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ANALYSIS OF LOCAL RISK PERCEPTION IN THE EVENT OF A TSUNAMI – A CASE STUDY IN MANTA, COASTAL ECUADOR

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ABSTRACT

Local perception of risk is a determinant of urban vulnerability. Accordingly, this research addresses the analysis of local perception of the risk of tsunami hazards occurrences and this case study focuses on an area of the Tarqui parish in the city of Manta in coastal Ecuador. This work also presents the possible tsunamigenic seismic source in the subduction zone of the study area. The Tarqui Zone is located within a coastal and fluvial landscape that currently the enlargement of the urban limit has obstructed the free flow of these systems. Based on the tsunami hazard map for the city of Manta, we determined that there are 392 sites in an area with high susceptibility to flooding. There are also 996 sites with medium susceptibility to floods in a zone of maximum influence between the levels of 7 to 20 m.a.s.l, sites in which the flood processes and corresponding erosion may not be very intense. In addition, the perception of this hazard was strengthened using context indicators on local tsunami risk perception based on a survey format for heads of households. In this regard, the given surveys indicate that 29 per cent of the population is in a state of high vulnerability, 63 per cent are in a situation of medium vulnerability and only 8 per cent are in a position of low vulnerability. With the obtained results we realized curves of frequency of perception of the population regarding this hazard, which will serve for the authorities to improve their response plans

Keywords: Tsunami, hazards, flooding, social vulnerability, Ecuador.

1. INTRODUCTION

Ecuador is a country which suffers of a variety of natural hazards due to its geodynamic setting, based on the conjunction of several oceanic and continental plates such as the Pacific, Cocos and Nazca oceanic plates on the one side as well as the Caribbean and South American continental plates on the other side (Meschede & Barckhausen, 2000; Meschede, 1998; Gutscher et al., 1999; Gutscher, 2002; Lonsdale, 2005; Chunga et al., 2017). Based on this constellation, there is active and even long-lasting volcanism (Aguilera and Toulkeridis, 2005; Toulkeridis et al., 2007; Toulkeridis et al., 2015; Vaca et al., 2016; Toulkeridis and Zach, 2017; Toulkeridis et al., 2021; Melián et al., 2021), yearly multiple events of mass mass movements such as landslides and subsidence (Zafrir Vallejo et al., 2018; Jaramillo Castelo et al., 2018; Chunga et al., 2019a; Suango Sánchez et al., 2019; Palacios Orejuela and Toulkeridis, 2020; Reyes-Pozo et al., 2020; Poma et al., 2021; Salcedo et al., 2022; Albán-Campaña et al., 2022), drought and extensive flooding of a wide area in various parts of the country (Mato and Toulkeridis, 2017; Toulkeridis et al., 2020; Sandoval et al., 2022; Moncayo-Galárraga et al., 2023; Gutiérrez Caiza and Toulkeridis, 2023), severe earthquakes with corresponding geological faults (Toulkeridis et al., 2017; Toulkeridis et al., 2018; Mato, F. and Toulkeridis, T., 2018; Chunga et al., 2019b; Toulkeridis et al., 2019; Salocchi et al., 2020; Aviles-Campoverde et al., 2021; Toulkeridis et al., 2019; Ortiz-Hernández et al., 2022; Sani et al., 2023) and also tsunamis (Chunga and Toulkeridis, 2014). These natural hazards are often destructive to man and infrastructure, especially when preparation or mitigation is lacking (Toulkeridis, 2016; Rodriguez et al., 2017; Navas et al., 2018; Sandoval-Erazo et al., 2019; Echegaray-Aveiga et al., 2019; Sánchez-Carrasco et al., 2020; Padilla-Almeida et al., 2020; Robayo et al., 2020; Herrera-Enríquez et al., 2021; Padilla Almeida et al., 2022; Suango et al., 2022; Mosquera López et al., 2022). Hereby, tsunamis of different proportions in their destructive power and reach are the result mainly but not exclusively due to the interaction of the subduction of the Nazca plate with the South American continent, which is represented by the Caribbean and South American continental plates (Fig. 1; Pararas-Carayannis, 1974; Pararas-Carayannis, 1986; Pararas-Carayannis, 2012; Rodriguez et al., 2016; Matheus Medina et al., 2016; Yamanaka et al., 2017; Pararas-Carayannis, & Zoll, 2017; Vera San Martín et al., 2018; Suárez-Acosta et al., 2021; Del-Pino-de-la-Cruz et al., 2021; Toulkeridis et al., 2021; Ballesteros-Salazar et al., 2022).

Other origins of tsunamis may be from continental glacial lake impacts, regional or distant sources, such as the tsunamis of Chile in 2010, of Japan in 2011 and of Tonga in 2022 (Pararas-Carayannis, 2010; Pararas-Carayannis, 2011; Moreano et al., 2012; Chian et al., 2019; Ioualalen et al., 2011; Pararas-Carayannis, 2014; Toulkeridis et al., 2022). However, of the 58 tsunamis that have reached the Ecuadorian coast in recorded history, some 19% turned out to be destructive (Contreras López, 2014). Based on the past events of tsunami impacts and documented history, some lessons have been learned and resulted in several studies of tsunami resistance constructions, vertical evacuation assessment, relocation areas and a few programs of tsunami hazard awareness, which still are lacking towards a real tsunami hazard education of the public and the authorities (Pararas-Carayannis, 2014; Toulkeridis et al., 2017; Rodríguez Espinosa et al., 2017; Celorio-Saltos et al., 2018; Matheus-Medina et al., 2018; Martinez and Toulkeridis, 2020; Edler et al., 2020). In this respect, serious evaluations of the risk and hazard perception and awareness are useful tools in the planning of safe zones, land use and management as well as very valid for decision-making processes of authorities and first responders (Pararas-Carayannis, 1988; Yépez et al., 2020; Bird & Dominey-Howes, 2008; Lindell et al., 2021; Johnston et al., 2005; Dengler, 2005; Wei et al., 2017; Imamura et al., 2019).

Therefore, the current research addresses the analysis of the local perception of risk in the event of a tsunami and for this it is focused on a case study in the area of Tarqui, within the city of Manta in coastal Ecuador (Fig. 2). In addition, it is intended to determine the tsunamigenic subduction seismic source for the city of Manta, besides the description of the geomorphology of Tarqui, and a subsequent analysis through hazard mapping. This may identify the areas exposed to flooding due to tsunami occurrence, considering a flood height of 7 m.a.s.l. as a high risk level and a level of 20 m.a.s.l. as the level of maximum influence of flooding within the study area (Fig. 3). Finally, we intend to estimate the context indicators, local perception of risk, as well as aspects that are indicated in the surveys directed to heads of households.

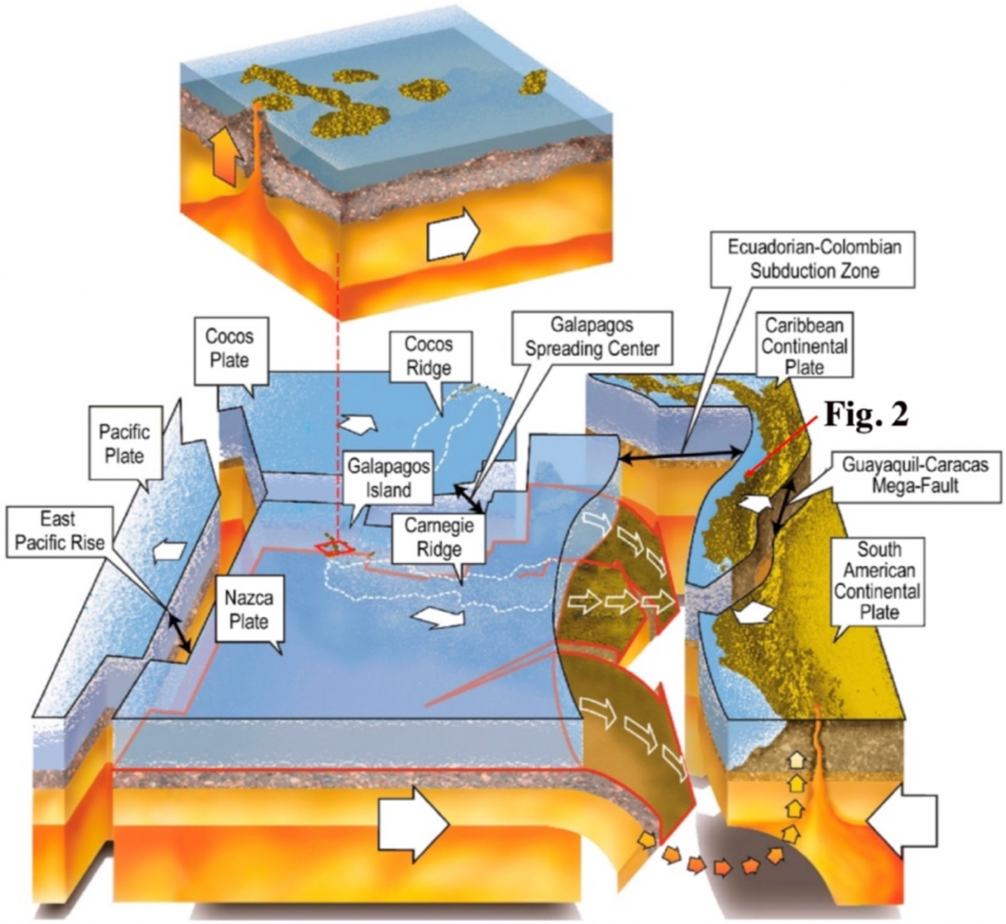

Fig. 1. Geodynamic setting of Ecuador with associated oceanic and continental plates and a variety of plate boundaries, such as the divergent plate boundaries named East Pacific Rise and Galapagos Spreading Center, the convergent plate boundary represented by the Ecuadorian-Colombian Subduction zone, as well as the transcurrent plate boundary represented by the Guayaquil-Caracas Mega-Fault. Also shown the Galapagos Islands and the Carnegie Ridge. Adapted from Toulkeridis et al., 2022.

In a post-disaster context, it may allow that both, the education of the head of the household and the health conditions of the family group, are key groups when facing highly complex contexts. Most likely as seen in a variety of other studies with similar issues, a low educational level is associated with precarious work and lower income, while the health of the family group, including the presence of at least one physically or mentally disabled person, translates into medical costs and dependency and even the loss of an individual who is able to contribute with income to the home in order to face the conditions of vulnerability typical of the given context (Polak et al., 2014).

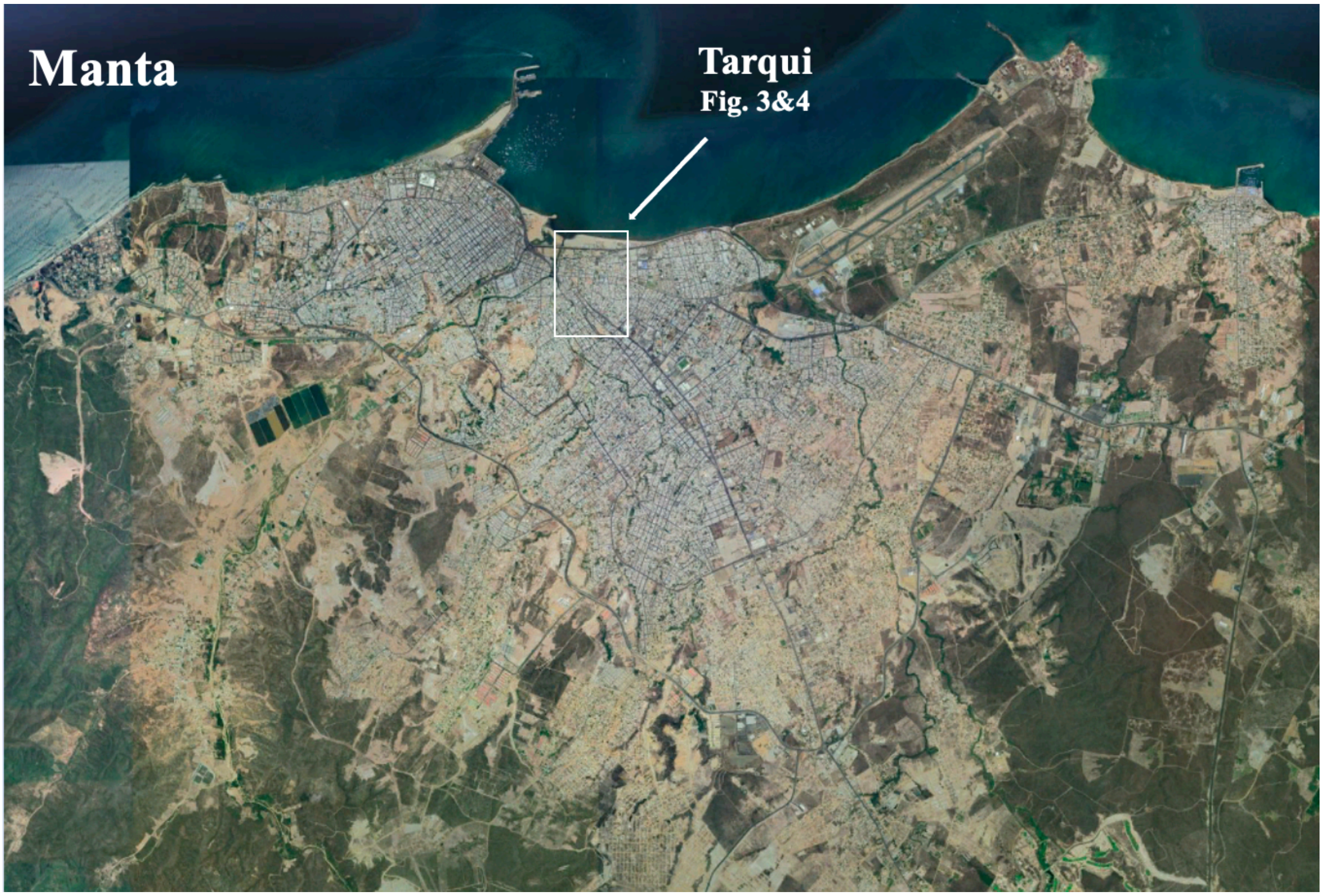

Fig. 2. The study area of Tarqui, within the city of Manta in the Manabí province. Image from Google Earth^{TM}. Width of approximately 16.6 km.

Additionally, processes of exclusion and social segregation may be observed, becoming to a permanent and systematic human occupation of areas exposed to natural hazards, in which the population with fewer resources has been located or chose to settle. The perceptions of natural risks, the forms of social organization and the expectations and frustrations of local communities constitute valuable lessons that should be the bases of the necessary social learning to prevent these tragedies from continuing to be repeated in still vulnerable countries such as Ecuador.

2. METHODOLOGY

In this study, a non-experimental, descriptive, explanatory and field research was developed. In this sense, it is a non-experimental investigation, because in the given and stated problems, the researcher do not have control of the causes that produce it and consequently the effect is already given. Non-experimental research is a retrospective approach, because the researcher do not manipulate the cause variable, as it is based on variables that also have already occurred (Hernández, 2014). The effect variable is known, but the cause variable is unknown. Therefore, the applied methodology is a design

in which no modifications are made to the independent study variables (Lavayen, 2010). It is based on observing events as they unfold in their natural state and then studying them. In fact, there are no conditions or stimuli to which the study subjects are exposed, they are only observed in their reality.
By using location maps and seismotectonic environment of the Intergovernmental Oceanographic Commission, segment number two corresponding to the Isla de la Plata around the Manta peninsula was determined as the tsunamigenic seismic source for the study area, with a rupture area 100 to 120 km from Bahía de Caráquez to Machalilla, where the estimated magnitude shall be approximately M7.8 (Avilés-Campoverde et al., 2021). Also, through ArcGIS tools, a hazard mapping was performed in order to identify the areas exposed to flooding due to the occurrence of tsunami between levels 0 to 7 m.a.s.l. and also levels of maximum influence between 7 to 20 m.a.s.l., in the Tarqui area of the city of Manta in coastal Ecuador (Fig. 3).

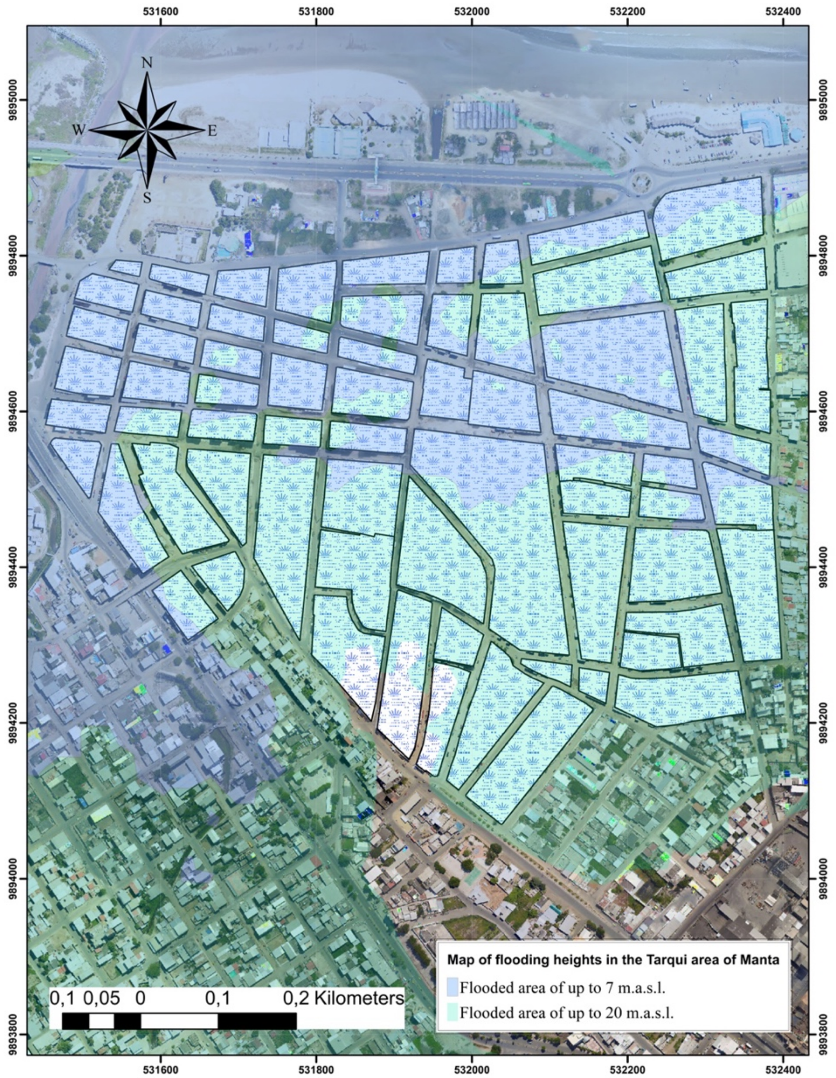

Fig. 3. Map of flooding heights within the study area of Tarqui, in the city of Manta.

An analysis of other studies focused on determining the geomorphology of the Tarqui Zone of Manta and research on local perception of risk in the event of exposure to flooding by tsunamis was conducted in order to collect baseline information for the application of context indicators. For this, some aspects needed to be considered. The geomorphological position of the axis of the hydrographic basin and the direction of the seismogenic structure (generating the earthquake) should be considered for seismic hazard studies, due to the attenuations of seismic waves that may be less in the area of few compact alluvial deposits. In the province of Manabí, the seismogenic source is located to the west (between 50 km for the Manta peninsula, and 98 km for Pedernales, the farthest point from the coastline), determined from the continental edge. In the Pacific Ocean, therefore, if the orientation of the hydrographic basin is in an East to West direction, there would be an unfavorable condition for the seismic behavior of the terrain (Chunga, 2016).

Fig. 4. Surveyed area of Tarqui.

In this regard, it is relevant that a study by Chunga (2016) served to identify this type of phenomenon in the study area under study. Hereby it was determined that another tsunami deposit at the Jaramijó site, near the canton of Manta, where it was estimated that it occurred some 1,170 years ± 30 years ago, a tsunami possibly of local origin reached these coasts with a run-up height of 6 to 7 meters. Recent studies determine that potential evidence of tsunami deposits has been found in several pits in the Tarqui area, close to the Burro riverbed, which could be related to the event recorded in Jaramijó. In order to perform a survey of the degree of preparation, perception and awareness of the public in Tarqui, we considered the complete population of 971 heads of family in the parish (Fig. 4, 5). The questionnaire included some 13 questions (Table 1).

Fig. 5 Aerial view of Tarqui from the seaside, meaning from north to south. Note the river Río Burro on the far right side of the image.

Table 1. Questionnaire of the perception of vulnerability

VARIABLES	**Vulnerability perception**	
	Indicator value Yes	**Indicator value No**
1. Within your area, do you identify tsunamis as a source of a geological hazard?	0	1,00
2. Do you think that tsunami hazards are identified in your community?	0	1,00
3. Do you know if your home is located in a high risk area for tsunami?	0	1,00
4. Do schools in your area teach about the risks and disasters generated by tsunamis?	0	1,00
5. Have information campaigns about the danger of tsunami ever been performed in your community?	0	1,00
6. In the event that information campaigns have been conducted, how did you find out about them?	0	1,00
7. Is there an early warning system for tsunamis in your community to notify the population about an emergency?	0	1,00
8. Have you ever participated in a tsunami evacuation drill?	0	1,00
9. Do you think that an earthquake with characteristics similar to those of the 16 April 2016 (16A) could cause a tsunami?	0	1,00
10. Based on the experience of the 16A earthquake, do you consider that your community is ready to face a tsunami disaster situation?	0	1,00
11. Do you know the evacuation route to take in case of a tsunami?	0	1,00
12. Do you know of any institution that works to reduce the effects of tsunami (construction of early warning systems, buildings for vertical evacuation in case of tsunamis, dissemination of information, drills, etc.)?	0	1,00
13. Referred to the danger tsunami and if you were living in a risk area, would you be willing to relocate?	0	1,00
TOTAL/AVERAGE (VULNERABILITY INDEX)	**Average**	

3. ANALYSIS AND DISCUSSION OF THE RESULTS

3.1 The concept of risk

The approach of the local perception of risk for the approach of the proposed investigation in the framework of the eventuality of a tsunami in the Tarqui area, Manta canton, Manabí province, is highly relevant. An approximation to this concept makes it possible to identify it as the core part to assess the magnitude and impact of future natural or anthropogenic events, since it is directly related to social conditions, the quality of housing and infrastructure, and in general the level of development of an area. The results of the first question ("Within your area, do you identify tsunamis as a source of a geological hazard?") of the survey indicate that 68.8% of the heads of household do identify tsunamis as a source of geological hazard, while 31.2% do not (Fig.6a;b). In this regard, geological risks include internal processes of the earth, such as earthquakes, volcanic activity and gas emissions, as well as other geophysical processes related to them, such as mass movements, landslides, etc. land, rockfalls, surface collapses, and debris or mud flows (Molerio, 2018). Furthermore, hydrometeorological factors are also major forces. Hereby, tsunamis associated with earthquakes are difficult to categorize. Although they are triggered by mainly by marine earthquakes and other geological events, they are essentially an oceanic process that manifests as a coastal water-related hazard.

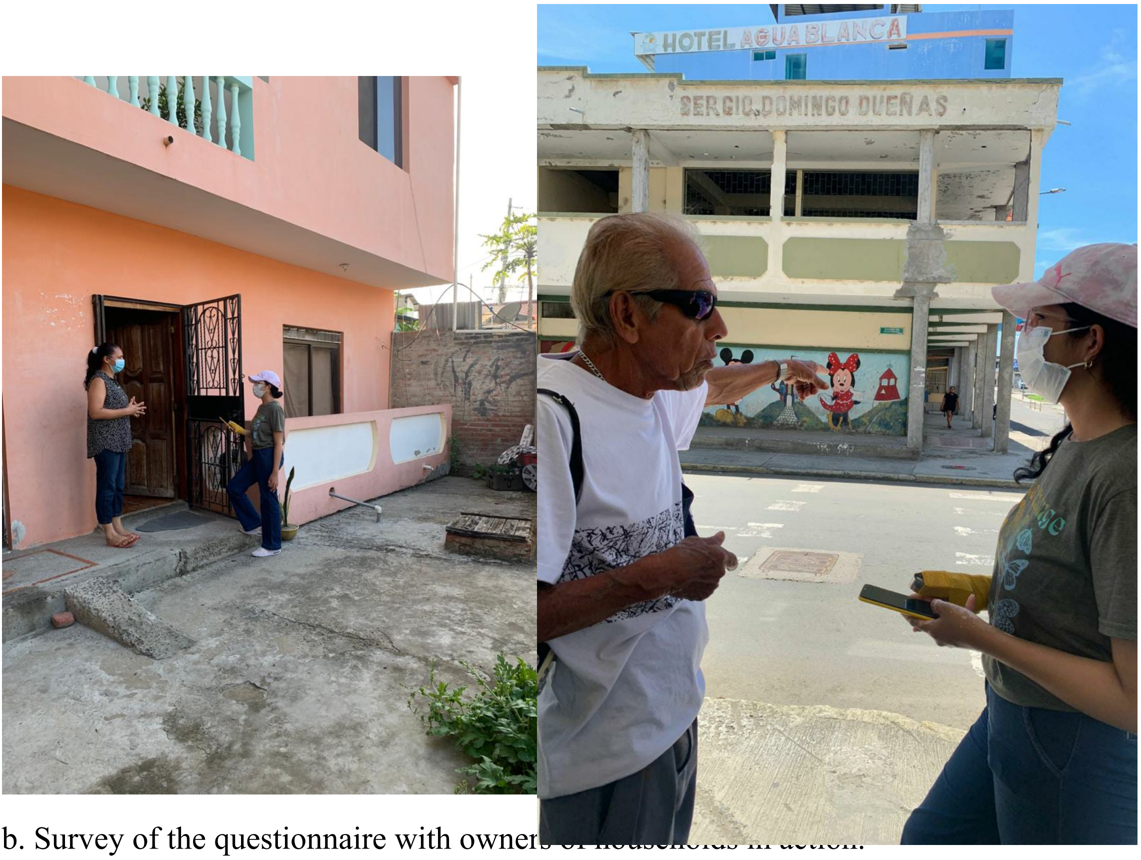

Fig. 6a;b. Survey of the questionnaire with owners of households in action.

In the second question of the survey ("Do you think that tsunami hazards are identified in your community?"), 62.5% of the heads of households consulted affirm that the dangers of tsunami are identified in their community, instead, 37.5% mentioned the opposite. In a previous study, it has been indicated that the dangers of tsunami are felt in various ways by the population as a whole and not all communities are prepared for an event of these characteristics (Pararas-Carayannis, 1999; Geist et al., 2006; Becker et al., 2022). Therefore, it has been suggested that when a tsunami occurs and if you were at home, at school or at work, keep in mind that in threatened coastal areas, you have only a few minutes to act, being as short as 5 to 10 minutes, so one needs to evacuate immediately (Eisner, 2005; Mat Said et al., 2011; Morgan et al., 2006). Once the tsunami has passed, evacuate as quickly as possible on foot. Always follow the instructions on the evacuation plans. Some beaches have tsunami evacuation signs.

In the third question of the survey, 62.7% of the heads of households consulted affirm that their home is located in a high-risk area due to tsunami. On this aspect, it has been considered that to avoid problems with nature, families must acquire land in habitable areas to locate their homes (Amri & Giyarsih, 2022; Tanikawa et al., 2014; Alexander et al., 2006). The destructive potential of a tsunami is the result of flooding, wave impact on buildings, and erosion. Tsunami waves apply forces on structures in the form of hydrodynamic pressure, buoyancy, uplift, scour, and impact of objects carried by the current. The damage produced by tsunami originates when the mass of water, followed by a strong current, impacts the built space and its surroundings. At that time, the tsunami demonstrates its tremendous destructive force and destroys everything in its path, especially homes (Fig. 7, 8).

Fig. 7. Residential building in Tarqui, Manta, where the exterior walls collapsed. The roof also fell in this property. Adapted from Nicolaou et al. 2016.

In the fourth question of the survey ("Do schools in your area teach about the risks and disasters generated by tsunamis?"), 68.5% of the heads of households consulted affirm that in the educational centers of their area they do not teach about the risks and disasters generated by a tsunami. In this sense, it has been established that the education provided at school about a tsunami is essential (Khew et al., 2015; Onoda et al., 2018; Maly, 2018). For example, disaster reduction begins from these institutions. Therefore, it must be ensured that disaster risk reduction is fully integrated into school curricula in high-risk countries and that school buildings are modernized to withstand natural hazards.

In the fifth question of the survey ("Have information campaigns about the danger of tsunami ever been performed in your community?"), 81.9% of the heads of households consulted assured that information campaigns about the danger of tsunami have not been conducted. Contreras (2014) points out that information campaigns about the occurrence of a tsunami are important, since they teach people to immediately look for a high point and protect themselves. Therefore, it is fundamental to periodically instruct the local community, and with trained personnel, on how to act in the event of an eventuality. It must be considered that the common citizen has little knowledge of the phenomenon and of the actions to adopt.

In the sixth question of the survey ("In the event that information campaigns have been conducted, how did you find out about them?"), 13.6% of the heads of households consulted assured that through the dissemination of information campaigns through social networks they found out about the tsunami risks, while the vast majority, the 83.3% mentioned that they were not aware of any activity in this regard. In this context, it is relevant to determine the enormous influence that social networks have due to their potential to disseminate information. Recent studies highlight that currently social networks are a useful tool to shorten times, mobilize resources and improve disaster response (Kim & Hastak, 2018; Houston et al., 2015; Phengsuwan et al., 2021; Abedin et al., 2014). Through these platforms help is requested, the situation of the affected community is reported, attempts are realized to locate missing persons and images of disaster damage are indicated in real time and with a worldwide expansion.

Fig. 8. This is how the building looked after the earthquake in Tarqui, due to the collapse of two floors it was decided to demolish it.

In the seventh question of the survey ("Is there an early warning system for tsunamis in your community to notify the population about an emergency?"), 98.9% of the heads of households consulted assured that there is a tsunami early warning system in their community to notify the population of an emergency. Ecuador possesses of an Early Warning System (Fig. 9), but not for mass dissemination, which allows citizens to be alerted to the risks of tsunami and overflow of rivers and dams, which prevents the population from being transmitted in advance and with certainty when a tsunami or overflow can trigger imminently dangerous situations. In this context, the alarm to citizens who are in potential risk areas could not be disseminated sufficiently in advance. It is thus that, before the generation of a tsunami or the overflow of rivers or dams in our country, a significant loss of life, personal injuries, damage to property and the environment could not be avoided, due to the absence of essential technological equipment. so that the activation of an evacuation alert is effective (Inamhi, 2016). Early Warning System for tsunami risks, river overflows or dams is a set of instruments through which a threat of tsunami or overflows is monitored from its generation, captures and automatically processes your information, instantaneous forecasts of action and possible effects are obtained and the population living in the sectors of probable affectation are immediately alerted (Sayers et al., 2015). Millions of people around the world save their lives and their livelihoods thanks to the implementation of these systems.

Fig. 9. Early warning system (right side of the image) represented by the siren in Tarqui.

In the eighth question of the survey ("Have you ever participated in a tsunami evacuation drill?"), 94.7% of the heads of households consulted stated that they had not participated in any tsunami evacuation drill. Recent investigations established that the improvement of the environment and the ability of the community to react adequately when faced with a great disturbance is essential, since poor preparation gives rise to vulnerable environments (Mas et al., 2015; Chen & Zhan, 2008).

Therefore, the fact that citizens actively participate in simulation activities is essential to help save lives when a natural phenomenon such as a tsunami occurs. It is relevant, to recognize the existence of evacuation routes, as well as public spaces that are planned for multiple uses that also allow evacuation due to the occurrence of a tsunami, and the evaluation of the conditions given by the existing environment (León et al., 2019; Fathianpour et al., 2023).

In the ninth question of the survey ("Do you think that an earthquake with characteristics similar to those of the 16 April 2016 (16A) could cause a tsunami?"), 56.3% of the heads of households consulted assured that they do believe that an earthquake with characteristics similar to those of 16A could cause a tsunami. It is important to highlight that from the earthquake in 2016 a high part of the population in Manabí was left with a deep trauma (Fig. 10).

In the tenth question of the survey ("Based on the experience of the 16A earthquake, do you consider that your community is ready to face a tsunami disaster situation?"), 51.3% of the heads of households consulted assured that they do not consider that their community is ready to face a tsunami disaster situation, taking prevention efforts into consideration. No one is prepared enough for the worst adversities. The community needs to be better prepared for complex circumstances in the event of events such as earthquakes or tsunamis. Both the unpredictability of the event and its immediate consequences can cause the lives of millions of people to depend on decisions that must be made in a matter of seconds. Hence the importance of being prepared for these events (Equal et al., 2017).

Fig. 10. Destroyed building due to 16A in Tarqui

In this eleventh question of the survey ("Do you know the evacuation route to take in case of a tsunami?"), 86.3% of the heads of households consulted assured that they do know the evacuation route to take in the event of a tsunami, while the remaining 13.7% indicated the opposite. A report from Inamhi (2016) indicates that communities are permanently trained in carrying out the drill, informing them of the evacuation routes, meeting points and safe areas. Several preparatory exercises were conducted, where the public is accompanied while carrying out the drill and at the end the drill is evaluated.

