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RESEARCH TRENDS AND MAPPING OF TSUNAMI EARLY WARNING SYSTEM (TEWS) DURING 2002-2022

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ABSTRACT
Natural disasters occur regardless of time and place. They become one of the problems that the world continues to anticipate in the future. The present article discusses one of the steps taken with technology, namely the Tsunami Early Warning System (TEWS). The specific objective is to provide information regarding trends and mapping of the TEWS over the last twenty years, and to use a type of bibliometric approach which contains multiple corresponding analyses. In addition, the source database used is Scopus is used with the help of visualization from VosViewer, Bibliometrix, Rstudio, and Ms-Excel methods. The aim of the report is to describe the relationship and correlation between the TEWS field, the individual writer, and the country. In addition, reported in this study is Lotka's Law and Bradford's Law contribution from some articles, authors, and countries. Additionally, the present study discusses the niche, motor, emerging or declining, and basic themes of TEWS. It is expected that this study can be used as a springboard for researchers before conducting investigations directly in the field.

Keywords: *Bibliometric, Bibiometrix, Tsunami, Early warning system, VosViewer*

1. INTRODUCTION

Natural disasters are frequent physical catastrophic phenomena which occur unexpectedly in various countries. Such natural disasters include volcanic eruptions, floods, droughts, hurricanes, landslides, earthquakes, and tsunamis (Alexander, 2018; Amezquita-Sanchez et al., 2017; Rosselló et al., 2020). All such disasters always come unexpectedly and generate destressing experiences for affected societies. The development of advanced technology is expected to create effective disaster detecting warning systems in order to assist people who live in endangered areas, to increase their awareness, and their timely and adequate preparation for the worse possible disaster situations before they occur. The most dangerous and often fatal disasters are earthquakes and tsunamis (Mimura et al., 2011; Parwanto & Oyama, 2014; Gaillard et al., 2008; Zatsev et al., 2021; Imamura et al., 2019). Earthquake and tsunami disasters are closely related and need more attention to anticipate what their impact will be (Iemura et al., 2006). Figure 1 illustrates the different interaction mechanisms of crustal movements of convergence, divergence and transformation that generate earthquakes and tsunamis.

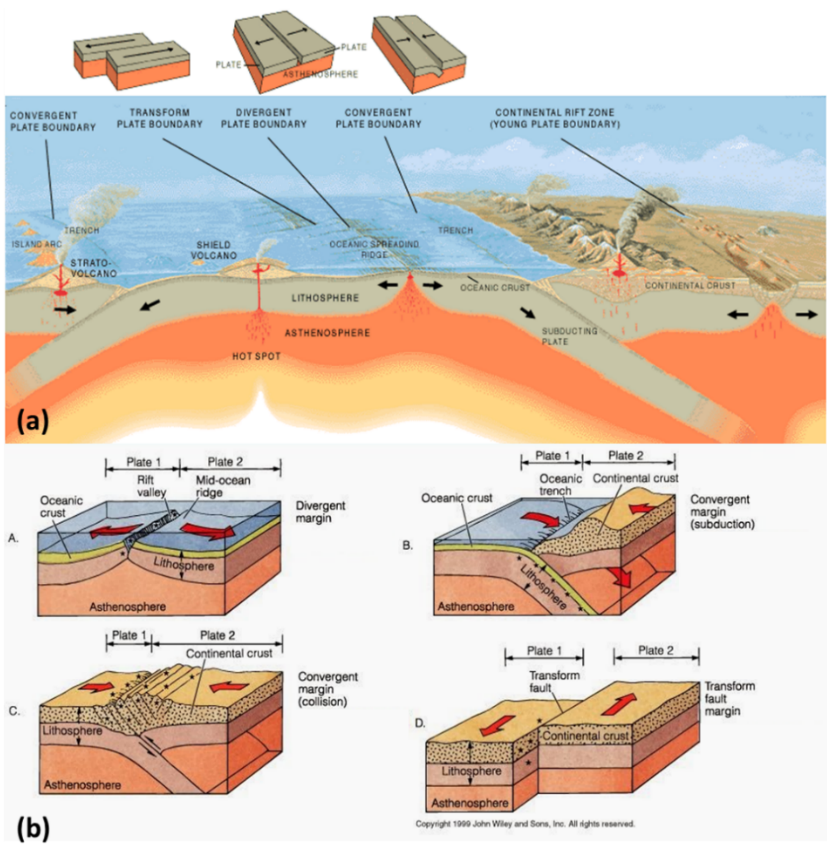


Figure 1. The Relationship Between the Earthquake and the Tsunami

(Source:(a) Cross section by José F. Vigil from This Dynamic Planet -- a wall map produced jointly by the U.S. Geological Survey, the Smithsonian Institution, and the U.S. Naval Research Laboratory., (b) Skinner et al., 1999)

As illustrated by Figure 1 earthquakes caused by different source mechanisms, if they occur near a body of water – whether a lake, the sea or the ocean – can generate tsunami waves. In open bodies of water such tsunami waves can travel great distances and be further enhanced in height by effects of refraction, convergence, refraction, or resonance (Pararas-Carayannis, 2011). The generation of the tsunami waves at the source area will depend on the magnitude and energy release of the earthquake and the volume of water that is displaced. Based on quick estimates of such parameters at the source region in real time, and by using numerical modeling approaches, the potential height, energy impact and of a tsunami's travel time can be estimated and advisories or warnings can be issued.

