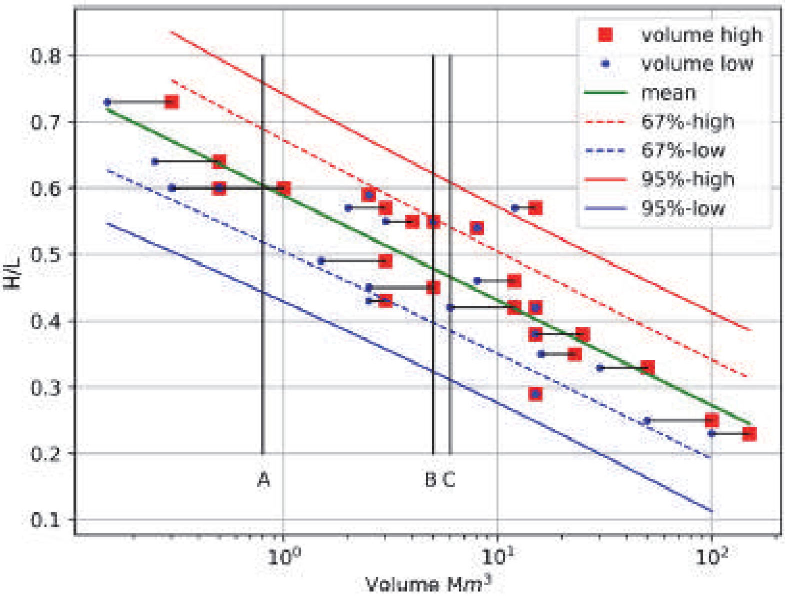


Fig. 1 The regression analysis of the run-out statistics of rock slides in Norway: H is the fall height, L is the total horizontal run out. The vertical lines A, B and C indicate the volumes 0.8, 5 and 6 Mm^3, respectively (Fig. 7 in Løvholt et al. 2020)

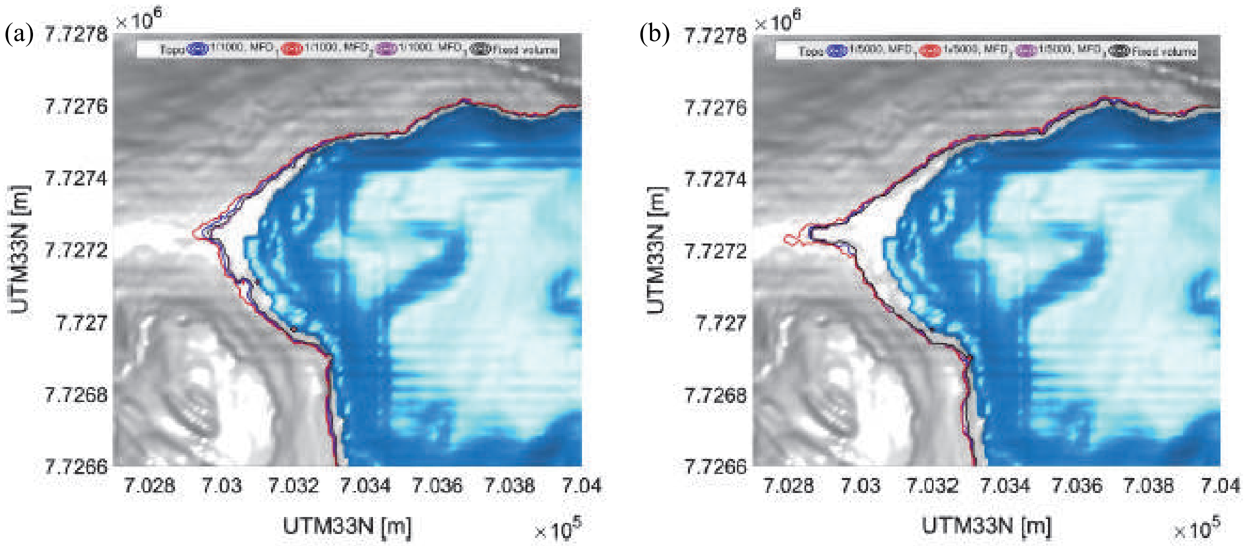


Fig. 2 Comparing tsunami inundation maps using different synthetic MFDs: (a) 1/1000 year^{-1} and (b) 1/5000 year^{-1} exceedance probability (Fig. 9 in Løvholt et al. 2020)

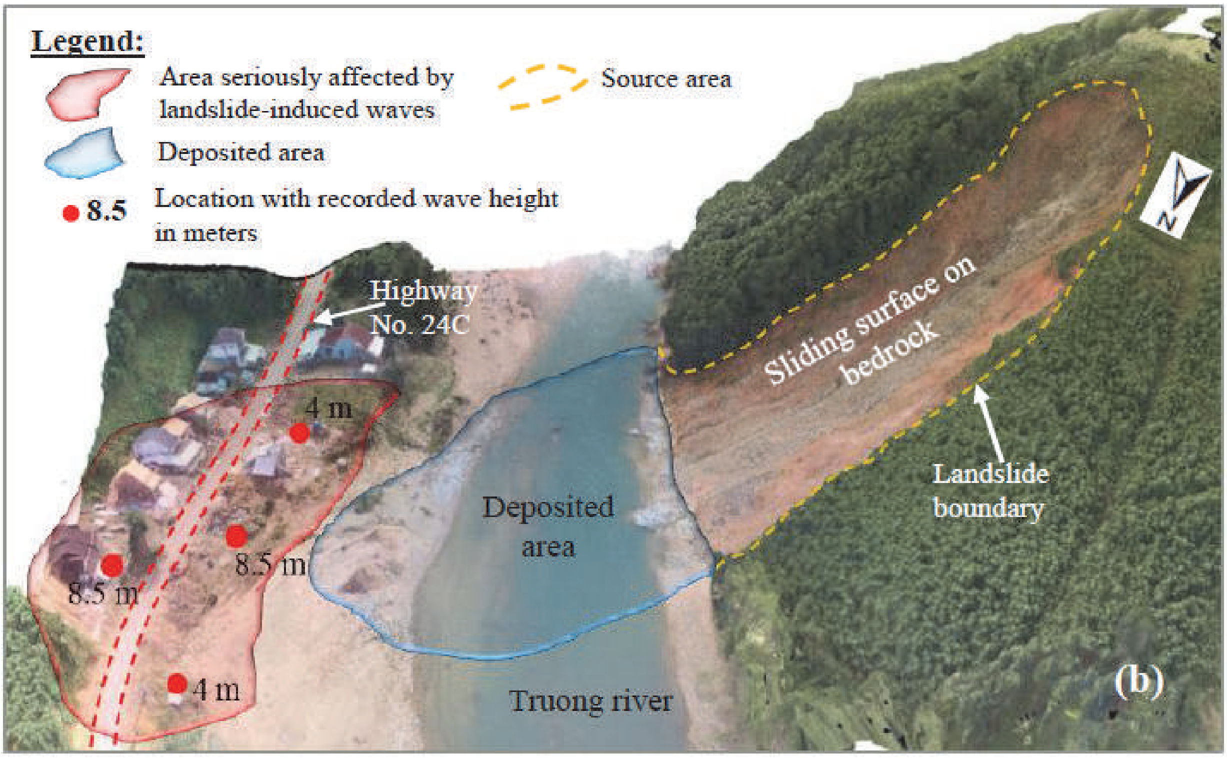


Fig. 3 3D view of the landslide in the Truong river, Vietnam (Fig. 1(b) in Minh Duc et al. 2020)

scarp, deposit and tsunami traces indicate that a rapid landslide motion with a maximum speed of 16.4 m/s generated a maximum wave height of 5m (Fig. 4).

J. Blahůt reported an attempt to model a tsunami genesis and propagation from an incipient volcano slope failure termed San Andres Landslide on Canary Islands, Spain. The scenario comprised a subaerial failure of a block more than 2.5 km long and 7.5 km wide (Fig. 5). The landslide-induced initial wave could reach 80m with its propagation through Atlantic Ocean. The results show that a more accurate landslide dynamic modelling is crucial to obtain realistic behaviour of the sliding mass to assess possible tsunami scenarios.

K. Ikehara showed the linkage between upper-slope submarine landslides and mass transport deposits in the hadal environment. There are many submarine landslides distributed along the upper slope of the Hidaka Trough, Japan (Fig. 6). The results of the investigations on the sediment cores in the Japan Trench indicate that the upper slope is the origin of mass transport deposits (MTD), and therefore an area of large sediment movements, which should be considered in the context of tsunami hazard mitigation.

S. Sassa summarized the landslide-induced tsunami papers for the Fifth World Landslide Forum, and presented a review of large-scale coastal mass movements and their impacts worldwide, showing the importance of liquefied flows in tsunami generation. The dynamics of liquefied

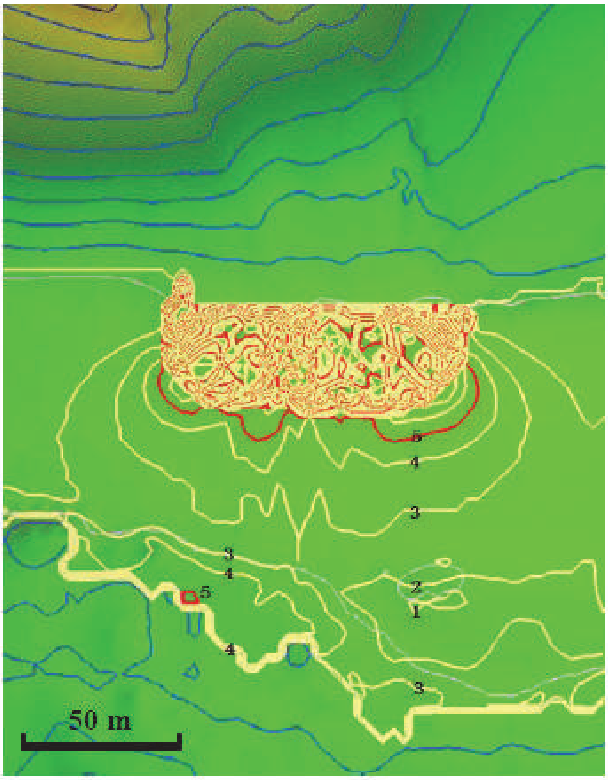


Fig. 4 Contour of the maximum tsunami height simulated. The reaching out line is shown in bold yellow where the tsunami wave moved up to the land with the maximum height of 5m. (Fig. 11 in Minh Duc et al. 2020)