In addition, they are trained on how to act in cases of emergency or in a situation generated by an adverse event, in a way that allows decision-making in a timely manner in order to safeguard life. In addition, the preparation of the Family Emergency Plan is a very useful tool, since it is the set of activities that a family must conduct in order to reduce the risks that could affect their well-being. It also allows preparations to react appropriately in case of an emergency.

In the twelfth question of the survey ("Do you know of any institution that works to reduce the effects of tsunami (construction of early warning systems, buildings for vertical evacuation in case of tsunamis, dissemination of information, drills, etc.)?"), 82.8% of the heads of households consulted assured that they do not know of the existence of any institution that works to reduce the effects of tsunami. In this regard, it has been determined that the institutions in charge of the security of citizens must diversify the way of publicizing their programs and emphasizes the fact that the technology of social networks has made access and dissemination easier information quickly and easily ((Lovari & Bowen, 2020; Kongthon et al., 2014; Zhang et al., 2019). Internet users spend about 101.4 minutes a day browsing social networks. Communication has also adapted to this growing technological development. Therefore, social networks are useful and essential tools to facilitate communication during disasters and emergencies.

In the last question of the survey ("Referred to the danger tsunami and if you were living in a risk area, would you be willing to relocate?"), 80.8% of the heads of households consulted stated that they would not be willing to relocate because they are in a risk area due to the tsunami. This is a sensitive point for the community, since most citizens are reluctant to abandon the place they own, since it has been, in most cases, the product of their efforts. From the perspective, the tsunami hazards to homes should not be interpreted as a restriction on urban and rural development in coastal areas (Khew et al., 2015; Onoda et al., 2018; Maly, 2018). However, the lessons learned in the last decade should allow to reflect on how people build their homes on the coast, where they located them, and what their response would be in the presence of a tsunami. Certainly, a whole line of research is presented for the design and construction of anti-tsunami housing. It should not be forgotten that large tsunamis are infrequent events, however, when they do occur they are highly destructive.

3.2 Analysis of the social perception of the tsunami risk hazard

The results are linked to the equation proposed by the Colombian National Risk Management Unit (2017). For this research, the indicators evaluated in the surveys were analyzed and those of the factors which had the greatest incidence on the local perception of risk were identified. From the weights obtained for each of the surveys applied, it was possible to determine that 29% of the population is in a condition of high vulnerability, on the other hand, 63% in a situation of medium vulnerability and finally, 8% in a low vulnerability position (Table 2).

Table 2. Results of the range of the vulnerability conditions of the current questionnaire

Range	Vulnerability condition	N	%
> 9	High	281	29%
4.1 - 8.9	Average	614	63%
0 - 4	Low	76	8%

The results determine that the local perception of risk is culturally determined by society. Additionally, it is conceived as the probability that the disaster will occur as a consequence of the combination of hazards with conditions of vulnerability. In this respect, various studies have addressed this perspective. One of them, refers to the fact that vulnerability is an internal risk factor of a subject, object or system, exposed to the hazard, which corresponds to its intrinsic willingness to be damaged (Dake, 1992; Beck, 1992; Earle & Cvetkovich, 1994). While when social is added to this type of vulnerability, it refers to the extent to which it expresses the socioeconomic conditions of the population, the prevention and response capacity of civil protection units and the local perception of risk, in the face of a phenomenon and the local perception of the risk of the same population.

4. DISCUSSION

4.1 Local perception of risk in the context of hazard detection

A hazard is defined as the probability of a potentially disastrous event occurring during a certain period of time at a given site. According to Ley et al. (2016), the perception of risk is, in many aspects, an elaborated and socially shared appreciation, which implies the symbolic marking of images and their recovery in a context of meaning, since one of the functions of the cultural process is to provide ready categories to store and retrieve information, without forgetting that the use that the subject makes of classification systems depends on his position in a social group. Ante (2017) points out the following precision, that unlike the hazard that acts as a trigger, the local perception of risk is a condition that remains continuously over time and is closely linked to cultural aspects and the level of development of the communities.

The hazard or external risk factor of a subject or system is represented by a latent danger associated with a physical phenomenon of natural or technological origin that can occur in a specific place and at a certain time, producing adverse effects on people, goods and/or the environment (Yang et al., 2001). Mathematically it is expressed as the probability of exceeding a level of occurrence of an event with a certain intensity in a certain place and in a certain period of time. It has been considered that the hazard or danger refers to the potential occurrence of physical events of natural or anthropogenic origin that may have adverse effects on vulnerable and exposed elements (Calvo et al., 2012). In other words, the hazard or threat is only one of the risk elements and, therefore, it should not be assumed that they are similar terms. In this context, the hazard is conceived as a phenomenon, substance, human activity or dangerous condition that can cause death, injury or other health impacts, as well as property damage, loss of livelihood and services, social and economic disruption, or environmental damage (Wachinger et al., 2013; Chen et al., 2006; Joyce et al., 2009).

Hazards are related to the environment and define them as extreme expressions of natural phenomena (Martínez and Aránguiz, 2016). For example, the climate, composed of a series of elements that vary in periods or seasons and facilitate agricultural production, the provision of services and populations adapt to its operation. However, this same regular climate undergoes sudden changes and becomes storms, hurricanes or, depending on its intensity, becomes floods, droughts that threaten the development of a society. The occupation and development of society are eventually threatened by the manifestation of extreme climatic phenomena, as phases of the same process.

The hazard is interpreted as a physical phenomenon that could harm society and is assumed based on its relationship with a vulnerable social group. The hazard does not exist as an object external to society, while vulnerability is defined based on the social conditions created, not only in reference to losses and damages, but as the one responsible for disaster processes (Dake, 1992; Beck, 1992; Earle & Cvetkovich, 1994).

It is for this reason that studies conceive the hazard as the possible condition of alteration or disorder of a continuous process (Yoon, 2012; Zhou et al., 2014; Wei et al., 2004). This condition would be caused by a change in the complex interrelationship of various elements and processes, influenced by factors of various types such as physical, natural, social and human environmental that occur in uncertain places and times. In short, the hazard can also be considered as a condition of the nature-society interrelation processes, being a social interpretation that presents different perspectives.

A hazard is a fundamental component of the disaster risk structure (Thomalla et al., 2006). It is defined as a phenomenon, object or activity that can cause harm. Therefore, an infinity of phenomena and situations that exist and can alter an environment must be considered from a diversity of forms where multiple elements, factors and specific space-time conditions are interrelated.

Hereby, the fundamental difference between the threat and the risk is that the hazard is related to the probability that a natural event or a provoked event will manifest itself, while the risk is related to the probability that certain consequences will manifest, which are closely related not only to the degree of exposure of the elements subjected, but also to the vulnerability of said elements to being affected by the event (Roncancio et al., 2020; Aksha et al., 2019; Davis, 2013; Lixin et al., 2014).

In this context, floods can be defined, as a temporary coverage of the land by water outside its normal limits and can occur in basins, estuaries, coasts, urban areas, among others (Papathoma et al., 2003; Tarbotton et al., 2015; Dominey-Howes & Papathoma, 2007). Flooding in most cases is a natural phenomenon that, for example, in natural floodplains cannot be classified as a hazard. However, floods are generally influenced by humans through inappropriate land use.

4.2 The risk perspective

The risk can be estimated by the probable number and characteristics of human losses, injuries, damaged properties and interruption of economic activities that could occur after a disaster (Wachinger et al., 2013; Chen et al., 2006; Joyce et al., 2009). Risk is the result of the interaction between the dynamics of the natural environment and the built environment, however, the expression built for risk implies exposure to a natural hazard, hence the concept is taken up again for a better understanding of the topic to be investigated (Dall'Osso et al., 2009; Omira et al., 2010).

Natural risk has been also considered as an aggregate of elements of the physical and biological environment that are harmful to people and caused by forces outside of them and being defines as the possibility that a territory and the society that inhabits it may be affected by a natural phenomenon of extraordinary range (Stoleriu et al., 2020). Hereby, the risk is considered as a latent condition, that is to say that by not being modified or mitigated by the human being or by means of a change in the physical-environmental environment, the risk announces a level of social and economic impact for the future. This level of risk will be conditioned by the intensity or possible magnitude of the physical events, and the degree of exposure and vulnerability (Vega, 2016).

In this context, the basic components of risk management are prevention, mitigation, transfer, preparation and care as well as rehabilitation and reconstruction (Freeman & Kunreuther, 2002). Hereby prevention serves to prevent risk situations from being generated, being a process that starts with the identification of potential risk through perception and evaluation, and anticipatory measures are taken to prevent the risk from consolidating. The mitigation corrects or reduces risk (reduces vulnerability and increases resilience, it is done based on the risk that already exists). Risk reduction encompasses not only its physical dimension, but also includes social, political and economic aspects. In this sense, risk transfer, as the risk management component that seeks to transfer the replacement cost associated with losses among a greater number of citizens than those directly and mostly exposed, is considered a reduction or mitigation measure of the risk. Preparation and care includes emergency management, preparations, planning and response protocols, institutional coordination for the efficient management of disaster situations (the risk is not acted upon, the level of physical exposure is not reduced). Finally, rehabilitation and reconstruction includes the post-disaster management, which seeks to restore the normal flows on which social and economic development depends. In many cases, rehabilitation and reconstruction are processes of creating security conditions that did not exist before the occurrence of the triggering natural or socio-natural phenomenon.

Regarding risk analysis and assessment, it has been defined as the process that consists of the identification and characterization of hazards, the determination of vulnerabilities and the assessment of the result of the interaction of these variables (Batista, 2018; Giannakidou et al., 2019; Surjan et al., 2016). The risk scenario is an anticipated vision of what could happen if a hazard to a community or to a vulnerable system were to appear or become real. In other words, it is the space and time where the risk components come together (hazards and vulnerabilities) together with the forecast of the possible consequences of this confluence (Fig. 11). Risk can be organized or broken down into activities such as identification of the nature, extension, intensity and magnitude of the hazard; determination of the existence and degree of vulnerability; identification of the measures, capacities and resources available; construction of probable risk scenarios; determination of acceptable levels of risk, cost-benefit considerations of possible measures aimed at avoiding or reducing it; assigning of priorities in terms of time and movement of resources; and designing effective and appropriate management systems to implement and control the above processes (Kulawiak & Lubniewski, 2014; Godschalk, D. R. (2003; Burby et al., 2000; Zou et al., 2017).

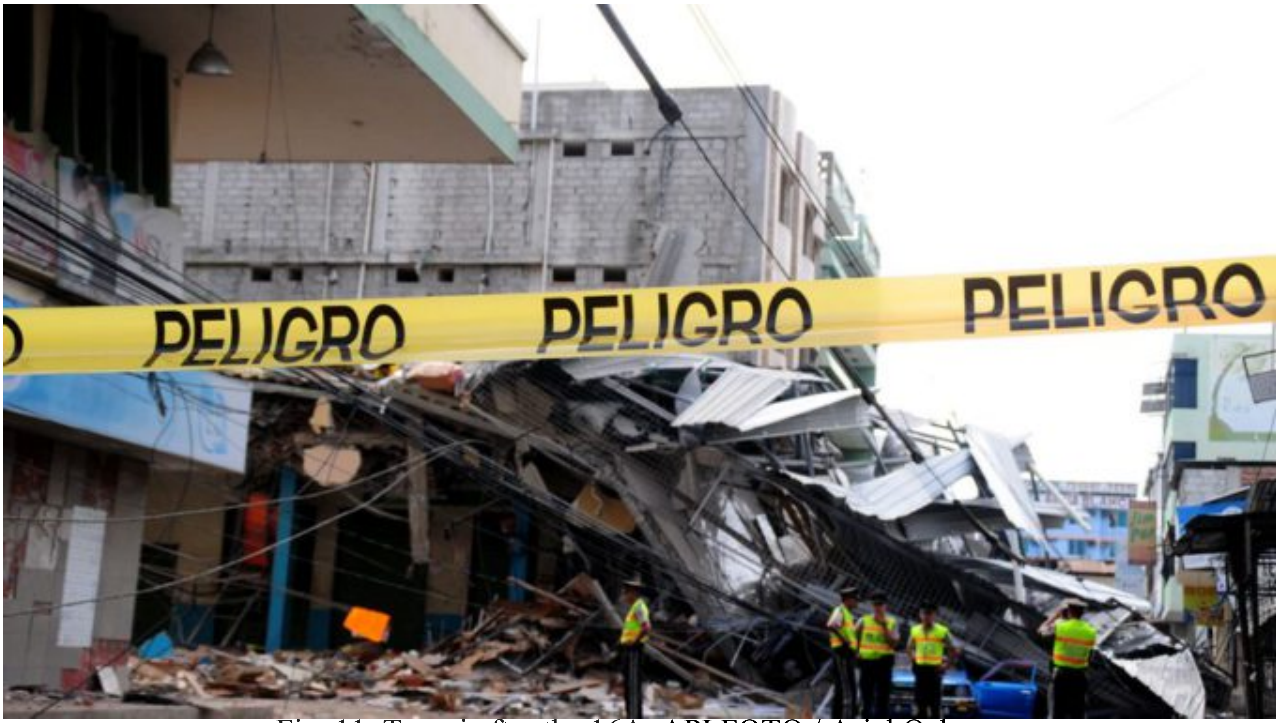

Fig. 11. Tarqui after the 16A. API FOTO / Ariel Ochoa

Concomitant with the aforementioned, for the risk analysis a six-step procedure needs to be followed (Cutter, 2010; Lummen & Yamada, 2014; Douglas, 2007). It starts with the identification of the hazards, meaning identification of all activities or hazards that imply risks.

Secondly follows the estimation of the probabilities. Once the hazards or possible aspects initiating events have been identified, the probability of occurrence of the incident or event must be estimated, based on the specific characteristics. The third step includes the estimation of the vulnerabilities. Estimation of the severity of the consequences on the so-called vulnerability factors that could be affected such as people, environment, systems, processes, services, goods or resources. The fourth step handles the risk calculation. The risk level calculation or assignment needs to be realized. The Risk (R) is defined based on the hazard(s) and vulnerability as the product between Probability (P) and Severity (S) of the scenario. The next step treats the prioritization of the scenarios. The results of the risk analysis allows to determine the scenarios in which intervention should be prioritized. Finally follows the intervention measures, where it is necessary to establish the need to adopt planning measures in order to control and reduce risks.

Risk is the combination of hazard and vulnerability. This is important to the extent that risk is assumed as the probability of suffering economic, social, and environmental negative consequences (damages and losses) that may occur in the event of a dangerous phenomenon, in relation to the ability to resist and recovery of the different social actors in the face of this phenomenon. The risk scenario is the representation of the interaction of the different risk factors (threat and vulnerability) in a territory and at a given time and, in addition to this, it must represent and allow the identification of the type of damage and losses that may occur in in the event of a dangerous event occurring in given conditions of vulnerability.

4.3 Local perception of tsunami risk

Vulnerability represents a configuration of objective and subjective conditions of existence and is associated with fragile elements of a community or human group that generate a predisposition to suffer harm. According to Martínez and Aránguiz (2016), these fragile elements or conditions can be grouped into different dimensions, such as physical, social, organizational, educational, and others. The factors that originate it depend on the degree of exposure to the event, social fragility and the lack of resilience or inability to respond to absorb the impact. Within the framework of local risk perception, a tsunami is defined, according to a study by Sulla and Tavera (2016), as a wave or series of waves in a train of waves generated by the vertical displacement of a water column. The gravity waves of tsunamis propagate through the vast ocean, being very different from ordinary wind waves, so, due to the longer wavelengths and periods, the tsunami wavelength can travel from ten kilometers up to hundreds of kilometers.

It has been argued that when analyzing the scope and consequences that a tsunami can bring, it is considered to carry out a vulnerability study, since it is an important factor for determining risks, knowing its variables and indicators (Zuccaro et al., 2018; Castro et al., 2017; Mignan et al., 2016; Marulanda Fraume et al., 2020). This allows the understanding of risk scenarios (in this case of natural origin). Many times the exposed elements can present low intensity threats. Therefore, vulnerability analysis is a platform for the achievement of three fundamental aspects. Understanding the usefulness of information generated by different institutional sources and its application to vulnerabilities. The construction of information based on variables and indicators necessary to understand vulnerabilities and easy replication for local authorities. The inter-institutional and multidisciplinary work of actors responsible for information, territorial management and development at a national and cantonal level.

In the field of vulnerability analysis, it is pertinent to address the origin of tsunamis. The source of tsunamis is mainly produced by earthquakes, which represent the majority and are approximately 96%, on the other hand, volcanic eruptions represent 3%, likewise, there are also tsunamis generated by submarine or coastal landslides represent 0.8%, and lastly, although they are very anomalous, the tsunamis that are generated by the impact of meteorites (Paris, 2015). Seismic events with magnitudes greater than 7.0 Mw are considered the main source of tsunami generation, if the earthquake is generated on the seabed or very close to it at focal depths of less than 60 km. Usually these anomalous events occur near the convergence of tectonic plates that cause the rise and collapse of the continental crust. In this phase, the mass of water is violently propelled by the plate to release accumulated energy. These explosions of energy can generate huge waves that can be very destructive.

According to Chunga (2016), the tsunami alerts associated with the intermediate and far fields allow establishing better response plans during an emergency due to the range of sufficient hours before the first wave impact, for example a strong earthquake generated in the area of subduction of Chile that would generate Tsunami, would take between four to five hours to have its first impact on the coasts of the Jambelí archipelago, in the province of El Oro, south coast of Ecuador, which displays enough time to displace people through evacuation routes to safe places.

5. CONCLUSIONS

The social development of a community vulnerable to natural phenomena such as a tsunami is linked to the local perception of risk, because this perception plays a preponderant role in people's decision-making.

The characteristics of the population and social groups determine their level of incidence in the face of natural hazards and influence their ability to respond and recover adequately. Likewise, population dynamics and economic activities influence this type of perception. The spatial location of the population is decisive in the magnitude of the impact of disasters.

With regard to a tsunami, it is clear in pointing out that the role played by the local perception of risk in the affectation by disasters is essential. Some sectors of the population due to the economic and physical conditions they live in, or due to the difficulty of recovery, they have are extremely vulnerable to events that affect their living conditions, or their means of production. The causes of a greater local perception of risk are complex and constitute an argument for debate in society. The hazard or danger refers to the potential occurrence of physical events of natural or anthropogenic origin that may have adverse effects on vulnerable and exposed elements.

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A COMPARATIVE STUDY OF TSUNAMI TRENDS IN INDONESIA AND TAIWAN OVER A DECADE

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ABSTRACT

Tsunami is one of the deadliest disasters in the world. Tsunamis in Indonesia (TI) and Taiwan (TT) are now wide open in all research fields. The purpose of this study is to analyze a comparison of research related to TI and TT from 2013-2023. This study used bibliometric analysis with metadata collected from the Scopus database and visualized using VOSviewer and Biblioshiny-Bibliometrix. The findings of this study indicate that the trend of research related to TI is more consistently increasing linearly than research on TT from 2013-2023. Citation trends per year in TI and TT research vary depending on the popularity of research topics and the impact of publications. The most dominant trend keywords used are Tsunami, Indonesia, and Taiwan. The authors who contributed the most to TI research were Syamsidik and Wu TR in TT research. Indonesia and China are countries that contribute and collaborate a lot. The highest and most relevant sources in TI research are the IOP Conference Series Earth and Environmental Science and Terrestrial Atmospheric and Oceanic Sciences in TT research. Syiah Kuala University and National Central University are top TI and TT research affiliations. Based on the network visualization, there is a very close relationship between tsunamis and earthquakes. This research aims to demonstrate the popularity of writing about Taiwan's and Indonesia's tsunamis so that future research might demonstrate more advantages of this subject. Researchers can learn about the advantages and disadvantages of each subject and discover updates for additional research with the help of this article. Recommendations for future researchers are to conduct research related to tsunamis and earthquakes with in-depth studies because of the high potential for further research.

Keywords: Disaster, Tsunami, Indonesia, Taiwan, Bibliometric

1. INTRODUCTION

One of the deadliest disasters in the world is the tsunami. Tsunamis occur when huge sea waves are formed (Sari & Soesilo, 2020) and propagate toward the coast (Sudaryatno et al., 2022; Suppasri et al., 2017), often caused by earthquakes under the sea (Pongponrat & Ishii, 2018), volcanic eruptions (Nagata et al., 2022), or underwater landslides (Imamura et al., 2019). The waves can reach hundreds of meters high and travel at high speeds. Tsunamis can cause enormous physical damage (Adriano et al., 2021; Suppasri et al., 2021), including damage to buildings and infrastructure (Moon et al., 2022), and take lives (Adriano et al., 2021; Ahmadun et al., 2020; Sudaryatno et al., 2022; Sugawara, 2021).

Indonesia and Taiwan have a relatively large potential for a tsunami disaster because both are located in the Pacific Ring of Fire (Masum & Ali Akbar, 2019), known as seismically active areas (Klug, 2021; Martire et al., 2023). Earthquake activity in this region can trigger dangerous tsunamis (Fuady et al., 2021). Indonesia experienced its biggest tsunami disaster in 2004, caused by a magnitude 9.1 earthquake off the coast of Sumatra. This tsunami killed more than 230,000 people in 14 countries. Meanwhile, in Taiwan, the biggest tsunami disaster occurred in 1946 when an earthquake measuring 8.1 on the Richter scale shook the east coast of Taiwan (Cheng et al., 2023b). A tsunami more than 10 meters high hit coastal areas, killed around 2,000 people and damaged many houses and infrastructure (Cheng et al., 2023a; Yu et al., 2022).

Research on tsunamis is ongoing to deepen our understanding of tsunamis and how to reduce their associated risks. Such as research conducted by many researchers recently, such as by Alex et al. (2023) regarding perspectives from Nanggroe Aceh Darussalam, Indonesia, on women in local politics. Rana & Akbar (2023) reviewed submerged floating tunnel research advancements. A Narrative Review of Infectious Diseases in the Post-Disaster Period With a View to Disaster Risk Reduction: The Effect of Earthquakes on Public Health has also been done by Mavrouli et al.(2023). Moreover, Roy and Matsagar (2023) researched on “structures' multi-hazard design and analysis: current state of the art and future directions”. Then, Bhardwaj & Singh (2023), reviewed landslip susceptibility assessment using GIS and remote sensing. Srinivasa Kumar & Manneela (2021) have also reviewed Tsunami Early Warning Systems' Development, Issues, and Future Trends.

Therefore, a bibliometric analysis related to trend and visualization research of tsunamis in Indonesia and Taiwan is a novelty in this study. Bibliometric research on tsunamis is essential to provide a better understanding of research trends and directions. By using bibliometric analysis techniques, it is possible to identify the most relevant publications and the most cited research in the tsunami disaster field (Suprapto et al., 2021, 2022). In addition, bibliometric research also helps understand the interrelationships between different research topics and sub-fields (Hidaayatullaah & Suprapto, 2022) in the context of the tsunami disaster. It can help improve collaboration and exchange of information between researchers and strengthen early warning systems and mitigation strategies to reduce the impact of the tsunami disaster.

This research aims to compare tsunami trends in Indonesia and Taiwan over a decade using bibliometric analysis techniques. The specific research objectives are:

a) Comparing research trends related to TI and TT during 2013-2023.
b) Analyze comparing top productive and author impact in TI and TT research.
c) Identify comparisons of co-authorship and collaboration countries in TI and TT research.

d) Analyzing comparisons of top source fields, affiliations, and countries contributing to TI and TT research.
e) Analyzing top cited global in TI and TT research during 2013-2023.
f) Analyze mapping visualization and updates information about TI and TT.

2. RESEARCH METHOD

The research method is bibliometric research using descriptive analysis by tracking the frequency and impact of citations to scientific publications, authors, and institutions. Bibliometric analysis analyzes and evaluates the performance of these parties (Hidaayatullaah et al., 2021; Schiuma et al., 2023; Suprapto et al., 2021; Yang et al., 2023). This study uses the Scopus database (www.scopus.com). Scopus is a bibliographic database that gives users access to thousands of journals, conference proceedings, and other publications from various fields (Ali et al., 2023; Hidaayatullaah & Suprapto, 2022). This research also provides the latest updates regarding the Tsunami in Indonesia through the Meteorology, Climatology and Geophysics Agency website (https://www.bmkg.go.id/) and Taiwan through the Central Weather Bureau website (https://www.cwb.gov.tw/eng/). The four bibliometric stages, in general, are (1) data collection, (2) data cleaning and processing, (3) analysis, and (4) interpretation and visualization (J. Li et al., 2021; X. Li & Long, 2020). In this study, screening was carried out twice against the data criteria. The research analyzes TI and TT in all fields during 2013-2023. Then, the researcher determines the keywords to determine the impact or contribution of TI and TT research (Figure 1).

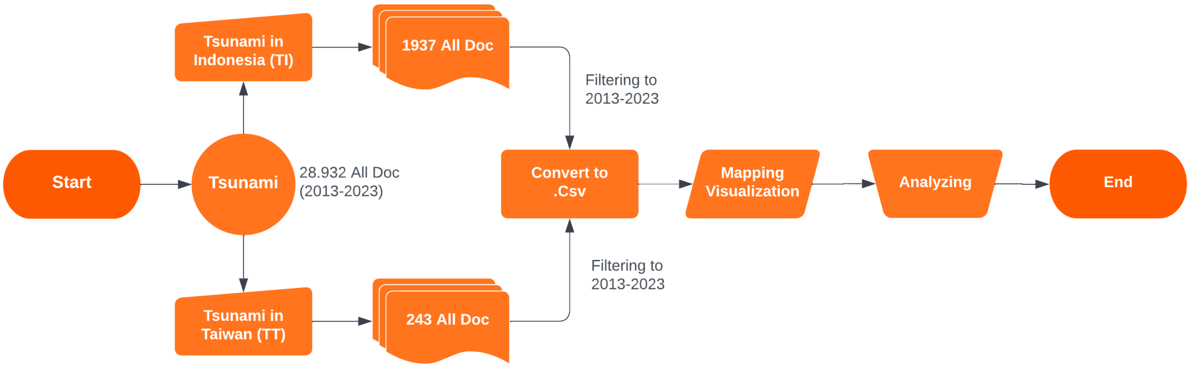


Figure 1. Research flowchart

Data was collected on April 13, 2023, and retrieved with the 2013 – 2023 limit. 28,932 all documents were obtained on searches with the keyword TITLE-ABS-KEY (tsunami). Researchers focused on searching for Tsunamis in Indonesia and tsunamis in Taiwan and obtained data for the last ten years (2013-2023), respectively, namely 1149 and 131 documents. Then, the data is downloaded in .csv format. In displaying detailed data and visualizing bibliometric assignments, the data is uploaded to the VOSviewer and Biblioshiny-Bibliometrix in R studio software. In the final stage, the data visualization results are analyzed and interpreted according to the research objectives.

3. RESULTS AND DISCUSSION

3.1 Comparison of Trends Research TI and TT during 2013-2023

Based on screening and analysis of data through Scopus metadata, it is known that research trends regarding TI and TT in all research fields during 2013-2023. This trend shows the interest of researchers to research the research subject, namely the tsunami. Research related to TI and TT in all fields in the last ten years is visualized in Figure 2.

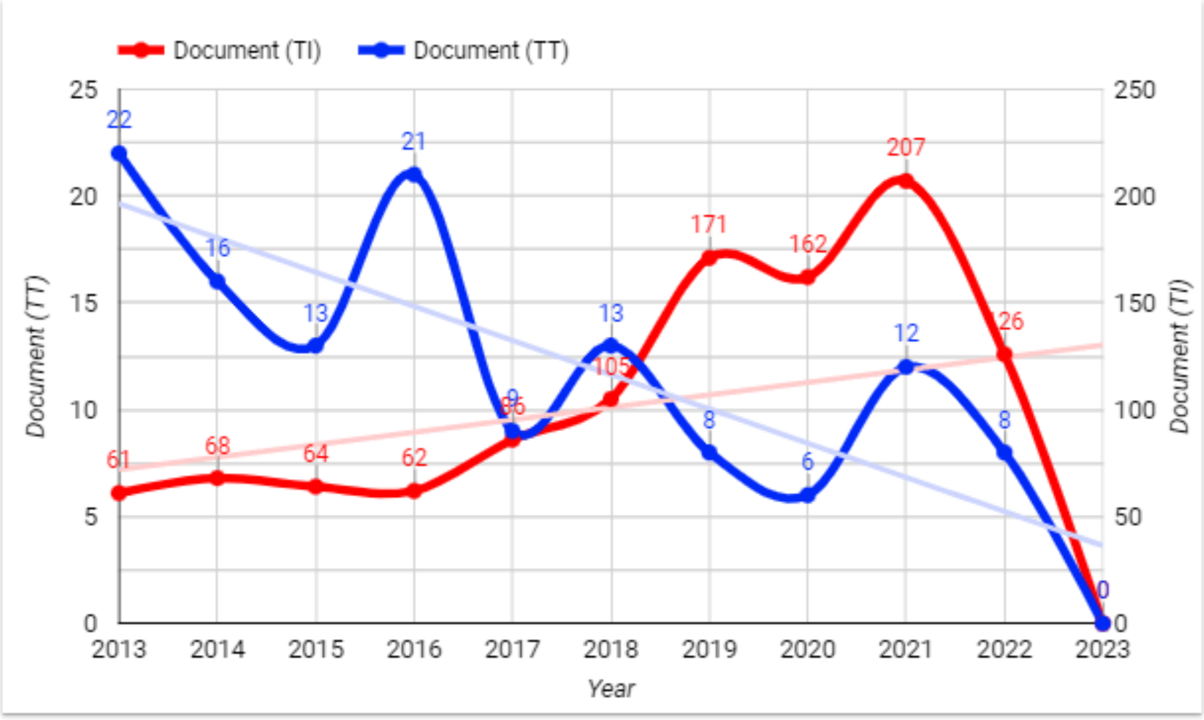


Figure 2. Comparison of TI and TT trend researches during 2013-2023

Based on Figure 2, research trends related to TI in all fields tend to increase linearly. Meanwhile, research trends related to TT tend to decrease linearly in all fields. This shows that TI-related research continues to increase and is an interesting topic for research. TI and TT documents from 2013 to April 2023 the last documents detected in 2022 with the document types of articles, books, book chapters, and review papers. The article is the most dominant type of document and is the most published at conferences.

While the trend of citations in TI and TT research from 2013 to April 2023 is presented in Table 1. The highest mean total citations per year (MTCpY) was in the TI research, namely in 2019 (3.82) and in the TT research, the highest MTCpY was in the same year at 3.84. In the TI study for MTCpY with the lowest value, namely in 2022 (0.79), and the TT study it occurred in 2013 (0.52). While the highest value in the mean total citations per article (MTCpA) in the TI study occurred in 2014 (23.41) and in the TT study it occurred in 2019 (15.38). The MTCpA with the lowest value occurs in the same year, namely 2022 in the TI (0.79) and TT (1.00) studies.

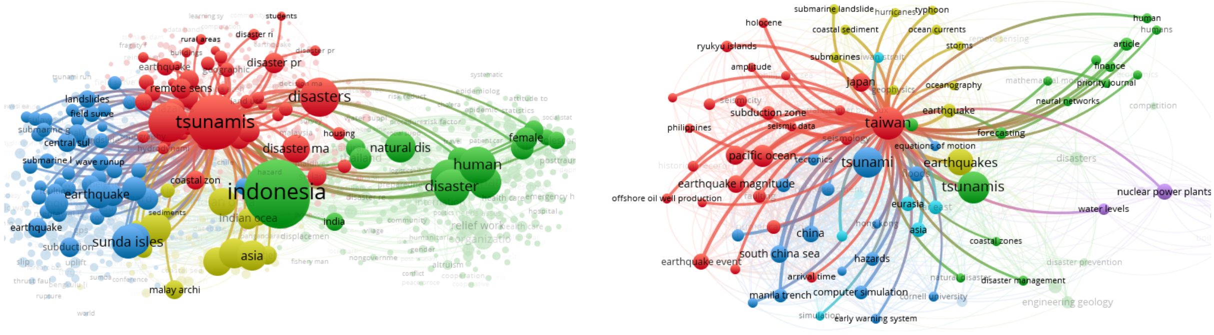
Table 1. Total citation per year and article in TI and TT research

Year	TI Research			TT Research		
	N	MTCpA	MTCpY	N	MTCpA	MTCpY
2013	61	16.07	1.61	22	5.18	0.52
2014	68	23.41	2.6	16	11.88	1.32

Year	TI Research			TT Research		
	N	MTCpA	MTCpY	N	MTCpA	MTCpY
2015	64	13.75	1.72	13	6.54	0.82
2016	62	12.29	1.76	21	5.43	0.78
2017	86	7.97	1.33	9	9.56	1.59
2018	105	8.88	1.78	13	6.23	1.25
2019	171	15.27	3.82	8	15.38	3.84
2020	162	6.71	2.24	6	3.83	1.28
2021	207	2.32	1.16	12	03.08	1.54
2022	126	0.79	0.79	8	1.00	1.00

Description.
N: Number of Documents; MTCpA: Mean Total Citation per Article; MTCpY: Mean Total Citation per Year

Annual citation trends in tsunami research can vary depending on many factors, including the popularity of the research topic, the impact of publication (Aldrighetti et al., 2019; Shanmugam, 2022), and how the research is accessed and used by the scientific community. However, in general, research on tsunamis generally has a fairly high citation trend in the first few years after publication (Suprapto et al., 2022), and then tends to decrease over time. Nevertheless, it is research on tsunamis that has significant scientific contributions. Trend keywords used in TI and TT research based on network visualization using VOSviewer are presented in Figure 3.