Measurements of the various seismic signals generated by the earthquakes and of tide gauge recordings have a tremendous potential for proper evaluation of tsunami generation, for issuing timely warning and for the initiation of evacuation procedures for endangered coastlines. Such evaluations are made by several organizations, immediately after an earthquake is recorded. In addition to the Pacific Tsunami Warning Center (PTWC) which issues mainly watches and warnings for the Pacific Ocean region (Lamarche et al., 2010), since the 2004 Great Sumatra earthquake and tsunami, an Indian Ocean Tsunami Warning System (IOTWS) was established for the Indian Ocean region (Fakhruddin, 2015), and a Consolidated Reporting System for Earthquakes and Tsunamis (CREST) was also installed for the west coast of the United States (Oppenheimer et al., 2001). Additionally, established was the Deep-Ocean Assessment and Reporting of Tsunamis system (DART) which Japan also installed in the Pacific Ocean, and Indonesia installed Tsunami Early Warning System (InaTEWS) in several coastal and marine areas in Indonesia (Harjadi, 2008; Lauterjung et al., 2010; Harig et al., 2020). Apart from the above, several local national tsunami warning systems were also developed worldwide, as part of joint cooperative efforts.

By examining the various sophisticated tools which have been developed for the detection of earthquakes and tsunamis, this matter was given additional study and further development of tools for timely tsunami disaster determination, known as the Tsunami Early Warning Systems (TEWS). However, because of the proximity to potentially active seismic zones, Indonesia is still unable to predict and warn about impending earthquakes and tsunami generation in the immediate area. Based on the analysis of seismic parameters such as epicenter and magnitude, predictions were subsequently made whether or not a tsunami was generated or not (Dixon et al., 2014; Angove et al., 2019; Han & Drake, 2016; and Buulolo et al., 2017).

Although earthquake occurrence cannot be predicted, the subsequent tsunami generation can be evaluated and predicted (Satake, 2014; Melgar et al., 2016; Chen et al., 2020). Moreover, predictions can be made on the potential degree of destruction and of the impact on the economic sector and on other important aspects in society (Fontana et al., 2020; Potter et al., 2015). It takes a long time to recover from the impacts of destruction from earthquake in the immediately stricken areas, as well as for the far-reaching destruction caused by tsunami waves. Based on the description above, the need of knowing the technology development - related NEWS is an effort to anticipate natural disasters that will strike, especially tsunamis. The development of this technology is needed for specific countries which have a significant tsunami threat. TEWS should be installed to anticipate the upcoming disasters. For now, as to what extent TEWS developments have been developed, and one of the sources that can be used as a reference, is the publication of scientific articles. Their publication provides to the public information related to recent findings that are beimg developed through the research results. Trusted journal sources that can be used as references are the articles indexed by the Scopus abstracts and citation database.

Through the analysis of bibliometrics, all broad and global scopes in the field of TEWS can be an indispensable resource for researchers to continue potential development of natural disasters topics, especially focusing on earthquakes and tsunamis. The designated research will discuss related development publications beyond the Tsunami Early Warning System based on the Scopus database using analysis of bibliometrics. The research will answer the following questions:

Q1: What are the publication trends TEWS during 2002-2022?
Q2: Which countries have contributed the most to the sector TEWS during 2002-2022?
Q3: Who are the most contributing authors to the field of TEWS during 2002-2022?
Q4: What element journal has the most impact on the field of TEWS during 2002-2022?
Q5: How did articles contribute to the TEWS field during 2002-2022?

2. METHODS

The present study uses quantitative and qualitative bibliometrics analysis (Santos et al., 2017; Prahani et al., 2022; Suprapto et al., 2022b; Lima & Bonetti, 2020). The data source being used comes from the Scopus database. Figure 2 shows the research flowchart. Bibliometrics analysis starts with several stages and criteria as follows:

1. Determining the keyword, namely within 'TITLE ABSKEY (tsunami AND early AND warning AND system),
2. Limiting the year the database will be used, namely the years 2002-2022,
3. Downloading the database in the form of Csv, Ris, and BibTex,
4. Analyzing content, and
5. Providing conclusions.

In the process of analysis and visualization data, the authors use the package Bibliometrics from Rstudio, which includes various forms of visualization (Aria & Cuccurullo, 2017; Rodríguez et al., 2022; Dervish, 2019). In addition, the authors also use software Ms-Excel and VosViewer to make data and network visualization appear more attractive (Prahani et al., 2022; Suprapto et al., 2022c; Hariyono et al., 2022). According to Mukherjee et al. (2020), Narváez-Bandera et al. (2020), and Prahani et al. (2022) the VosViewer and Rstudio are two of the programs many used in the bibliometric analysis.

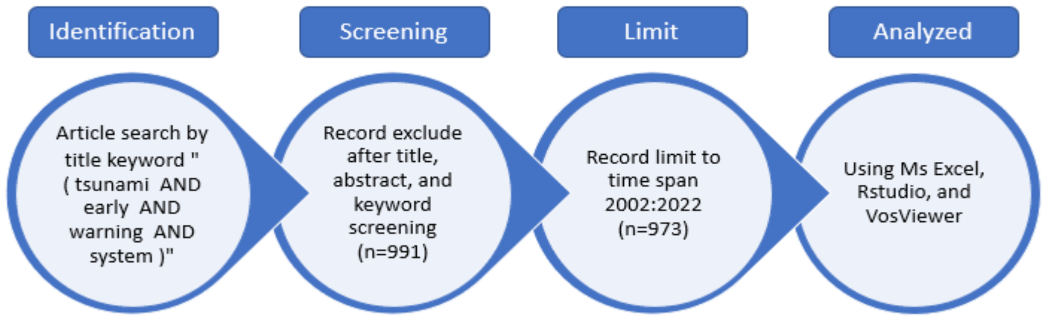


Figure 2. Research Flowchart.