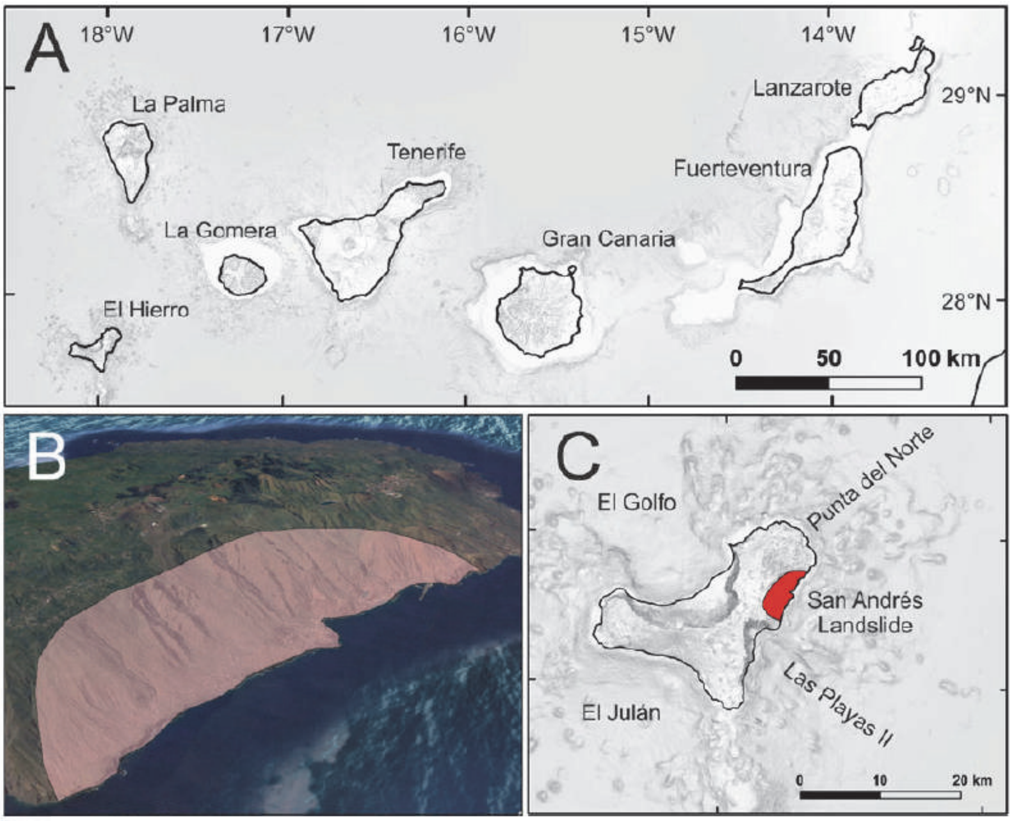


Fig. 5 A: Location of the study area within Canary Islands. B: Oblique Google Earth image of the tsunami source landslide. C: Detailed map of EI Hierro with historically known slope failures. The tsunami source landslide is highlighted in red (Fig. 1 in Blahůt and Luna 2020)

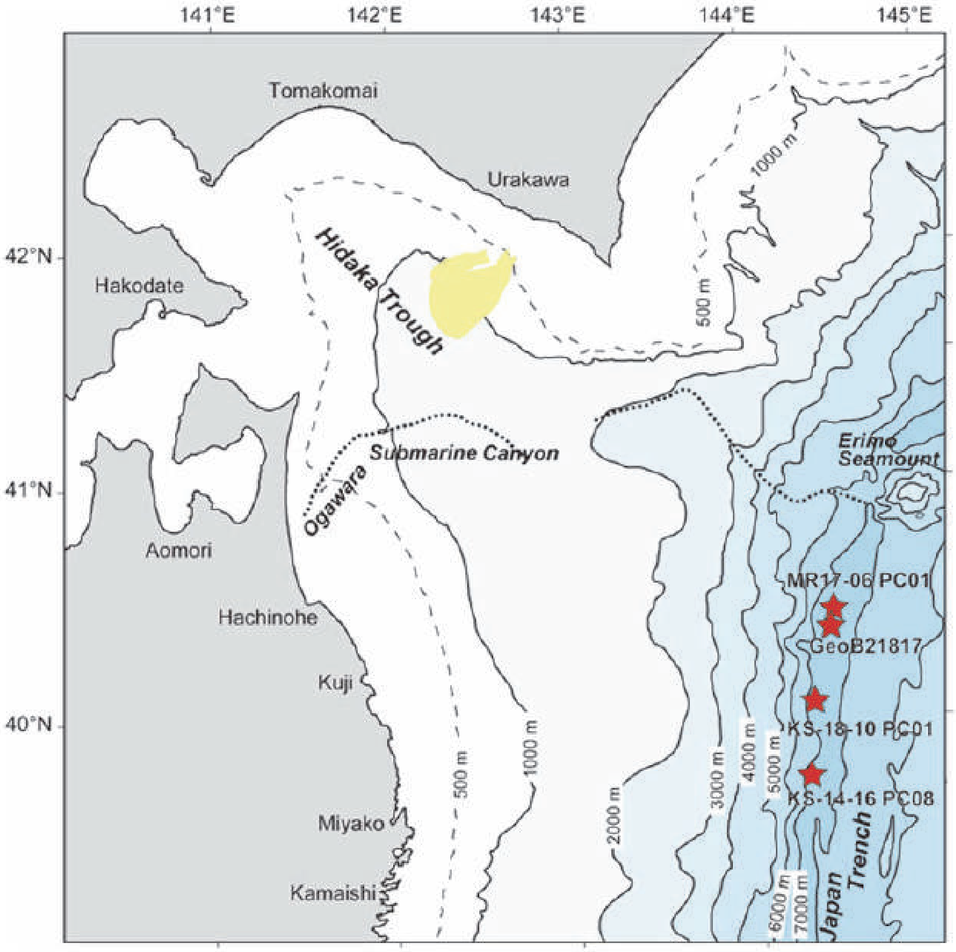
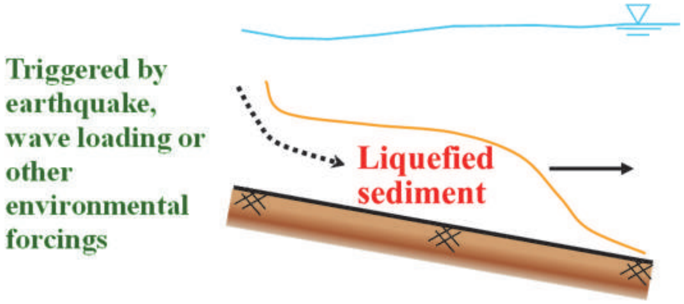
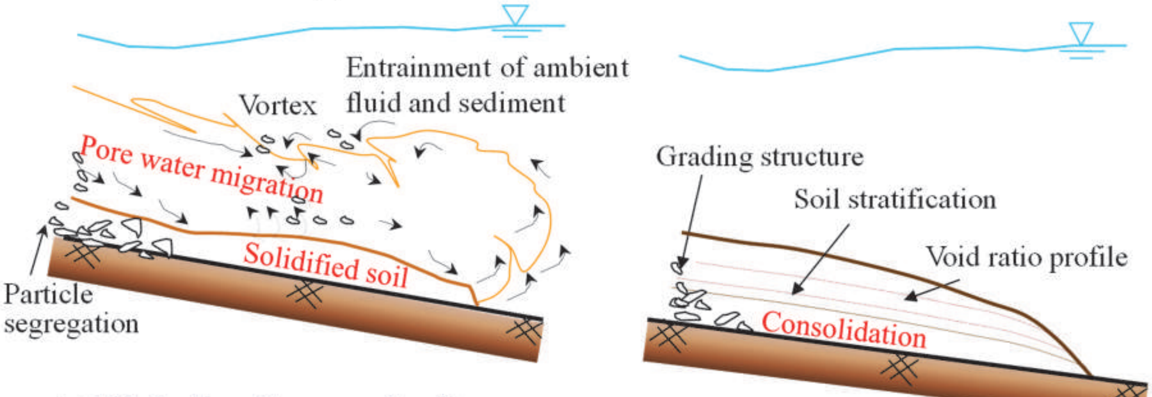


Fig. 6 Bathymetry of the study area and location of the cores. The areas of the upper slope of the Hidaka Trough marked in yellow are the youngest submarine landslides studied by Noda and Katayama (2013) (Fig. 1 in Usami et al. 2020)



(a) **Coastal and submarine landslide**



(b) **High-density gravity flow**

(c) **Deposition**

Fig. 7 Relevant features of liquefied gravity flows

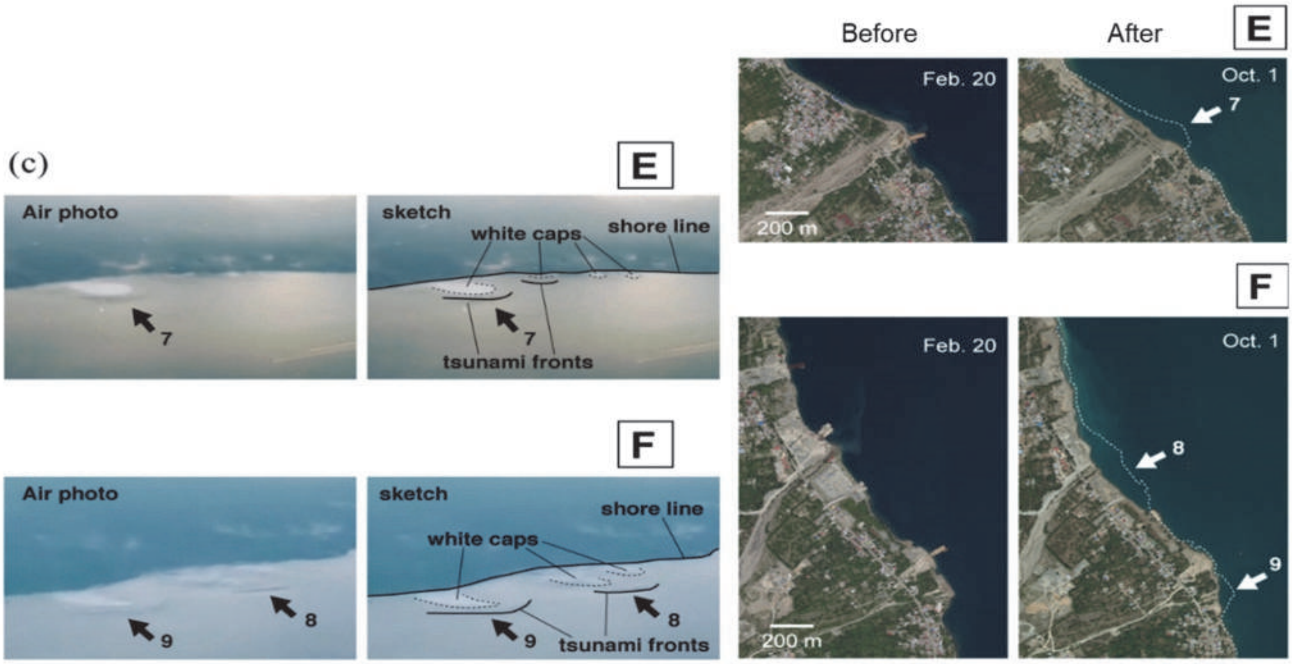


Fig. 8 Comparing the locations of multiple tsunami generations, alongshore distributions and directions with the locations, distributions and directions where the coastal lands collapsed and flowed due to the occurrence of liquefaction in the 2018 Indonesia Sulawesi earthquake (Fig. 4(c) in Sassa and Takagawa 2019)

gravity flows is governed by the multi-phased physics (Fig. 7). The cascading mechanisms of the 2018 Indonesia Sulawesi earthquake and tsunami disasters are highlighted in light of the concurrent processes involving liquefaction, coastal and submarine landslides, and multiple tsunamis (Fig. 8).