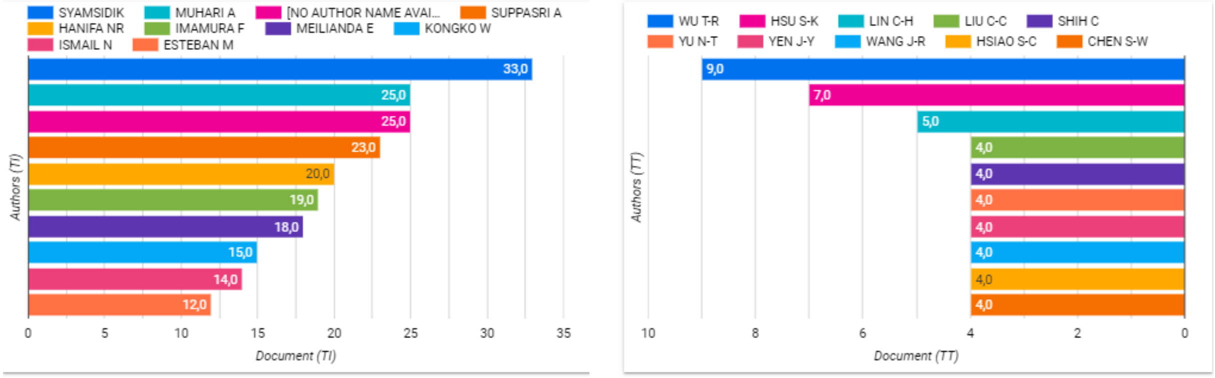
(a) (b)

Figure 3. Trend keywords mapping in TI dan TT research during 2013-2023

Figure 3a shows that the keywords used in TI research are 4 clusters (red, green, blue, yellow) and the dominant keywords are Indonesia and tsunami. The Indonesian keyword is in cluster 2 (green) with 835 links and 10,382 total link strength. While the tsunami keyword is in cluster 1 (red) with 791 links and 7046 total link strength. In Figure 3b are the keywords used in the TT research. There are 6 clusters with the two most dominant keywords being Taiwan (cluster 1) and tsunami (cluster 3). There are 75 occurrences, 80 links, and 483 total link strengths for the Taiwan keyword. Whereas in the keyword tsunami, there are 65 occurrences, 74 links, and 431 total link strength. The use of keywords in VOSviewer can help identify trends, patterns, or groups of emerging words (Ding & Yang, 2022).

3.2 Comparison of Top Authors Productive and Impact in TI and TT Research

The metadata results on Scopus can show Authors on TI and TT research. In the TI study based on Scopus metadata through bibliometric analysis using Biblioshiny-Bibliometrix there were a total of 3346 and 437 authors in the TT study. The top 10 Authors in TI and TT research are presented in Figure 4. Meanwhile, Table 2 presents the top 10 local impact authors in TI and TT research from 2013 to 2023.



(a) (b)

Figure 4. (a) Top 10 authors productive in TI; (b) Top 10 authors productive in TT

Table 2. Top 10 authors' local impact in TI and TT research during 2013-2023

TI Research					TT Research				
Author	**h_index**	**g_index**	**m_index**	**TC**	**Author**	**h_index**	**g_index**	**m_index**	**TC**
Muhari A	13	25	1.182	731	Hsu S-K	4	7	0.400	65
Syamsidik	12	22	1.091	525	Lin C-H	3	4	0.273	24
Suppasri A	11	20	1.000	431	Liu H	3	3	0.300	41
Daly P	8	9	0.889	272	Ren Z-Y	3	3	0.300	41
Esteban M	8	12	0.727	322	Wu T-R	3	6	0.273	36
Kongko W	8	15	0.800	394	Ando M	2	3	0.182	19
Fahmi M	7	9	0.778	85	Chang C-C	2	2	0.500	13
Imamura F	7	17	0.636	311	Chen G-Y	2	3	0.200	13
Mikami T	7	11	0.636	242	Chen W-S	2	2	0.182	21
Munadi K	7	9	0.636	141	Chung L-H	2	2	0.182	16
Description. TC: Total Citation									

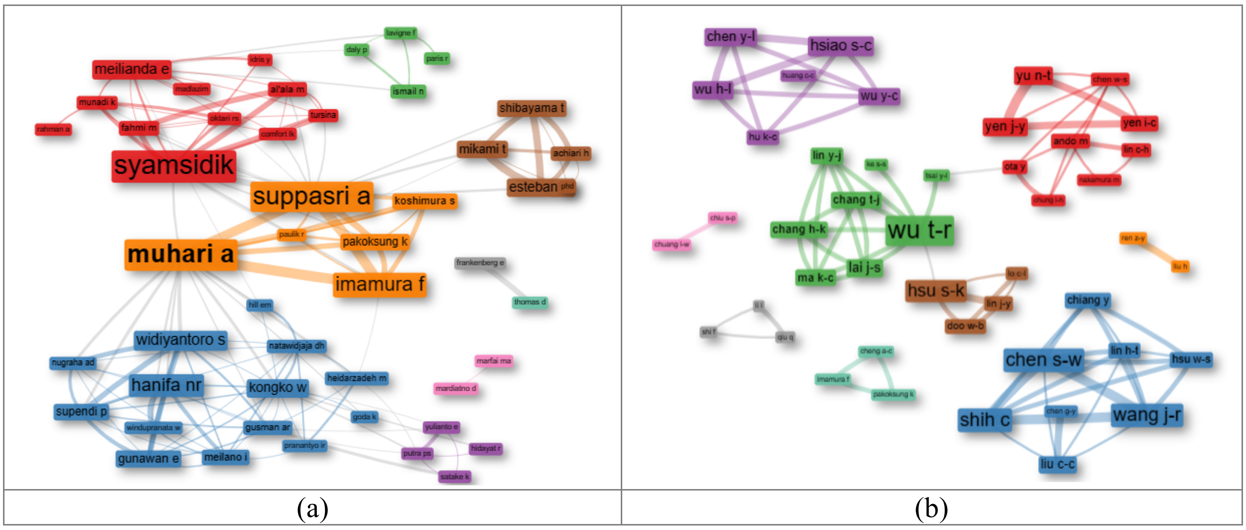
Based on Figure 4a, it can be seen that the author who has contributed the most to TI research over the last 10 years is Syamsidik with 33 documents. The second and third positions respectively are Muhari A and no author name available with the same contribution over the last 10 years, namely 25 documents. While the top author in the TT research (Figure 4b), the biggest contribution over the last 10 years is in the first position, namely Wu T-R with 9 documents). Then followed by Hsu S-K (7 documents) in the second position and the third position is Lin C-H (5 documents).

The top 10 local impact authors on TI and TT research in the last 10 years are presented in Table 2. It can be seen that the author with the highest h-index in TI research is Muhari (13) and in TT research is Hsu S-K (4). The author also has the highest g-index scores in the

TI and TT studies, namely Muhari A (25) and Hsu S_K (7). While the highest m-index values were in the TI and TT studies respectively, namely Muhari A (1.182) and Chang C-C (0.400). The h-index, g-index, and m-index are bibliometric metrics used to measure the impact of the quality of a researcher's publications and their values vary depending on the research field, period, or data source used (Chaturbhuj & Motewar, 2021; Singh, 2022). The top three positions for authors with the most total citations in IT research in the last ten years are Muhari A (731), Syamsidik (525), and Suppasri A (431). Whereas in the TT research, namely Hsu S-K (65), Liu H (41), and Ren Z-Y (41).

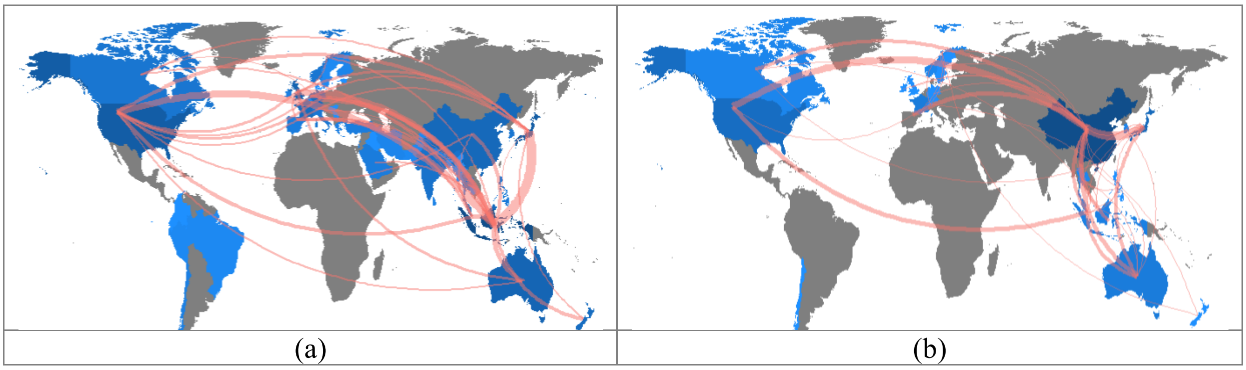
3.3 Comparison of Co-Authorship and Collaboration Countries in TI and TT Research

Based on the bibliometric analysis of TI research during 2013-2023, the co-authors per document were 4.23 and 32.46 international co-authorships. Meanwhile, in the TT study, there were 4.22 co-authors per document and 22.14 international co-authorships. Collaboration network authors in the TI and TT studies are presented in Figure 5.



(a) (b)

Figure 5. Co-authorship in TI and TT research



(a) (b)

Figure 6. Collaboration network Countries in TI and TT research

Collaboration network authors are presented in Figure 5a (TI) and Figure 5b (TT). There are 9 clusters in both studies. It can be seen that in the TI research, there are 3 major clusters, namely clusters 1, 2, and 5. In cluster 1 (red) the collaboration network consists of 11 authors, namely Syamsidik, Meilianda E, Madlazim, etc. Cluster 2 (blue) consists of 14 authors, namely Hanifa NR, Konko W, Heidarzadeh M, etc. Cluster 5 (orange) has 6 authors consisting of Muhari A, Suppasri A, Imamura F, etc. Whereas in the TT study (Figure 5b) there are 4 major clusters namely clusters 1, 2, 3, and 4. In Cluster 1 (red) there are 9 authors consisting of Lin CH, Yen JY, Yu NT, etc. Cluster 2 (blue) consists of 8 authors, namely Chen SW, Liu CC, Shih C, etc. Cluster 3 (green) has 8 authors namely Wu TR, Lai JS, Tsai YL, etc and in cluster 4 (wait) there are 6 authors which include Hsiao SC, Chen YL, Wu HL, etc. In line with research by Lansford et al. (2019) namely, collaboration can improve quality, impact research, and provide greater opportunities for academic career development.

Figure 6 is a network of countries that have contributed to conducting TI and TT research over the last 10 years. The thickness of the network shows that the collaboration of researchers from these countries has contributed to and produced many documents. In Figure 6a it can be seen that in TI research, a country that contributes a lot and collaborates with other countries is Indonesia. The top 5 highest countries collaborating in TI research are Indonesia to Japan with a frequency of 102, Indonesia to USA (56), Indonesia to UK (43), Indonesia to Australia (25), and Indonesia to Germany (25). Whereas in Figure 6b, the Top 5 countries that collaborate and contribute a lot to TT research are China to Japan (8), China to the USA (6), China to Australia, France, and Singapore with the same frequency, namely 3. Collaboration between countries in TI and TT research will continue to increase every year. Because, cooperation between countries in research is very important to strengthen the capacity of researchers and institutions around the world (Zhang et al., 2022).

3.4 Most Relevant Sources, Affiliations, and Countries in TI and TT Research

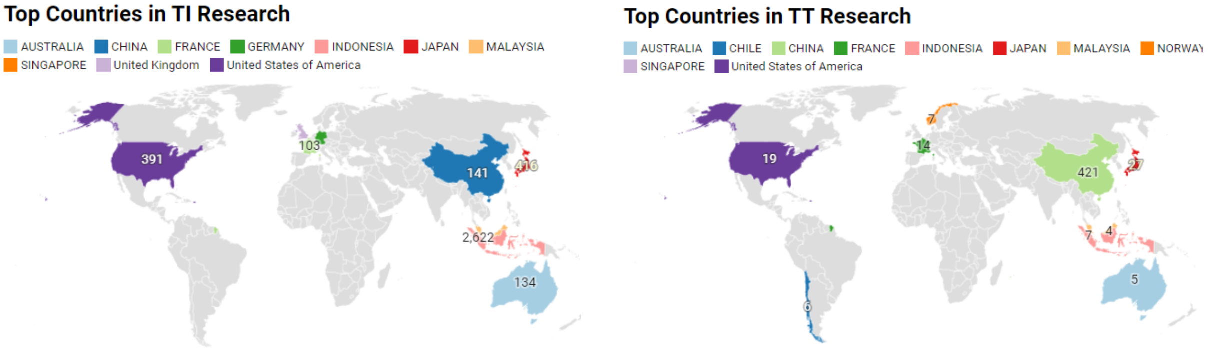
A comparison of TI and TT research based on the most relevant sources and affiliations in the last 10 years is presented in Table 3. The top most relevant sources in TI research are the IOP Conference Series: Earth and Environmental Science with 187 documents in the last 10 years. Meanwhile, the top most relevant Affiliation is Syiah Kuala University with 171 documents. In contrast to TT's research, the top most relevant sources are Terrestrial, Atmospheric, and Oceanic Sciences with 7 documents and the top most affiliation is the National Central University with 64 documents.

Table 3. Sources and affiliation in TI and TT research

TI Research				**TT Research**			
Sources	**N**	**Affiliation**	**N**	**Sources**	**N**	**Affiliation**	**N**
IOP Conference Series: Earth and Environmental Science	187	Syiah Kuala University	171	Terrestrial, Atmospheric, And Oceanic Sciences	7	National Central University	64
International Journal of Disaster Risk Reduction	40	Universitas Syiah Kuala	165	Journal of Earthquake and Tsunami	5	National Cheng Kung University	25
Pure and Applied Geophysics	40	Tohoku University	121	Natural Hazards	4	National Taiwan University	17
E3s Web of Conferences	31	Institut Teknologi Bandung	120	Natural Hazards and Earth System Sciences	4	Institute of Earth Sciences	11
Journal of Physics: Conference Series	26	Universitas Gadjah Mada	108	Proceedings of The International Offshore and Polar Engineering Conference	4	Institute of Nuclear Energy Research	11
AIP Conference Proceedings	25	Nanyang Technological University	103	Seismological Research Letters	4	Ocean University of China	11
Science of Tsunami Hazards	24	Universitas Indonesia	45	Tectonophysics	4	Shanghai Jiao Tong University	10
Natural Hazards	21	Andalas University	40	Journal of Coastal	3	National Taipei	9

TI Research				TT Research			
Sources	**N**	**Affiliation**	**N**	**Sources**	**N**	**Affiliation**	**N**
				Research		University of Technology	
IOP Conference Series: Materials Science and Engineering	20	Bandung Institute of Technology	39	Journal of Geophysical Research: Solid Earth	3	Tohoku University	9
Natural Hazards and Earth System Sciences	16	Tadulako University	33	Applied Mechanics and Materials	2	Not reported	8

Figure 7 is a comparison of the top countries in TI and TT research. Top countries in TI research (Figure 7a) show that Indonesia is the most contributing country with 2622 frequencies. Then followed by Japan (416), the USA (391), the UK (151), and China (141). Meanwhile, the top 5 countries in TT research (Figure 7b) ranked in the top 5 consecutively, namely China (421), Japan (27), USA (19), and France (14).



(a) (b)

Figure 7. Comparison of top countries in TI and TT research

The State of Indonesia has contributed a lot to research related to T, both scientists, academics, and government agencies. This is because Indonesia is one of the countries where tsunamis frequently occur. Research by Arfianti et al. (2021) said that Indonesia is located on the Pacific Ring of Fire and has some active volcanoes, which makes it vulnerable to earthquakes and tsunamis. In addition, Indonesia also has a long coastline that is prone to high waves (Madlazim et al., 2021). Meanwhile, in the TT research, the country that contributed the most was China. China also has a long history of tsunamis. Some natural disasters that occurred on the east coast of China, including a large earthquake and tsunami (Wang et al., 2023), have caused significant damage and caused many casualties. Therefore, China also has a great interest in research on tsunamis. In addition, research by Li et al. (2022) stated that China also plays an important role in international efforts to strengthen tsunami early warning systems around the world.

3.5 Top Cited Global in TI ad TT Research during 2013-2023

Documents with global citations on TI and TT research are presented in Table 4. Murray Nj (2019) is the top author on TI research in the last ten years. The document that discusses “Tidal flats' global distribution and trajectory” has 392 total citations, 78.40 total citations per year, and 25.67 normalized total citations. The top global cited document written by Murray et al (2019) in the journal Nature explains that the increase in human population around global coastlines threatens coastal ecosystems, including tidal mudflats, which experience significant losses and have negative projections. Whereas in the TT study, the top global cited document was written by Fujii et al. (2013) in the Ocean Science Journal regarding "An overview of oceanographic radar networks' evolution and uses across Asia and Oceania". The document counts to date 57 total citations, 5.18 total citations per year, and 11.00 normalized total citations.

Table 4. Top 5 global cited documents in TI and TT research on last ten year

TI Research				
Paper	**DOI**	**Total Citations**	**TC per Year**	**Normalized TC**
Murray Nj, 2019, Nature	https://doi.org/10.1038/s41586-018-0805-8	392	78.40	25.67
Hiwasaki L, 2014, Int J Disaster Risk Reduct	https://doi.org/10.1016/j.ijdrr.2014.07.007	179	17.90	7.65
Socquet A, 2019, Nat Geosci	https://doi.org/10.1038/s41561-018-0296-0	157	31.40	10.28
Frankenberg E, 2013, Ecol Soc	https://doi.org/10.5751/ES-05377-180216	141	12.82	8.78
Grilli St, 2019, Sci Rep	https://doi.org/10.1038/s41598-019-48327-6	140	28.00	9.17
TT Research				
Fujii S, 2013, Ocean Sci J	https://doi.org/10.1007/s12601-013-0007-0	57	5.18	11.00
Sepúlveda I, 2019, J Geophys Res Solid Earth	https://doi.org/10.1029/2018JB016620	39	7.80	2.54
Huang Jp, 2018, Neural Network World	https://doi.org/10.14311/NNW.2018.28.009	39	6.50	6.26
Løvholt F, 2014, Int J Disaster Risk Reduct	https://doi.org/10.1016/j.ijdrr.2014.04.003	38	3.80	3.20
Gabuchian V, 2017, Nature	https://doi.org/10.1038/nature22045	37	5.29	3.87

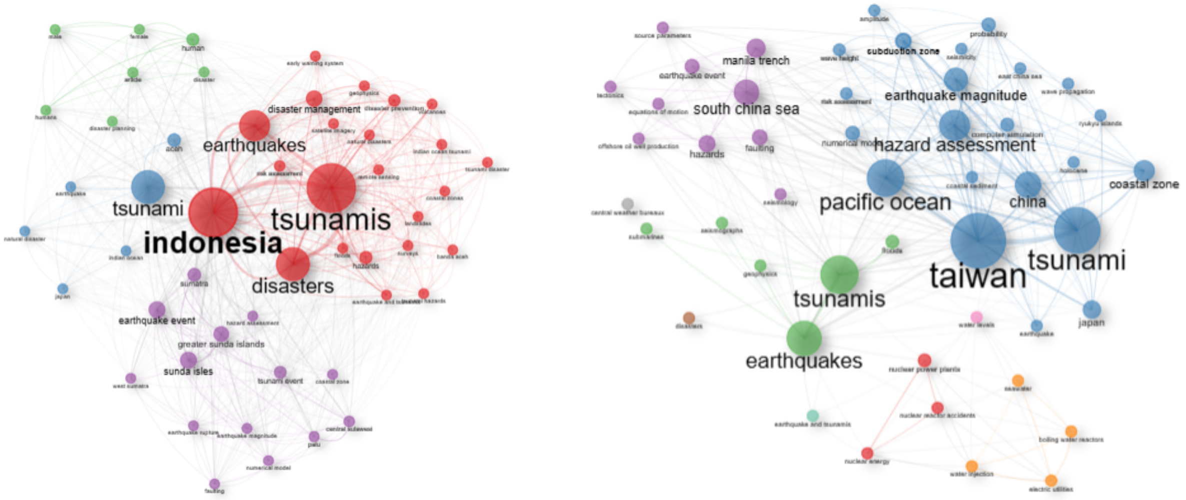
In addition, bibliometric analysis can determine the top cited counties in TI and TT research during 2013-2023 (Table 5). In the TI research, the top cited countries namely Indonesia are ranked first with 1835 total citations. The second to fifth ranks with the highest total citations respectively are Japan, the USA, Australia, and the UK. Meanwhile, in the TT study, the top cited country was China with 407 total citations. Then in the next position followed by Korea, France, Japan, and the USA. Of the 10 top-cited countries in Table 5, the average article citation in the TI study with the highest score was Portugal (29.67), and in the TT study, namely the USA (39.00).

Table 5. Top 10 cited countries in TI and TT research on last ten year

TI			**TT**		
Country	**TC**	**Average AC**	**Country**	**TC**	**Average AC**
Indonesia	1835	4.83	China	407	5.65
Japan	1308	16.35	Korea	59	29.50
USA	1206	16.52	France	56	18.67
Australia	939	31.30	Japan	53	7.57
United Kingdom	648	17.05	USA	39	39.00
Singapore	493	18.96	Norway	38	38.00
France	485	25.53	Singapore	29	29.00
Germany	378	18.00	Thailand	6	6.00
China	202	08.08	Indonesia	3	1.50
Portugal	178	29.67			

3.6 Mapping Visualization and Updates Information about TI and TT

The results of network visualization related to TI and TT research using bibliometric analysis are presented in Figure 8. There are 4 clusters related to trend keywords in TI research (Figure 8a) with terms related to each cluster presented in Table 6. Meanwhile, Figure 8b and Table 7 present 9 clusters which is a trend keyword in TT research. The most dominant terms in TI research based on network visualization results are Indonesia, Tsunamis, Earthquakes, Disasters, and Sunda Isles. Taiwan, Tsunami, Pacific Ocean, Earthquakes, Hazard Assessment, and China



(a) (b)

Figure 8. Network visualization related to TI dan TT research during 2013-2023

Table 6. Terms of the cluster in network visualization on TI research

Clusters		Terms
Cluster 1	:	Indonesia, Tsunamis, Disaster, Earthquakes, Disaster Management, Disaster Management, Disaster prevention, Hazard, Risk assessment
Cluster 2	:	Tsunami, Aceh, Indian Ocean, Natural disaster, Japan, Natural disaster
Cluster 3	:	Human, Article, Female, Male, Humans, Disaster planning, Disaster
Cluster 4	:	Sumatra, Hazard assessment, Faulting, Coastal zone, Earthquake rupture, West Sumatra, Central Sulawesi, Greater Sunda islands

Table 7. Terms of the cluster in network visualization on TT research

Clusters		Terms
Cluster 1	:	Nuclear power plants, nuclear energy, nuclear reactor accidents
Cluster 2	:	Taiwan, Tsunami, Pacific Ocean, Hazard assessment, Wave height, Amplitude, Coastal sediment
Cluster 3	:	Tsunamis, Earthquakes, floods, geophysics, seismographs, submarines
Cluster 4	:	South China Sea, Earthquakes event, faulting, hazards, tectonics, equations of motion
Cluster 5	:	Electric utilities, Seawater, boiling water reactors, water injection
Cluster 6	:	Disasters
Cluster 7	:	Water levels
Cluster 8	:	Central weather bureaux
Cluster 9	:	Earthquake and tsunamis

Based on the results of network visualization, the TI and TT studies show that there is a very close relationship between tsunamis and earthquakes. This is because tsunamis can be triggered by earthquakes that occur under the sea. Tsunamis generated by earthquakes are often referred to as "seismic tsunamis" (Widiyantoro et al., 2020). Research by Suppasri et al. (2017) said that the greater the magnitude of the earthquake, the more likely the resulting tsunami will be larger and more dangerous (Katsumata et al., 2021). In addition, countries that have a close relationship with the tsunami are Indonesia, Taiwan, and China. Because these three countries are located in areas that are prone to tsunami natural disasters. Several tsunamis that have occurred in Indonesia include the Aceh Tsunami in 2004 and the Palu Tsunami in 2018 (Mutaqin et al., 2019). In 2009, Taiwan experienced a small tsunami after an earthquake measuring 6.4 on the Richter scale shook the southwestern coastal region of Taiwan (Liu et al., 2022). Meanwhile, China also experienced a tsunami in 2004 following an earthquake measuring 9.1 on the Richter scale off the coast of Sumatra, Indonesia (Wang et al., 2023).

To maintain the safety of yourself and others and reduce the damage caused by the tsunami, it is very important to always follow the latest information about the condition of the tsunami, either through the government's official website or through mass media coverage. Some websites to find updates and information about tsunamis are shown in Table 8.

Table 8. Update information about Tsunami

Name	Website	Description
Pacific Tsunami Warning Center (PTWC)	https://ptwc.weather.gov/	This website offers up-to-date details about earthquakes and tsunamis that may occur in the Pacific, along with tsunami warnings, advisories, and bulletins.
National Oceanic and Atmospheric Administration (NOAA)	https://www.noaa.gov/tsunamis	This website offers details on tsunamis, including their creation, the science underlying them, and the most recent alerts and warnings.
Tsunami.gov	https://www.tsunami.gov/	Real-time tsunami alerts and information are provided for the United States and its territories through this collaboration between multiple US government entities.
The International Tsunami Information Center (ITIC)	https://itic.ioc-unesco.org/	This is a central repository for data about tsunamis and related dangers. The website offers connections to information and resources from diverse sources throughout the globe.
Central Weather Bureau (CWB)	https://www.cwb.gov.tw/eng/	Taiwan's CWB, the country's national meteorological service, offers up-to-date information on the weather and natural calamities, such as tsunamis.
Badan Meteorologi, Klimatologi, dan Geofisika (BMKG)	https://www.bmkg.go.id/	The BMKG is Indonesia's official agency in charge of keeping track of the country's weather, climate, and geophysics and offers real-time updates on all types of natural disasters, including tsunamis.

It is essential to stay abreast of tsunami-related information. To help prepare for, respond to, and recover from potentially damaging natural disasters (Madlazim et al., 2021). Information updates related to the tsunami in Taiwan can be through CWB and BMKG for tsunamis in Indonesia. CWB also updates hurricanes, floods, and other weather-related events that can trigger tsunamis. In addition to the CWB website, we can contact local authorities and emergency services in Taiwan for the latest information and guidance during a tsunami event.

Meanwhile, on the BMKG website, we can find information about current and past earthquakes, warnings, alerts, and tsunami bulletins. The BMKG also provides up-to-date information on weather-related events such as typhoons, floods, and landslides that can trigger tsunamis. Table 9 is the latest information update regarding the tsunami in Taiwan through the CWB website (https://www.cwb.gov.tw/eng/). The latest information regarding the tsunami in Indonesia can be accessed through the BMKG (https://www.bmkg.go.id/) is presented in Table 10.

Table 9. Top 10 latest updates related to information about Tsunami in Taiwan

No	Issued Time	Origin Time	Location	Magnitude
1	2023/03/16 10:01 (Taiwan Time: GMT+08:00)	2023/03/16 10:01 (Taiwan Time: GMT+08:00)	2023/03/16 10:01 (Taiwan Time: GMT+08:00)	2023/03/16 10:01 (Taiwan Time: GMT+08:00)
2	2023/03/16 09:06 (Taiwan Time: GMT+08:00)	2023/03/16 09:06 (Taiwan Time: GMT+08:00)	2023/03/16 09:06 (Taiwan Time: GMT+08:00)	2023/03/16 09:06 (Taiwan Time: GMT+08:00)
3	2023/01/18 14:54 (Taiwan Time: GMT+08:00)	2023/01/18 14:54 (Taiwan Time: GMT+08:00)	2023/01/18 14:54 (Taiwan Time: GMT+08:00)	2023/01/18 14:54 (Taiwan Time: GMT+08:00)
4	2023/01/18 14:14 (Taiwan Time: GMT+08:00)	2023/01/18 14:14 (Taiwan Time: GMT+08:00)	2023/01/18 14:14 (Taiwan Time: GMT+08:00)	2023/01/18 14:14 (Taiwan Time: GMT+08:00)
5	2023/01/08 21:47 (Taiwan Time: GMT+08:00)	2023/01/08 21:47 (Taiwan Time: GMT+08:00)	2023/01/08 21:47 (Taiwan Time: GMT+08:00)	2023/01/08 21:47 (Taiwan Time: GMT+08:00)
6	2023/01/08 21:09 (Taiwan Time: GMT+08:00)	2023/01/08 21:09 (Taiwan Time: GMT+08:00)	2023/01/08 21:09 (Taiwan Time: GMT+08:00)	2023/01/08 21:09 (Taiwan Time: GMT+08:00)
7	2023/01/08 20:42 (Taiwan Time: GMT+08:00)	2023/01/08 20:42 (Taiwan Time: GMT+08:00)	2023/01/08 20:42 (Taiwan Time: GMT+08:00)	2023/01/08 20:42 (Taiwan Time: GMT+08:00)
8	2022/11/22 11:58 (Taiwan Time: GMT+08:00)	2022/11/22 11:58 (Taiwan Time: GMT+08:00)	2022/11/22 11:58 (Taiwan Time: GMT+08:00)	2022/11/22 11:58 (Taiwan Time: GMT+08:00)
9	2022/11/22 10:45 (Taiwan Time: GMT+08:00)	2022/11/22 10:45 (Taiwan Time: GMT+08:00)	2022/11/22 10:45 (Taiwan Time: GMT+08:00)	2022/11/22 10:45 (Taiwan Time: GMT+08:00)
10	2022/11/22 10:13 (Taiwan Time: GMT+08:00)	2022/11/22 10:13 (Taiwan Time: GMT+08:00)	2022/11/22 10:13 (Taiwan Time: GMT+08:00)	2022/11/22 10:13 (Taiwan Time: GMT+08:00)

Table 10. Top 10 latest updates related to information about Tsunami in Indonesia

No	Origin Time	Latitude	Longitude	Magnitude	Depth	Location
1	2023-01-10 00:47:33	-7.37	130.23	7.5	130 Km	136 km BaratLaut MALUKUTENGGARABRT
2	2023-01-10 00:47:34	-7.25	130.18	7.9	131 Km	148 km BaratLaut MALUKUTENGGARABRT
3	2021-12-14 10:20:23	-7.59	122.24	7.4	10 Km	113 km BaratLaut LARANTUKA-NTT
4	2021-12-14 10:20:23	-7.59	122.24	7.4	10 Km	113 km BaratLaut LARANTUKA-NTT
5	2021-12-14 10:20:23	-7.59	122.24	7.4	10 Km	113 km BaratLaut LARANTUKA-NTT
6	2021-12-14	-7.59	122.26	7.5	12 Km	112 km BaratLaut LARANTUKA-

No	Origin Time	Latitude	Longitude	Magnitude	Depth	Location
	10:20:22					NTT
7	2019-11-14 23:17:43	1.67	126.39	7.1	73 Km	137 km BaratLaut JAILOLO-MALUT
8	2019-11-14 23:17:43	1.67	126.39	7.1	73 Km	137 km BaratLaut JAILOLO-MALUT
9	2019-11-14 23:17:43	1.67	126.39	7.1	73 Km	137 km BaratLaut JAILOLO-MALUT
10	2019-11-14 23:17:43	1.67	126.39	7.1	73 Km	137 km BaratLaut JAILOLO-MALUT

4. CONCLUSION

The research results related to the bibliometric analysis related to the Tsunami in Indonesia (TI) and the Tsunami in Taiwan (TT) obtained several conclusions. The conclusion is that the TI research trend is more consistently increasing linearly than research on TT from 2013-2023. Citation trends per year in TI and TT research vary depending on the popularity of research topics and the impact of publications. The highest mean total citations per year occurred in 2019, namely TI (3.82) and TT (3.84). The highest value in the mean total citations per article from TI research occurred in 2014 (23.41) and TT in 2019 (15.38). The most dominant trend keywords used are Tsunami, Indonesia, and Taiwan. The authors who contributed the most to TI research were Syamsidik and Wu TR in TT research. Indonesia and China are countries that have contributed a lot to and collaborated on TI and TT research. In TI research, the top 5 countries collaborating with Indonesia are Japan, the USA, the UK, Australia, and Germany. Whereas in the TT research, namely from China to Japan, USA, Australia, France, and Singapore. The highest and most relevant sources in TI research are the IOP Conference Series Earth and Environmental Science and Terrestrial Atmospheric and Oceanic Sciences in TT research. Syiah Kuala University and National Central University are top TI and TT research affiliations. The top document in TI research was written by Murray NJ, 2019, Nature, with the title "Tidal flats' global distribution and trajectory," which has 392 total citations, 78.40 total citations per year, and 25.67 normalized total citations. Whereas in the TT research, there is a document written by Fujii S, 2013, Ocean Scientific Journal regarding "An overview of oceanographic radar networks' evolution and uses across Asia and Oceania" with 57 total citations, 5.18 total citations per year, and 11.00 normalized total citations.