3. RESULTS AND DISCUSSION

3.1 Main Information of TEWS

Limiting the search to twenty years from 2002-2022, the finals produced many works in the form of internationally indexed articles from 2,743 authors from various countries who have expertise in the field of disaster mitigation, especially on earthquakes and tsunamis. Table 1 shows the primary information from the TEWS field based on the Scopus database, assisted by the program Bibliometrix in Rstudio.

Table 1. Main Information.

Description	Result	Description	Result
Key Information		**Types of Documents**	
Sources (Journals, Books, Articles, etc.)	447	Article	552
Documents	973	Book	5
Average citation per document	14.04	Book Chapter	34
References	29962	Conference paper	302
Document contents		Conference review	12
Keyword plus (ID)	4759	Editorial	3
Author's keywords (DE)	1871	Erratum	1
Author Collaboration		Letter	4
Single-authored documents	157	Note	7
Co-Author per documents %	4.12	Review	48
International co-authorships %	29.19	Short survey	5
Author			
Authors	2743	Author of single-authored documents	123

Based on Table 1, the profile of TEWS for twenty years from 2002 to 2022 is documented as final. Additionally, the profile provides information that the types of documents indexed by Scopus are not just articles, but also books, notes, letters, and other miscellaneous papers. In addition, and in relation to the author, the profile also indicates that the work is not only of a single researcher but of a joint collaboration with other researchers from various countries. According to Kirschner et al. (2008), Un, C. A and Asakawa (2015), and Nokes-Malach et al. (2015), such mutual collaboration brings better ideas, greater in-depth knowledge, reinforces a clear discussion, and therefore produces better results.

3.2 The Annual Publication in TEWS 2002-2022

For 2002-2022, research in TEWS has experienced ups and downs in total, as shown on the data presented in Table 2. Table 2 presents publication data for the number of final articles for the 2002-2022 in the TEWS field. As shown, the number of articles presented fluctuates every year.

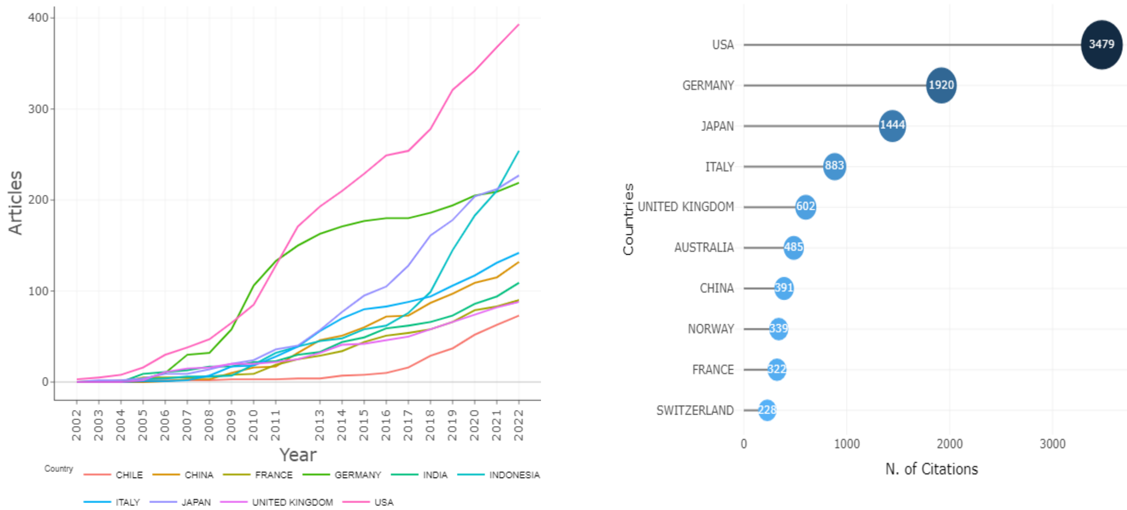
Table 2. The Annual Publication in TEWS 2002-2022

Year	N	Mean TC per Article	Mean TC per Year	Citable Years	Year	N	Mean TC Per Article	Mean TC Per Year	Citable Years
2002	1	115.00*	5.48	20	2013	68	23.37	2.34*	9
2003	4	18.00	0.90	19	2014	54	16.30	1.81	8
2004	4	26.50	1.39	18	2015	57	12.02	1.50	7
2005	37	13.19	0.73	17	2016	48	14.40	2.06	6
2006	23	36.57	2.15	16	2017	33	9.33	1.56	5
2007	28	15.46	0.97	15	2018	64	8.34	1.67	4
2008	29	22.93	1.53	14	2019	74	8.70	2.18	3
2009	47	20.51	1.47	13	2020	77	6.40	2.13	2
2010	57	16.33	1.26	12	2021	63	3.16	1.58	1
2011	71	21.65	1.80	11	2022	58	1.14	1.14	0
2012	76	18.67	1.70	10					
TC: Total cited, N: total, *= Top									

If analyzed carefully, there is a very significant increase in 2005 from 4 to 37 articles. This increase was due to an earthquake which generated a tsunami in Aceh (Borrero, 2005); (Samarajiva, 2005); and (Puspito & Gunawan, 2005). After that, the trend fluctuated up and down in 2017. Subsequently from 2018 to 2020, there was an increase and then a decrease again due to the Co-19 pandemic, which limited the social public contact and interaction.

3.3 Top 10 Countries' Production Over Time and Most Cited Countries

In the scientific field, what we can be sure of is that there are countries that have an advantage alone. This can be proven by completed publication. Figure 3 below presents the publication production data from the top 10 countries in the world.