N. Casagli presented monitoring and early warning of landslides with special reference to Stromboli landslide induced tsunami. The Stromboli island volcanic activity has induced mass flows causing tsunamis with an average of 1 tsunami every 20 years (Fig. 9). The integration of space-borne and ground-based Synthetic Aperture Radar displacement data with the analysis of change detection (Fig. 10) allowed the identification of the evolution of the slope instability phenomena and hence could be an effective tool for early warning of eruptions, landslides and tsunami.

K. Sassa presented the history of development of the undrained dynamic-loading ring-shear apparatus and the integrated simulation model for the evaluation of the initiation and motion of landslides as well as a new landslide induced tsunami model based on the aforementioned landslide dynamics. The validity has been confirmed with the world's largest well- documented landslide tsunami disaster with 15,153 deaths in Unzen, Japan in 1972. The application to potential retrogressive Senoumi landslides in Suruga bay shows tsunami inundation depths of 20-50m in Yaizu city (Fig. 11).

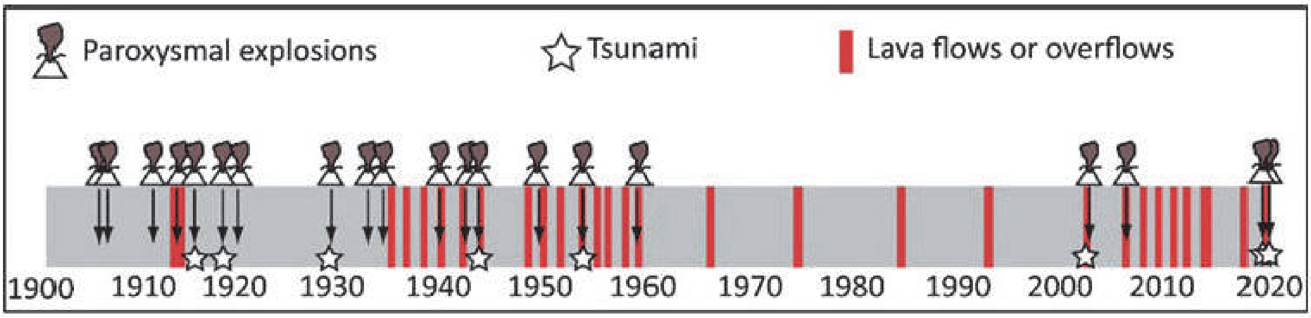


Fig. 9 Volcanic activity and tsunamis at Stromboli volcano (Fig. 3 in Traglia et al. 2020)

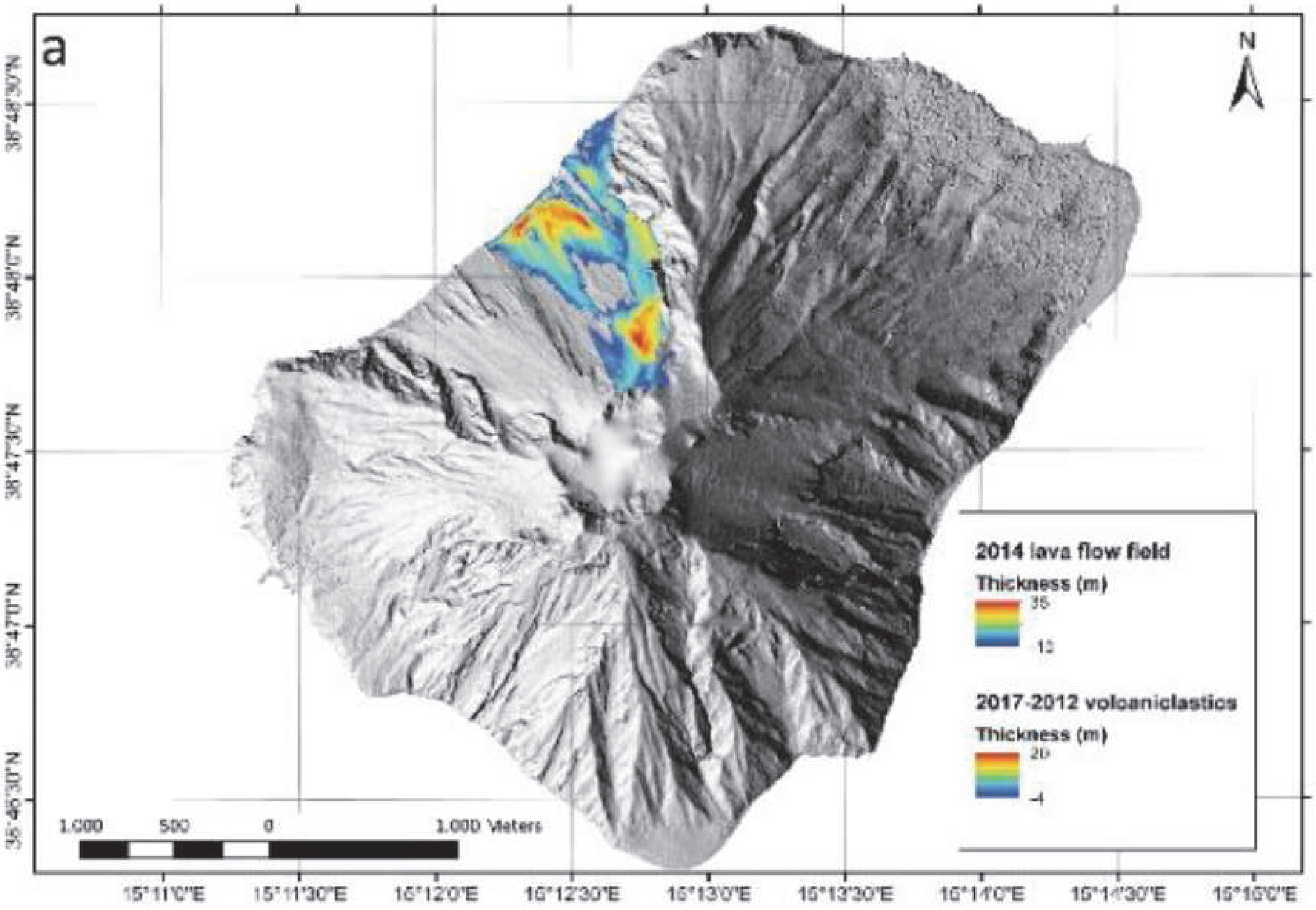


Fig. 10 Change detection from a topographic data (2012-2017) (Fig. 5(a) in Traglia et al. 2020)

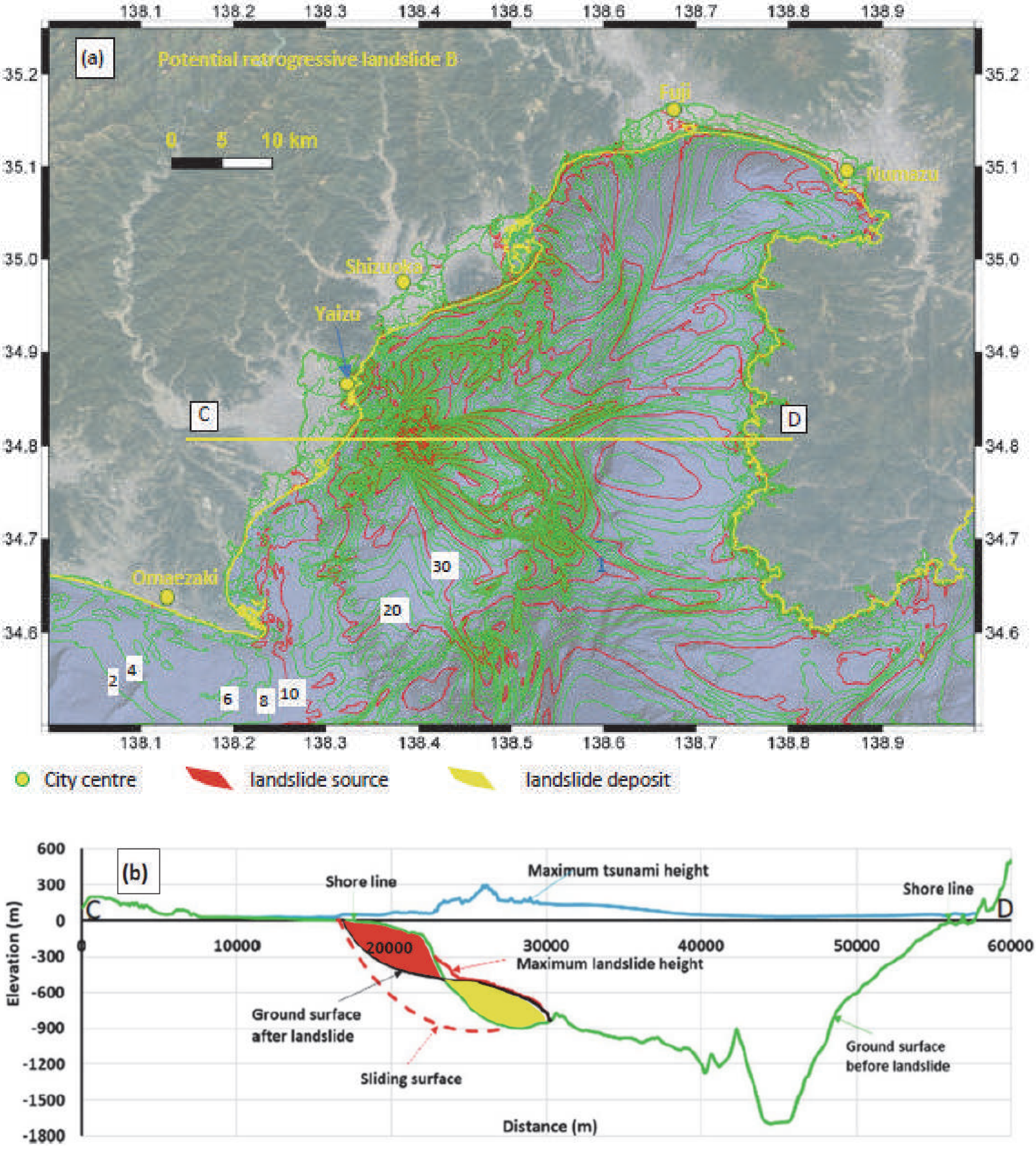


Fig. 11 (a) Contour of the maximum tsunami height caused by a potential retrogressive landslide in Neogene sand triggered by 0.7 ×Tohoku earthquake record (MYG004). Tsunami heights are in meters above sea level with 2m contours in green and 10m contours in blue. (b) The profile of the maximum tsunami height at each mesh along section C-D (Fig. 32 in Loi et al. 2020)