Based on the results of the network visualization, there is a very close relationship between tsunamis and earthquakes. It is because tsunamis can be triggered by earthquakes that occur under the sea (seismic tsunamis). Countries that have a close relationship with the tsunami are Indonesia, Taiwan, and China. Because these three countries are located in areas prone to tsunami natural disasters, several tsunamis have occurred in Indonesia, including the Aceh Tsunami in 2004 and the Palu Tsunami in 2018. In 2009, Taiwan experienced a small tsunami after an earthquake measuring 6.4 on the Richter scale shook the southwest coast of Taiwan.

Meanwhile, China also experienced a tsunami in 2004 following an earthquake measuring 9.1 on the Richter scale off the coast of Sumatra, Indonesia. The latest information updates regarding the tsunami natural disaster in Indonesia can be through the Meteorology, Climatology, and Geophysics Agency (BMKG). The tsunami in Taiwan can be through the Central Weather Bureau (CWB).

The implication of the research is to demonstrate the popularity of writing about Taiwan's and Indonesia's tsunamis so that future research might demonstrate more advantages of this subject. Researchers can learn about the advantages and disadvantages of each subject and discover updates for additional research with the help of this article. Recommendations for future researchers are to conduct research related to tsunamis and earthquakes with in-depth studies because of the high potential for further research.

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WHEN A TSUNAMI THREAT IS IMMINENT AIR-SEALED TYPE OF ENCLOSURES CAN SERVE AS TEMPORARY SHELTERS TO SAVE LIVES RELIABLY AND ECONOMICALLY

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ABSTRACT

Twenty-two thousand people died when the 11 March 2011 Tohoku earthquake and tsunami struck Japan with little or no warning from Civil Defense authorities. Both the earthquake and the tsunami also resulted in the failure and destruction of the Fukushima Daiichi Nuclear Power Plant and in large-scale distribution of radioactive elements. The seawalls along the affected coasts were easily destroyed by the tsunami, which also stirred up sludge and sediments from the seabed on land, thus making evacuation extremely difficult. Therefore, it becomes obvious that when a destructive tsunami hits again Japan, all coastal plains will continue to be dangerous zones. People living in such areas do not have enough warning time – particularly from local earthquakes and tsunamis - to evacuate to safer areas inland. Therefore, and in order to protect the people in such vulnerable coastal areas, tsunami shelters must be used or constructed to provide for their short-term protection until the tsunami danger subsides. Rapid escape of the people in danger areas to air-sealed type of existing or constructed enclosures serving as temporary shelters, can save their lives. Specifically, air-tight shelters, even in tsunami flooded coastal areas, can provide temporary protection until there is no threat. Such temporary shelters can be cheaply constructed and reliably save lives. Building codes can be amended for building air-filled tsunami shelters in oceanfront buildings, and thus provide safety from normal-level tsunamis at relatively low cost. Tsunami shelters can be constructed even in subway facilities or underground shopping malls, and thus minimize or reduce to zero losses of human lives, not only from tsunamis, but also from large fires, If coastal towns were equipped with tsunami shelters, the number of deaths from tsunamis as well as from large fires could be minimized and even be reduced to zero.

Keywords: *Japan; tsunami; seawalls; air-reservoir-type tsunami shelter; submarine-type tsunami shelter; Sanriku Coast; Okawa Elementary School; debris flow; tsunami warnings.*

INTRODUCTION

If a local destructive tsunami is generated near an inhabited coastal area from an earthquake source within a distance generally less than 200 km away, it is characterized as a near-field event according to the revised first edition of the tsunami glossary (Pararas-Carayannis, http://www.drgeorgepc.com/TsunamiGlossary.pdf), since there is no sufficient time for the authorities to give a timely warning for inland evacuation of local residents. For such low-lying, inhabited coastal areas, the earthquake's strong shaking motions should be a warning that a tsunami may be shortly arriving and that people should take immediate measures to save their lives. Even if a short term warning of an expected tsunami is announced by civil defense authoties, the given estimate of its height may not be properly forecast for the areas that will be affected and in fact it may be much greater.

Based on current tsunami prediction technology, the actual height of a tsunami could be between half or even double the predicted height, depending on the state of the local tide at that time and the coastal topography (Ministry of Land, et al., 2011). The "height" of a tsunami is defined as the difference in sea level compared to the normal tide level. However, based on local topography and the concurrent arrival of waves from different directions of the source area, the run-up height (elevation) of the tsunami could significantly increase from that on the coast. In some instances, the run-up height of the tsunami can be significantly augmented by as much as four times the initial height on the coast.

Some local governments in Japan have created hazard maps (inundation prediction maps) showing areas that are likely to be flooded in the event of a tsunami. According to the "Table of Tsunami Wave Height and Degree of Damage" (modified from Shuto (1993)), even reinforced concrete buildings can be destroyed by a tsunami with a height of 18 m.

However, it is dangerous to claim that the actual height of a tsunami is one-half to twice the predicted height. This would mean that a tsunami forecast to have a height of 10 m, its actual run-up height could range between 5 and 20 meters. Tsunami countermeasures that are based on height predictions with this varying degree of accuracy, could result in many deaths.

For example, damage caused by the tsunami of March 11, 2011 could have been predicted as the seawalls in the affected areas were not sufficiently high and the tsunami easily exceeded them. As a result, residents who had trusted that the seawalls would protect them did not try to escape and thus they were killed. In addition, the danger zones shown in existing tsunami hazard maps are narrow, and the 2011 tsunami affected people who thought that no tsunami would reach them. Also, existing shelters were also located at elevations that were too low.

In brief and as a result of these mistakes, 22,000 people were killed by this tsunami, and a serious accident also occurred at the Fukushima Daiichi Nuclear Power Plant and the resulting and long-lasting effects of radiation (Pararas-Carayannis, 2011). These misjudgments indicated the need for Japan to use more complete tsunami countermeasures, which must be based on the collection of more accurate data and of proper interpretation. Because a tsunami can have a run-up heights of up to four times of its initial, it can be expected that a height of 10 meters can have a run-up height of up to 40 meters, based on the momentum of motion. In reality this means that all coastal plains are danger zones and that people should not simply rely on the tsunami hazard maps produced by local governments. Also, local authorities responsible for tsunami protection should provide better guidance to residents on how to interpret these hazard maps.

Historically, the Great Meiwa Tsunami that hit Ishigaki Island in 1771, is reported to have had a run-up height of 85 m (AIST, 2018). An undersea landslide generated this catastrophic tsunami. Another earthquake on 15 June 1896 in Sanriku, killed 22,000 people and another one on 2 March 1933 in the same area, resulted in 3,000 deaths (Pararas-Carayannis 2011; 2014).

In brief, Japan's high seismicity is attributed to its location near oceanic trenches where the oceanic plate subducts under the Japanese archipelago – these being the Chishima, the Japan, and the Nansei Islands trenches, as well as the Sagami and the Nankai troughs. This high seismicity of Japan has also led to the formation of cliffs that rise from the sea floor, meaning that even a weak earthquake can result in undersea cliff collapses and in the generation of larger tsunami waves.

All coastlines on Japan are vulnerable to tsunamis striking with little or no warning at all, thus preventive measures that rely on present estimates of wave heights cannot prevent damage. For example, the height of the 2011 tsunami was much greater than anticipated, and easily destroyed seawalls for about 190 km of the 300 km seawall along the Sanriku Coast (Tarui et al., 2012). In addition, a tsunami with a height of 18 m or more can even destroy buildings constructed with reinforced concrete (Ministry of Land, Infrastructure, Transport and Tourism, 2011). Tsunami waves can also generate debris flows that lift up sediments from the ocean floor, as indicated from past inland tsunami deposits on shore that have thicknesses of up to 50 cm. Furthermore, a large tsunami accompanied by debris flows can easily destroy seawalls, and even tall concrete buildings reinforced with rebars. Thus, all tsunami protection shelters must be able to withstand such great destructive forces. The following sections of this report recommend that air-sealed enclosures can serve as temporary shelters, as well as properly constructed submarine-type of shelters.

2. AIR-SEALED ENCLOSURES CAN SERVE AS A SAFE TEMPORARY, RELIABLE AND ECONOMIC SHELTERS FOR LOCALLY GENERATED TSUNAMIS IN VULNERABLE COASTAL AREAS WHEN A STRONG EARTHQUAKE IS FELT

At the basement level of a building, the momentum of a tsunami is reduced and drifting objects cannot enter. In such environment—although they would be immersed in seawater—people would be safe as long as diving equipment with adequate air supply was available.

Similarly, in ships that have sunk, air pockets form, and people can survive as long as they can reach one of these air pockets. An air reservoir-type tsunami shelter based on the same principle is easy to make: it simply requires the construction of a room from which air is prevented from leaking through the ceiling. Seawater that enters the room will rise and fall according to the height of the tsunami, but air pockets will form near the ceiling.

To provide a suitable location for a tsunami shelter, the building in which it is housed also needs to be able to withstand the pressure produced by tsunamis and the impact of drifting objects. When tsunamis strike, debris flows lift up sediment from the ocean floor, and the destructive power of a tsunami varies greatly depending on the state of the seabed, the location and elevation of buildings, and other factors.

A building does not need to withstand the pressure caused by the height of the tsunami because the tsunami heights inside and outside the building are almost identical. Therefore, a room in an ordinary building can be made into a tsunami shelter simply by ensuring that the air cannot leak through the ceiling. As shown in Fig. 1, even wooden houses can be considered safe if the basement is used as a tsunami shelter. Alternatively, one room can be converted to a shelter by reinforcing it against the outside hydrostatic pressure of tsunamis. Even if the upper part of the house is washed away by the tsunami, a properly constructed air-tight basement will survive, so this can be the safest part of such a house. Therefore, a revision of the building structure could incorporate the installation of tsunami shelters provided that the ceiling is sealed and contained air does not escape.

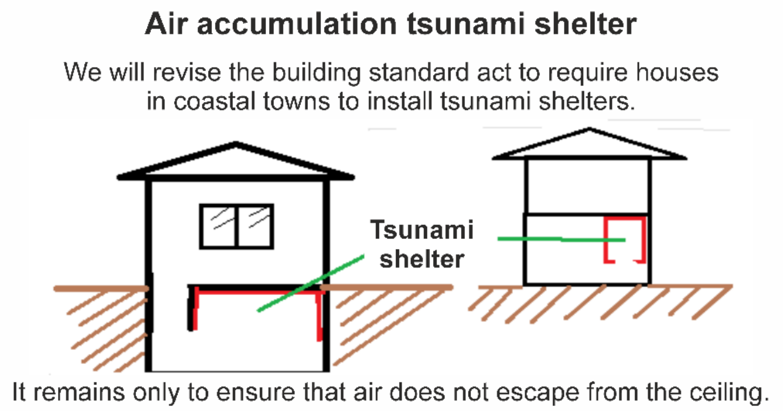

Fig. 1 Construction of an air accumulation tsunami shelter.

To convert a high-ceilinged room into an air-reservoir-type tsunami shelter, scaffolding-enabling access to the air reservoir near the ceiling could be constructed.

The main disadvantage of this type of shelter is that people get wet, which is a serious problem in winter. However, it is also easy to create a dry space by constructing the shelter in such a way that large air pockets that can easily be accessed form; people lying or sitting on top of floating furniture, who will not get wet, can perhaps access these. The disadvantage is that pressure associated with the height of the tsunami will also affect the human body. A 10 meter high tsunami will exert a pressure of 1.0 kg/cm^2 on the human body, causing no serious harm. In scuba diving, even beginners can dive up to 20 m, so this level of water pressure is relatively safe.

Larger tsunamis are more problematic but are encountered less frequently. A tsunami can strike suddenly at any time (even during the night) without any warning. Therefore, a safe tsunami shelter must be reachable very quickly. Moreover, when a tsunami warning is issued during the daytime, not all workers can cease working and escape rapidly. Thus, many tsunami shelters are needed along vulnerable coasts, where the imminent occurrence of a tsunami can be monitored before ordering evacuation.

An adult diver requires 15 liters of air per minute, or 0.9 m^3/hour. Therefore, 50 m^3 of air (5 m × 10 m × 1 m) will support five people for 11 hours. However, in a real tsunami situation, the people will not be submerged for that long.

Submarines make use of well-established technologies that are based on the amount of air required by the crew and the need to remove carbon dioxide. The construction of tsunami shelters can be based on the same principles.

At atmospheric pressure, the above amount of air is sufficient. In an air reservoir during a tsunami, the pressure exerted by the tsunami reduces this volume. During the 2011 tsunami, one person survived within a 20 cm–high pool of air formed in the ceiling of an apartment building.

To protect houses in coastal areas against moderate tsunamis, the relevant building codes can be amended to require one room with airtight ceilings. Seawalls are expensive: they cost about 2.5 billion yen/km to construct and are easily destroyed by large tsunamis. This was the subject of the NHK special broadcast “Black Tsunami: The Unknown Reality” (NHK, 2019).

At the time of the 2011 tsunami, samples of seawater were taken. The seawater was black and was found to consist of 10% sludge. Seawater containing this amount of sludge would hit the seawall with twice as much force as ordinary seawater. The bottom of the bays adjacent to large cities such as Tokyo and Osaka are covered with deep sludge. Any tsunami hitting those bays would stir up this sludge and destroy the seawall.

One year after the 2011 tsunami, another tsunami warning was issued, and radio and television broadcasts instructed people to evacuate to higher ground. However, the tsunami that actually hit was a small one with a height of about 1 m. People who heeded the warnings, left work, and fled to higher ground then faced criticism.

Because seawalls protect against small tsunamis, residents often ignore tsunami warnings. This means that when a large tsunami subsequently hits, many residents again trust the seawall to protect them and thus become victims. This has happened repeatedly along the Sanriku Coast since ancient times. In 1896, 21,959 people died in the Meiji Tsunami, 3,034 people died in the Showa Tsunami of 1933, and 22,000 people died in the 2011 Heisei Tsunami; in addition, 142 people died in the tsunami that hit Chile in 1960. In just 115 years, these four large tsunamis have caused a great number of casualties. It is, therefore, clear that current tsunami countermeasures are not effective.

A tsunami shelter such as the one shown in Fig. 2 constructed in the center of an office building would allow people to escape from a tsunami. As a tsunami with a height of 18 m or more can destroy even buildings made of reinforced concrete, it is safer to shelter in a low-rise building than a high-rise one. By collecting air from a large space into one room, a secure, dry space that offers protection from a tsunami can be created, thus avoiding the need for people to flee to higher ground.

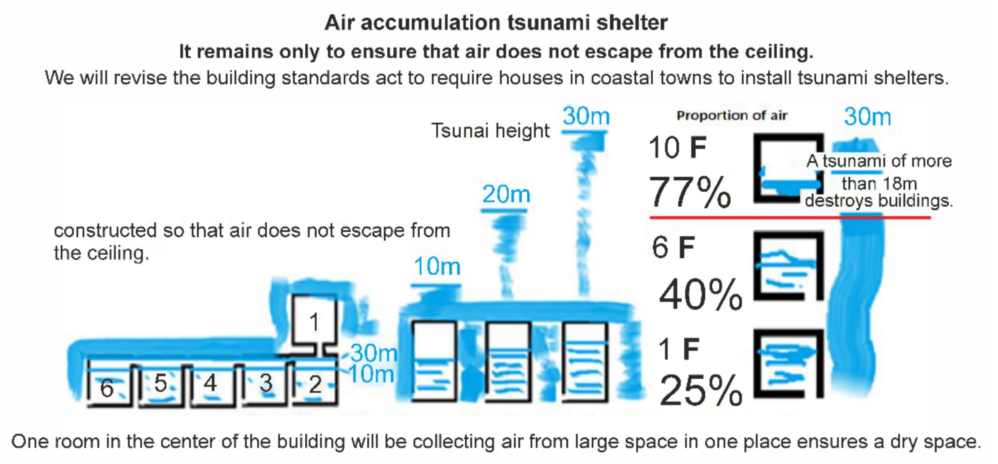

Figure 2. Details of a tsunami shelter that could be installed in buildings in coastal areas.

3. SUBMARINE-TYPE OF TSUNAMI SHELTERS

Fig. 3 shows a submarine-type tsunami shelter that could be used to offer short-term protection of people in coastal areas from a future large locally generated tsunami. This type of suggested shelter is essentially an easy-to-build sealed structure on the coast that could remain dry until the tsunami danger ends and could provide a safe space for everyone, including children and vulnerable adults. The shelter is equipped with an oxygen supply and a means of removing the carbon dioxide produced by the users. It could also be equipped with an emergency power supply, an external communication system, a toilet, and an emergency air-intake valve.

The shelter is designed to withstand the destructive power of a tsunami and is built of reinforced concrete with a thickness of 2 m. Further details of how such a shelter could be constructed are the are as follows. The proposed shelter consists of a 2 m–thick reinforced concrete box with internal dimensions of 10 m × 10 m × 3 m, outer dimensions of 14 m × 14 m × 7 m, and an approximate weight of 2600 tons. The entrance passage is 1m wide and 2m high, with watertight doors on the inside and sturdy iron doors on the outside. Within this space, 20 m^2 is used for oxygen storage, automatic oxygen supply equipment, carbon dioxide absorbers, toilets, lighting, communication equipment, emergency food supplies, and other commodities.

Applying the permanent capacity standard of trains in Japan (0.14 m^2/person), this area can accommodate 571 people in an emergency. However, the capacity of the proposed shelter is set for 200 people, allowing for adequate sitting down. The estimated cost of this shelter can be calculated as follows.

3A. Construction of Submarine-type of Tsunami Shelters

For proper construction of a submarine-type of tsunami shelter it is estimated that 1072 m^3 of reinforced concrete is required. The estimated cost of such construction would be 1072 m^3 × 80,000 yen/m^3 = 85,760,000 yen. The shelter would require an oxygen supply system and another for the removal of the carbon dioxide. The amount of oxygen which will be required will be 15 liters/min × 60 min × 0.21 = 0.189 m^3/person/hour.

Therefore, based on such rate of consumption, if 571 people remain in the shelter for 10 hours, they will require up to1,080 m^3 / 7 m^3/cylinder = 155 cylinders of oxygen. The cost of 1 cylinder of oxygen = 30,000 yen 30,000 yen × 155 = 4650,000 yen, which is not a large amount of money. The amount of carbon dioxide that would be generated will be 4%, equivalent to 15 liters/min per person × 60 min × 0.04 = 0.036 m^3/person/hour. The 206 m^3 of carbon dioxide that would be produced by 571 people sheltered for 10 hours can be absorbed by a slaked lime suspension. Thus, the volume occupied by the oxygen cylinders and other equipment, and the cost of these, will not be a problem.

A watertight door, an outer door, an automatic oxygen supply device, a carbon-dioxide absorption device, an emergency power supply, an external communication device, a toilet, emergency food, and other necessary commodities can be prepared for less than 100 million yen. Based on the above calculations, the total construction cost of this shelter is around 200 million yen/unit. Fig. 3 is a diagram depiction of this type of reinforced concrete submarine-type of tsunami shelter, with thickness of walls of two meters, weight of 2,800 tons and a capacity to provide protection for 200 people for a reasonable time and until the termination of the tsunami danger.

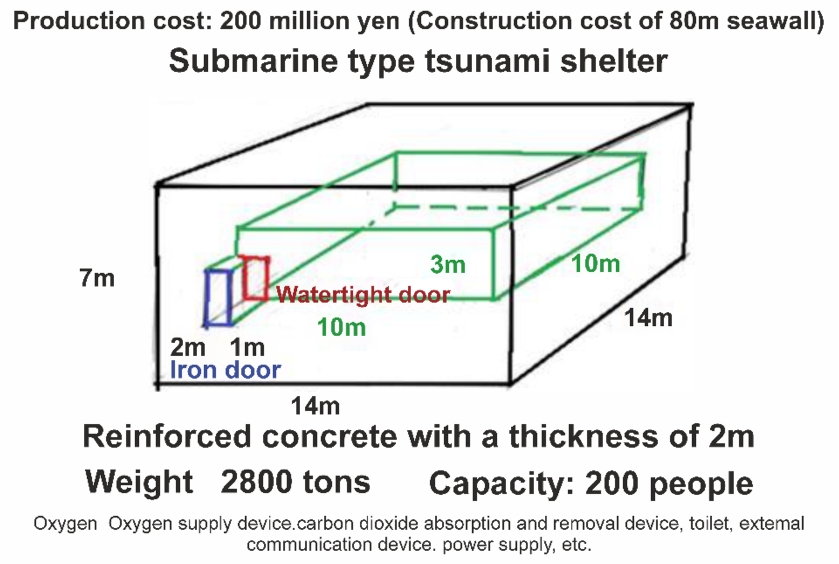

Figure 3. Diagram of a submarine-type shelter designed to withstand large tsunamis

Specifically, such submarine-type of shelters could be constructed in populated cities vulnerable to inundation by locally generated tsunamis, like Yamada-Machi, a town located in central Iwate Prefecture, which is part of the Sanriku Region of Japan on the coastline on the Pacific Ocean. The main industries of this city are fishing and tourism, which are centered on the Rias Coast and also include some small and medium-sized factories in the mountainous areas inland.

The 2011 tsunami completely destroyed the seawall of the city of Yamada-machi. The sturdy iron gates on the road between the port and the city were also easily swept away, and houses on the flat areas near the ocean were destroyed. A total of 825 people out of a population of 19,270 were killed, and the remaining population was reduced to 14,821.

Regarding the expenditure for the construction of a submarine-type of tsunami shelter for 200 people the cost 200 million yen per shelter, and it would cost 15 billion yen to build the 75-tsunami shelters which would be needed to accommodate the entire population of Yamada-machi. This can be compared with seawalls, which are more expensive - 2.5 billion yen/km. Thus, tsunami shelters that could accommodate the entire population of Yamada-machi could be built for the same cost as only 6 km of seawall which – as it has been explained - do not protect adequately against tsunamis.

When implemented, the revised Building Standards Law in Japan will require the installation of air reservoir-type tsunami shelters in all homes built on flat land close to the coast. This will provide protection from moderate tsunamis at little cost. However, in order to protect against larger tsunamis, which have tremendous destructive power, submarine-type shelters could also be built. In the case of warehouses and factories, banks of soil can be used to provide a cushion against tsunamis and turn them into air reservoirs.

Unfortunately, the most worrying thing about the 2011 tsunami is that it was not large enough to be considered as a giant tsunami. The tsunami had a maximum height of 19.0 m (as measured at Miyako Island) (nippon.com, 2011), and can thus be considered to be a moderate size of a tsunami - although it killed 22,288 people, destroyed 1.153 million buildings, forced 347,000 people to move to evacuation centers, and caused damage estimated at approximately 16.9 trillion yen (Pararas-Carayannis, 2011; 2015).

If a giant tsunami were to occur, the seawalls in the affected areas would easily be destroyed. It is thus, impossible to prevent a giant tsunami from entering residential areas, and tsunami shelters would be the only way to save lives.

If there was a tunami shelter at Okawa elementery school, 74 people would not have died.

Strengthen the walls of the classroom, add watertight doors, and you’re done.

If you prepare oxygen cylinders and carbon dioxide absorbers, many people can stay in the room forever.
Tsunami shelters protect lives cheaply and reliably.

Figure 4. Okawa Elementary School, where 74 people died in the 2011 tsunami

In 2011, 74 people died at Okawa Elementary School as a result of failings in national tsunami countermeasures. Back then, if we had tsunami shelters like Fig. 4, these people wouldn't have died. Following national government guidance, the government of Miyagi Prefecture had produced a tsunami hazard map that was based on the height of tsunamis known to have hit the area in the past. According to this map, Okawa Elementary School is located in a safe zone and has been designated as an evacuation center by Ishinomaki City authorities. Nevertheless, this school is only one meter above the sea level. On the day of the tsunami, both the teachers and students who had lined up in the schoolyard were swept away and died. If the school had not been designated as an evacuation center, these people would have climbed the mountain behind the school and survived; in fact, one student and one teacher did manage to save themselves in this way.

Neither the national government nor tsunami researchers understand the basic nature of tsunamis. A giant tsunami that scoops up sediment from the seabed can easily destroy seawalls. In addition, the height of a tsunami that hits land can be dramatically affected by the local topography. A tsunami sourced from the front of a bay will hit the coast of that bay at a large height. However, the neighboring bay may be much less seriously affected because the cape between the bays will block the tsunami to some extent. A seawall built in the neighboring bay will prevent small tsunamis such as those occurring in the past but will not deter large tsunamis occurring in front of the bay. Thus, countermeasures based on the known heights of past tsunamis are flawed. Both the government and tsunami scientists are developing tsunami countermeasures based on the erroneous premise that a tsunami of the same magnitude as past tsunamis will occur where they were reported in the past.

3B. Proposed use of subways and underground shopping malls as tsunami shelters

Subways and underground shopping malls are the best locations for tsunami shelters. As can be seen from Fig. 5, it is easy to create a large dry space underground.

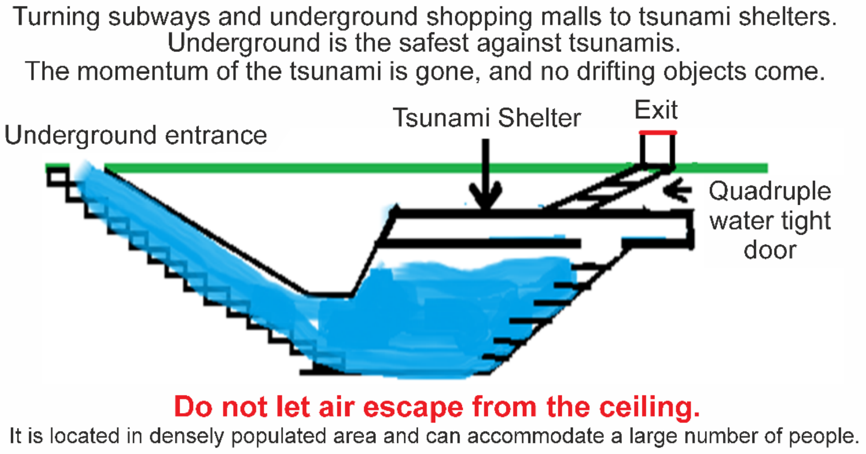

Figure 5. Proposal for adapting subway stations and underground shopping malls to act as tsunami shelters

Also, underground, people are protected against the destructive power of a tsunami and drifting debris. In densely populated areas, shelters such as this can accommodate travelers and other people who are out and about. However, subway stations can be used as gigantic tsunami shelters if water entry through the subway entrances is blocked and water coming along the tracks is contained. Such technology has already been implemented in New York subways (Teresa McKemer, 2019). In 2012, Hurricane Sandy flooded the New York City subway tunnels and nine stations, causing billions of dollars of damage to the city's transportation system. The Metropolitan Transportation Authority (MTA) has implemented measures to protect the subway from flooding.

Flex gates are among several tools that protect low-lying metro stations from storm surges and unusual seawater rises caused by strong storms that bring seawater ashore. Developed by the engineering firm ILC Dover, a flex gate is a Kevlar-woven balloon that can block a subway entrance in minutes when operated by a single person. The MTA has already installed 65 flex gates at various locations.

Subway tunnels have also been blocked with 32-foot-long balloons called "resilient tunnel plugs." Such devices are very useful during tsunamis that can suddenly strike without warning. The tunnel can be immediately blocked within a safe location. Moreover, underground tunnels have countless holes leading to the surface, which must be closed simultaneously. Any hole left unclosed will admit the tsunami into the underground passageway. If the underground passages are divided into smaller sections and blocked with such devices in advance, the risk of underground flooding remains low and damage is minimized.

The methods implemented in New York are intended to protect subways from flooding. In Tokyo and Osaka, there is marked ground subsidence and most areas are below sea level. If seawalls and waterproof gates at the coast were destroyed, seawater would flood into these areas. The subways would also be completely submerged within a few hours. Because of this, disaster prevention plans based on the policy of escaping from subways as quickly as possible have been devised. However, these plans should be revised as the safest place to be in the event of a tsunami or flooding is underground.

As has been stated, buildings used as evacuation centers can be completely destroyed by a tsunami with a height of 18 m or more. However, even a ship that has sunk to the bottom of the sea will contain air reservoirs. Similarly, in a subway, as long as air cannot leak through the ceiling, it will store there. If air can be collected from a large volume, a dry space where people can shelter can then be created. However, if the area above ground is flooded, watertight doors will also be needed to keep the water out.

The oxygen requirement of one person is small: One 7-m^3 oxygen cylinder can supply one adult with oxygen for 150 hours. The carbon dioxide produced by people in a shelter can be removed using wet slaked lime. The same technologies are already used in submarines. The exit allows passage out above the water on the ground.

During the Second World War, the London Underground was used as an air-raid shelter. Even in the event of large fires that can occur after a major earthquake, subways can offer a safe refuge. Also, even if smoke from distant fires drifted along the tracks, air bags such as the ones described above can be used to prevent its spread.

In contrast to the above-described measures, Japan's tsunami countermeasures were of limited use in 2011. Instead, they magnified the amount of damage caused. If suitable tsunami shelters were installed along the coast of Japan, the number of deaths due to tsunamis could be reduced to zero.

As has been demonstrated four times in the last 115 years, seawalls cannot protect against large tsunamis. However, even after the 2011 tsunami, the Japan government spent 1 trillion on the construction of useless new seawalls. A submarine-type tsunami shelter for 200 people that could withstand a giant tsunami would cost 200 million yen. Thus, at a cost of one trillion yen, shelters that could accommodate one million people could be built. Of the Iwate Prefecture's population of 1.2 million, more than 1 million live inland and only about 200,000 live on the coast. This means that the cost of making the 200,000 people living in the coastal areas of Iwate Prefecture safe from a giant tsunami is only 200 billion yen, which is equivalent to the cost of only 80 km of seawall.

The government has announced that 230,000 people will die in the massive tsunami following the Tonankai earthquake, which is predicted in the near future (Miyazaki and Nagamatsu 2020). The chance of this earthquake occurring within the next 30 years has been estimated as 70%–80%. Thus, day-care centers and schools in coastal towns need to be equipped with tsunami shelters urgently.

The Japanese archipelago is a disaster zone where 40% of the world's major earthquakes have occurred. Since ancient times, people in Japan have lived in fear of the tsunamis that strike at intervals of several decades. However, if enough suitably equipped tsunami shelters were constructed, it would be possible to reduce the number of deaths from tsunamis and large fires to zero.

CONCLUSIONS

The ineffectiveness of the Japanese government's tsunami countermeasures has been demonstrated by the fact that four tsunamis have severely damaged Japan in the 115 years since the Meiji Tsunami. Besides the three large tsunamis occurring nearby, a tsunami sourced from distant Chile caused casualties. Seawalls can easily be destroyed by tsunamis that scoop up sludge and sediment from the seabed, and all flat areas near to the coastline should be considered danger zones.

Tsunami shelters that are designed to remain at the bottom of a tsunami are inexpensive and offer reliable protection. If the Building Standards Law is revised to require the creation of air reservoir-type tsunami shelters in buildings in coastal areas, this will provide relatively inexpensive protection from moderate tsunamis at little cost.

To protect against giant tsunamis, submarine-type tsunami shelters should also be built. This type of shelter, which can accommodate 200,000 coastal residents in Iwate Prefecture, can be built for 200 billion yen, the cost of 80 km of seawall. Subways and underground malls could also be used as tsunami shelters if they were suitably equipped. By installing shelters such as these in coastal areas, the number of deaths due to tsunamis and large fires could be reduced to zero.

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EARTHQUAKE AND TSUNAMI SAFETY OF NUCLEAR POWER PLANTS – Case Study: The San Onofre Nuclear Plant in California, USA

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Tsunami Society International

ABSTRACT

The present study addresses briefly the safety and design requirements of nuclear power plants from earthquakes and tsunamis that may affect the structure or cooling systems of their reactors, and which may result in additionally and longer term destructive impacts on nearby communities and marine life due to the additional release of radioctivity - as was the case with the 11 March 2011 Fukushima Daichi nuclear plant in Japan, as well as with the release of radioactivity by other nuclear power plants by tsunamigenic earthquakes in other parts of the world.

The vulnerability of nuclear power plants to earthquakes and tsunamis was specifically examined by the author in conducting a comprehensive study of historic earthquakes and tsunamis, as well as by an extensive air and land field survey of Southern California, undertaken under contract with the U.S. Nuclear Regulatory Agency (NRC), and the U. S. Army Coastal Engineering Research Center (CERC), in connection with the licencing of the San Onofre Nuclear Power Plant near San Clemente in California, and of subsequent attempts to licence the additional Units 2 and 3 of the same facility of the Southern California Edison Company (the licensee).

The present evaluation is also based on historical records extended back in time for determining earthquake and tsunami events when California was still under Spanish control under Gaspar de Portolá, the Spanish military officer from Catalonia in Spain, the first governor of Upper California, and founder of Monterey and San Diego, before California was annexed by the United States as a State of its Union. Also researched were archives in Seville, Spain.

Keywords: *Nuclear Power Plants safety; San Onofre power plant; Fukushima Daichi Nuclear plant Japan disaster; cooling system failure; licencing U.S. Nuclear Regulatory Agency (NRC)*

INTRODUCTION

As consultant to the U.S. Nuclear Regulatory Agency (NRC) for the licencing and construction of units 2 and 3 of the San Onofre Nuclear Plant (SONGS), the author of the present study undertook a thorough physical examination and mapping of major seismic faults in Southern California on the main San Andreas fault, and on other adjacent faults up to Baja California in northern Mexico. The main purpose of the conducted survey was to evaluate the impact of past Southern California earthquakes and possible tsunamis in this general region, their frequency of reccurrences, and the potential impact that future events on land and on offshore faults could have in the vicinity of the planned additional San Onofre nuclear plant construction site for units 2 and 3.