3(a) 3(b)

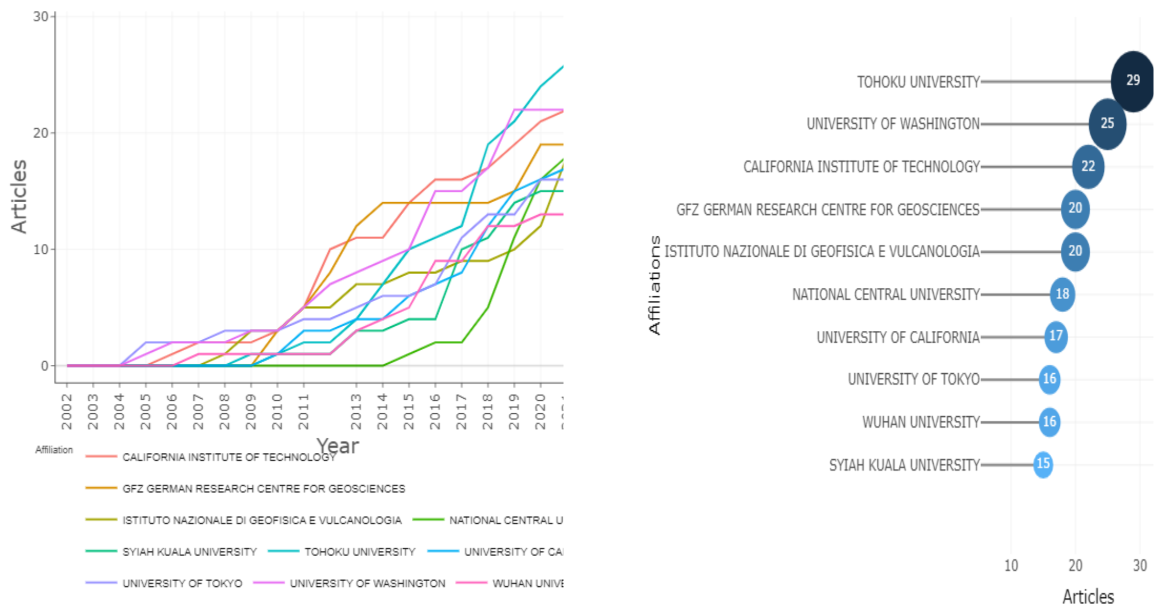
Figure 3. (a) Top countries' Production, (b) Most Cited Countries.

Figure 3 presents the top 10 countries based on the number of production and number of citations - the most throughout 2002-2022. Based on Figure 3(a) USA prevailed (199 docs) with the highest number of articles produced during the last twenty years, followed by Germany (129 docs), Indonesia (129 docs), and Japan (128 docs).

By comparison, the most cited countries which prevailed in production and number of citations were the USA (3479 cited), followed by Germany (1920 cited) and Japan (1444 cited). Some of Indonesia's published articles are included in the TEWS top three publications but not included in the top ten cited articles. - This demonstrates that the number of publications does not affect the number of citations but influences the quality of the article published, which is in agreement with research by Haslam and Laham (2010), Sandström than van den Besselaaret al. (2016), and Torres et al. (2015), which state that quantity does not affect the quality of a published article. Thus, it can be concluded that quality does not depend on the number of existing articles but on excellence alone.

3.4 Top 10 Affiliation Production Over Time and Most Relevant Affiliation

Related to publications carried out by researchers, it indeed cannot be separated from their institutional affiliations. Figure 4 below presents the top and most relevant affiliations for the twenty years period (2002-2022).



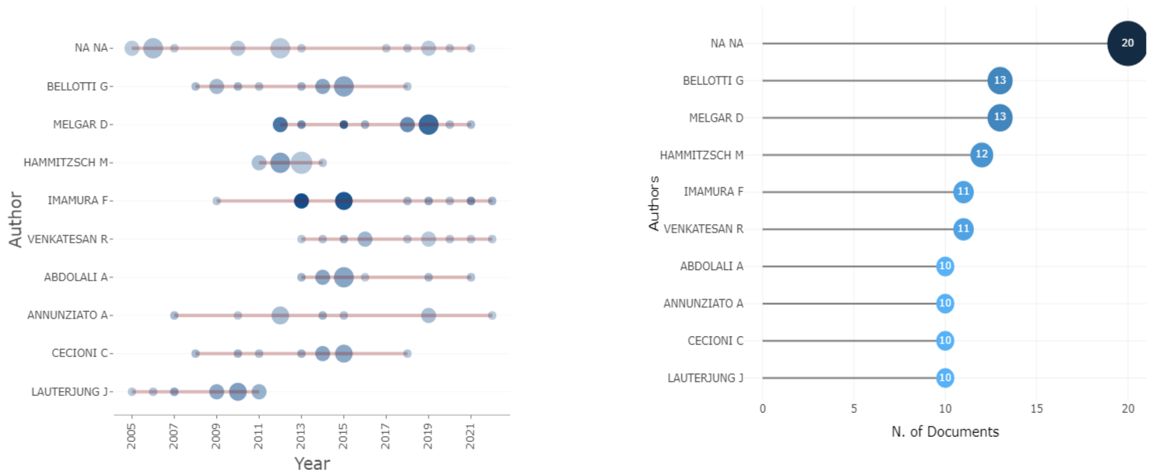
4(a) 4(b)

Figure 4. (a) Top 10 Affiliations, (b) Most Relevant Affiliation.