S. Grilli presented a series of studies on tsunami generation by the 2018 volcanic flank collapse of Anak Krakatau in the Sunda Straits of Indonesia. New numerical slide/tsunami modelling was developed with a new AK collapse geometric model based on a high-resolution bathymetry-topography data and satellite images. Simulations for viscous or granular slides (Fig. 12) were conducted and the maximum surface elevations/runup were successfully compared with the field survey data from various researchers. An improved modeling of catastrophic events such as AK 2018 can help us better prepare for and mitigate hazard posed by future similar events.

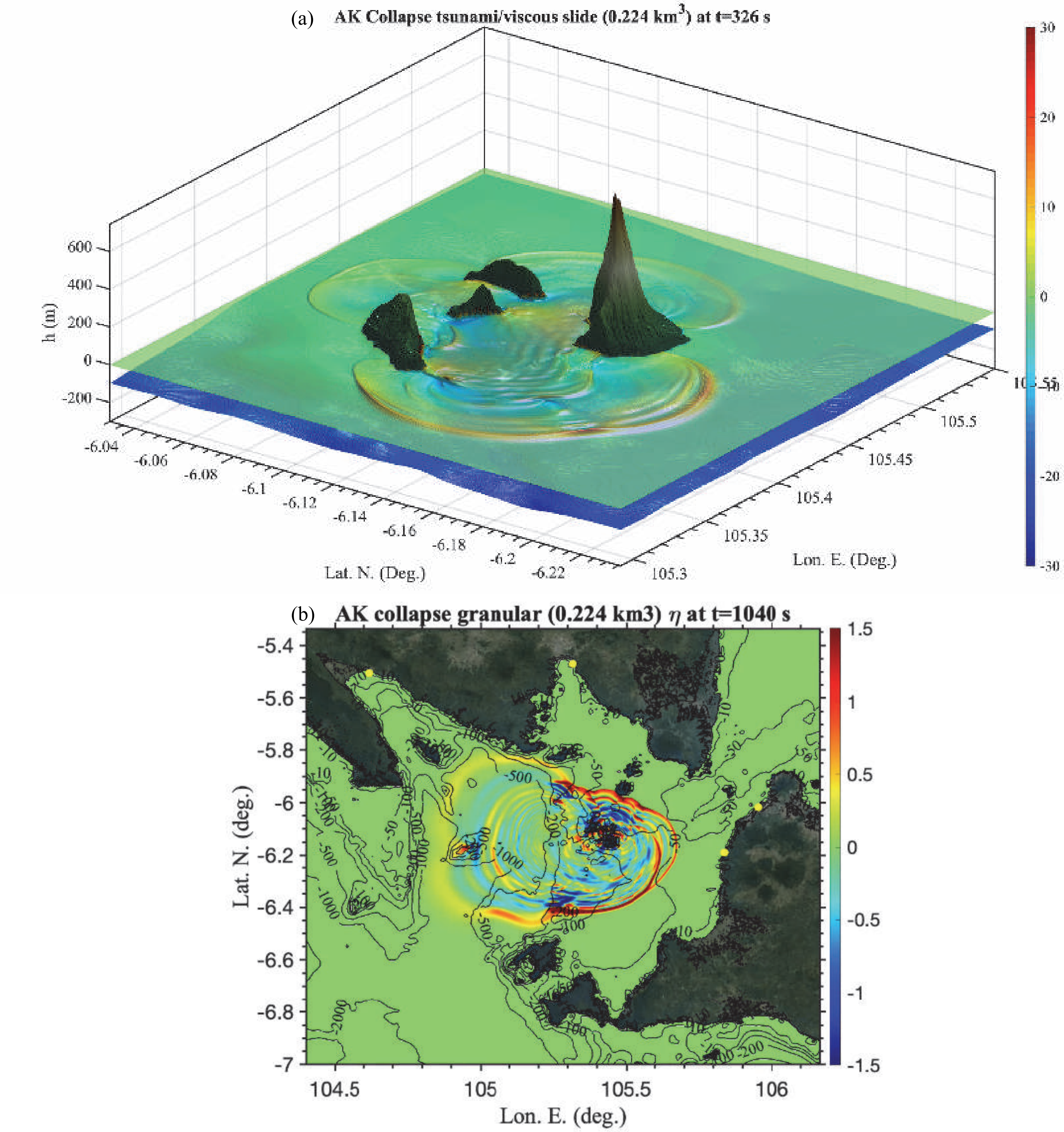


Fig. 12 Tsunami generations from the 2018 volcanic flank collapse of Anak Krakatau for (a) viscous slides and (b) granular slides. (Snapshots from S. Grilli's presentation based on Grilli et al. (2019, 2021))

D. Tappin highlighted the continuing underestimated tsunami hazard from submarine landslides. Recognition of the tsunami hazard from submarine landslides has been possible mainly because of the recent development of advanced technology such as multibeam echosounders. Accordingly, submarine landslide tsunamis are now seen from all geological environments; passive, convergent and strike-slip margins as well as volcanoes (examples are shown for the 1908 Messina tsunami in Fig. 13 and for the 2011 Tohoku tsunami in Fig. 14). Despite these new advances in understanding, however, recognition of the tsunami hazard from submarine landslides is still limited.

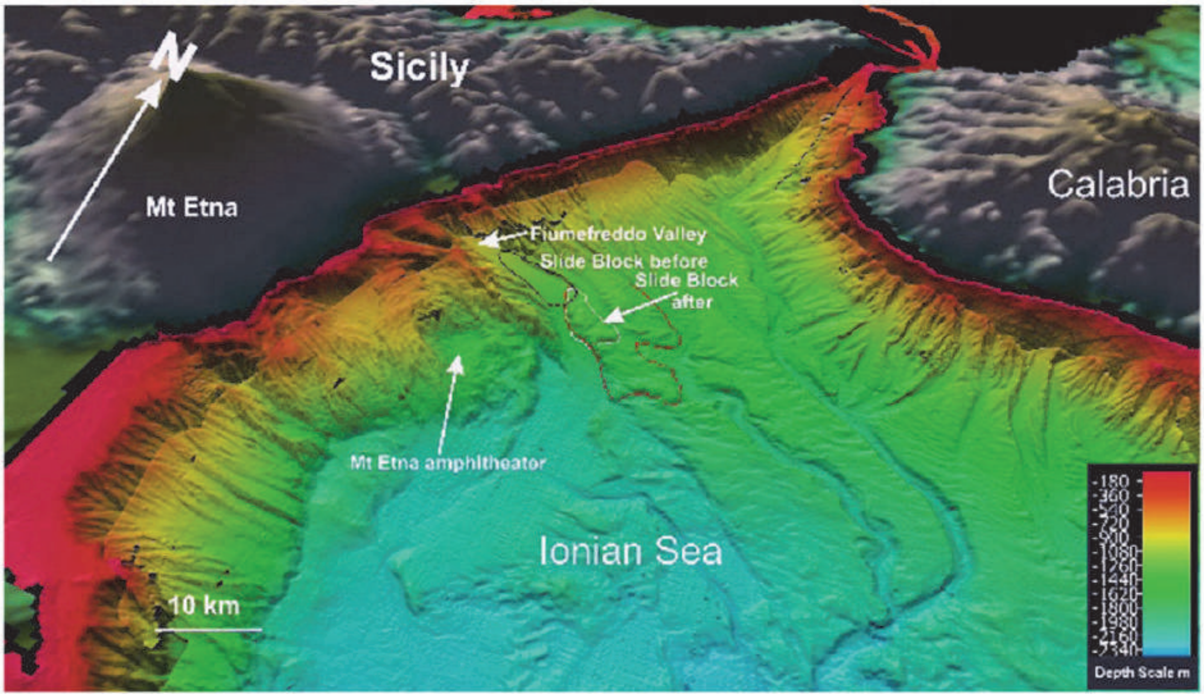


Fig. 13 3D image of the landslide block that contributed to the 1908 Messina tsunami (reproduced from Schambach et al. 2020) (Fig. 5 in Tappin and Grilli 2020)

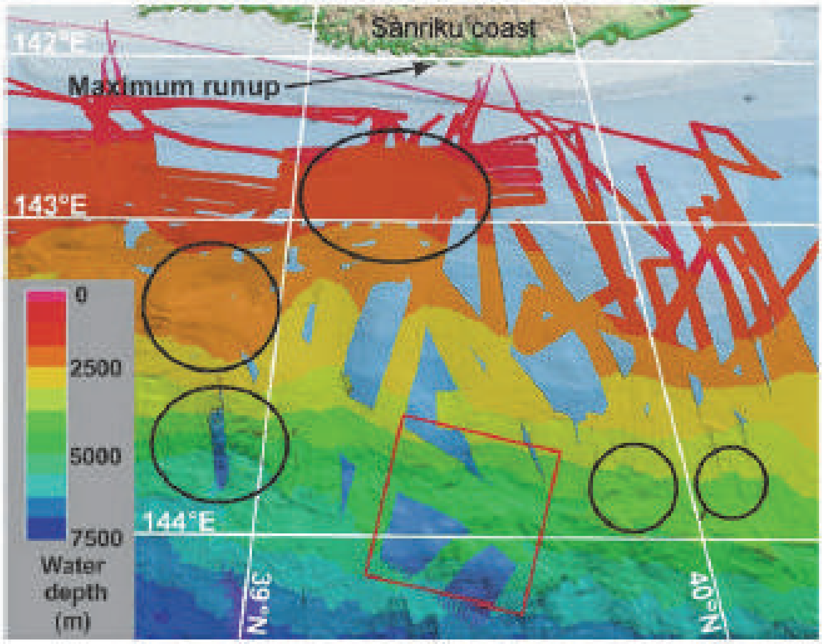


Fig. 14 Mutibeam bathymetry of the east coast of Japan, showing submarine landslides (SLs). Black ellipses/circle are SLs: Red square is the location of the SMF triggered by the March 2011 earthquake (reproduced from Tappin et al. 2014) (Fig. 6 in Tappin and Grilli 2020)