At the time of the investigation, there was also concern about the proximity of the additional nuclear power plant construction to the California residence of then U.S. President Richard Nixon in San Clemente (4 miles away from the nuclear plant), and its relative safety. Thus the field investigation was additionally extended by a helicopter survey of seicmic fault extensions on the offshore Island of Santa Catalina on the southern California coast – a survey which was subsequently intercepted, interrupted and aborted, following warnings by armed helicopters guarding the presidential house.

Although signicant destructive earthquakes occur frequently slong the San Andreas fault of California, most of them occur inland and involve strike-slip type of ground displacements. However some earthquakes which occur on extentions of faults into the sea, can and have generated destructive tsunami waves in the past. In general, and as mentioned and explained elsewhere in this present study, the relative tsunami threat for local tsunamis in California can be considered as being relatively low because of the low recurrence frequencies of such offshore California earthquakes.

A thorough and detailled study of historical earthquakes and tsunamis in California was published in a book by the author entitled “The Big One-The Next Great California Earthquake – Why, Where and When it will happen” (Pararas-Carayannis, 2000 Forbes Press). According to stated conclusions of this publication, large, locally-generated tsunamis in California are estimated to occur once every 100 years. Thirteen possible tsunamis have been observed or recorded from local earthquakes between 1812 and 1988. These tsunami events were poorly documented and some are very questionable. However, there is no doubt that earthquakes occurring along submarine faults off Santa Barbara, just North of Los Angeles, could generate large destructive local tsunamis. In fact, in December of 1812, local earthquakes occured, each capable of tsunami generation. Perhaps the size of the 1812 tsunami at Santa Barbara was exaggerated in the historical records, but one and possibly two large tsunami events did occur in the area that year according to substantiated accounts.

The following discussion provides summaries of such events along Southern California – events which were examined in relation to the licencing of units 2 and 3 of the San Onofre Nuclear Generating Station (SONGS). This station was granted a facility Operating License on January 1, 1968 and ceased operation on November 30, 1992. The licensee, Southern California Edison Company (SCE), completed defueling of the reactor on March 6, 1993, and the dismantlement and decommissioning of SONGS, Unit 1 by 15 December 1998.

Prior to the review of safety of the San Onofre Nuclear Plant based on the onsite inspections and findings (Parararas-Carayannis George, 1974), subsequent sections of this report document sequentially historical earthquake and tsunami events and evaluations of their occurences and reported impacts in Southern California, which could have had an impact until units 2 and 3 of the facility were completely decommissioned in June 2013, Unit 1 in 1998, and an 8-year dismantling plan of the entire facility was initiated in August 2022, at an estimated cost of 5 billion US dollars.

1. HISTORICAL EARTHQUAKES, TSUNAMIS AND OTHER DISASTERS IN SOUTHERN CALIFORNIA AND EVALUATION OF POTENTIAL IMPACTS

The following is a listing in chronological order of historical earthquakes and tsunamis that had impacts in Southern California, but particularly to those in close proximity to the San Onofre nuclear power plant. Also examined were potential failures of the reactor's cooling system from meteorological phaenomena causing sudden changes in atmospheric pressures and associated sudden sea level fluctuations. As stated, a thorough investigation of the literature of such events was undertaken by the author, initially in the early 1970's under contract as consultant to agencies funded by the the U.S. Nuclear Regulatory Agency (NRC), for the design, licencing and construction of units 2 and 3 of the San Onofre Nuclear Plant (SONGS) near San Clemente. The study was augmented later in a book for earthquakes of the entire state of California, and on the high probability of their reccurence along the San Andreas fault system and its adjacent seismic zones (Pararas-Carayannis, 2000).

This particular study includes a review of all available original records of the Fransican Missions of California established by the Spaniards, following Gaspar de Portolá y Rovira - the first governor of the "Californias" - and founder of Monterey and San Diego. The present review begins with the Santa Barbara Earthquake and tsunami(s) of 1812, and the controversies regarding local earthquakes in that year. These were the particular Santa Barbara earthquakes of December 1812. Also, all other historical earthquakes in Central and Southern California were particularly examined by the author, as consultant to the U.S. Nuclear Regulatory Commission in connection with the licencing of the San Onofre Nuclear Power Plant's Units 2 and 3 (Pararas-Carayannis, 1971), of the Crystal River (Florida) nuclear plant, and of proposed offshore nuclear plants - after reading all the impact statements that were filed by utilities, for evaluation of their adequacy and safety.

Parenthetically, for the Florida Crystal River nuclear plant – as well as for the San Onofre plant - the author also developed a mathematical model of a mega-hurricane - a hypothetical design hurricane striking the plant at a right angle. Based on this modeling study of the Crystal River plant, the Nuclear Regulatory Commission required the Utilities Company to redesign the cooling system, and build the cooling water pumps at a much higher elevation than Dames and Moore (the Engineering Consultants) were recommending.

The author was also present at the location of the San Onofre plant when the 1971 San Fernando earthquake occurred, and inspected the plant and its perimeter for possible damage. Subsequently, and under contract with the consulting firm "Marine Advisors", 'he undertook comprehensive studies of historical earthquakes and tsunamis in the Santa Barbara Channel, since he was particularly concerned about a possible repeat of the 1812 Santa Barbara earthquake and tsunami and the effects which they may have on the safety of the San Onofre plant (See also summary of author's subsequent book on "The Next Great California Earthquake" at http://www.forbesint.com/Book.htm . Chapter 15 of the book is devoted to the assessment of the California Tsunami hazard and includes maps of the faults in the Santa Barbara Channel that could generate earthquakes and potential tsunamis (Pararas-Carayannis, 1973).

Other specific references by the author refer to "Tsunami Guidelines at Power Reactor Sites", Guidelines For the Siting, Design. Construction, and Operation of Thermal Power Plants (Pararas-Carayannis, 1974), "Tsunami Hazard and Design of Coastal Structures" (Pararas-Carayannis, 1976), and "Guidelines For the Siting, Design. Construction, and Operation of Thermal Power Plants" (Pararas-Carayannis, 1979).

1A. The Santa Barbara Earthquakes and Tsunami(s) of 1812 - A Source of Controversy

There is great controversy regarding the generation of tsunamis from local earthquakes in California about events which occurred along the Santa Barbara coast region in December of 1812. These reported earthquakes and the accounts of resulting tsunami waves have been the subject of research by many scientists. Indeed, historical accounts reported large tsunami waves, but with no clear documentation on the chronology of such events.

There is no doubt that one and possibly two large tsunami events were generated by the December 1812 earthquakes in the Santa Barbara region. However, these tsunamis could not have been as large as they have been described in the historical accounts. Furthermore, tsunami events of such magnitude would place in different perspective the suseptibility of Southern California to the tsunami hazard (from local earthquakes).

Accounts of the 1812 Santa Barbara earthquakes and tsunami waves were found in numerous publications, including mission records (Padre José Señan, O.F.M., 1974; Carpenter, 1921; Sieh, EtAl, 1989; Iida, K. EtAl, 1967 a and b; Pararas-Carayannis, 1973)). Some of the existing historical descriptions of events which occurred in December of l8l2 in the Santa Barbara region are presented here to illustrate the difficulty of analyzing conflicting historical information and reaching definite conclusions as to their validity.

1B. Historical Accounts of the Effects of the December 1812 Santa Barbara Earthquakes on the Fransiscan Missions of Southern California

The intensity of the Santa Barbara earthquake described by Wood and Heck was given as 10 on the Rossi/Forel scale of 10 grades and the epicenter of the earthquake was stated to be in the offshore region in the vicinity of the Transverse Ranges (Wood and Heck, 1951.

In the same publication, the description of the earthquake effects of the 1812 events are as follows but without specific reference, beginning with events in Santa Barbara, Ventura and the Northern Los Angeles Counties, based prinarily on mission records.

"Damage to Santa Barbara, Ventura, and Northern Los Angeles Counties. The Church of Purissima Mission was destroye , together with many mission buildings. The strong fore-shock at about 10:30 am, which did alarming damage, caused the people to leave the building, and undoubtedly saved many lives when the main shock came. There were no deaths, but some injuries. At Santa Ynez Mission, a corner of the church fell and many new homes were destroyed. At Santa Barbara, old mission buildings were severely damaged, and the church was later rebuilt; some buildings were some buildings were ruined, and the remaining structures damaged at the Presidio. At Santa Buena Ventura Mission, the tower was wrecked and much of the facade of the church had to be rebuilt. At San Fernando Mission, thirty beams were used to keep the walls from falling. Strong aftershocks occurred until February, and lesser shocks continued until April, 1813."

The following account of the effects of the the Santa Barbara, December 1812 earthquakes on the California Spanish Missions can be found also in Padre Señan's Biennial Report of 1811-1812 from Mission San Buenaventura (Padre José Señan, O.F.M., 1974, translated from Spanish by Maynard Geiger). Severe damage from the earthquake was also reported from Mission Santa Ines, Mission Santa Barbara, the Santa Barbara Presidio, Mission San Buenaventura (Ventura), and Mission San Fernando, covering a distance of over 100 miles. The report states:

"The already severe conditions have been rendered even more severe by the horrible temblors and earthquakes that have been experienced in this province and which will constitute a special epoch in it because of the great resulting damages. The violence of these occurrences have been extraordinary.

As a result of the ruinous events we have to build anew the churches of Missions San Fernando and Santa Barbara. ...... Mission San Gabriel suffered somewhat. At Missions Santa Ines (Santa Ynez, CA)and San Buenaventura (Ventura, CA) quite some time will be required to repair the damage which I consider annoying to describe in detail. Concerning the last named mission I will say only that the tower partially fell and that the wall of the sanctuary was cracked from top to bottom"

At Mission Purisima (Lompoc, CA) the bells rang out without the aid of a bell ringer and in a few minutes the mission was reduced to rubble and ruin presenting the picture of a destroyed Jerusalem. With the permission of the government the mission is to be rebuilt at a place about a league and a fourth distant called Los Berros which offers notable and known advantages" .

1C. Earthquake Effects at Mission La Purisima

The most serious damage from this earthquake was reported at Mission La Purisima, located at Lompoc Valley. On December 21, 1812, around 10:00 or 10:15 in the morning, a strong eartquake and ground motions frightened the mission's residents - - priests, Indians and soldiers - who rushed out of the mission buildings. This first shock turned out to be only a foreshock. Fifteen minutes later, a still stronger earthquake occurred. The shaking of this second earthquake was so intense that the mission's church bells rang out. The adobe walls of the mission buildings were shattered, and in some instances collapsed, reducing Mission La Purisima to "rubble (Fig. 1).

Fig. 1 Photograph(1935): Ruins of Mission La Purisima after the Santa Barbara Earthquakes of December 1812

Regarding specific earthquake effects of th 1812 Santa Barbara Earthquake at Mission La Purisima, Fathers Payéras and Ripoll reported:

"The extraordinary and horrible earthquake, which this Mission suffered on the memorable day of the glorious Apostle St. Thomas, entirely destroyed the church and vestry, buried under the walls the various images and paintings, and ruined the greater part of the furniture. ... Some of the work shops went down ... One hundred houses of neophyte Indians and the community kitchen, the walls of which were an adobe and a half thick, and roofed with tiles, have become inserviceable. The garden walls of adobe, covered with tiles, have collapsed or threaten to fall. ... Experience may teach us the best method of constructing other buildings".

In a letter to the Spanish governor of California, Father Payéras wrote:

"We have observed with sorrow that all of the structures are ruined from the foundations to the roof: that the church is demolished from the foundation up: and that neither Fathers, nor soldiers, nor neophytes will or can, without terror or risk, live in their habitations, which have partly fallen, are partly out of plumb, and are in many parts seriously cracked".

According to a report and letter from Mission La Concepcion Purisima de Maria Santisima, by Zeyphyrin Engelhardt, Mission Santa Barbara, Santa Barbara, CA, 1932.

"At the time of the disaster 999 Indians, two Padres, and ahandful of soldiers resided at Mission La Purisima. These missions were working ranches: at the time of the earthquake, Mission La Purisima had 4000 cattle,12000 sheep, 1150 horses, and grew wheat, corn, and beans. The Mission even had vineyards, from which the good Padres made wine".

1D. Earthquake Effects at Presidio Santa Barbara

The soldiers at the presidio in Santa Barbara were so disturbed by the earthquake that they abandoned the presidio, building thatched huts near the Santa Barbara Mission, where the shaking from the earthquakes was said to be more moderate. Strong earthquakes continued to rock the region through February of 1813. The Spanish soldiers from the presidio did not return to their former home until March, almost three months after the first earthquake.

Fig. 2 Photograph Santa Barbara Mission presently.

Repairs to the Missions made subsequently to the 1812 Earthquakes: The church at Mission Santa Barbara was rebuilt with thicker walls and was completed in 1820. The church was damaged again in the 1925 earthquake and repaired. The San Fernando Mission was repaired, but destroyed by the February 9, 1971, San Fernando earthquake. It has also been rebuilt (Fig. 2). Mission La Purisima was moved from its original site in Lompoc, California to a site a few miles away. This mission is now a California historical monument and is preserved roughly as it appeared around 1820 (see photo above). The earthquake damages at Mission San Gabriel could not have been too much of a surprise to the Spanish--the full name of that mission is Mission San Gabriel de los Temblores, or Saint Gabriel's Mission of the Earthquakes - a name quite appropriately given)

1E. Historical Accounts with Reference to the December 1812 Tsunami Waves

The following account of the 1812 tsunami is being quoted from a 1961 revised edition of the publication entitled "Earthquake History of the United States: Part II, Stronger Earthquakes of California and Western Nevada," by H.O. Wood and N.H. Heck, originally published in 1951.

"This earthquake was associated with by far the largest seismic sea wave ever reported for one originating in California. Descriptive accounts indicate that it may have reached elevations of 15 feet at Gaviota, 30 to 35 feet at Santa Barbara, and 15 feet or more in Ventura. It may have even shown visible effects in the San Francisco harbor. "

Reference to Bancroft's History of California, which has used original mission records, found in Holden's Catalog of Earthquakes, gives the following entry regarding the earthquake and tsunami of December 21, 1812, with the following item on the tsunami stated as follows:

"*P. Gil reported that there was a huge earthquake wave at sea. A stick with a pendant ball was set up at the mission (Santa Barbara), and that the ball vibrated continuously for eight days, and later at intervals for fifteen days. A ship at Refugio was carried up a canyon by the wave and returned to the sea. "*

According to Bancroft's History of California, P. Gill was in charge of Mission Santa Barbara until 1813, and according to the records, he was born on May 1, 1773 and died December 1833.
An item in a San Francisco newspaper stated that:

"*Senora Juana Priones relates that in 1812, the earthquakes were so severe as to cause tidal waves which covered the ground where the plaza now is. "*

Also, under the heading, "1812 September, October, or December ? Sunday? " appears a report credited to J.B. Trask's register of earthquakes in California from 1800 to 1863, stating :

"A Spanish ship anchored 38 miles from Santa Barbara was injured by the shock. "

1F. Tsunami Effects at Gaviota Canyon

Gaviota Canyon is not far from Lompoc, California. It is located at the northwestern end of the Santa Barbara Channel. At the time of the 1812 earthquakes, the coast along the northwestern shore of the Santa Barbara Channel was part of the Rancho del Refugio, a tract of ranch land that had been given to the first commandante of the Santa Barbara Presidio, upon the commandante's retirement. It was a favorite place for American smugglers to trade their goods for otter pelts. These American smuggling ships traveled between the Spanish-controlled coast of southern and central California, the Russian-controlled coasts of Alaska and northern California, and the Hawaiian Islands (then known as the Sandwich Islands).

There is a report of a tsunami at Gaviota Canyon (San Francisco Bulletin, March 16, 1864)

A Boston ship, the Thomas Newland, known before as the"Charon", commanded by Capt. Isaac Whittemore, was lying off anchorage, not far from the Gaviota Pass, Santa Barbara County, when the sea was seen to retire all at once and return in an immense wave, which came roaring and plunging back, tearing over the beach fit to crack everything to pieces. This wave penetrated the low lands of the gulches a mile from the shore, forming one of the most terrific sights possible to conceive. That old ship, then under the name "Charon", afterwards got 1,800 otter skins to the Sandwich Islands (Hawaiian Islands), and landed them, too; but a few days afterwards she was captured by the English man-o-war Cherub and taken as a prize to London".

1G. The 1812 Earthquake and Tsunami at Santa Rosa Island

One of the last outposts for the Chumash Indians was Santa Rosa Island which the Chumash called Mascui. At the time of the 1812 earthquakes, the Franciscan priests were trying to convince the remaining Chumash Indians to relocate to the missions on the mainland. When the 1812 tsunami at Santa Rosa caused the waters to recede several hundred yards from the island, the Indians became fearful that the island was about to be engulfed, so they abandoned totally their villages. They rowed out to in their oceangoing canoes to the mainland and settled in bands of three or four hundred at the several missions in the area. The Chumash Indians who moved to the missions did not fare well, many of them succumbing to European diseases. (H. W. Henshaw, quoted in Anthropological Records, California Linguistic Records, v. 15, no. 2)

1H. Conflicts of Historical Accounts on the 1812 Tsunami Event(s)

Obviously, there was some confusion in the literature about the dating of the 1812 earthquakes, but it is assumed that this account relates to the December 21, 1812, earthquake. Another interesting account of the 1812 tsunami appears in a 1921 paper entitled, "Early Records of Earthquakes in Southern California" by Ford A. Carpenter, which had been compiled from the records of the "mission fathers" and from Englehardt's Franciscans in California. This paper gives a lengthy account of the 1812 earthquakes in

Southern California with one item of interest, related to San Buenaventura, during the earthquake of 21 December 1812.

"The whole mission site appeared to settle, and the fear of being engulfed by the sea, drove all away to San Joaquin in Santa Anna, where they remained until April, 1813. "

Another account in a 1960 paper, "California Earthquakes" by Harry O. Wood states that;

"The sea wave at Refugio and the strong shock experienced by the ship 38 miles from Santa Barbara point emphatically to an earthquake of great energy having a submarine origin. "

There is also another item dated 1812, in the San Francisco papers relating to the origin of the earthquake and the tsunami. It reads:

"Severe shocks with tidal waves. Tidal waves from the great shock in the south entered San Francisco Bay, and washed over the sides of the plaza at Point Arena. The San Joaquin segment of the San Andreas Fault, or the Hayward Fault are the more probable places of origin for these earthquakes. Mention of tidal waves makes the San Andreas Fault the more probable source in this instance. "

If this is true or not, is not known, but it is doubtful that the earthquake that produced the largest tsunami in California had its origin on land where the Hayward Fault was. Suggestions have been made in the literature that this is a possibly mislocated report of December 21 waves at Santa Barbara, while others have claimed that the waves observed in 1812 in San Francisco originated from a different quake on a fault across the San Francisco Bay.

Review of additional references shows extensive descriptions of the earthquake of 1812 at Santa Barbara, but little information relating to the tsunami. Various references and accounts of these events can be found, but these descriptions are somewhat unclear as to the size of the tsunami in Southern California.

Bancroft's History of California documents the 1812 - 1813 and the 1956 translation of the manuscript of Angustias De Li Guerra Ord, entitled "Occurrences in Hispanic California as related by Mrs. James L. Ord to Thomas Savage for the H. Bancroft Collection in 1878." Mrs. Ord was the daughter of Don Jose De La Guerray Norieja, who replaced Jose Arguello as Commandant of Santa Barbara Presidio in the autumn of 1815. She had been borne on the 11th of June of the same year. In this account she relates:

"When I went to the north in 1833, several of the northern missions were in charge of Fernandinos namely, San Louis Obisbo and Padre Louis Gil Taboada (a Mexican by birth, but very Spanish in sentiments). In speaking to Padre Louis Gil Toboada, he told me that in 1812 there had been very strong earthquakes at Santa Barbara while he was there. That on the eighth of December while at the Presidio, there occurred an earthquake so violent that the sea receded and rose like a high mountain. He, with all the people of the Presidio, went running to the mission chanting supplications to the virgin. I asked him humorously, why he had not gone to see if there was a ship at the foot of the mountain of water. He also

assured me that they had placed a pole with the ball to it. It was fastened to the ground where the air would not move it, and it was in continuous motion for eight days. After eight days the ball was still for two or three hours and then started to move again, and this lasted for about 15 days. "

Obviously, this account throws more confusion because the date is given as 8 December. This account would indicate that two major earthquakes occurred on 8 and 21 December, both producing large tsunamis.

John Boardman Trask, a medical doctor, who was appointed President of the California Academy of Sciences in 1864, gave the following description of the tsunami at Santa Barbara in a paper he presented on the history of the 1812 earthquake as obtained from accounts of native inhabitants of the coast.

" The sea was observed to recede from the shore during the continuance of the shocks, and left the latter dry for a considerable distance, when it returned in five or six heavy rollers, which overflowed the plain on which Santa Barbara is built. Inhabitants saw the recession of the sea and, being aware of the danger on its return, fled to the adjoining hills near the town to escape the probable deluge. The sea on its return flowed inland a little more than a half of a mile, and reached the lower part of town, doing but trifling damage destroying three small adobe buildings."

In the same paper, Trask, making reference to a writer unknown to him, quotes him and adds this account.

" The sea was seen to retire all at once, and return in an immense wave, which came roaring and plunging back over the beach. This wave penetrated the lowlands and gulches a mile from the shore, forming one of the most terrific sights possible to conceive. "

2. SEISMIC FAULTS IN THE LOS ANGELES AREA

In the vicinity northeast of Los Angeles, along the Transverse ranges, there are a number of other faults, such as the Garlock and Big Pine, and other east-west trending faults that seem to extend into the ocean in the Santa Barbara channel. Both the Garlock and Big Pine faults intersect the San Andreas fault system. Seismic activity on these two faults has been very low within 40 to 50 km of the San Andreas. However, small clusters of earthquake epicenters can be found on either side of their junction with the San Andreas, suggesting higher seismicity.

Closer to Los Angeles, dozens of smaller faults stem from beneath this great metropolis, faults we have already discussed such as the San Jacinto, Cucamonga, and Garlock. Of these faults, the San Jacinto fault has been the most active branch of the San Andreas Fault System with several moderate earthquakes in recent times. Another potentially dangerous fault is the Newport-Inglewood fault. This is a major fault traversing beneath Los Angeles, along which strain is building up. This fault starts in Whittier and continues west, cutting directly below the downtown Los Angeles area.

The existence of about two dozen other “blind” faults in the Los Angeles area is suspected. These faults are characterized as “blind” faults because they have no surface expression or are buried by sediments. A number of such faults may be low-angle thrust faults, running beneath some of the most heavily developed and densely populated neighborhoods of the Los Angeles Metropolitan Area. One of them for example, the Elysian Park fault, is 11 miles long and about 10 miles deep and runs through downtown Los Angeles. Even earthquakes of relatively small magnitude occurring along such blind faults can be extremely destructive because of their proximity to highly populated areas. Geologists search for blind thrust faults throughout southern California by modeling the system of folds and uplifts believed to be produced by slip on these faults.

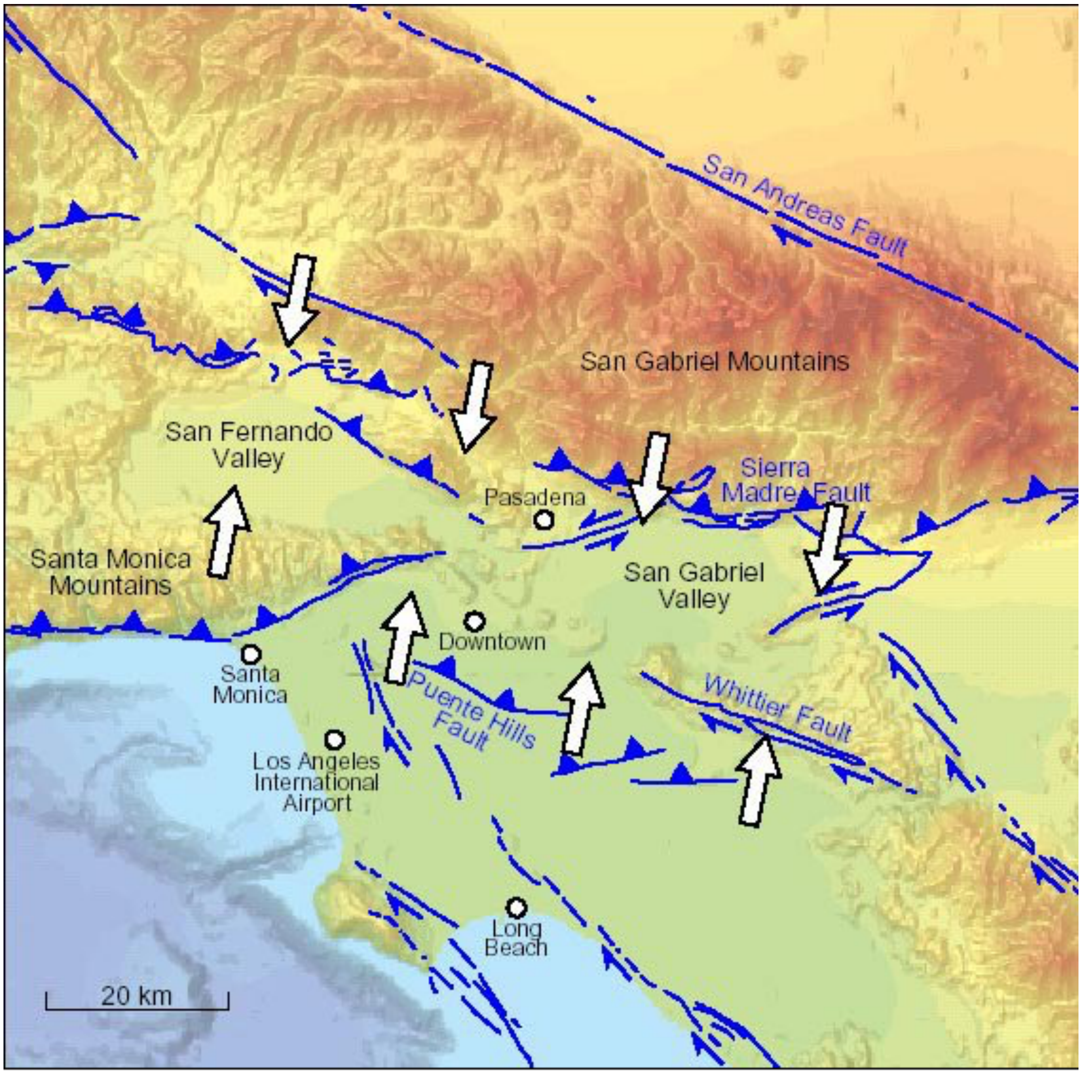


Fig. 3 Map of the Greater Los Angeles area, showing the location of selected major faults and directions of seismic stresses.

2.1 Newport-Inglewood Fault Zone

As we mentioned above, the Newport-Inglewood fault is a major fault traversing beneath Los Angeles. It parallels the San Andreas Fault system and is considered active. It begins a little north of Culver City, continues through the Baldwin Hills, Inglewood, the Dominquez Hills and Signal Hill, reaching the coast along Seal Beach, Sunset Beach, Huntington Beach, and entering the ocean near Newport Beach. Then the fault continues under the ocean and may extend as far south as San Diego.

This fault has been responsible for a number of earthquakes in Southern California, including the destructive Long Beach earthquake of March 10, 1933. There is a strong possibility that an earthquake of moderate size could occur along this fault, which could be even more destructive to Los Angeles than earthquakes occurring along the San Andreas Fault system. Seismic waves from such an earthquake could be quite damaging to structures sitting on top of fairly recent and unconsolidated alluvial soil in the area, most of which is only 3,000 years old.

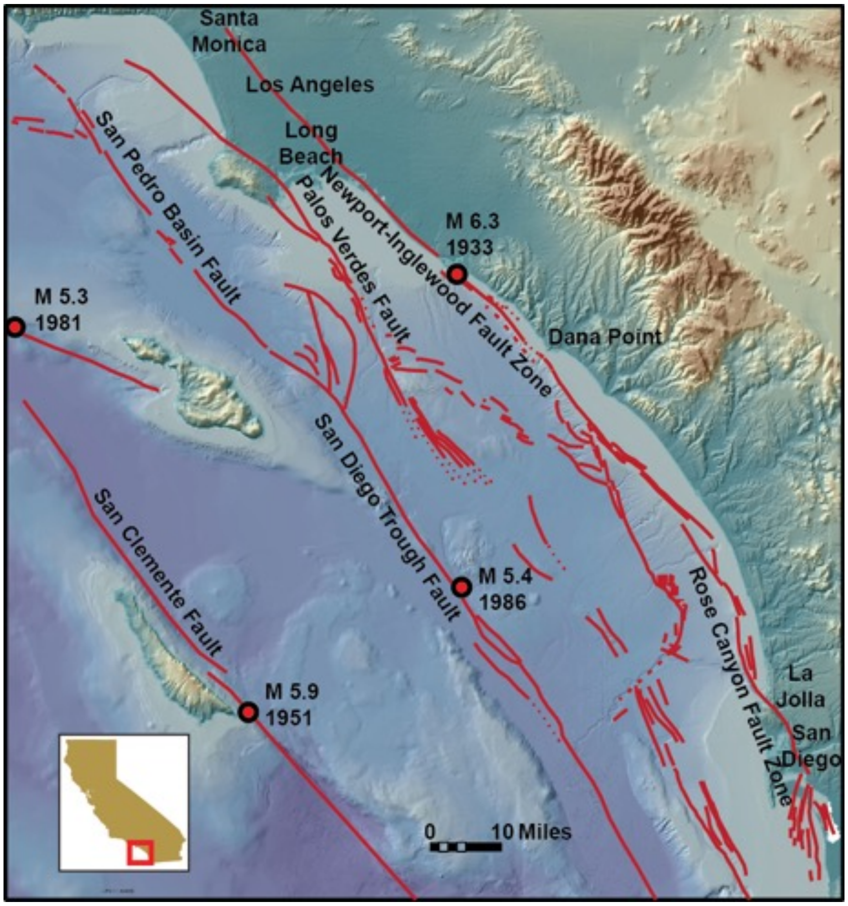


Fig. 4 Offshore faults in Southern California and epicenter of a 1986 earthquake on the San Diego Trough fault and of a 1951 earthquake on the San-Clemente fault (Pacific Coastal and Marine Center, 2022).

As seen in Fig. , the epicenter of the 1933, magnitude 6.3 earthquake was in the offshore underwater segment of the Newport-Inglewood Fault Zone and occurred prior to the construction of the San Onofre nuclear plant, thus the author concluded that a recurrence of such an event on this fault could have had an adverse effect on either the structure or the cooling system of its reactor facility – something which was not adequately considered when the nuclear station was licensed (Parararas-Carayannis, 1974).

2.2 Norwalk Fault

The Norwalk fault is another small, but active fault, situated in a densely populated area southeast of Los Angeles. The fault extends for only about five miles from the general area of Norwalk, Cerritos, and Artesia, through La Mirada and Buena Park to Fullerton. Numerous small earthquakes have occurred along the Norwalk fault. The most notable is a magnitude 4.7 event, which caused damage in the Whittier area.

2.3 Whittier Fault

The Whittier fault is considered to be the northern extension of the much longer Elsinore fault. The fault extends along the base of the Puente Hills, beginning in the vicinity of Whittier through the area of La Habra, Brea, Fullerton, Placentia, and Yorba Linda. Because of its proximity to the Norwalk fault, a number of earthquakes in the area have been confused as having occurred on the Whittier. The Whittier fault is composed of a web of faults crossing numerous towns in the area, and there is a strong possibility of a damaging earthquake in the future.

2.4 San Fernando Valley Faults

The Sierra Madre fault zone, and a number of smaller faults listed below, transverse the heavily populated area of the San Fernando Valley and adjacent foothills presenting a significant risk to the area. The San Fernando fault which transverses the valley has two major segments. The Sylmar segment which crosses the heavily populated Sylmar - San Fernando area, and the Tujunga portion which consists of only one or two parallel breaks and extends along the foothills of the San Gabriel Mountains, the Tujunga Valley to the east of San Fernando.

The Northridge Hills Fault is considered to be the most potentially dangerous fault in the area. It extends through the populated region of the valley from the vicinity of Chatsworth to Northridge where it changes into an eastward direction to the east central valley from where it disappears beneath deep alluvium deposits.

Many of these smaller faults in the San Fernando Valley are deeply buried; blind thrust faults that have produced very destructive earthquakes in the past. The 1971 San Fernando and the 1994 Northridge earthquakes are the most recent examples. Both of these destructive earthquakes occurred beneath the San Fernando Valley on a deeply buried blind thrust fault that may be eastern extensions of the Oak Ridge fault system.

2.5 Sierra Madre Fault Zone

The Sierra Madre Fault Zone is one of the major geologic features of the Los Angeles Basin, extending from the base of the San Gabriel Mountains to the northern edge of the San Fernando Valley. The fault zone starts in the vicinity northwest of Altadena, through the foothills of the San Gabriel Mountains and Sierra Madre to Monrovia, Duarte, Azusa, and Glendora. It is believed that the first recorded earthquake of 1769, in California, occurred along this fault.