Figure 4 shows the top affiliate as article production and the most relevant article with an affiliate. Over the last twenty years, the publication of articles that carry the name of the affiliate experience from year to year. However, from 2002-2022, the most influential and relevant affiliations with the TEWS topic were the Tohoku University, the University of Washington, and the California Institute of Technology. The trend in Figure 4(a) indicates that research on the field of TEWS of relevant institutions continues to grow. The trend also indicates that each insist certainly has a top priority area in one field of science, but it cannot be denied that it will continue to work and can be evenly distributed since it consists of various scientific fields (Mi et al., 2021; Said & El-Shafei, 2021; Ellis et al., 2021)

3.5 Top 10 Author Production Over Time and The Most Relevant Author

It not only discusses the country and the affiliate which excels in the field of TEWS but also discusses who is deep into TEWS. This information can be found through analysis and visualization based on the number of publications they do. Figure 5unite database author production and most relevant. Visualization of Figure 5 presents the top author in the TEWS field. Figure 5(a) implies the presence of small round shapes in a straight line. The straight line gives the meaning of the duration of the active time used inside the writer's effort publication, whereas, for small numbers, it means the number of publications made in that year. This matter means that the more the size of the circle then, the more that article is published by the author. In addition, it can be seen that the author is not continuously active in publications. This is shown by the presence of a line that is not filled by a circle in a given year.



5(a) 5(b)

Figure 5. (a) Top production author, (b) most relevant author

With the cumulative amount, publication could be traced based on the most relevant author based on the document. Figure 5(b) serves several documents from each top 10 authors. The first place is held by Na Na (20 docs), the second place by Bellotti (13 docs) and Melgar (13 docs), and the third place by Hammitzsch (12 docs). From the description of the analysis carried out, it can be known that top author production also becomes the most relevant author in the field of TEWS. Entered authors in top production, and the most relevant author have a more in-depth study of the field compared with other authors (Didegah & Thelwall, 2013; Suprapto & Prahani, 2021a; Halevi et al., 2016).

3.6 The Most Relevant Country by The Corresponding Author

The quality of an article, indeed, cannot be separated from a supervisor. In this case, the supervisor is responsible for one article and becomes the correspondent of the submitted article. Correspondents have a critical role in the smooth administration of the publication process article (Shazad et al., 2020; Dembek et al., 2020). Table 3 presents the country with the most correspondence with many publications published for twenty years in the TEWS field.

Table 3. Most relevant country by author

Country	Articles	SCP	MCP	MCPR	Country	Articles	SCP	MCP	MCPR
USA	108	77	31	0.287	China	46	33	13	0.283
Germany	84	56	28	0.333	India	39	33	6	0.154
Japan	71	51	20	0.282	United Kingdom	32	15	17	0.531
Italy	53	40	13	0.245	France	24	12	12	0.5
Indonesia	51	44	7	0.137					

SCP=Single-country publication, MCP= Multiple-country publication, MCPR= Multiple-country publication ratio

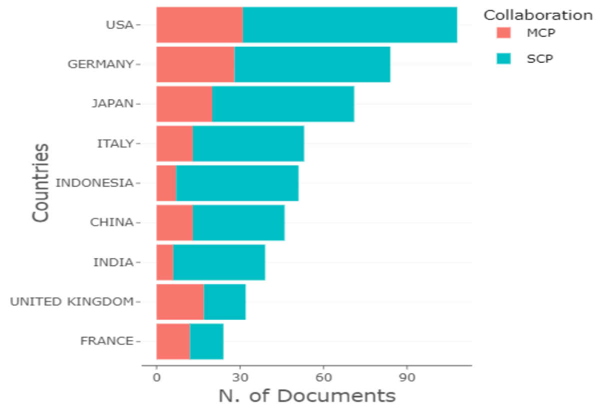


Figure 6. Visualization collaboration between author's countries.

Table 3 and Figure 6 present information about the most relevant author country based on collaboration. The USA obtained the top ranking in the total articles (108) with details of SCP (77), MCP (31), and MCPR (0.287). Then level two was followed by Germany with the number of articles (84) with details of SCP (56), MCP (56), and MCPR (0.333). Additionally again, the third stage was filled by Japan with details of articles (71), SCP (51), MCP (20), and MCPR (0.282). From this information, collaboration momentum is a necessary skill used to reach common goals. In this case, it expands the development of related science TEWS regularly and globally.

3.7 Top 15 source impact in TEWS 2002-2022

Analysis of the source of the impact of research is a significant effort looking for linear sources with the researcher's goals. In addition, the existence of a source of impact can be material for development in other journals. Table 4 presents the source impact based on the journal element.

Table 4. Top 15 journal source impact.

Journal Element	h-index	g-index	m-index	Total Citation	Journal Element	h-index	g-index	m-index	Total Citation
Geophysical Research Letters	20	34	1	1376	Seismological Research Letters	8	12	0.667	157
Natural Hazards and Earth System Science	20	32	1.333	1055	Earth, Planets, and Space	7	10	0.438	494
Pure and Applied Geophysics	15	28	0.938	840	Journal of Geophysical Research: Oceans	7	7	0.35	198
Geophysical Journal International	12	20	0.75	877	Journal of Disaster Research	6	10	0.5	112

Journal Element	h-index	g-index	m-index	Total Citation	Journal Element	h-index	g-index	m-index	Total Citation
Journal of Geophysical Research: Solid Earth	11	16	0.647	431	**Science of Tsunami Hazards**	6	11	0.353	142
Natural Hazards and Earth System Sciences	11	17	0.786	306	Disaster Prevention and Management: An International Journal	5	6	0.236	299
Natural Hazards	9	21	0.429	448					
Scientific Reports	6	10	0.6	164					
Coastal Engineering	5	5	0.313	143					

Table 4 denotes the top 15 source impacts on field TEWS based on journal elements. Additionally, it shows the h-index, g-index, m-index, and total citations of each journal. Journal elements from Geophysical Research Letters, Natural Hazards, and Earth System Science have the best h-index, namely, a significant 20. The H-index becomes one indicator of effort measure impact productivity from a journal (Ding et al., 2020; Al-Mosawi, 2019; and Ding et al., 2020). The g-index is part of the h-index, which allows the citation of higher cited articles to support articles which fewer quotes. The G-index is calculated from the distribution of citations received from research publications (Roldan-Valadez et al., 2019; Robinson et al., 2019; Chattopadhyaya et al., 2022). The number of citations has an evident influence on the h-index value owned by a journal.