Fig. 15 General view of the landslide scar on the southern bank of the Bureya water reservoir and the body of the landslide with a passage, initially made 1 February 2019 and then extended by the spring flood in April-May 2019. The top left panel shows damaged stumps and exposed tree roots on the gentle coastal slope directly opposite the landslide on the northern bank of the Bureya river (Figs.3 and 9 in Gusiakov and Makhinov 2020)

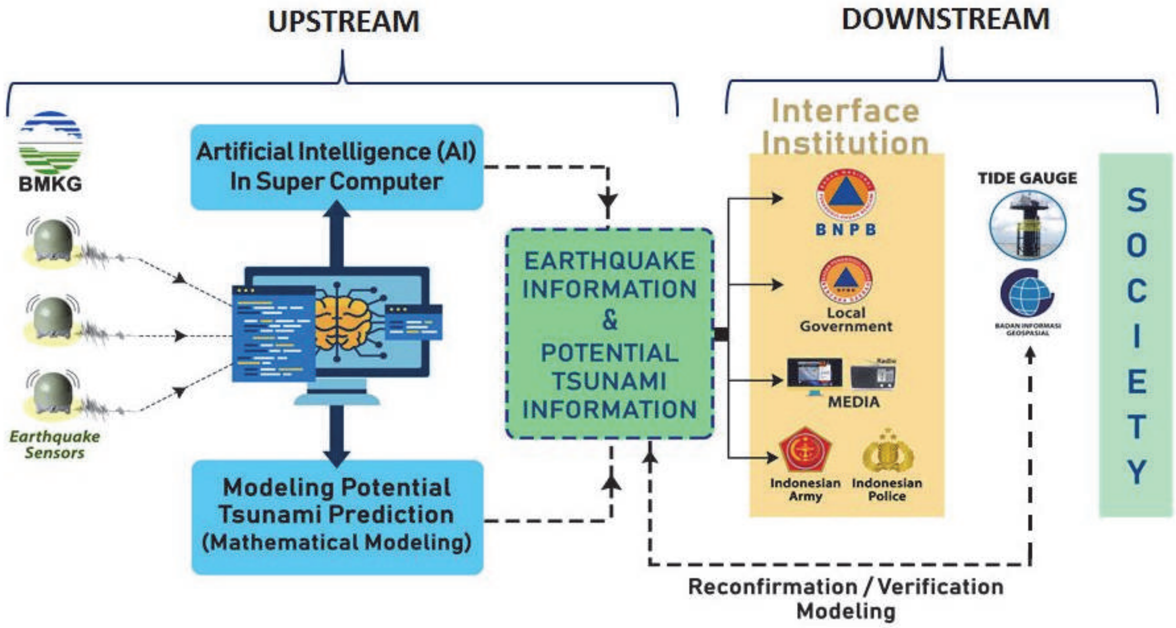


Fig. 16 End to end system for tsunami early warning in Indonesia (Karnawati 2020)

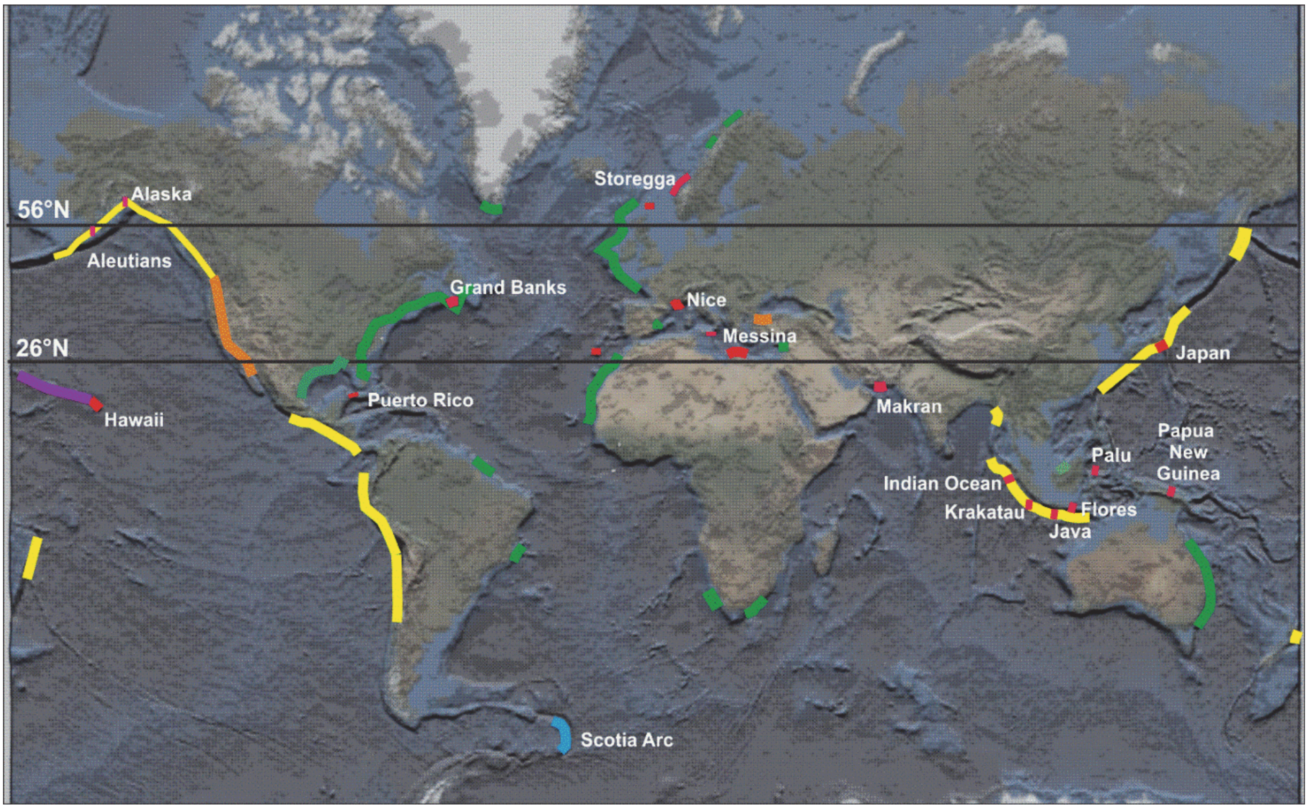


Fig. 17 Global distribution of mapped submarine landslides (SLs): Green, SLs on passive margins; Yellow, SLs located along convergent margins; Orange, SLs on strike slip margins; purple, volcanoes; Red, tsunamis associated with SLs (Tappin and Grilli 2020). Submarine landslide tsunamis (in red) are mainly located along convergent margins, but also along passive and strike slip margins and on flanks of volcanoes

V. Gusiakov reported the December 11, 2018 landslide and the landslide-induced icy tsunami in the Bureya water reservoir, Russia. The landslide with an estimated volume of up to 25 million cubic meters generated a destructive tsunami-like wave whose impact on the shore was emphasized by a thick (up to 20cm) ice cover (Fig. 15). The maximum run-up height turned out to be equal to 90 m above the initial water level. The event has demonstrated the potential threat of the slope instability and the landslide-induced waves for the safety of hydropower plant (HPP) dams in a mountain region.

D. Karnawati presented an innovation in tsunami early warning system in Indonesia. The system aims at a timely detection of earthquake event and provides tsunami warning within 5 minutes after the earthquake takes place. The end to end system adopted for tsunami early warning is shown in Fig. 16. It facilitates an appropriate response from the community to reduce and minimize the impact of tsunami disasters. The 2018 catastrophic events highlighted the impact of volcanic flank collapse- and landslide-induced tsunamis, showing the importance of multi-hazard risks.

Outcome of the Panel Discussion

This section presents an outcome of the panel discussion. The essential content from each panelist will first be presented, followed by a summary of the general discussion moderated by the coordinator.

Essential content from each panelist

S.G. presented three fundamental and important issues, namely: 1. Triggering: when, where, how?; 2. Tsunami generation and propagation: magnitude, where, how?; 3. Landslide tsunami detection: magnitude/where?. These are described as below:

1. Triggering => when, where, how

For subaerial/submarine mass failures (SMF), simulating slide triggering requires topography/bathymetry and soil properties (physical, cohesiveness/rheology etc.) as well as statistics//probability of peak ground acceleration (PGA). A question here is whether predictive slope stability analyses could be performed together with an estimate of the factor of safety. For tsunami, coupled modeling of slide motion/tsunami generation is necessary. For volcanic tsunamis caused by pyroclastic flows (PF), pyroclastic density currents (PDC) and flank/caldera collapse, assessing triggering requires topography/bathymetry, volcano material/PF/PDC properties (physical, cohesiveness/rheology etc.), and estimates of PF/PDC flow rates and total volume. Monitoring of volcanic physical triggers (e.g., internal pressure, PGA) is also required. For tsunami, coupled modeling of collapse/PF/PDC motion/tsunami generation is necessary.