2.6 San Fernando Fault (Sylmar and Tujunga segments)

The San Fernando fault can be divided into two segments: The Sylmar segment crosses the heavily populated Sylmar - San Fernando area, as a zone of ground breaks up to one mile wide. The Tujunga portion of the San Fernando fault, consists of only one or two parallel breaks and extends along the foothills of the San Gabriel Mountains, the Tujunga Valley to the east of San Fernando. Since 1971, this fault has become the focus of extensive studies because of its location across a major metropolitan region of California.

2.7 Raymond Hill Fault

This is a short fault traversing the area between South Pasadena and Monrovia where it joins the Sierra Madre fault. It extends eastward from the vicinity of South Pasadena in close proximity to San Marino, Temple City, Sierra Madre, and Arcadia. The fault is considered active and potentially dangerous.

2.8 Northridge Hills Fault

The Northridge Hills Fault is considered to be an active and potentially dangerous fault in the San Fernando Valley. It extends through the populated area of the valley from the] vicinity of Chatsworth to Northridge where it changes into an eastward direction to the east central valley, disappearing beneath deep alluvium deposits.

2.9 Elsinore Fault

The Elsinore fault, one of the longest in Southern California, parallels the San Jacinto fault some 20 to 25 miles west, and extends for approximately 150 miles from where the Whittier fault ends in the vicinity of Yorba Linda, through Lake Elsinore, Wildman, Murrieta, Temecula, Palomar Mountain, and Santa Isabel, crossing the Borrego Desert and the Coyote Mountains towards Mexico. A secondary branch of the fault runs through Aguanga, Oak Grove, and Warner's Hot Springs. Few significant earthquakes have occurred on this fault. The Elsinore fault is considered active.

2.10 Imperial Fault

One of the most active faults of the San Jacinto fault system is the Imperial. The fault was first identified by the major earthquake of May 18, 1940, in El Centro (Imperial Valley). Other smaller earthquakes have occurred in recent times, causing little damage, but small displacements along the fault.

2.11 Submarine Faults

A number of earthquakes have been observed in the past, with epicenters in the Santa Barbara channel where water depths can range from up to 2,000 meters. The Santa Barbara channel is one of the more seismic active regions of California, and several major and moderate earthquakes have caused considerable damage to coastal communities in California. A number of destructive earthquakes have occurred, some of them having epicenters offshore. The most important historical earthquakes in the area were those of December 1812, which also produced a destructive local tsunami.

It is difficult to study the existence of these submarine faults with conventional means as only on-shore extensions of submarine faults can be observed. A number of such offshore faults are considered to be active and could pose a potential threat in the future for destructive earthquakes and locally damaging tsunamis.

3. LARGER EARTHQUAKES IN CALIFORNIA FROM 1769 to 2000

Numerous early large earthquakes which occured from 1769 to the year 2000 have been documented in a publication entitled, "Early Records of Earthquakes in Southern California", which is a paper compiled from the records of the "mission fathers" and from Englehardt's Franciscans in California (Carpenter Ford, 1921). Also, stronger earthquakes in California have been documented in publications entitled "Earthquake History of the United Sates from 1882 to 1953 part I, and in part II entitled "Stronger Eartquakes of California and western Nevada" by Heck (Heck/Nicholas Hunter, 1947) and by (Iida EtAl, 1967 a and b). Several other Central California earthquakes of the 1830's were documented (Louderback, 1947), but these would not have been expected to have an impact on the San Onofre nuclear plant because they were distant and not of sufficient magnitude.

3.1 Earthquake of 28 July 1769

The first strong earthquake listed in Spanish records, is an earthquake of great intensity (VII-IX), which affected the Los Angeles region on 28 July 1769, probably near the San Andreas Fault. No real details on this event exist.

3.2 Earthquake of 8 December 1812

This was the first of a series of earthquakes that struck Southern California in December 1812. The Gaspar de Portola Expedition, in camp about 30 miles southeast of Los Angeles center, recorded four violent shocks. Particularly affected was the Santa Barbara region, with extensive damage to San Buena Ventura and Santa Barbara Missions. The strong earthquake that destroyed the church killed forty persons attending church at San Juan Capistrano on December 8, 1812. Many mission buildings were severely damaged there and at San Gabriel. The mission records are not very clear on exact dates. Most authorities speculate, even though the record is very incomplete, that this was a major earthquake and that subsequent earthquakes were strong aftershocks. Based on damage reports, the intensity of the first of the series of earthquakes of December 1812 must have been approximately VIII to IX. The quake probably centered on a submarine fault in the offshore area of Santa Barbara.

3.3 Earthquake of 21 December 1812

This was another of the reported December 1812 earthquakes. It occurred near the Santa Inez fault zone and other related faults of the Santa Barbara region. According to mission records, the quake destroyed the Santa Barbara Mission and the Mission Purisima Concepcion, the latter being located about 10 miles northeast of Point Arguello. An earlier foreshock that occurred at 10:30 a.m., on 21 December caused considerable damage and served as a warning to people who evacuated outdoors. This saved their lives when the main earthquake struck.

Fig. 5 Photograph (1935): Ruins of Mission La Purisima

In addition to the Santa Barbara Mission and the Mission Purissima Concepcion, which were extensively destroyed, the other missions in the region were heavily damaged. At

Santa Ynez Mission, a corner of the church fell and many new homes were destroyed. All roofs were ruined and walls cracked. A new church had to be built. At San Ventura Mission, the tower was wrecked and much of the facade of the church had to be rebuilt. At San Fernando Mission, thirty beams were used to keep the walls from falling. Strong aftershocks continued until February, and aftershocks of lesser magnitude, until April 1813. According to mission records, the earthquake generated a large tsunami along the north coast of the Santa Barbara Channel. Eyewitness accounts on the effects of the earthquake and resulting tsunami, are discussed in detail in a subsequent chapter on tsunamis and the California coast.

3.4 Earthquake of 19 January 1857 - The Great Fort Tejon Earthquake

One of the largest earthquakes to have occurred in the recorded history of California, and the largest in Southern California, was the Fort Tejon earthquake of 1857. In fact, there were two major earthquakes on that day. The first occurred at approximately 6:30 a.m. on Friday, January 19 (Wood, 1955, 1951; Sieh EtAl, 1989). The second, and most powerful shock occurred at 8:33 a.m. (Spall, 1977). It was felt throughout California, from San Francisco and Sacramento in the north, to Fort Yuma in the South. However its intensity was greater in the Fort Tejon area. The violent shock threw down buildings and large trees at the military Fort. It was also severe in Los Angeles, San Francisco, and Sacramento (Agnew, and Sieh, 1978; Earthquake Information Bulletin, 1981).

A total of four other foreshocks occurred earlier with estimated magnitude between five and six near the northwestern extent of the fault rupture of the main shock, in the Parkfield/Cholame area. The main earthquake, with an estimated magnitude of over 8 on the Richter Scale, occurred along a 225-mile segment of the San Andreas fault, that extends from the vicinity of Cholame near Parkville, in Central California, southwards to San Gorgonio Pass, north of Palm Springs. In some locations, the earthquake's surface-fault rupture had a strike slip displacement of as much as 28 feet. The epicenter was in the vicinity of Fort Tejon, on the Tejon Pass through the Tehapachi Mountains (Sieh, 1978a and b).

3.5 Earthquake of 26 March 1872 - The Great Owens Valley Earthquake

This earthquake occurred in Owens Valley, east of the Central Sierra, along the Owens Valley fault of the Sierra - Nevada Fault system on March 26, 1872. This quake is considered to be one of the largest that ever occurred in California, if not the largest. Its felt area and the maximum fault displacements were comparable to the 1857 Fort Tejon and the 1906 San Francisco earthquakes on the San Andreas fault (.

The US Geological Survey assigned it a magnitude of 7.8, but invariably in the literature the magnitude has been estimated to be about 8.3 to 8.4 on the Richter scale. Its effects were felt throughout California, Nevada and several western states. According to reports, the quake stopped clocks and awakened people as far away as San Diego to the south, Red Bluff to the north, and Elko, Nevada, to the east. Intensities of VIII or greater on the Modified Mercalli scale were assigned over an area of about 25,000 square kilometers.

Intensities of IX or larger were assigned to an area of about 5,500 square kilometers. In some areas estimated intensities were reported to be as much as X and XI. Thousands of aftershocks followed the main event, some severe. The largest ground displacements of up to 20 feet in the horizontal direction and up to 23 feet in the vertical direction occurred between Lone Pine and Independence.

The observed faulting involved both dip-slip and right-lateral components of movement. Surface escarpments extended for at least a distance of 160 kilometers - from Haiwee Reservoir, south of Olancha, to Big Pine. Near Owens Lake, numerous depressions formed between fissures in the earth. One area 200 to 300 feet wide sank from 20 to 30 feet forming several long, narrow ponds. Ground cracks were reported from as far north as Bishop. The vertical offsets were smaller, averaging about 1 meter with the downthrown crustal block on the east. The rupture of the 1872 earthquake along the Owens Valley fault was not as great as those caused by the 1857 Fort Tejon (300 kms) or by the 1906 San Francisco (430 kms) earthquakes on the San Andreas fault.

Although the region was sparsely populated at that time, the death toll was considerably high. A total of 60 people lost their lives primarily from the collapse of adobe buildings. 27 of the deaths occurred at Lone Pine, the rest in other parts of Owens Valley. Property damage at Lone Pine was most severe. Of the 59 adobe or stone houses, 52 were completely destroyed. According to reports, all the main buildings in almost every town in Inyo County were leveled by the shock. Even as far away as Indian Wells, 100 kilometers south of Lone Pine, adobe houses sustained cracks. Property loss was estimated at $250,000 (in1872 dollars).

3.6 Earthquake of 11 April 1885

A major earthquake of undetermined magnitude caused property damage in San Luis Obispo and to a lesser extent to Visalia and Monterey.

3.7 Earthquake of May 1889

A quake in May 1889 caused damage at Antioch and Collinsville.

3.8 Earthquake of 24 February 1892

This was a very large earthquake in the Imperial Valley. Its magnitude was estimated at 7.8. It was felt throughout the area, as far east as Yuma, Arizona, as far north as the coastal area of Santa Barbara and as far south as San Quintin, in Baja California. According to one report the shock was felt at Visalia, Tulare County, about 700 kilometers north of San Quintin. During a 12-hour period following the main shock about 155 aftershocks were felt at Campo. Observers reported that 135 aftershocks were felt as far away as National City, on San Diego Bay. The aftershocks continued to April 1892.

This quake caused extensive damage at the old Carrizo station in San Diego County, where all adobe buildings were destroyed. Chimneys and plaster were reported broken in San Diego. In Paradise Valley, a church and schoolhouse were destroyed. Ground fissures were reported at McCain Valley and Jewel Valley. Rockslides were reported between Campo and Carrizo and at Dulzura and Jewel Valley.

3.9 Earthquake of 19 April 1892

A strong earthquake, centered north of Santa Rosa in the Healdsburg Fault area, destroyed nearly all the brick structures and damaged many frame buildings in Vacaville. Similar damage occurred at Winters and Dixon, two small towns nearby. Ground cracks were reported in the area.

3.10 Earthquake of 30 March 1898

An earthquake along the Calaveras fault with a magnitude of about 6, known as the Mare Island earthquake, caused considerable damage at Vallejo.

3.11 Earthquake of 22 July 1899

A strong earthquake with its epicenter near Cajon Pass shook San Bernardino County with great intensity (up to IX) causing extensive damage in San Bernardino, Highland, and Patton, and some damage in Riverside, Pomona, Pasadena, Redlands, and Los Angeles. Many landslides blocked the roads in Lytel Creek Canyon in Cajon Pass.

3.12 Earthquake of 25 December 1899

On Christmas Day of 1899, a strong earthquake with a magnitude estimated to be between 6.2 and 7 on the Richter scale, occurred on the San Jacinto Fault in the vicinity of Hemet and San Jacinto. This shock caused considerable damage in the area. At nearby Hemet, nearly all the brick buildings were severely damaged, with only two chimneys remaining upright. Six persons lost their lives and several more were injured at Saboba, near San Jacinto. The quake was felt as far south as San Diego. The intensity of this earthquake and has been compared to that which occurred later, on April 1918 (magnitude 6.8) in the same region.

3.13 Earthquake of July 1902

An earthquake in northern Santa Barbara County was responsible for extensive property damage at Lompoc and Los Alamos, the latter being nearer to the epicenter. All houses and chimneys in the area were damaged, according newspaper accounts in the San Francisco Chronicle.

3.14 Earthquake of 29 June 1925

This was one of the better-known earthquakes to affect Santa Barbara in more recent times. The quake occurred in the Santa Barbara Channel, on an extension of the Mesa Fault or the Santa Ynez fault system. It had a magnitude of 6.3 and was particularly damaging in the Santa Barbara business district, which the Mesa fault crosses. On State Street, the principal business section, most buildings sustained significant damage, while several collapsed. One building located on marshy ground withstood the shaking well, but its foundation sank 19 feet. The quake killed 13 people and caused about $8 million damage in Santa Barbara. Deaths and injuries would have been much greater but, fortunately, the quake occurred at 6:42 in the morning when people had not reported for work and when the streets were still not crowded.

3.15 Earthquake of 4 November 1927

A large earthquake with a magnitude of 7.5 struck the southwestern corner of Santa Barbara County. Its epicenter was offshore, near Point Arguello, but it was particularly damaging at Surf and inland communities, in the towns of Honda, Santa Maria, Los Alamos and Lompoc (Gawthrop, 1978, 1981; Hanks, 1979, 1981). Earlier, shortly after midnight on the 4th of November, a small earthquake foreshock awakened residents of the coastal community of Casmalia. Another strong foreshock occurred at 3:10, which awakened most of the inhabitants of Lompoc. This foreshock was followed by three other smaller foreshocks within half an hour. At 5:51 in the morning, the main earthquake struck. Damage from the quake was substantial at Lompoc and other communities. The shock wrecked chimneys, shifted a house off its foundation and caused heavy earth and rock slides on steep slopes. Water was reported to spurt from the ground in many places and sand craters formed.

A small tsunami was generated and observed along the coast at the western end of Santa Barbara County. The tsunami was estimated at six feet near Pismo and five feet at Port San Luis. No tsunami damage was reported. Small tsunami waves of a few inches were recorded on tide gauge records at San Francisco, La Jolla, Honolulu, and Hilo, Hawaii.

3.16 Earthquake of 20 August 1927

This particular earthquake had its epicenter 30 miles off the coast, northwest of Eureka. It caused little damage in Eureka and Ferndale. Although its magnitude is not known, it had a maximum intensity of VIII on the Modified Mercalli scale.

3.17 Earthquake of 6 June 1932

An earthquake with a magnitude of 6.4 shook Humboldt County and was felt as far north as Coos Bay, Oregon, and south, to San Jose. The earthquake triggered numerous landslides around Humboldt Bay and caused sever damage in Eureka.

3.18 Earthquake of 10 March 1933 - The Long Beach Earthquake

The Long Beach earthquake, as this event became known, was the second most destructive earthquake to strike Southern California up to that time. The quake's epicenter was offshore, southeast of Long Beach near Newport Beach, on the Newport - Inglewood Fault. It occurred at 5:55 p.m. Although its magnitude was relatively small, 6.25 to 6.3, and there was no surface faulting, maximum intensities of VIII to IX were experienced and major damage occurred in the densely populated district from Long Beach to the industrial section south of Los Angeles, where unfavorable geological conditions exist. The quake was destructive at all the coastal cities, particularly at Long Beach. Compton was practically leveled (US. Geological Survey, 1933; Binder, 1952).

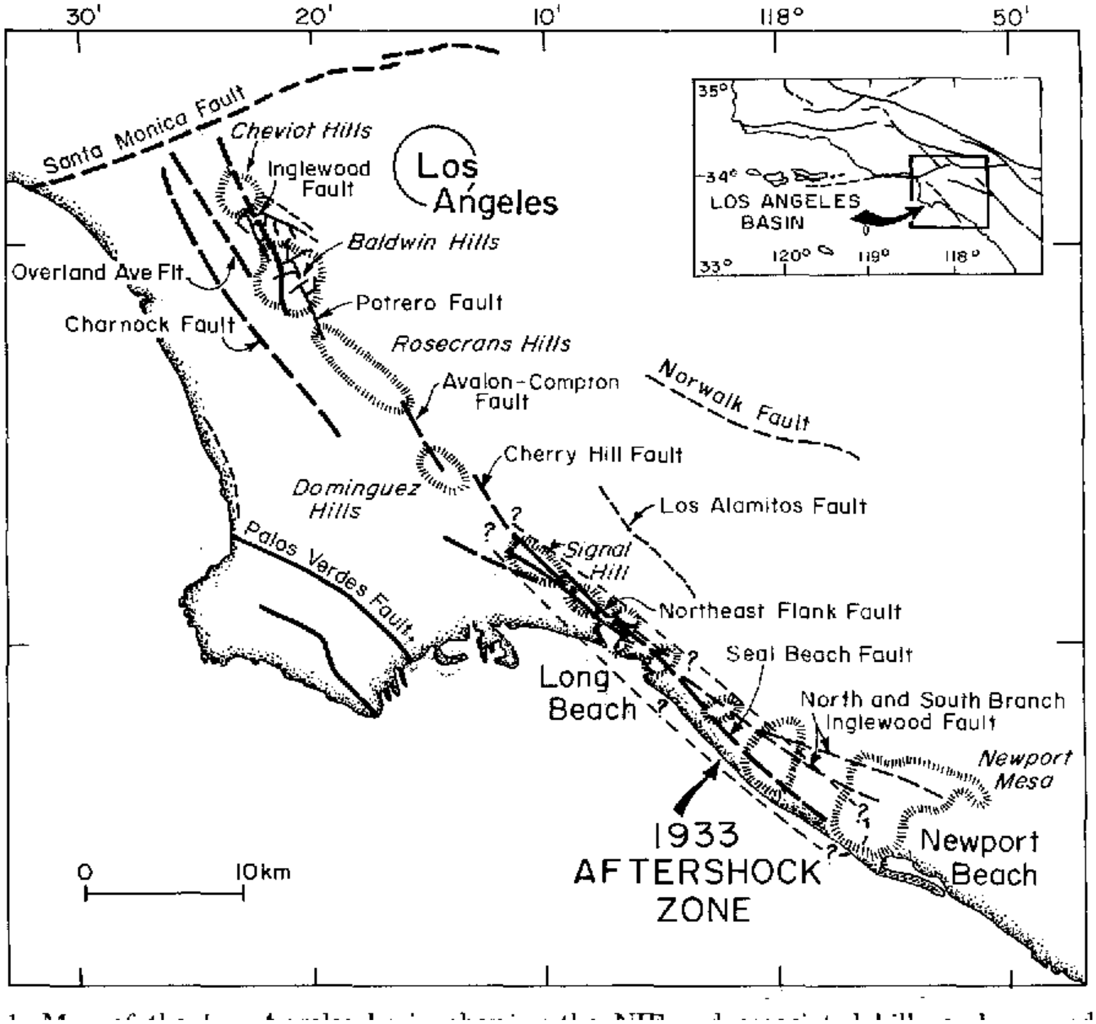


Fig. 6 The Newport-Inglewood fault which runs 47 mikes underneath Los Angeles

About 120 people were killed. largely from the collapse of houses, small buildings or from falling debris. Property damage was extensive and estimated at more than 50 million (in 1933 dollars). Approximately 20,000 dwellings and 2,000 apartments and office buildings, stores, warehouses, factories, churches, and theaters were damaged ranging from cracks to complete destruction. Reinforced concrete buildings fared quite well and sustained little or no structural damage. Most of the damage occurred to brick buildings with unreinforced masonry walls.

At Long Beach, buildings collapsed, tanks fell through roofs, and houses displaced on foundations. School buildings were among those structures most generally and severely damaged. Many school buildings in Long Beach and surrounding areas, built of brick with no reinforcement for lateral forces, were totally destroyed. However, reinforced concrete school buildings survived the quake with no structural damage. Fortunately the earthquake struck when school was not in session, otherwise the loss of life would have been much greater.

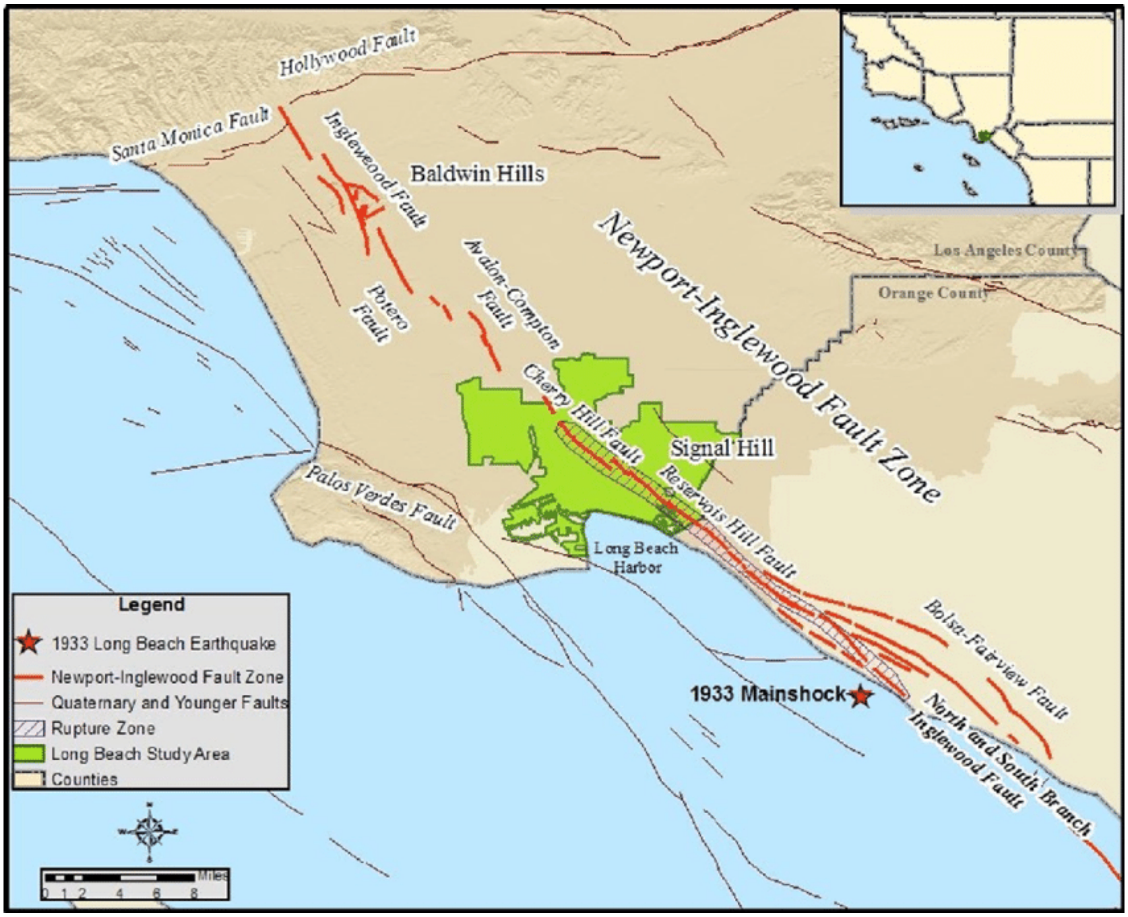


Fig. 7 Epicenter of the 1933 earthquake near the Newport-Inglewood fault

Fig. shows the 1933 earthquake's main epicenter on the Newport-Inglewood fault, as well as its proximity to Long Beach and Los Angeles, and to other faults on land and at sea close to the San Onofre nuclear plant. The reason for the 1933 quake's extreme and disproportionate destruction is attributed to the density of population and to the development of the area without proper earthquake disaster planning. As a direct result of the structural failures of unreinforced masonry schools, a law known as the Field Act was passed on April 10, 1933, requiring earthquake-resistant design and construction for all public schools.

Fig. below is a photograph of destruction of a building by the Long Beach earthquake of 10 March 1933,

Fig. 8 Destruction of building by the Long Beach earthquake of 10 March 1933 (photo; U.S. Geological Survey

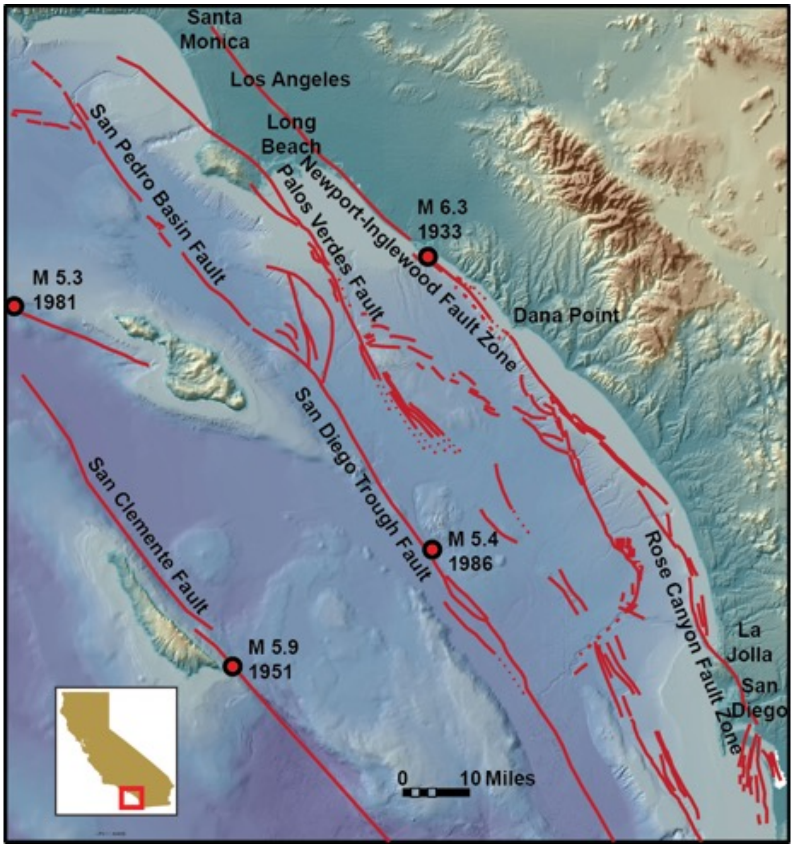


Fig. 9 Offshore Southern California map showing active faults and earthquakes since 1933 with magnitudes 5 or larger.

As shown in Fig, above, detailed views of the seafloor have greatly enhanced the understanding of active faults off Southern California, and have improved hazard assessments for the region. For example, this information contributed to an update of the seismic hazard assessment of the San Onofre Nuclear Generating Station in 2014, and the 2014 National Seismic Hazard Mapping Project, which included faults located entirely offshore for the first time.

3.19 Earthquake of 16 May 1933

This large earthquake along the Hayward fault caused extensive damage to dwellings in Niles and Irvington (Wood. 1933).

3.20 Earthquake of 2 October 1934

A moderate earthquake, with its epicenter near Colma, was responsible for considerable damage in Colma, Daly City, South San Francisco, and the Portola district of San Francisco.

3.21 Earthquake of 18 May 1940

A large earthquake with a magnitude of 7.1 on the Richter scale struck the Imperial Valley. Its epicenter was in the vicinity of El Centro, on the Imperial fault, which is part of the San Andreas Fault system in southern California. The fault rupture was about five miles east of the towns of El Centro, Imperial, and Calexico but overall the shock caused about 40 miles of surface faulting along the Imperial Fault (Trifunac abd Brunem 1970). Damage in all the towns in the area was heavy, and the irrigation system of the Imperial Valley was practically destroyed by displacements of up to 19 feet. At Imperial, 80 percent of the buildings were damaged to some degree. In the business district of Brawley, all structures were damaged, and about 50 percent had to be condemned. This earthquake was the first test of public schools designed to be earthquake resistant after the 1933 Long Beach earthquake. Fifteen such public schools in the area had no apparent damage. The earthquake killed a total of nine people and property damage was estimated at about $6 million.

3.22 Earthquake of 30 June 1941

This earthquake had its epicenter in the Santa Barbara Channel, approximately five miles south of the coast between Santa Barbara and Carpinteria. It was particularly damaging in Santa Barbara.

3.23 Earthquake of 14 November 1941

Another earthquake on the Newport-Inglewood fault zone caused about one million dollars in damage to the towns of Gardena and Torrance.

3.24 Earthquake of 4 December 1948

A major earthquake with a magnitude of about 6.5 occurred in the vicinity of Desert Hot Springs. Maximum intensities of this quake were felt in the Desert Hot Springs-Mecca area. Light damage was reported from the towns of Twenty-Nine Palms and Indio. However, the area was sparsely populated there.

3.25 Earthquake of 21 July 1952 - The Kern County Earthquake

This was the largest earthquake in Southern California since the great earthquakes of 1857 and 1906. Its magnitude was 7.7 on the Richter scale. It occurred along the White Wolf fault in Kern County. Six major aftershocks with magnitude 5.0 or greater occurred on the same day. In the following days and weeks, through September 26, the California Institute of Technology recorded 188 aftershocks of magnitude 4.0 or greater.

The main shock was felt over most of California and in parts of western Arizona and western Nevada at such distant points as Stirling City, California, Phoenix, Arizona, and Gerlach, Nevada. Long-period surface waves from the main shock caused water to splash from swimming pools as far away as Los Angeles, and from pressure tanks on tops of buildings in San Francisco.

Maximum intensity of XI on the Modified Mercalli scale was assigned to a small area southeast of Bealville where the earthquake cracked reinforced concrete tunnels with walls almost half a meter in thickness. In the same area, the shock reduced by about 2.5 meters the distance between the entries to two tunnels and bent the steel rails on both sides. Elsewhere, maximum intensity did not exceed VIII. At Owens Lake, about 160 kilometers from the epicenter, there were reports of shifted salt beds and of brine lines bent into irregular curves shapes.

Ground displacements of up to two feet in a horizontal direction, and up to four feet in a vertical direction occurred for many miles along the White Wolf fault zone. Surface ruptures were reported along the lower slopes of Bear Mountain and in the valley below. The movement indicated that the mountain itself moved upward and to the north. Brick and adobe structures were primarily damaged and to a lesser extent wood-frame buildings. Multistory steel and concrete structures sustained minor damage with the exception of the Kern General Hospital where damage was extensive. Reinforced tunnels with walls 18 inches thick near Bealville were cracked, twisted, and caved in; rails were shifted and bent into S-shaped curves. Near Caliente, reinforced concrete railroad tunnels were demolished. At Tehachapi, Bakersfield, and Arvin, old and poorly built masonry and abode buildings were cracked, and some collapsed. In Los Angeles extensive damage occurred on the nonstructural components of tall buildings. At least one building was damaged in San Diego. Even as far as Las Vegas, Nevada, a building under construction was damaged and required realignment of its structural steel frame. Finally, on August 22, an aftershock Near Bakersfield with magnitude 5.8 killed two people and caused extensive damage to many already weakened buildings and structures.

The death toll was relatively low. A total of twelve people lost their lives, 9 in Tehachapi and three more in other towns. Property damage estimated at $60 million, occurred in much of Southern California but it was particularly concentrated in the Bakersfield area. Although severe, property damage was not nearly as extensive as that of the 1933 Long Beach earthquake. Fig. shows the collapse of a school building in Kern County, California from the 1933 Long Beach strike-slip earhquake on the White Wolf fault.

Fig. 10 Collapse of school building in Kern County, California from the 1933 Long Beach earhquake

3.26 Earthquake of 9 February 1971

This earthquake, with a magnitude of 6.6, was the most destructive event to affect the greater Los Angeles Metropolitan area since the magnitude 6.3 Long Beach Earthquake of 1933 (Heaton, 1982). It struck the populated San Fernando Valley and surrounding areas, causing extremely heavy destruction. Earthquake intensities varied from VII to XI. The quake occurred in the lightly inhabited area in the middle of the San Gabriel (USGS, 1971. In the mountains along the San Fernando fault where most of the energy was released at least 10 miles of surface rupture was observed. Strong ground shaking occurred only at the northeastern end of the valley. The quake was responsible for extensive destruction at the Sylmar Veterans Hospital, where two older buildings completely collapsed, killing 45 people in that locality along. A total of 58 fatalities and approximately 2,000 injuries were reported. A major overpass at the interchange of Interstate 5 and State Route 14 collapsed. Direct damage to buildings and other structures in this suburban Los Angeles area was estimated at more than half a billion dollars (1971 dollars). Because of extensive earthquake damage there was extensive reevaluation and revision of the building codes in the area.

3.27 Earthquake of 1 August 1975

An earthquake measuring 6.0 in magnitude occurred in the vicinity of Palermo, a small community south of Oroville. The quake was felt as far as Fresno, 380 kilometers south of the epicenter. In the immediate area, the quake was reported to have caused about a dozen injuries and approximately six million dollars in damage. This was the largest earthquake to strike California since the disastrous San Fernando earthquake (6.6) of February 9, 1971. The main earthquake shock was preceded by two smaller quakes earlier on that day. Several strong aftershocks with magnitudes greater than 4.0 followed the main shock, and two exceeded magnitude 5.0.