3.8 The Most Globally Cited Author During 2002-2022

Developed TEWS discussion becomes one of the references source currently. This is because the theory put forward by the author is still related to the discussion of a researcher's study. Hence, they still use references even though their period is long enough.

Table 5. Most globally cited author.

Author's Paper	TC	TCPY	NCT	Author's Paper	TC	TCPY	NCT
Basher R, 2006, *Philos Trans R Soc A Math Phys Eng Sci*	285	15.83	7.79	Suppasri A, (2013). *Pure Appl Geophys*	158	14.36	6.76
Kanamori H, (2008*). Geophys J Int*	264	16.50	11.51	Doocy S, (2013). *Plos Currents*	156	14.18	6.68
Cochard R, (2008). *Perspect Plant Ecol Evol Syst*	206	12.88	8.98	Chatfield At, (2013). *Gov Inf Q*	139	12.64	5.95
Blewitt G, (2006*). Geophys Res Lett*	192	10.67	5.25	Makela Jj, (2011*). Geophys Res Lett*	123	9.46	5.68
Duputel Z, (2012*). Geophys J Int*	160	13.33	8.57	Wright Tj, (2012). *Geophys Res Lett*	120	10.00	6.43

Table 5 shows the top 10 authors with the most citations globally during 2002-2022 in the TEWS field. The first ranked is by Basher, 2006 with 285 citations. Both ranks are those by Kanamori, 2008 with as much 264 being cited. The third ranking is held by Cochard, 2008 with 206 citations. All of the three authors with the most citations mark work extensively published over the last twenty years. In accordance with studies by Huffman et al., 2013; Terán-Yépez et al., 2022, 2019, state that there is a trend increase in citations over such a long period with a record of quality articles.

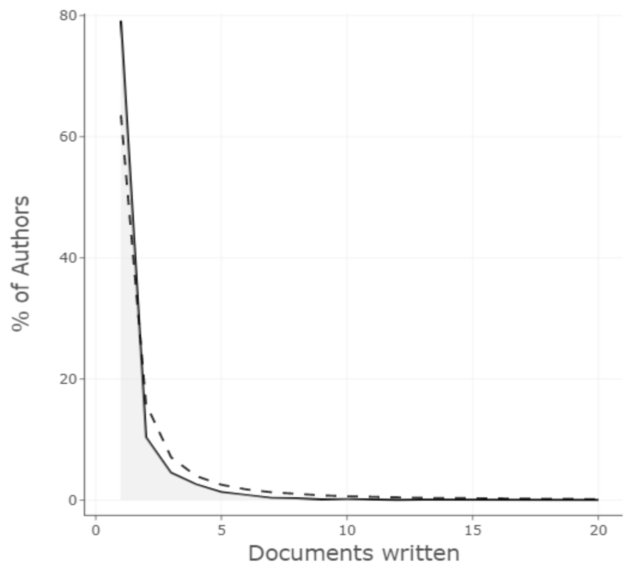


Figure 7. Percentage productivity distribution author.

3.9 Frequency Distribution of Scientific productivity (Lotka's Law)

Corresponding with a statement from Lotka that, respectively, writers in their fields certainly contribute. However, it has just been distinguished by the contribution percentage in that field. The Figure 7 above and Table 6 show the data from the distribution productivity based on Lotka's Law. The coefficient percentage of publications in the field of TEWS during 2002-2022 can be calculated using bibliometric analysis with the help of bibliometrics. Author publication frequency could be seen in the article that has been written according to Figure 7. Figure 7 can be known as author productivity according to Lotka's Law.

Table 6. Correlation document distribution with author.

Documents written	N. of Authors	Proportion of Authors	Documents written	N. of Authors	Proportion of Authors
1	2171	0.791	6	24	0.009
2	285	0.104	7	10	0.004
3	124	0.045	8	8	0.003
4	71	0.026	9	3	0.001
5	36	0.013	10	5	0.002

Based on Table 6, parameters can be found, not only in the field of study, but can be viewed from country, study period, productivity contribution, and collaboration between writers. As seen on Table 6, the number of authors for (1 doc) consists of 2,171 writers with a proportion of authors of 0.791. That distribution, furthermore, is shown in Table 6.

3.10 Top Rank productivity journal (Bradford's Law)

Under Bradford's Law, it is a known productivity journal with assisted bibliometric analysis database Scopus. Here are the results served in Table 7.