2. Tsunami generation propagation => magnitude, where, how

Models of tsunami generation (near-field) must feature relevant physics to simulate both slide and tsunami, and their coupling, including strong nonlinearity (in both geometry and flow), dispersion (vertical accel.) in deep water, and three-dimensionality. Models of tsunami propagation (near-to-far-field) must include dispersion and

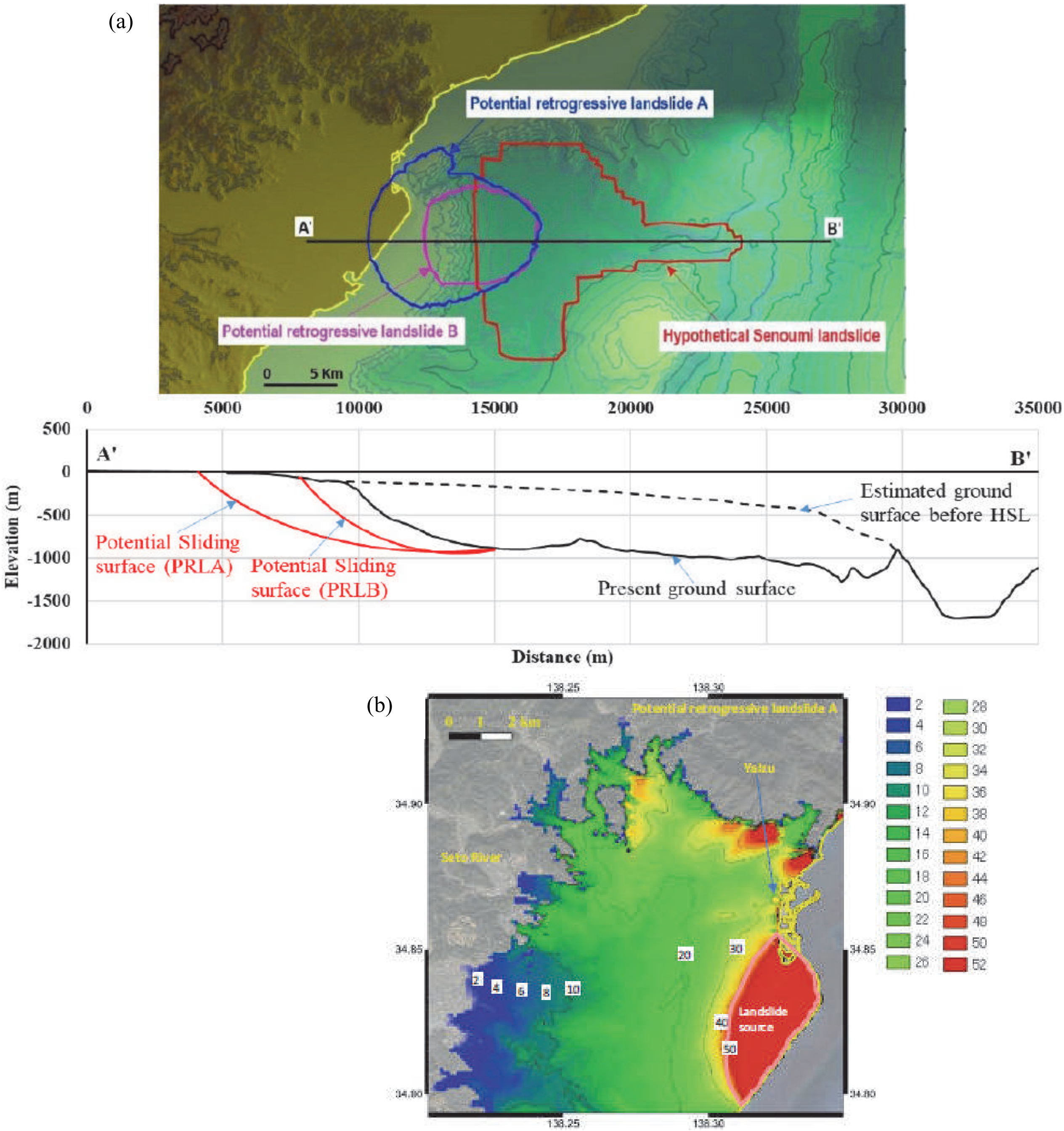
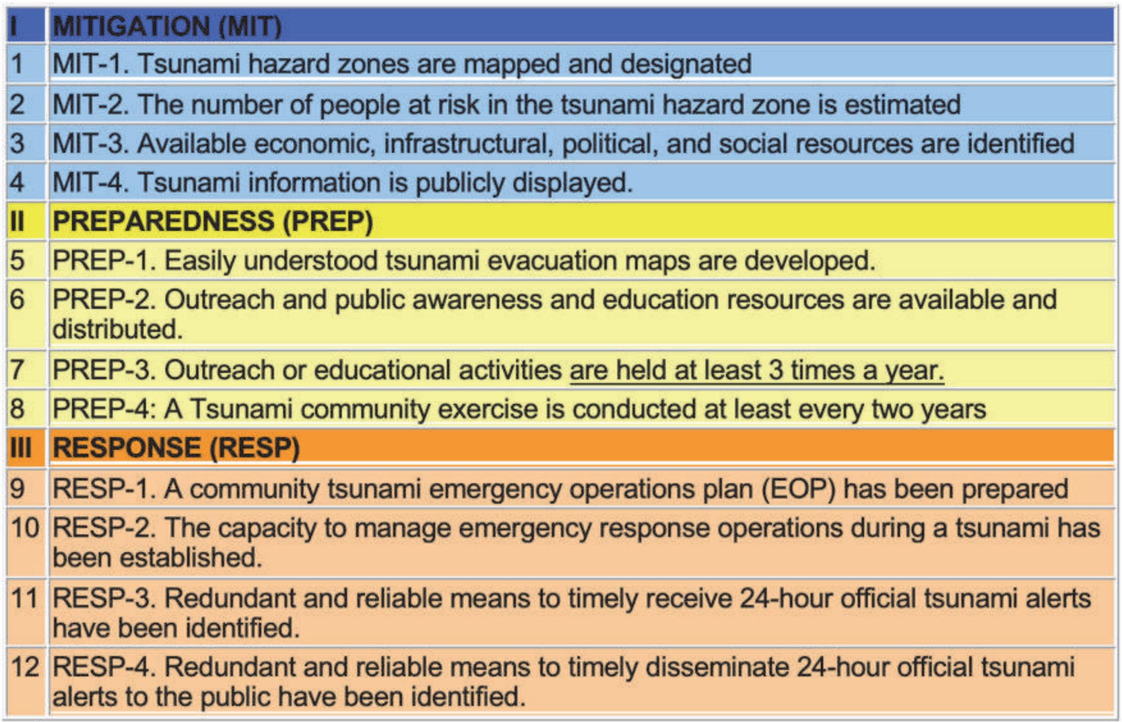


Fig. 18 (a) Shapes and cross sections of hypothetical Senoumi landslide (HSL) and potential retrogressive landslides A and B (PRLA and PRLB, respectively) (b) Inundation map at Yaizu City center caused by PRLA. Inundation depth (color scale in meter) = maximum tsunami height – ground elevation (Figs. 31 and 34(a) in Loi et al. 2020)



I	MITIGATION (MIT)
1	MIT-1. Tsunami hazard zones are mapped and designated
2	MIT-2. The number of people at risk in the tsunami hazard zone is estimated
3	MIT-3. Available economic, infrastructural, political, and social resources are identified
4	MIT-4. Tsunami information is publicly displayed.
II	PREPAREDNESS (PREP)
5	PREP-1. Easily understood tsunami evacuation maps are developed.
6	PREP-2. Outreach and public awareness and education resources are available and distributed.
7	PREP-3. Outreach or educational activities are held at least 3 times a year.
8	PREP-4: A Tsunami community exercise is conducted at least every two years
III	RESPONSE (RESP)
9	RESP-1. A community tsunami emergency operations plan (EOP) has been prepared
10	RESP-2. The capacity to manage emergency response operations during a tsunami has been established.
11	RESP-3. Redundant and reliable means to timely receive 24-hour official tsunami alerts have been identified.
12	RESP-4. Redundant and reliable means to timely disseminate 24-hour official tsunami alerts to the public have been identified.

Fig. 19 A list of 12 indicators from UNESCO-IOC TSUNAMI READY COMMUNITY PROGRAM (excerpt from D. Karnawati's presentation)

sufficient nonlinearity. Depth-integrated/averaged models are adequate. The necessary slide/wave models exist for the most part: such as in near-field, multi-material Navier-Stokes and various multi-layer non-hydrostatic models, including various rheologies, Newtonian and non-Newtonian such as Boussinesq wave model in the near-to-far-field. These models have been applied and validated on many field case studies, e.g., Storegga, Grand Bank 1929, PNG 1998, Messina 1908, Palu 2018 etc.

3. Landslide tsunami detection/warning => magnitude/where

There may not be an earthquake trigger or even a volcanic eruption. Simulations of potential landslide tsunami scenarios and their induced hazard need to be done in advance for areas deemed at risk that will be monitored. Non-standard detection methods must be implemented, such as High Frequency (HF) radar remote sensing combined with relevant tsunami detection algorithms.

D.T. presented a global map of submarine landslide tsunami locations (Fig. 17), noting that a broad global understanding of the hazard and mapping is required. A learning curve for submarine landslide tsunamis can be described as follows: Most (80%) of tsunamis from earthquakes, but also from seabed slumps, landslides, dual mechanisms and volcanic collapse. Landslide tsunamis over past few decades improve our understanding of their tsunami hazard. Each new event provides data from new technology such as multibeam bathymetry and new numerical tsunami models, however, there are still too few data to provide a broad global understanding of the hazard. Mitigation and warning are only confined to earthquake events, with 20% of oceans mapped, so major mapping programmes are required. Recent events flag non-seismic mechanisms, and form basis for improved mitigation and warning.

K.S. presented simulations of coastal and submarine landslide-induced tsunamis and highlighted the important role of landslide motion in tsunami generation. A hazard assessment of landslide-induced tsunamis along Suruga bay in Japan was presented for a hypothetical Senoumi landslide and potential retrogressive landslides arising from a future mega earthquake along Nankai Trough together with their hazard map (Fig. 18). How to prepare for possible landslide causing tsunamis was highlighted. Namely, retrogressive landslides are common in many landslides. However, to investigate the possibility of potential retrogressive landslides at Senoumi, a set of 800 m deep drillings and geophysical exploration are needed. Hence, we have to discuss how to promote the understanding and reducing landslide disaster risk including both landslide causing tsunami and landslide-induced tsunami for KLC2020.

D.K. first illustrated some case examples of Palu earthquake and tsunami with liquefaction and submarine landslide, Sunda Straits tsunami due to volcanic eruption, and historical earthquakes and tsunamis in Ambon, Indonesia. Controlling factors and characteristics of areas typically prone to landslides were presented with reference to geology and bathymetry such as a fault distribution in coastal or near shore areas and position of alluvial fan. Triggering sources involve earthquake and volcanic eruption. A mitigation strategy based on hazard maps and evacuation plans was then provided with six levels of field verification and fact findings in order to (a) verify the hazard levels and zones (tsunami hazard map), (b) select and check most appropriate evacuation route (shortest and fastest) with appropriate sign, (c) empower the local capacity to take the rapid or spontaneous actions in response to any ground shaking, coastal subsidence and landslides, by following the determined evacuation route toward the higher/saver area, (d) promote public education and regular drill for self-evacuation (integrate the local wisdom and knowledge), (e) establish appropriate land use management based on appropriate hazard map and (f) relocate the people from hazard area. A list of 12 indicators from UNESCO-IOC tsunami community program was presented (Fig. 19).