3.28 Imperial Valley Earthquake of 15 October 1979

An earthquake occured earlier on 6 August 1979 in the area of Coyote Lake in California by a larger earthquake on 15 October 1979 - the largest earthquake in California in the past decade, and which occurred on the Imperial fault and northern Baja California, 5 km south of United States-Mexican border, and was felt from Las Vegas, Nevada, to Northern Mexico. The moment-magnitude (M) 6.5 event damaged structures in and near the town of El Centro, in California, was felt from Las Vegas, Nevada to the Pacific Ocean, and was accompanied by surface movement on four other fault zones. The main quake and its aftershocks were distributed primarily along the Imperial and Brawley faults. Extensive surface movement was measured along a 19.3-mile (30 km) segment of the northern section of the Imperial fault and along eight miles of the Brawley fault. Maximum horizontal displacements were measured to be 31 inches near the southern end of the surface rupture, decreasing to 0.6 inches in the northern end (Heaton, 1982).

Fig. 11 Imperial Valley, California Earthquake of October 15, 1979 (USGS)

The earthquake damage was extremely heavy at El Centro. Overall, it caused an estimated $21.1 million in damage and injured 73 people, but no deaths were reported in the United States. The small number of injuries is indeed fortunate, and is no doubt related to the fact that the areas of greatest population and number of manmade structures were not situated in the most strongly shaken area.

The earthquake and its aftershocks occurred in a region that has undergone several similar-size earthquakes in the recent historical past, including the well-known M=7.0 earthquake near El Centro on May 18, 1940. Because of the frequent recurrence of moderately strong earthquakes, this region has been under intensive study for many years by seismologists, geologists, and engineers of the U.S. Geological Survey and other research institutions. Their efforts have included the design and installation of numerous types of seismologic, strong-motion, geodetic, and other earth quake-monitoring instruments, as well as in depth studies of various earthquake-related topics. As a consequence of this preparatory work, the 1979 earthquake provided the seismologic and geologic sciences and the field of earthquake engineering with a wealth of important information, much of it unprecedented.

3.29 Earthquake of 2 May 1983

An earthquake measuring 6.5 on the Richter scale was particularly damaging at Coalinga in Southern California where damage was estimated at approximately thirty-one million dollars (Rymer and Ellsworth, 1990; Stein and King, 1984). This was the most damaging earthquake in California since the San Fernando earthquake of 1971. Damage was most severe to older, unreinforced masonry and older wood-framed structures.

The earthquake was felt as far away as Sacramento, Los Angeles, Carson City, and Las Vegas. At least 6,000 aftershocks were measured in the Coalinga region during the following days and weeks. Six of those had magnitudes greater than 5.0 Surface rupture of about 2 miles with vertical displacement of over 23 inches were measured along the Nunez fault following an aftershock of magnitude 5.2, which occurred, subsequently, on June 11.

3.30 Earthquake of 24 April 1984

A moderate earthquake of magnitude 6.1 occurred along the Calaveras fault east of San Jose. Earthquake damage estimated at seven-point-five million dollars occurred primarily in the southern Santa Clara Valley area near the town of Morgan Hill and the south end of Anderson Reservoir (Bakun EtAl, 1984; Hartzell, and Heaton, 1986).

3.31 Earthquake of 1 October 1987

A strong earthquake, followed by fifteen aftershocks, struck Southern California at 7:42 a.m., killing three people, injuring dozens more, collapsing buildings, touching off fires from ruptured gas lines, toppling walls, and closing freeways. The magnitude of the quake was 6.1 on the Richter scale, and its epicenter was nine miles south-southeast of Pasadena, in the Montebello-South Gate-Downey area on the north end of the Whittier-Elsimore fault.

In Los Angeles, there were at least 24 injuries and two deaths. Forty-six fires were reported from natural gas leaks, 26 structural fires, 36 heart attacks, 14 traffic accidents, and 21 elevators with people stuck in them. In Pasadena, one vacant brick building collapsed. One of the worst hit areas was downtown Whittier, where several buildings collapsed, and cars were crushed by bricks. In Bellflower, 15 miles southeast of downtown Los Angeles, the roof collapsed at Kaiser Permanente Hospital. The quake set off a fire at a small shopping center.

3.32 Earthquake of 10 June 1988

An earthquake of magnitude 5.2 was felt widely across Southern California at 4:06 in the afternoon. The quake had its epicenter on the Garlock fault in a sparsely populated area northwest of Los Angeles. The Garlock fault extends from the south end of Death Valley to an intersection with the San Andreas fault in the general vicinity of Lebec, about 70 miles northeast of Los Angeles. The quake was felt strongly in Lebec and nearby Gozman. It was felt mildly in downtown Los Angeles, and as far north as the San Joaquin Valley. No injuries or damage was reported, but the California Aqueduct was shut down over its entire 440 miles as a result of a power failure at two pumping stations.

3.33 Earthquake of 17 October 1989 - The Loma Prieta Earthquake

This was the strongest earthquake to strike the San Francisco Bay region since the great earthquake of 1906 (Ward and Page, 1989). It was felt over an area of approximately 400,000 square miles, from the California-Oregon border on the north to Los Angeles on the south and to Western Nevada on the east. It occurred at 5:04 in the afternoon (October 18 0004 UTC) and had a magnitude of 7.1. Its epicenter was about 10 miles northeast of the city of Santa Cruz and 60 miles southeast of San Francisco at 37 2.19 North and 121 52.98 West. It was named as the Loma Prieta earthquake, after the highest peak of the Santa Cruz Mountains. The earthquake ruptured a large segment of the San Andreas Fault beneath the Santa Cruz Mountains.

The quake was particularly damaging in the Marina District of San Francisco. Also, severe damage occurred south of San Francisco. Throughout the region homes were shattered. Hardest hit were towns like Watsonville, Los Gatos, Aptos and Davenport, where thousands were left homeless the historic downtown district in Santa Cruz was virtually devastated.

The earthquake resulted in 67 known deaths, 3,757 injuries and left more than 12,000 people homeless. It destroyed 1,018 homes and damaged 23,408 others. Among businesses, 366 were destroyed and 3,530 damaged. The earthquake disrupted transportation, utilities, and communications. It caused over $6 billion in property damage in 10 northern California counties. Since this is one of the most recent of destructive earthquakes to strike California in recent times. Because of the great distance, no potential impact on the San Onofre nuclear plant would be expected.

3.34 Earthquake of 28 June 1991

A strong earthquake rocked Southern California, at 7:43 in the morning, killing one person, injuring 46 and damaging buildings and homes in suburbs east of Los Angeles. The magnitude of the earthquake was 6 on the Richter scale and its epicenter was 7 miles north of suburban Monrovia, beneath the San Gabriel Mountains, on the long-dormant Sierra Madre fault. The tremors were felt 100 miles northwest in Santa Barbara, 225 miles to the east in Las Vegas, and south to the Mexican border. Damage was relatively light because the quake had a shallow depth of about 7 miles beneath the mountains.

The greatest damage confined to the San Gabriel Mountain foothill communities 10 to 20 miles northeast of downtown Los Angeles. Store windows crashed down in Pasadena and part of the facade of a four-story brick apartment building fell onto Colorado Boulevard. In the small town of Sierra Madre at least150 homes and buildings suffered structural damage. In Monrovia 125 homes, buildings and other structures were damaged and 331 chimneys were destroyed. In Arcadia, at least 100 homes sustained some damage. Damage was reported at the Pasadena City Hall and the historic Pasadena Playhouse.

In downtown Los Angeles high rise buildings swayed but no damage was reported. There were about 20 to 30 small aftershocks in the first 90 minutes with many more later. Estimates of damage from the quake were in excess of $20 million. A total of 380 buildings and homes suffered some damage to varying degree from this earthquake, which was the most strongly felt quake in the Los Angeles area since the October l, 1987 earthquake.

3.35 Earthquake of 28 June 1992

A large, 7.3 earthquake struck the Landers area at 11:57:34 UTC. It caused damage in excess of 92 million dollars in the Landers - Yucca Valley area. One person was killed as a result of the earthquake and two others died of heart attacks. More than 400 people were reported injured. The maximum earthquake intensity was IX. The shock was felt throughout southern California, southern Nevada, southern Utah, and Western Arizona and as far east as Denver, Colorado and Albuquerque, New Mexico, and as far north as Boise, Idaho.

Extensive surface rupturing was observed for a distance of 70 kms from Joshua Tree to near Barstow. Horizontal ground displacements were as much as 5.5 meters while vertical displacement were as much as 1.8 meters. Extensive seiching action was reported in lakes as far east as Aurora, Colorado, and Corpus Christi, Texas and as far north as Lake Union, Washington. A strong aftershock with a magnitude of 6.7 struck the same area at 15:05 UTC on the same day.

3.36 Earthquake of 17 January 1994 - The Northridge Earthquake

A moderate earthquake struck the densely populated San Fernando Valley, about 32 km northwest of downtown Los Angeles at 4:30 A.M., Pacific Standard Time (1230 UTC) on Monday, January 17. Its epicenter was located near Northridge along the San Fernando thrust fault at the northern edge of the valley, approximately 100 km to the west and south of the San Andreas. Although the earthquake had a moment magnitude (Mw) of only 6.7, it was very damaging because it struck a well-developed area within the San Fernando Valley with a population of nearly 3 million. Thousands of aftershocks occurred in the next few weeks, some with magnitudes of 4.0 to 5.0, causing additional damage.

This region has been frequently struck by moderate to large earthquakes. The last major, magnitude 6.6, earthquake had struck about 32 km to the northeast on February 9, 1971. However this 1994 quake resulted in far greater damage than the 1971 event, which had released most of its energy in the San Gabriel Mountains. Extremely strong ground motions - among the strongest ever recorded - were responsible for most of this damage. Accelerations in the range of 1.0 g were recorded over a large area. Fortunately, because the earthquake occurred in the early morning and on a holiday, its effects were not as bad as they could have been. The number of fatalities was about the same as in the 1971 quake. A total of 57 people lost their lives and more than 1,500 people were seriously injured.

In terms of financial losses and property damage, this earthquake was one of the worst natural disasters in U.S. history. The quake's intense shaking caused extensive ground liquefaction and triggered many fires. Most of the severe destruction occurred within 16 km of the epicenter area, however significant damage to structures was reported as far away as 77 km. There was extensive damage in Santa Monica, located directly south of the epicenter area; however building damage was widespread throughout the Valley. About 12,500 structures were moderately to severely damaged and thousands of people were left temporarily homeless. Major freeway damage occurred up to 32 km from the epicenter region. Collapses and other severe damage forced closing portions of 11 major roads to downtown Los Angeles. The Santa Monica Freeway (Interstate 10) was badly damaged. As with the 1971 earthquake, the interchange (Interstate 5 and State Route 14) sustained heavy damage. Damage to utilities was significant. For several days after the earthquake, more than 48,500 homes had little or no water, while 9,000 homes and businesses were without electricity and 20,000 more were without gas.

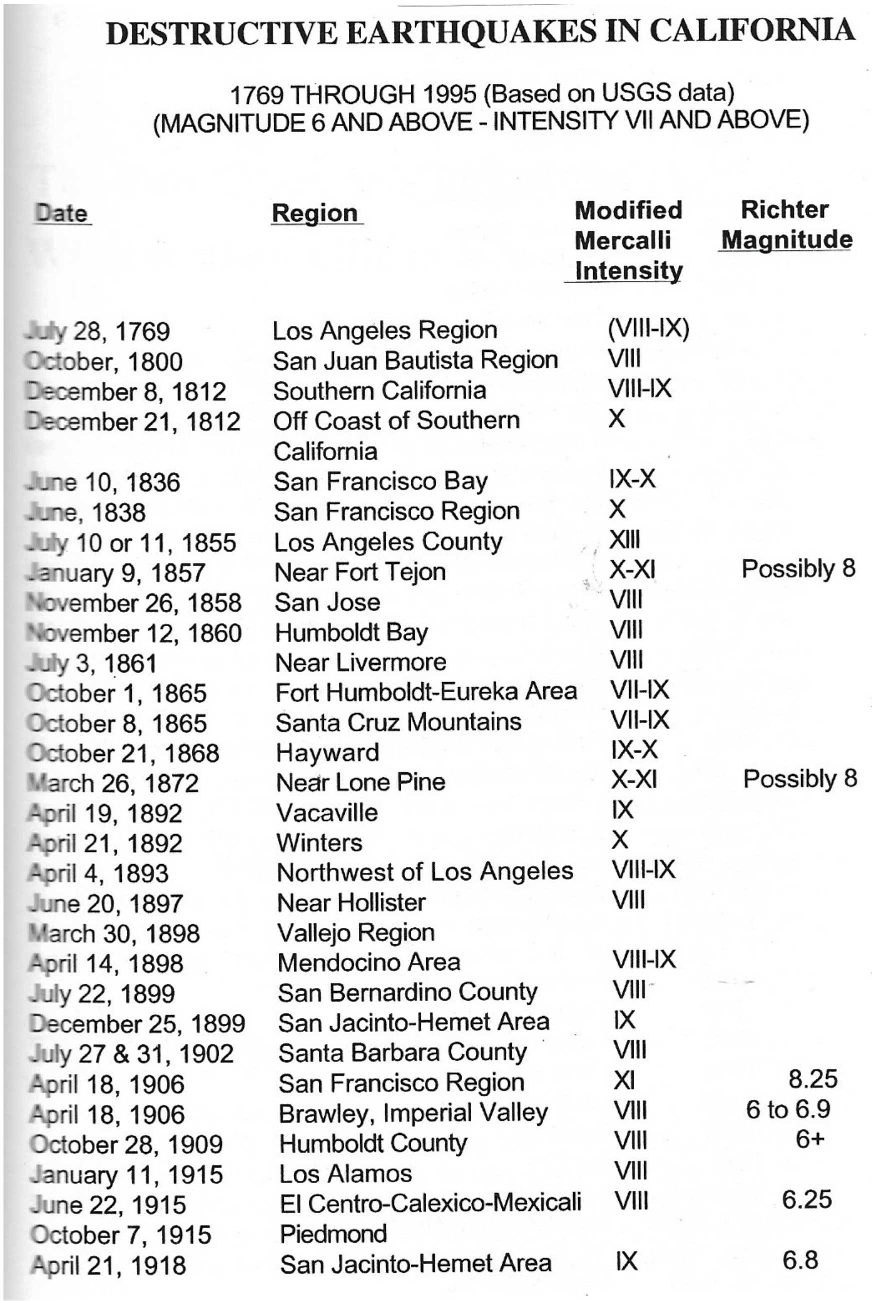
3.37 Earthquake of 1 September 1994

Another earthquake struck the offshore area of Northern California in the vicinity of the Mendocino Fracture zone. This event had and magnitude of 6.9. Its epicenter was close to where earthquakes had struck in 1991 and 1992, thus indicating a continuation of seismic activity and crustal movement along the Mendocino Fracture Zone. The quake occurred at 15:15, on September 1. There were no reports of damage.

3.38 Earthquake of 19 February 1995

The same offshore area of Northern California, west of Eureka was struck again by another earthquake. This event had and magnitude of 6.6. Its epicenter was very close to where earthquakes had struck in 1991, 1992 and as recently as 1 September 1994, thus indicating a continuation of seismic activity and crustal movement along the Mendocino Fracture Zone. The quake occurred at 04:03, on February 19 (UTC). There were no reports of damage.

Following are two tables listing all the California earthquakes with Richter magnitudes of 6 and above and intensity VII and above from 1769 through 1995.

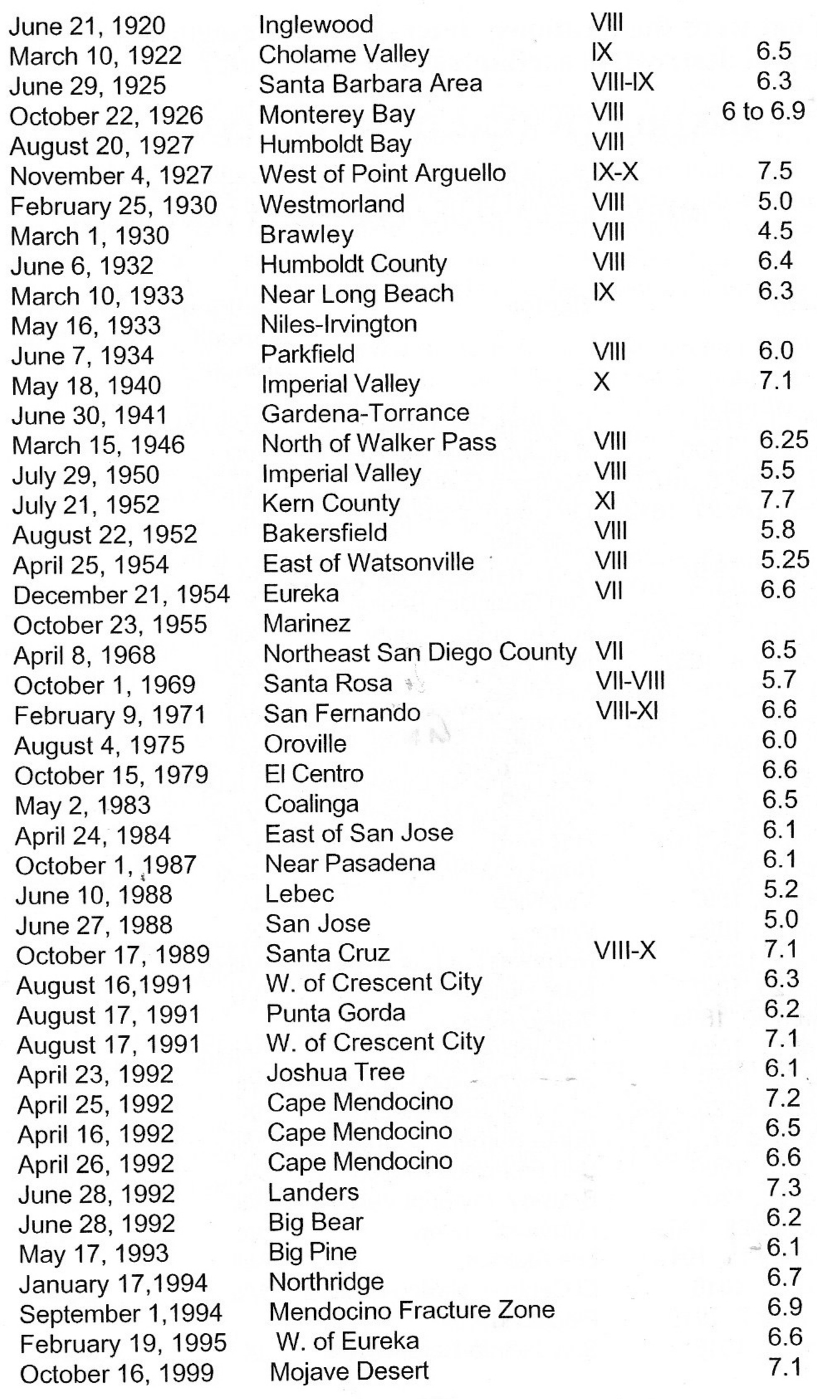


DESTRUCTIVE EARTHQUAKES IN CALIFORNIA

1769 THROUGH 1995 (Based on USGS data)
(MAGNITUDE 6 AND ABOVE - INTENSITY VII AND ABOVE)

Date	Region	Modified Mercalli Intensity	Richter Magnitude
July 28, 1769	Los Angeles Region	(VIII-IX)	
October, 1800	San Juan Bautista Region	VIII	
December 8, 1812	Southern California	VIII-IX	
December 21, 1812	Off Coast of Southern California	X	
June 10, 1836	San Francisco Bay	IX-X	
June, 1838	San Francisco Region	X	
July 10 or 11, 1855	Los Angeles County	XIII	
January 9, 1857	Near Fort Tejon	X-XI	Possibly 8
November 26, 1858	San Jose	VIII	
November 12, 1860	Humboldt Bay	VIII	
July 3, 1861	Near Livermore	VIII	
October 1, 1865	Fort Humboldt-Eureka Area	VII-IX	
October 8, 1865	Santa Cruz Mountains	VII-IX	
October 21, 1868	Hayward	IX-X	
March 26, 1872	Near Lone Pine	X-XI	Possibly 8
April 19, 1892	Vacaville	IX	
April 21, 1892	Winters	X	
April 4, 1893	Northwest of Los Angeles	VIII-IX	
June 20, 1897	Near Hollister	VIII	
March 30, 1898	Vallejo Region		
April 14, 1898	Mendocino Area	VIII-IX	
July 22, 1899	San Bernardino County	VIII	
December 25, 1899	San Jacinto-Hemet Area	IX	
July 27 & 31, 1902	Santa Barbara County	VIII	
April 18, 1906	San Francisco Region	XI	8.25
April 18, 1906	Brawley, Imperial Valley	VIII	6 to 6.9
October 28, 1909	Humboldt County	VIII	6+
January 11, 1915	Los Alamos	VIII	
June 22, 1915	El Centro-Calexico-Mexicali	VIII	6.25
October 7, 1915	Piedmond		
April 21, 1918	San Jacinto-Hemet Area	IX	6.8

Fig Magnitudes, Intensities and Locations of the Large Destructive Earthquakes in California



June 21, 1920	Inglewood	VIII	
March 10, 1922	Cholame Valley	IX	6.5
June 29, 1925	Santa Barbara Area	VIII-IX	6.3
October 22, 1926	Monterey Bay	VIII	6 to 6.9
August 20, 1927	Humboldt Bay	VIII	
November 4, 1927	West of Point Arguello	IX-X	7.5
February 25, 1930	Westmorland	VIII	5.0
March 1, 1930	Brawley	VIII	4.5
June 6, 1932	Humboldt County	VIII	6.4
March 10, 1933	Near Long Beach	IX	6.3
May 16, 1933	Niles-Irvington		
June 7, 1934	Parkfield	VIII	6.0
May 18, 1940	Imperial Valley	X	7.1
June 30, 1941	Gardena-Torrance		
March 15, 1946	North of Walker Pass	VIII	6.25
July 29, 1950	Imperial Valley	VIII	5.5
July 21, 1952	Kern County	XI	7.7
August 22, 1952	Bakersfield	VIII	5.8
April 25, 1954	East of Watsonville	VIII	5.25
December 21, 1954	Eureka	VII	6.6
October 23, 1955	Marinez		
April 8, 1968	Northeast San Diego County	VII	6.5
October 1, 1969	Santa Rosa	VII-VIII	5.7
February 9, 1971	San Fernando	VIII-XI	6.6
August 4, 1975	Oroville		6.0
October 15, 1979	El Centro		6.6
May 2, 1983	Coalinga		6.5
April 24, 1984	East of San Jose		6.1
October 1, 1987	Near Pasadena		6.1
June 10, 1988	Lebec		5.2
June 27, 1988	San Jose		5.0
October 17, 1989	Santa Cruz	VIII-X	7.1
August 16,1991	W. of Crescent City		6.3
August 17, 1991	Punta Gorda		6.2
August 17, 1991	W. of Crescent City		7.1
April 23, 1992	Joshua Tree		6.1
April 25, 1992	Cape Mendocino		7.2
April 16, 1992	Cape Mendocino		6.5
April 26, 1992	Cape Mendocino		6.6
June 28, 1992	Landers		7.3
June 28, 1992	Big Bear		6.2
May 17, 1993	Big Pine		6.1
January 17,1994	Northridge		6.7
September 1,1994	Mendocino Fracture Zone		6.9
February 19, 1995	W. of Eureka		6.6
October 16, 1999	Mojave Desert		7.1

Fig. Magnitudes, Intensities and Locations of the Large Destructive Earthquakes in California

Fig. 12 The San Onofre Nuclear Plant, including units 2 and 3 before completed defueling of the reactor on March 6, 1993, and the dismantlement and decommissioning of SONGS, Unit 1 by 15 December 1998.

CONCLUSIONS

An early study of historic earthquakes and tsunamis, as well as of an extensive air and land field survey of Southern California, was undertaken under contract with the U.S. Nuclear Regulatory Agency (NRC), and the U. S. Army Coastal Engineering Research Center (CERC), primarily in connection with the licencing for the additional Units 2 and 3 added to the original Unit 1 of the San Onofre Nuclear Power Plant near San Clemente in Southern California. During this initial study and subsequently, and in preparation of a book by the author, the study of earthquakes and tsunamis in California was extended for all major faults of the San Andreas fault zone which, although capable of strong earthquakes, cannot generate significant tsunamis. Only earthquakes in the Transverse Ranges, specifically along the seaward extensions in the Santa Barbara Channel and in the offshore area from Point Arguello, can and have generated local tsunamis of any significance, a recurrence of which could have had an impact on the San Onofre plant were considered. The reason for this may be that earthquakes occurring in these regions result in significant vertical displacements of the crust along these faults. Such tectonic displacements are necessary for tsunami generation.

The area offshore of Point Arguello in Southern California has sea-floor features which suggest such displacements, so local tsunamis from this area as well as from the Santa Barbara region, can be expected in the future. It is obvious from the historical accounts that one, and possibly two large tsunamis were generated from two major earthquakes in the Santa Barbara region in December of 1812. The size of these tsunamis may never be known with certainty, and the estimates of 15 feet at Gaviota, 30-35 feet at Santa Barbara, and 15 feet or more at Ventura, seem somewhat exaggerated. Which of the two earthquakes produced the bigger tsunami, or whether indeed there were two separate events, may never be known with certainty, as all the historical accounts are sketchy and ambiguous. Tsunamigenic earthquakes from the Santa Barbara were regarded as being the more significant sources that could have had an adverse impact in Los Angeles and the San Onofre nuclear plant, although the danger to San Onofre no longer exists, with the recent total decommisioning and total dismantling of the facility.

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ASSESSMENT OF THE MAXIMUM TSUNAMI WAVE HEIGHTS ON THE CRIMEA-CAUCASUS COAST OF THE BLACK SEA FROM POSSIBLE UNDERWATER EARTHQUAKES AND LANDSLIDES IN THE DZHUBGA AREA

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ABSTRACT

In the present work, the problem of tsunami wave generation is solved by considering two source mechanisms: a seismic source and a landslide source. The numerical simulation was performed with the localization of the source in the Dzhubga area, where the Blue Stream pipeline comes ashore. For both problem statements, different source localizations were considered: at depths of 350 m and 750 m. For the seismic setting, a two-block source with any directional movement of blocks was considered. The landslide problem was considered within the framework of a solid-block segmental model. Numerical simulation of the generation of the tsunami source and the propagation of tsunami waves over the Black Sea from Sochi to the Crimea peninsula has been performed. Landslide danger sections of the Turkish Stream and Blue Stream pipelines were examined in the most detailed way. For each scenario, the characteristics of wave fields in the computation water area were obtained. A comparison of the results obtained within the framework of the considered models is carried out.

Keywords: *tsunami waves, seismic and tsunami danger, tsunamigenic earthquakes, numerical simulation, Black Sea coast.*

1. INTRODUCTION

The assessment of the seismic and tsunami hazard of the Black Sea, both Russian and other coasts of this water area, is an actual task of recent decades (see, e.g., [1-9]). The importance of such computations is connected, in particular, with the problem of operation of the Russia-Turkey offshore gas pipelines connecting the territories of these countries along the bottom of the Black Sea, which operate in conditions of increased seismicity and landslide danger on the Russian and Turkish slopes of the Black Sea. The Turkish Stream gas pipeline, through which Russian gas flows through the Black Sea to Turkey and further to the south of Europe, started operating in January 2020. It consists of two parallel pipes. The Blue Stream gas pipeline started operating in 2003 (Fig. 1).

Fig. 1. The water area of the Black Sea; red and white lines are schematic representation pipelines "Turkish Stream" and "Blue Stream”.

It is well known that the safety of laying and operating underwater gas pipelines requires an assessment of seismic and landslide hazards in the area of underwater slopes where these gas pipelines come ashore. As known, the Blue Stream underwater gas pipeline connects the Russian coast near the Dzhubga point and the Turkish coast and goes on land in the area of the. Kiyikay and Ipsala. Located on the Russian Black Sea coast, the terminal section of the Blue Stream underwater gas pipeline is located in a zone with high seismicity (Fig. 1). This is due to the fact that the Krasnodar Territory, where this site is located, is one of the most dangerous areas of seismic risk in Russia. The Crimea-Caucasus coast of the Black Sea is a zone of high industrial potential (large ports, gas and oil pipeline terminals) and the largest Russian resort area, so assessing the risk of a tsunami attack on this coast is an important task. According to the map of maximum shaking in the North Caucasus, the Black Sea coast from Anapa to Sochi falls into the seven-magnitude earthquake zone [1,2]. This corresponds approximately to the magnitude $M = 6$. The risk of earthquakes, landslides and tsunamis also applies to such unique transport facilities as the offshore sections of the Russia-Turkey gas pipelines (the Blue Stream and Turkish Stream projects) connecting the territories of these two countries along bottom of the Black Sea and operating under conditions of increased seismicity and landslide hazard on the Russian and Turkish slopes of the Black Sea [11,12]. Detailed seismological observations with highly sensitive bottom stations in the Dzhubga region, where the Russia-Turkey gas pipeline terminal is located, revealed a very high level of activity for micro- and weak earthquakes. Seismic activity is associated not only with faults of the Caucasus strike, but also with transverse faults. During the preparation of the route of the Blue Stream gas pipeline at the test site in the Dzhubga region, observations were made with bottom seismographs. At the same time, a large number of weak ($M < 2$) earthquakes with hypocenter depths from 8 to 30 km or more were recorded. An extended large fault zone is distinguished in the water area, which can be traced in the area from Anapa in the northwest to Adler in the southeast, and is expressed in the form of ledges, hollows and gorges at the bottom of the sea. A feature of the seismicity of the northeastern part of the Black Sea region is the confinement of most earthquakes, including strong ones, to the coast, shelf, and continental slope of Crimea and the northwestern Caucasus [3, 12]. Because of this underwater earthquakes in the Black Sea are potentially dangerous from the point of view of excitation of tsunami waves on the Russian coast of the Caucasus, many works are devoted to this problem (see, e.g., [2–9]). The most adequate is to perform the numerical simulation with the maximum possible earthquake magnitude for a given point [13]. Figure 2 shows diagrams of active faults in the Crimea-Caucasus region, which depict various types of faults in the earth's crust [2, 12]. It is well seen that in the northeastern part of the Black Sea there is a large number of transverse faults that are highly active [12].

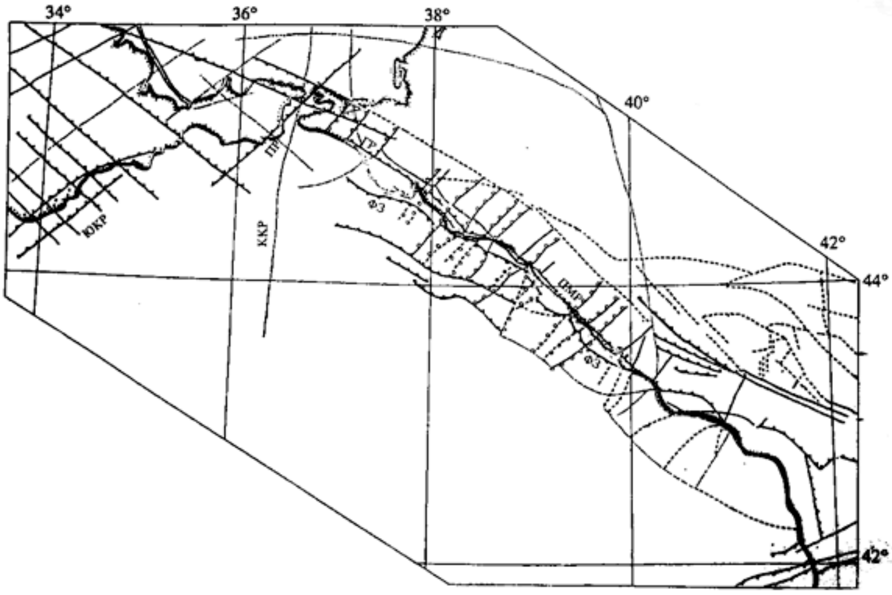

Fig. 2. Scheme of seismically active faults in the Crimea-Caucasus region [12].

Therefore, during the construction and operation of any underwater engineering structures (oil and gas pipelines, telecommunications, etc.), it is necessary to study in detail those sections of the Crimea and Caucasus coasts where breaks in oil pipelines and telecommunications lines are possible during events such as earthquakes and landslides. Intense tectonic activity, together with the frequent destruction of sedimentary masses, leads to the formation of landslide sections of underwater slopes. In addition, intensive industrial use of this offshore area may lead to a landslide process with further formation of tsunami waves.

In addition, seismic activity can also lead to the sliding of part of the slope, which can be the source of the formation of a surface long wave (tsunami), the movement of which will be directed against the movement of the landslide. In this paper, computations for a specific section of the Black Sea coast are performed (Fig. 3).