Table 7. Rank journal based on Bradford's Law

Core Journal	Rank	Freq	CF	Core Journal	Rank	Freq	CF
Pure and Applied Geophysics	1	40	40	**Science of Tsunami Hazards**	9	18	225
Geophysical Research Letters	2	34	74	Journal of Geophysical Research: Solid Earth	10	16	241
Natural Hazards and Earth System Science	3	33	107	Seismological Research Letters	11	14	255
Natural Hazards	4	22	129	Journal of Disaster Research	12	11	266
Geophysical Journal International	5	20	149	Journal of Physics: Conference Series	13	11	277
IOP Conference Series: Earth and Environmental Science	6	20	169	AIP Conference Proceedings	14	10	287
Natural Hazards and Earth System Sciences	7	19	188	Earth, Planets, and Space	15	10	297
Proceedings of the International Offshore and Polar Engineering Conference	8	19	207				
Freq= Frequency, CF= Cumulative frequency							

As shown in Table 7 most journals discuss the TEWS for two ten-year by Pure and Applied Geophysics with frequency counts of as much as 40. This publication can be a primary reference for researchers focusing on tsunamis and to get information from journals at the top rank, according to this table. In accordance to published research by Fudgier (2020), Alshater et al. (2022), and Gautam et al. (2019), who state that Bradford's Law is being used for known deployment information of articles from various journals, authors need to understand the methods related to this Bradford's Law in order to focus on research information of better quality.

3.11 The most frequent Keyword

In a field of research, keywords must be used as a template to find correlations with other fields. The most frequent keywords used in TEWS research during 2002-2022 are presented and listed in Figure 8.

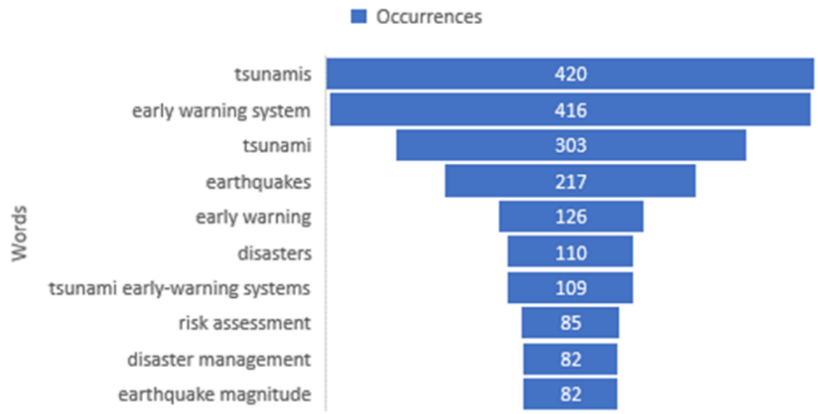


Figure 8. The most keywords being used.

Most keywords being used in the TEWS research field are "Tsunamis" (420 words), then followed by "early warning systems" (416 words), and "tsunamis" as much as (303 words). If traced deeper, the words used are linear with the research topic being studied. In addition, a word order of four to ten still closely correlates with TEWS. Keywords are not just words but have the main function of being the center of ideas for each article in an effort to help manage subsequently published articles (Lu et al., 2019; Fridell et al., 2020; Christy et.al., 2019).

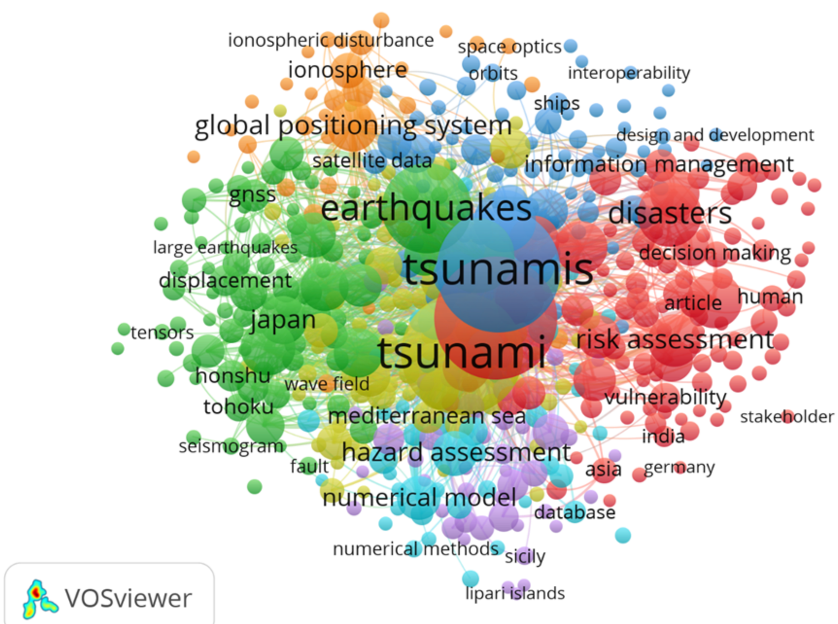


Figure 9. Network visualization of TEWS

Based on Figure 9, there are 7 clusters from each relationship between. The first cluster, colored red, consists of 107 items, with the dominating words "early warning system". The second cluster, colored green, consists of 89 items, with the most dominant word being, "earthquakes". The third cluster in blue consists of 75 items, with the most dominant word being "tsunamis". The fourth cluster, colored yellow, consists of 70 items, with the word that most dominates being "Tsunami". Cluster five colors young consists of 45 items. with word which most dominate being "landslides". The sixth light blue cluster consists of 44 items, with the most dominant word being "hazard assessment". Cluster seven colored orange, consists of 34 items, with the word that dominates being "global positioning system". The seven clusters consisting of the total amount of 464 items, have an inter-relationship. Based on this classification, readers could find new information on future research that needs to be studied greater depth. Cluster color is only a reference of a focus discussion, whereas for relationships, one should look at color clusters because all of them are included in the keyword "tsunami early warning system". With existing related words, searches can be conducted with appropriate regularity (Oliveira et al., 2019; Eberhard, 2021; Kroon et al., 2021).