V.G. demonstrated the close relationship between oceanic sedimentation zones and landslide-triggered tsunamigenic potential, which could directly contribute to improving tsunami early warning and long-term risk assessment. Specifically, the main zones of lithogenesis in the Pacific Ocean (1 - equatorial humid zone, 2 - northern and southern humid zones, 3 - zone of effusive-sedimentary lithogenesis, 4 - northern and southern arid zones), and the classification and locations of "red", "green" and "blue" Pacific tsunamigenic earthquakes were presented (Fig. 20). It demonstrates that there is a close relationship between oceanic sedimentation zones and tsunamigenic potential of submarine earthquakes. In spite of greater efforts in recent years to study the slumping mechanism of tsunami generation, this factor is almost completely overlooked in the early tsunami warning and in the long-term tsunami risk assessment (coastal tsunami zoning). Conditions of oceanic sedimentation are of extreme importance in understanding the tsunami generation mechanism, and that slumping has contributed significantly to at least 33% of the historical tsunami events rather than the 7% indicated in the historical tsunami catalogs for the Pacific. The contribution of underwater slumping to the tsunami generation mechanism was recognized long ago. However, little attention was given so far to the relationship of tsunami generation to conditions of oceanic sedimentation in the main tsunamigenic zones of the Pacific. Taking this into account can essentially change the strategy in improving the operational tsunami warnings and the long-term tsunami risk assessment. Specifically, the magnitude criterion for operational warning can be made variable, depending on the earthquake location within the basic zones of oceanic sedimentation (shallow water bays, marginal seas, island arc regions, remote deep-water trenches, middle ocean ridges). In estimating the long-term tsunami risk, it can be

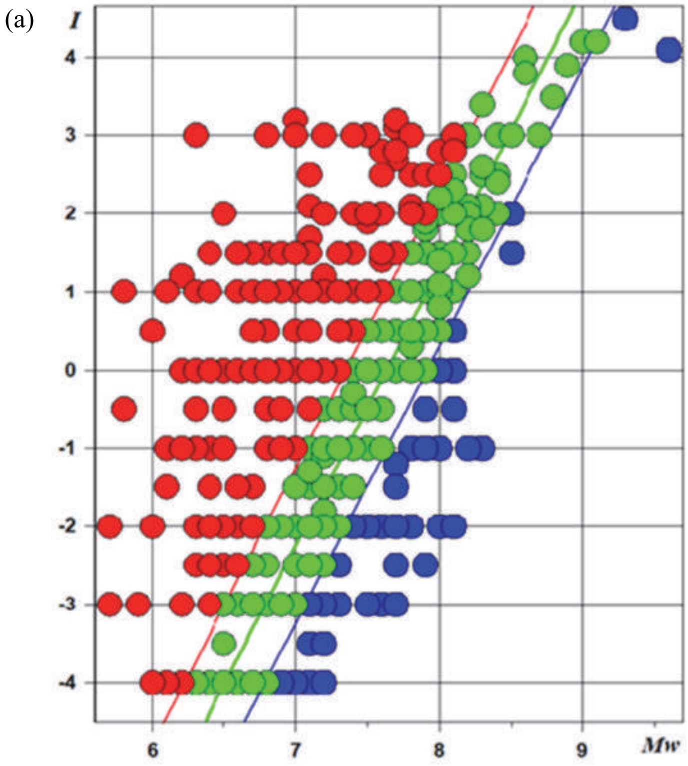
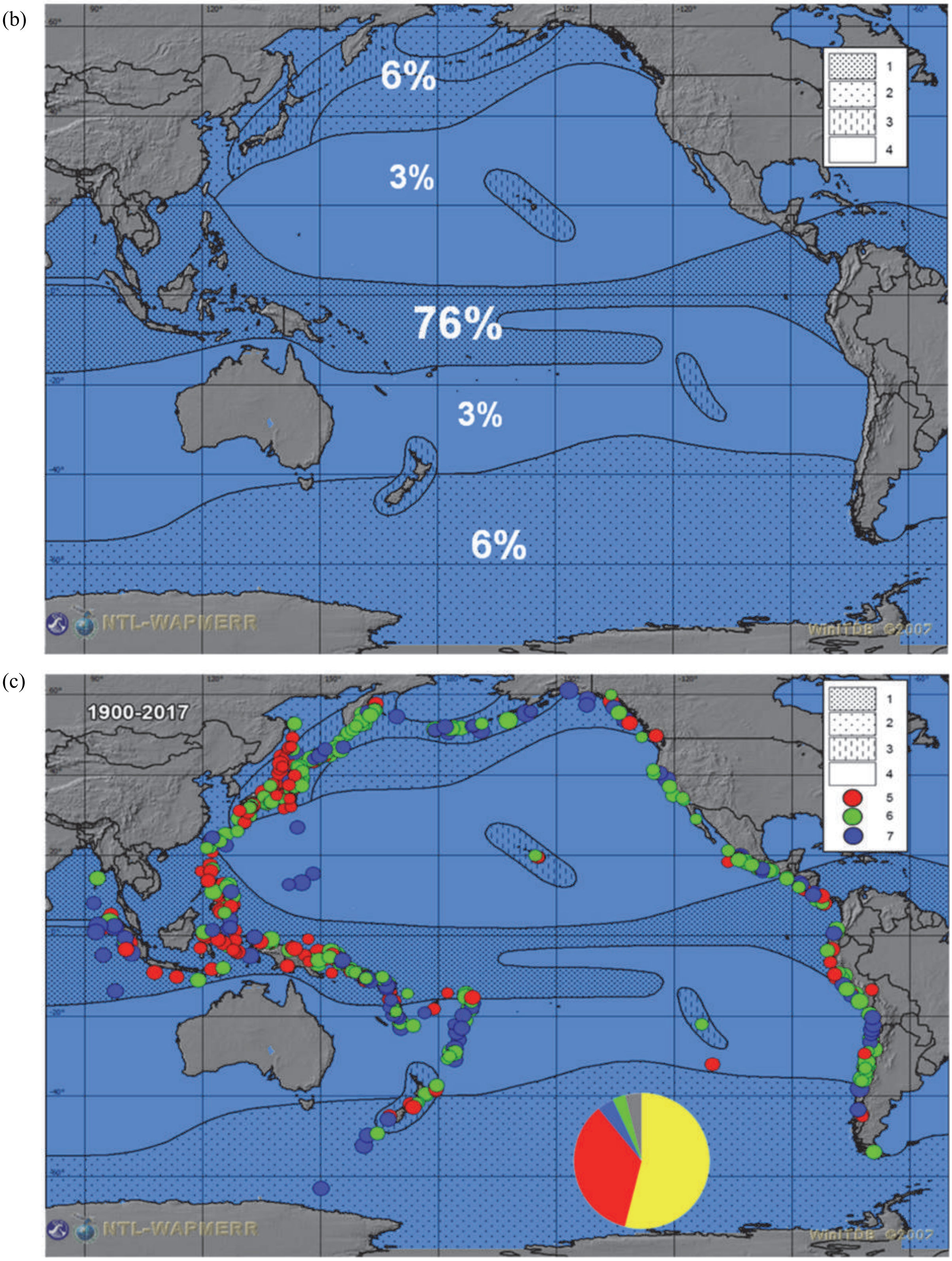


Fig. 20 (a) Classification of “red”, “green” and “blue” Pacific tsunamigenic earthquakes in the tsunami intensity I - moment magnitude M_w relationship according to Gusiakov (2001) (b) The main zones of lithogenesis in the Pacific Ocean (1 - equatorial humid zone, 2 - northern and southern humid zones, 3 - zone of effusive-sedimentary lithogenesis, 4 - northern and southern arid zones). The digits show a fraction of sediment volume in each zone in the total volume of marine sediments by Lisitsyn (1974) (c) Locations of the "red", "green" and "blue” tsunamigenic earthquakes. The insert figure shows the fractions of landslide-generated tsunamis (red color) in the total number of Pacific tsunamis (excerpts from V. Gusiakov’s presentation)



very important to consider the potential of submarine slumping in the tsunami-prone areas.

F.L. stressed the lack of data for landslide volume probability, resulting from limited seafloor sub-bottom mapping, and highlighted the uncertainty in landslide dynamics leading to tsunami genesis. Although physics of tsunami propagation and inundation are well established and sensitivity to the kinematics of the landslide (i.e. the