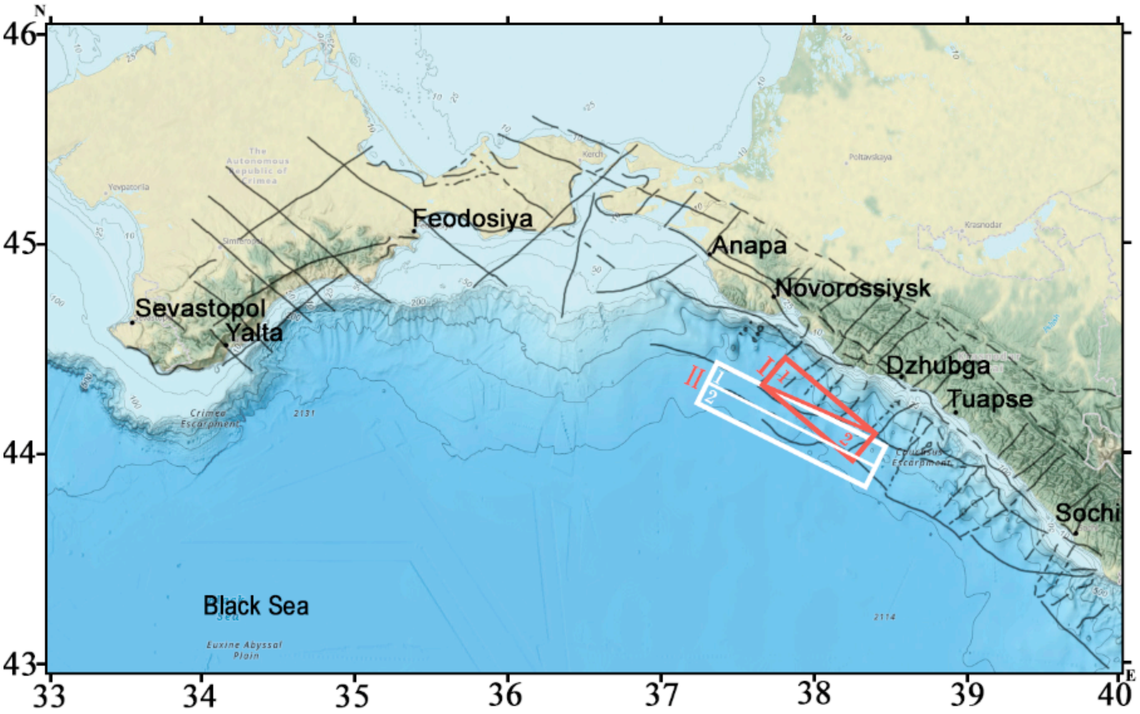

Fig. 3. Computation water area on a bathymetric map with a diagram of active faults in the Crimea-Caucasus region [4]. Dashed lines indicate parts of the Turkish Stream and Blue Stream pipeline routes; the red and white lines are a schematic representation of the localization of seismic sources at a depth of 350m and 750m, respectively.

Using information about possible zones of active faults and features of the main structures of various parts of the coast [2, 12], the position of possible seismic sources was determined. Estimated seismic sources are located in the sea area near the coastline of the Turkish Stream and Blue Stream gas pipelines. The shelf width in the Dzhubga area is 7450 m. The maximum depth is 981 m.

The study performed is related to the generation of tsunami waves by a kinematic source, considered within the framework of the keyboard model of an earthquake [14]. Any seismic or other impact in this area can trigger tsunami waves along the entire Black Sea coast, including in the areas of the terminals of the Turkish Stream and Blue Stream gas pipelines. To determine the possible tsunami waves that can be caused by earthquakes with magnitude M=7, M=7.5, M=8, formulas were used that relate the earthquake magnitude to the characteristics of ruptures at interplate boundaries in subduction zones [14,15]. Given that the probability of a tsunami even during moderate earthquakes with magnitude M = 7 is 0.81 [15], these magnitudes were chosen to assess the parameters of possible tsunamis in the considered water area (Fig. 3). The paper also considers the modeling of the process of slope slumping of the tsunamigenic landslide section of the coast located in the Black Sea in the Dzhubga area (between the cities of Gelendzhik and the city of Tuapse), where the offshore sections of the Russia-Turkey gas pipelines pass (Fig. 4).

The present study solves the problem of underwater landslides that generate a wave on the sea surface. A schematic representation of the localization of landslides on an underwater slope is shown in Fig. 4.

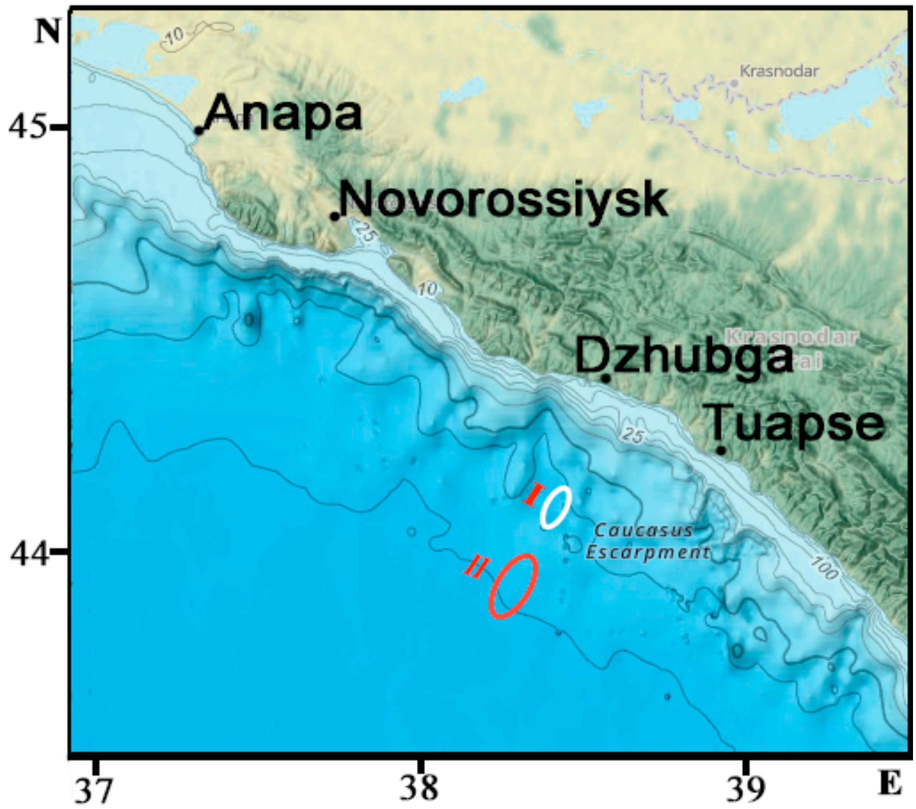

Fig. 4. Computation water area on the bathymetric map. Red and white ellipses schematically indicate the localization of landslide masses on the shelf.

2. NUMERICAL SIMULATION OF A POSSIBLE TSUNAMIGENIC EARTHQUAKE IN THE DZHUBGA AREA

Numerical schemes simulating waves caused by undersea collapses or landslides are usually based on the “shallow water” theory approximation (see for example [5,6]). Such numerical simulation was performed in the framework of nonlinear shallow water equations for possible strong tsunamis from two seismic sources in the Dzhubga area of the eastern part of the Black Sea basin (Fig. 4). Three scenarios of possible earthquakes were chosen, with magnitudes M=7.0, M=7.5, and M=8.

In order to estimate the initial parameters of tsunami waves that can be generated by a seismic source, such formulas were used relating to the relationship between earthquake magnitudes and the characteristic parameters of ruptures in the interplate boundary in the subduction zone, developed for active regions of the globe that determine the seismic source, and specifically the extent of the rupture in the source, the rupture’s width, and the possible height of the vertical displacement of the sea bottom at the source [16,17]. This part of the study is based on the keyboard mechanism of the earthquake source, in which the source is roughly assumed to be rectangular, divided into two blocks. Our estimates of this approximation allow us to use the connection relations available in [16] for this model as well.

During the first two computations, moderate earthquakes with magnitude M=7 were considered with the epicenter opposite Dzhubga point northwest of Sochi for depths of 350m (Scenario 1) and 750m (Scenario 2). Table 1 shows the nature of the movement of blocks, where the sign (-) determines the displacement of the block down, and the sign (+) up. Figure 6 shows the formation of a tsunami source when blocks are displaced in the seismic source for both scenarios.

Table 1. The character of the key-block movements.

Movement parameters	Scenario 1 Block N		Scenario 2 Block N	
	1	2	1	2
Start of motion (s)	0	40	0	40
Time of motion (s)	40	40	40	40
Height of shift (s)	-0.6	+1.7	-1.3	+2.6

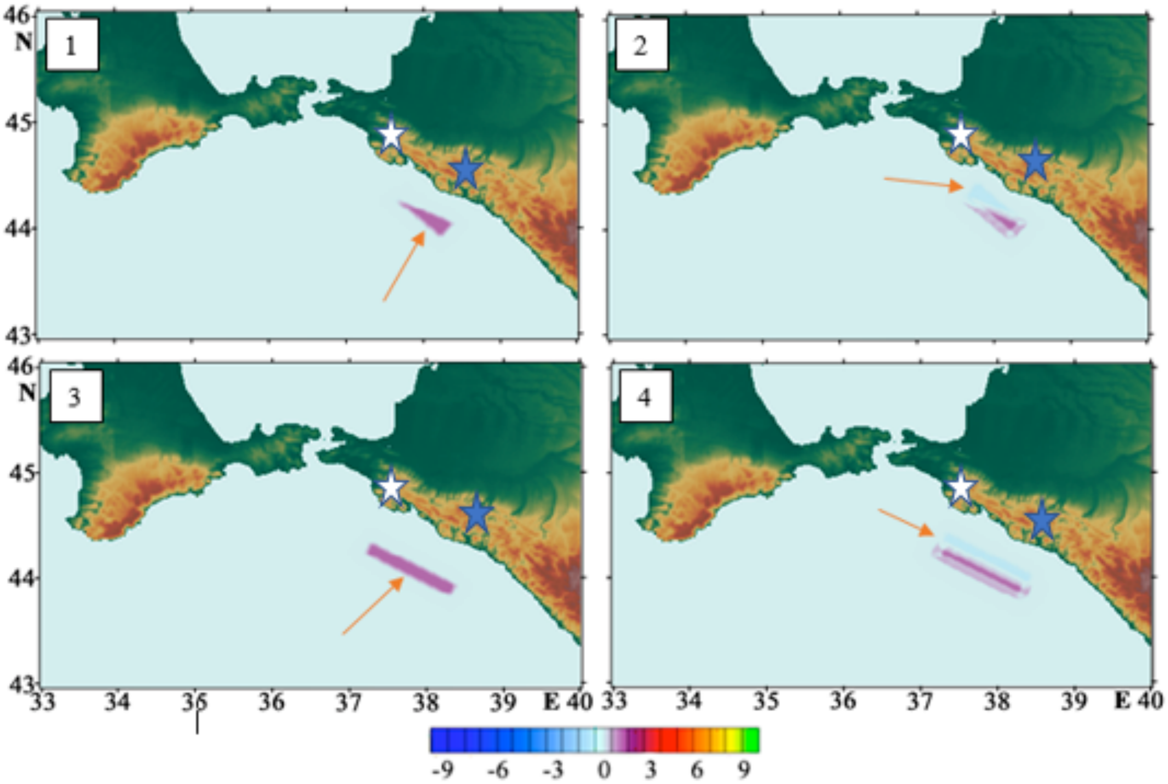

Fig. 5. Formation of a tsunami source to localize a seismic source at a depth of 350 m (Scenario 1, panels 1 and 2); at a depth of 750 m (Scenario 2, panels 3 and 4) for earthquake magnitude M=7.5 and M=8, respectively.

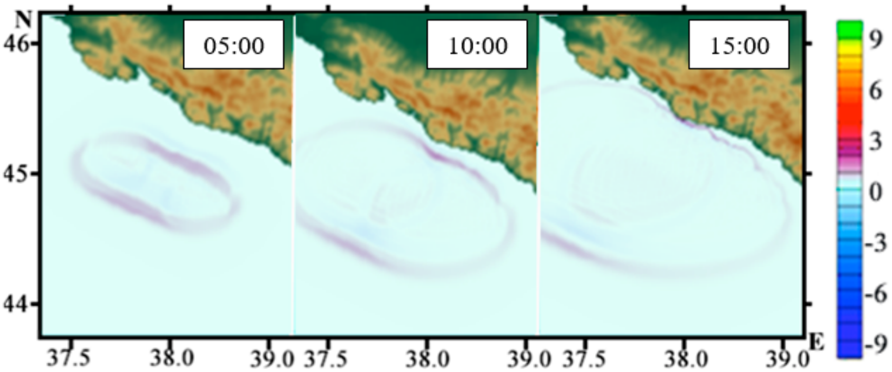

Fig. 6. Propagation of tsunami wave fronts for three time moments from a source localized at a depth of 750 m.

Figure 6 above, shows the propagation of tsunami wave fronts from a seismic source for 3 time moments. It is clearly seen that the first wave approaches with a negative phase, then the runup wave follows. Similar computations were performed for earthquake magnitudes *M*=7.5 and *M*=8.

Figure 7 shows one-dimensional histograms for 6 computations: three computations from a seismic source located at a depth of 350 m for magnitudes *M* = 7. 7.5 and 8 and the corresponding computations for a source located at a depth of 750 m.

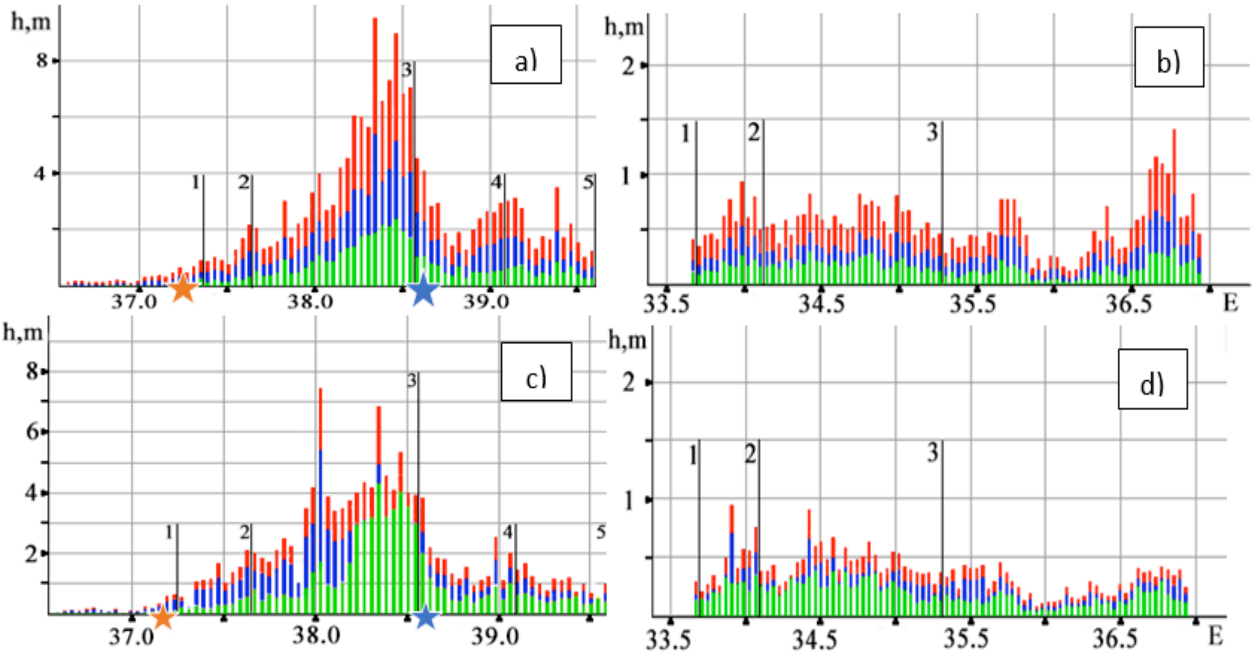

Fig.7. 2D histograms of tsunami wave heights along the coast for a part of the water area for the source at a depth of 350 m (a), (b) and at a depth of 750 m (c), (d) for three earthquake magnitudes: green *M*=7; blue *M*=7.5; red *M*=8. The cities are marked with numbers: a) 1 - Anapa, 2 - Novorossiysk, 3 - Dzhubga, 4 - Tuapse, 5 - Sochi; b) 1 - Sevastopol, 2 - Yalta, 3 - Feodosia. The red and blue asterisks indicate the exit points for the Turkish Stream and Blue Stream pipelines.

Figure 8 shows three-dimensional histograms for the maximum wave heights for Scenario 1, , in which the earthquake source is localized at a depth of 350 m. for the northeastern part of the Black Sea coast and for the Crimea peninsula.

It is clearly seen that at the maximum possible magnitude of the considered earthquakes for the Black Sea region, magnitude *M*=8, the wave heights on the Black Sea coast to the east of Anapa can reach very large values, up to 9 m. In the area of the Dzhubga point up to 7m. However, in the region of Anapa, the wave heights on do not reach 1m. On the Crimea coast, with such an earthquake magnitude, with a given localization of the source, the heights of tsunami waves do not exceed 1.4 m.

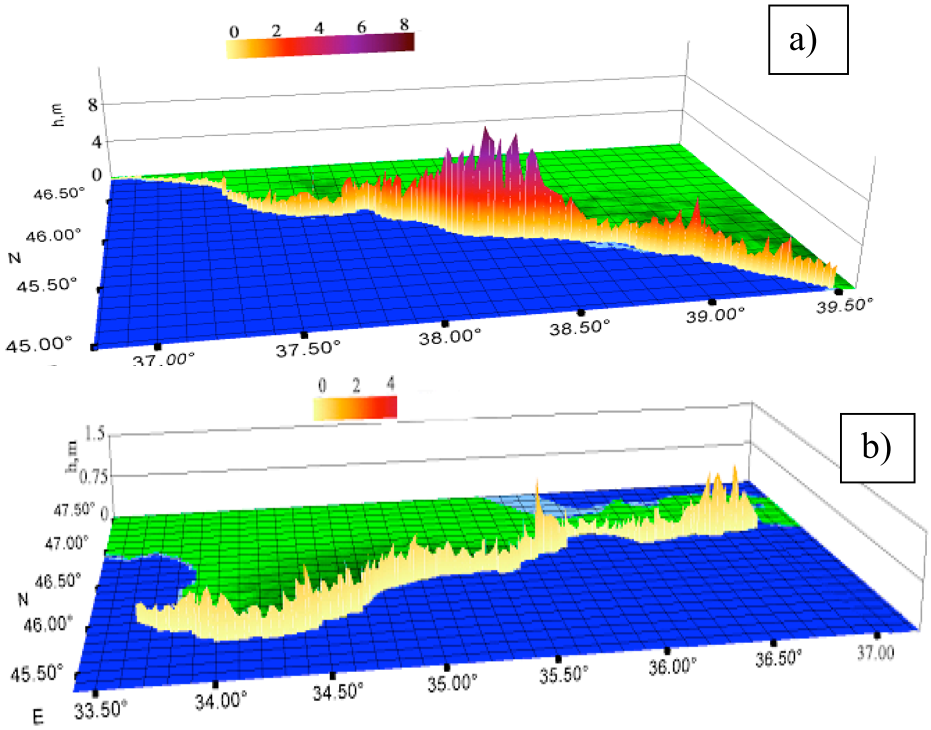

Fig. 8. 3D histogram of tsunami wave height along the coast for the northeastern part of the Black Sea and along the coast of the Crimea Peninsula (Scenario 1, M=8).

3. NUMERICAL SIMULATION OF POSSIBLE TSUNAMIGENIC LANDSLIDES IN THE DZHUBGA AREA

In most cases, landslide bodies are formed on the underwater slopes, which usually have a large extension. Most tsunami models generated by landslides are based on the response of the sea surface to the movement of a solid bottom. In this paper, the movement of a landslide is modeled as the movement of a rigid body divided into a number of blocks-segments, and the landslide process was modeled by the dynamic vertical displacement of segment blocks along the landslide slope, simulating the slumping of the landslide mass [18]. The kinematics of the movement of blocks is determined by the schematic behavior of the landslide movement, corresponding to a typical implementation of the computation in the framework of the elastic-plastic model - the sliding of the upper part of the landslide layer with a simultaneous increase in the thickness of the lower part of the slope (see, e.g., [19]). Figure 9 shows a schematic representation of the localization of landslide bodies on the underwater slope.

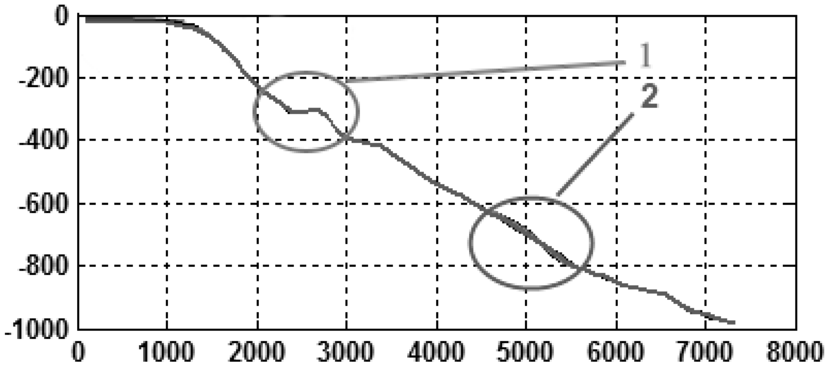

Fig. 9. Localization of landslide sources at a depth of 350 m (1) and 750 m

To implement this simulation, the landslide body is represented by 12 segmental blocks located along the slope (Fig. 10).

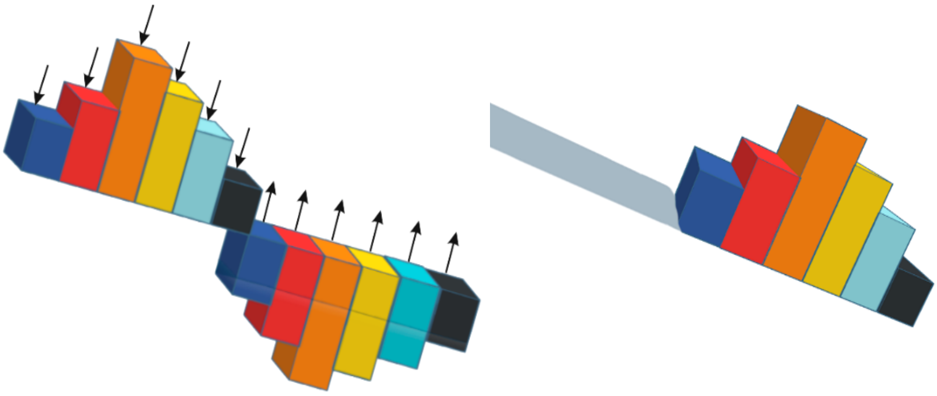

Fig. 10. Schematic representation of the movement of segmental blocks

This process can be principally approximated by the displacement of the upper segment blocks downwards, with the simultaneous displacement of the corresponding lower blocks upwards. To simulate landslide processes at a depth of 350 m and 750 m, options for shifting the segments into which the landslide is divided are proposed. At the same time, the upper segments sequentially shift down, with simultaneous sequential movement of the lower segments upwards (Fig. 11). So, for example, the height of the blue block on the left is reduced to zero and at the same time the blue block on the right is raised to the same height that the blue block on the left had. Then the red block moves down to zero and the corresponding red block on the right reaches the initial height of the red block. And so on. Each reverse movement takes 30 sec. In the problem, an underwater slope is considered, consisting of a layer of sediments lying on a solid basal plate (Fig. 10). The thickness of the layer of these sediments is about 4 m. Under seismic or other impact, the strength of this layer is violated, what can lead to its movement down the slope (sliding).

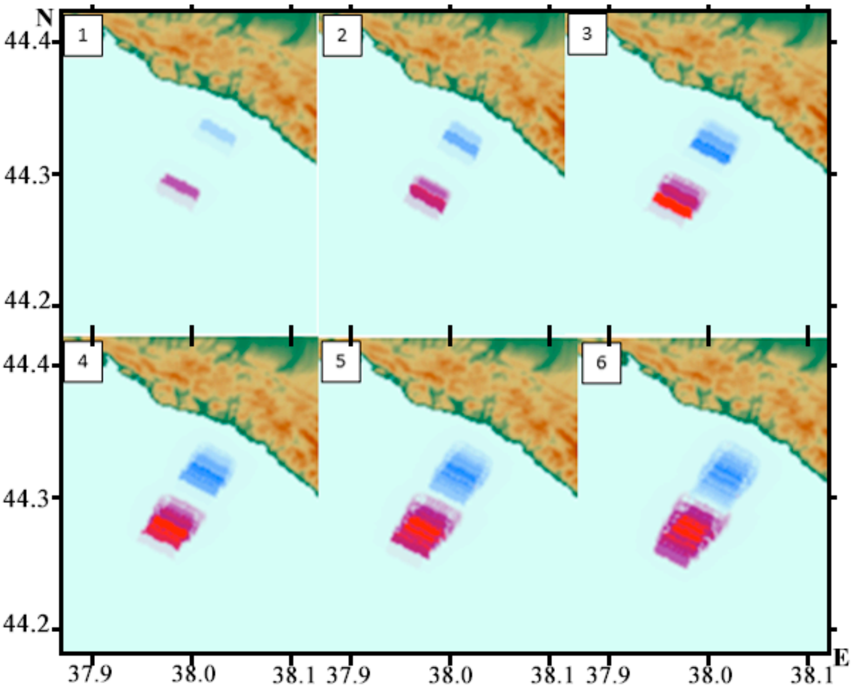

Fig. 11. Six time moments when the tsunami source is generated by segmental blocks into which the landslide body is divided. Panel (6) presents the moment when the movement of the segments has ended and the landslide has stopped

The movement of a landslide body is considered at a depth of 750 m slope, on the shelf, about 8 km long. The landslide source is about 2 km long and 600 m wide. For this case, a 12-segment source was constructed with a maximum displacement of a segmental block of 4m. Figure 11 shows 6 time moments of the tsunami source generation when moving up and down the slope of the corresponding two blocks (see Fig. 11).

Figure 12 shows 3 time moments for the propagation of wave fronts in the part of the water area closest to the exit to the Blue Stream pipeline terminal. It is clearly seen that, just as during a seismic impact, the first wave of depression approaches the coast, followed by a positive wave.

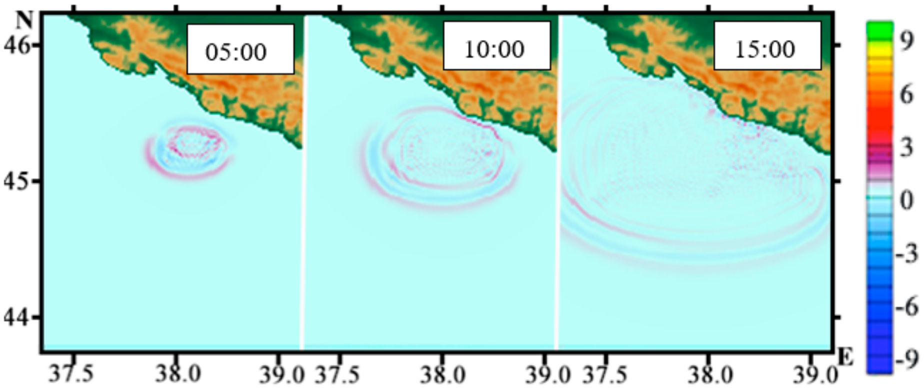

Fig. 12. Generation of a tsunami source when a landslide moves along a slope

Figure 13 shows two-dimensional histograms on a 3-meter isobath.

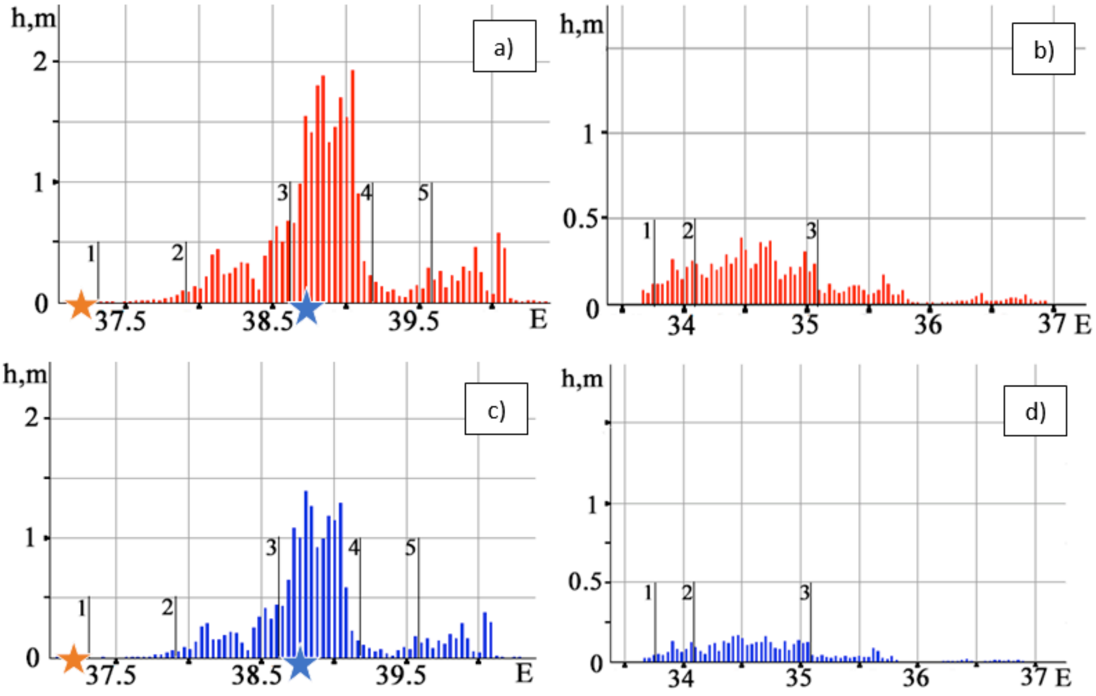

Fig.13. Histograms of tsunami wave heights along the northeastern coast (a) and the coast of the Crimea coast (b) during the implementation of wave processes from a landslide localized at a depth of 750 m. The cities are numbered 1 - Sevastopol, 2 - Yalta, 3 - Feodosia. The red and blue asterisks indicate the exit points for the Turkish Stream and Blue Stream pipelines.

Figure 14 shows a 3D histogram for a landslide source localized at a depth of 750 m. Figures 14 and 15 clearly show that in the areas where the pipelines exit, the possible heights of tsunami waves from a landslide localized in the Dzhubga area are either completely absent or their height will not exceed 1.4 m.

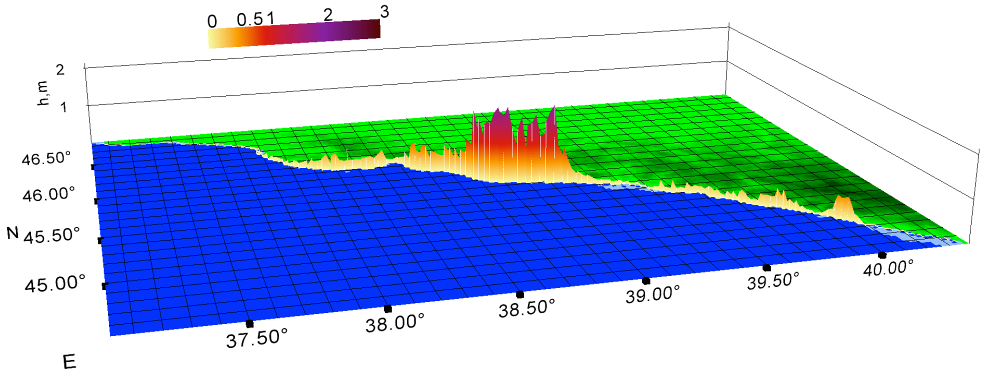

Fig. 14. 3D histogram of tsunami wave height along the coast for the northeastern part of the Black Sea and along the coast of the Crimean Peninsula

Computation data for possible tsunami wave heights at the places where the Turkish Stream and Blue Stream pipelines land on the coast are given in Table 2.

Table 2. Wave heights near pipeline terminals

	Seismic source						**Landslide source**	
Source depth, magnitude	**350 m**			**750 m**			**350 m**	**750 m**
	M=7	**M=7,5**	**M=8**	**M=7**	**M=7,5**	**M=8**		
Wave height (compressor station Russkaya (Anapa)), m	**0.4**	**0.7**	**1.1**	**0.1**	**0.4**	**0.6**	**0.05**	**0.05**
Wave height (compressor station Beregovaya (Dzhubga)), m	**0.9**	**2.3**	**4.2**	**2**	**2,8**	**3,8**	**1.05**	**1.5**

4. CONCLUSIONS

In this work, numerical simulation of tsunami wave generation by a dynamic seismic source and their propagation for specific coastal points in the Black Sea is performed. It is shown that with the considered limit values of earthquake magnitudes M=8, a seismic source can give values of wave heights near the exit points to the coast of the Blue Stream pipeline up to 4.2 m. Considering that the computation was performed up to a 3-meter isobath, recalculation of the wave height to a dry coast will provide additional gain. It is shown that with the landslide nature of the occurrence of tsunami waves, approximately at the same localization as the seismic source (approximately at $M = 7$, since the earthquake is a trigger, it "pushes" the landslide mass on the slope), it was obtained that more dangerous is a seismic event. The computation of possible catastrophic consequences from a tsunami for technological facilities in the northeast of the Black Sea coast showed that the Dzhubga area is most susceptible to tsunami wave attack, while the area of Anapa, where the Turkish Stream pipeline exits, is the most calm. The analysis also showed that with such localization of seismic and landslide sources, the coast of the Crimea peninsula will not be subject to any strong effects of tsunami waves.

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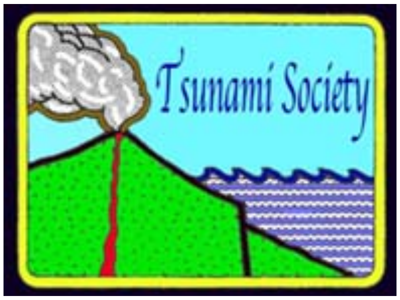

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