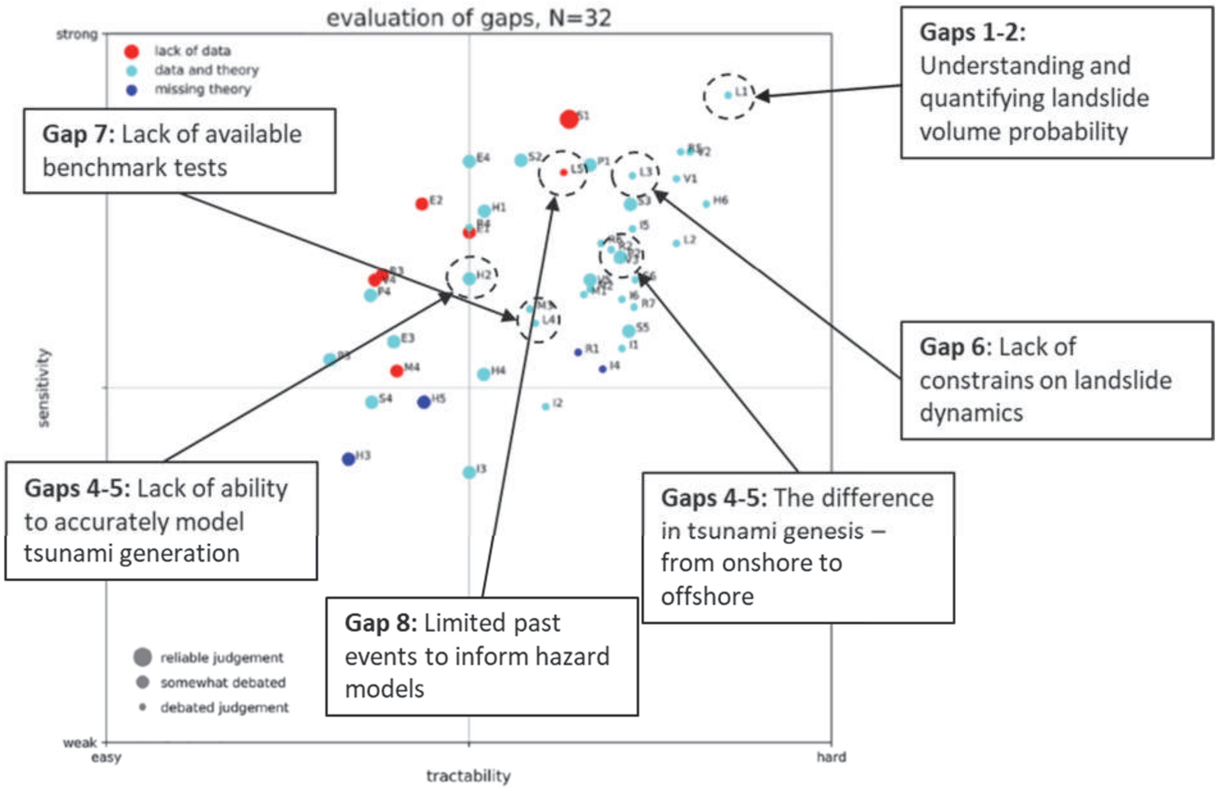
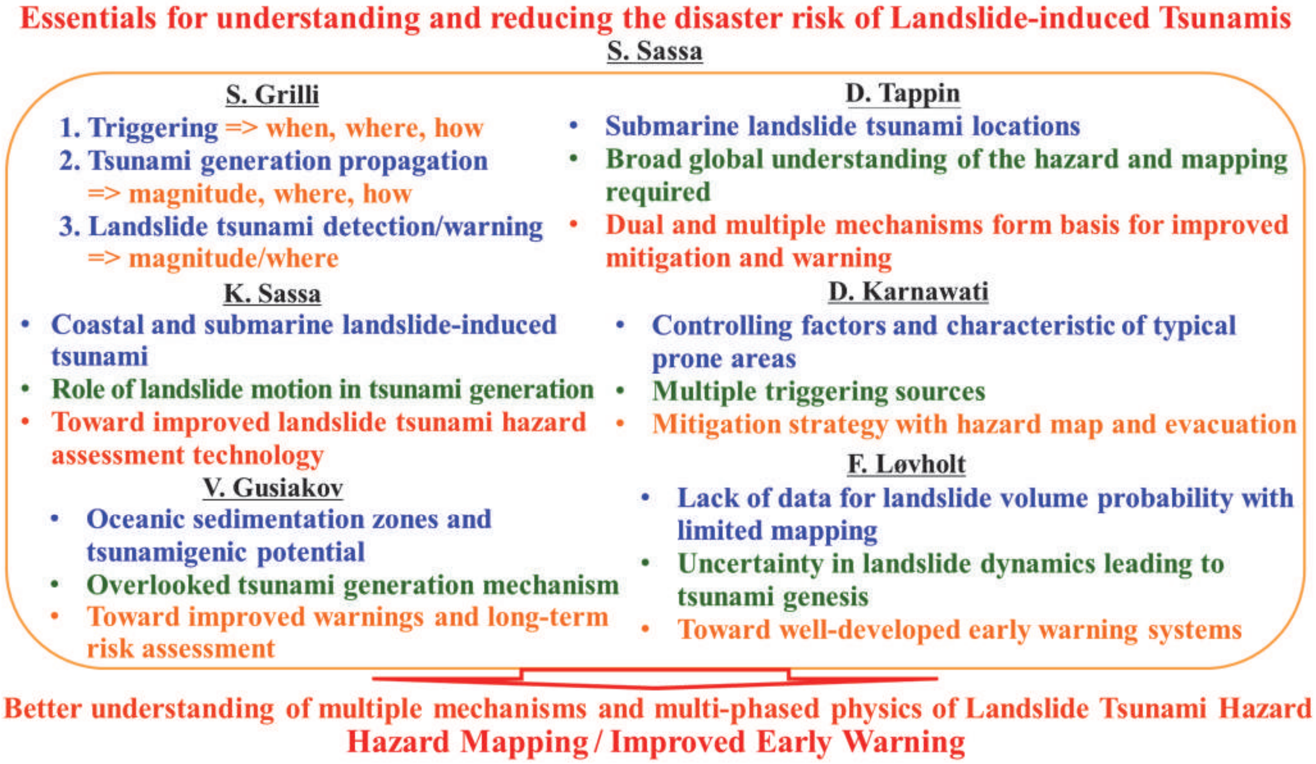


Fig. 21 Outstanding questions and gaps – the European tsunami community response (excerpt from F. Løvholt's presentation based on Behrens et al. (2021))

motion and path) is relatively well known, several cases thoroughly hindcasted represent mainly subaerial landslides. Accordingly, in most places around the world, we lack data for quantifying temporal landslide volume probability with limited and often non-existing mapping of substrata conditions, thickness of sediments, fractures, geotechnical parameters etc. Landslide friction scales with landslide size, however, implications for hazard are also not well known. Landslide dynamics controls tsunami-genesis, but is uncertain. Both material parameters and landslide water interaction are poorly constrained. Past landslide run-out distance observations constrain tsunami-genesis poorly and therefore calibration against past cases are associated with large uncertainties. In fact, there is a limited amount of well documented fully subaqueous landslide tsunami events. Transition from landslide failure to flow controls acceleration and rate of failure (retrogression), and how they can contribute to tsunami-genesis is crucial. In comparison with earthquake tsunami hazards, temporal landslide statistics is usually much less well constrained. Paleo-observations are important, dating necessary, but often highly uncertain. Longer time scales for hazard involves more uncertainty. Landslides can occur "everywhere" – while earthquakes are constrained to major faults and subduction zones. Greater variability lies in tsunami generation mechanisms: Subaerial vs submarine; Landslide dynamics; Slumping, Translation, Turbidity currents with different repeatability characteristics (sediment escape vs faults and plate motion). These lead to the lack of well-developed early warning systems. The outstanding questions and gaps from the European tsunami community are shown in Fig. 21.

Summary of the Panel Discussion

During the general Panel Discussion, each of the key items summarized in Fig. 22 was critically discussed among the panelists and the coordinator. The content of this Panel Discussion is summarized in Sassa et al. (2022) and the key discussion points are briefly reviewed in the following. Triggering and source mechanisms need to be well constrained and one needs to better understand how both of these affect tsunami generation, in order to more accurately predict/model landslide-induced tsunamis. There is still a lot to learn for better understanding and mitigating the disaster risk of landslide-induced tsunamis, regarding hazard mapping (Fig. 17) and improving warning. Dual and multiple mechanisms must be considered to achieve improved mitigation. However, our limited understanding and characterization of past events makes it difficult to well constrain landslide dynamics (Fig. 21). Landslide dynamics controls tsunami generation (genesis) but is inherently uncertain; hence, a better integrated understanding of



Essentials for understanding and reducing the disaster risk of Landslide-induced Tsunamis

S. Sassa

S. Grilli

1. Triggering => when, where, how
2. Tsunami generation propagation => magnitude, where, how
3. Landslide tsunami detection/warning => magnitude/where

K. Sassa

- Coastal and submarine landslide-induced tsunami
- Role of landslide motion in tsunami generation
- Toward improved landslide tsunami hazard assessment technology

V. Gusiakov

- Oceanic sedimentation zones and tsunamigenic potential
- Overlooked tsunami generation mechanism
- Toward improved warnings and long-term risk assessment

D. Tappin

- Submarine landslide tsunami locations
- Broad global understanding of the hazard and mapping required
- Dual and multiple mechanisms form basis for improved mitigation and warning

D. Karnawati

- Controlling factors and characteristic of typical prone areas
- Multiple triggering sources
- Mitigation strategy with hazard map and evacuation

F. Løvholt

- Lack of data for landslide volume probability with limited mapping
- Uncertainty in landslide dynamics leading to tsunami genesis
- Toward well-developed early warning systems

Better understanding of multiple mechanisms and multi-phased physics of Landslide Tsunami Hazard

Hazard Mapping / Improved Early Warning

Fig. 22 The framework, essential content and a short summary of the panel discussion in the World Tsunami Awareness Day Special Event of the Fifth World Landslide Forum (Sassa et al. 2022)

landslide dynamics as well as multi-phased physics of landslide-water interactions are crucial to reducing landslide tsunami disaster risk. Landslide dynamics itself features complex physics, such as liquefaction and evolutions of pore water pressures involving phase change processes (Fig. 7), and the in-depth understanding of such phenomena is important for improving landslide tsunami hazard assessment technologies. A closer investigation of landslides that have caused or potentially cause tsunamis (Fig. 18) is thus very important. In this respect, multiple triggering sources of tsunamis such as landslides caused by earthquakes and volcanic eruptions must be better understood. Large volcanic flank collapses have induced large tsunamis, e.g., recently Anak Krakatau 2018 (Fig. 12); hence, sites of potential future events should be closely monitored and new instruments, allowing for early detection and warning, deployed. In contrast, some landslide-induced tsunamis may impact shores very rapidly, such as in the cases of coastal and submarine landslides-induced tsunamis, e.g., recently Palu 2018 (Fig. 8). Therefore, in order to prepare for such fast arriving tsunamis, hazard mapping is critically important. Accordingly, both hazard maps and 24 hour warning are vital as mitigation strategies (Fig. 19). In light of multiple mechanisms, oceanic sedimentation conditions and zones have been overlooked as having high submarine landslide tsunami generation potential (Fig. 20); these can play a significant role in improving early warning and hazard maps. However, more data is needed to better constrain geological and geotechnical conditions for hazard mapping. Landslide-water interactions are currently poorly constrained and their better understanding, together with that of the complex multi-phased physics this entails, are crucial towards developing early warning systems. Overall, developing a better understanding of the multiple mechanisms and multi-phased physics governing landslide tsunami hazard is important and necessary for improving landslide tsunami hazard mapping and early warning.

Conclusion

This article has presented some recent advances, the current state and challenges in understanding and reducing the disaster risk of landslide-induced tsunamis. A worldwide perspective has been presented by showing the outcome of the panel discussion held across America, Europe, and Asia and a review of the World Tsunami Awareness Day Special Event of the Fifth World Landslide Forum. Hazard mapping and improved early warning are essential for better understanding and reducing the disaster risk of landslide-induced tsunamis, and this will require developing a better understanding of the multiple mechanisms and multi-phased physics of landslide tsunami hazard. An international collaborative network and platform would be important for such a multi-hazard risk reduction. It is therefore hoped that the content presented here will further promote understanding and reducing the disaster risk of landslide-induced tsunamis at both the regional and global scales.

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