3.11 Thematic map in the field TEWS

A thematic map is usually used to explain trends and patterns of owned data visualization pictures. There are four category trends which can be seen in Figure 10, below.

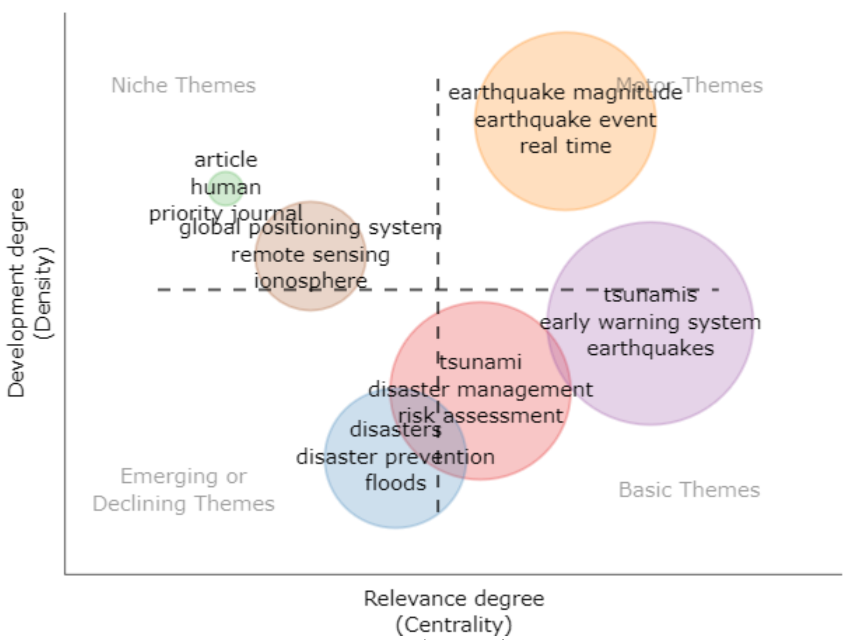


Figure 10. Thematic map.

Based on the thematic map above, it can be divided into four main categories on the field Limited TEWS bury centrality line. The first category is the Niche theme which can be seen on the Top left and consists of several words such as article, human, priority journal, and global positioning system. The second category is motor themes which consist of earthquake butte, earthquake events, and real-time. Category third is emerging or declining themes, consisting of some words like disaster, risk, disaster prevention, and floods. The fourth category is the primary theme: tsunamis, a warning system, and earthquakes. This information shows that the fundamental, niche, motor, and emerging or declining themes are in TEWS field research, thus becoming a new picture for the following search. study next Where to start research. For more details, as to where to start searches, see Table 8 which relates to nodes between categories which were also illustrated above in Figure 10.

Table 8. Thematic Co-Occurrence

Node	Cluster	Betweenness	Closeness	Page rank
Tsunamis	1	90.18152034	0.020408163	0.090484395
Early warning system	1	79.30464192	0.02	0.084220573
Earthquakes	1	34.14520499	0.020408163	0.058390097
Early warning	1	9.732163127	0.020408163	0.032923089
Disasters	1	3.868636212	0.016393443	0.024371491
Tsunami early-warning systems	1	2.645382104	0.018518519	0.022550292
Risk assessment	1	1.146267387	0.015384615	0.01695842
Disaster management	1	2.114444419	0.015873016	0.019194829
Hazards	1	2.740235401	0.018518519	0.020407212
Alarm systems	1	1.678169681	0.01754386	0.017195548

3.12 Multiple Correspondence Analysis Approach

The factorial maps shown in Figure 11 and Figure 12 show the relationship results between two variables tied to each other. The analysis uses multiple corresponding functional analyses as one of the methods that can connect the two variables in detail (Schöggl et al., 2020; Nita, 2019). Visualization in Figure 11 and Figure 12 is obtained based on the help software R Studio connected with bibliometrics biblioshiny.

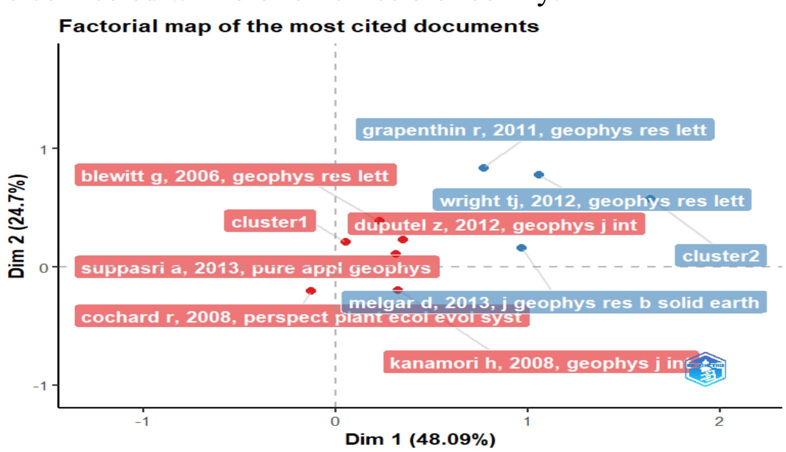


Figure 11. Factorial map using multiple corresponding analysis approaches by top cited related to TEWS during 2002-2022.

Based on Figure 11 and Figure 12, it is deduced that existing MCA (multiple corresponding analyses) can be one of the alternative efforts in looking for similarities between articles and for conceptual building in the identified field, in order to discuss similar concepts. With the use of MCA, then it is possible to know the dependency of known variables, in finding and considering other related variables.

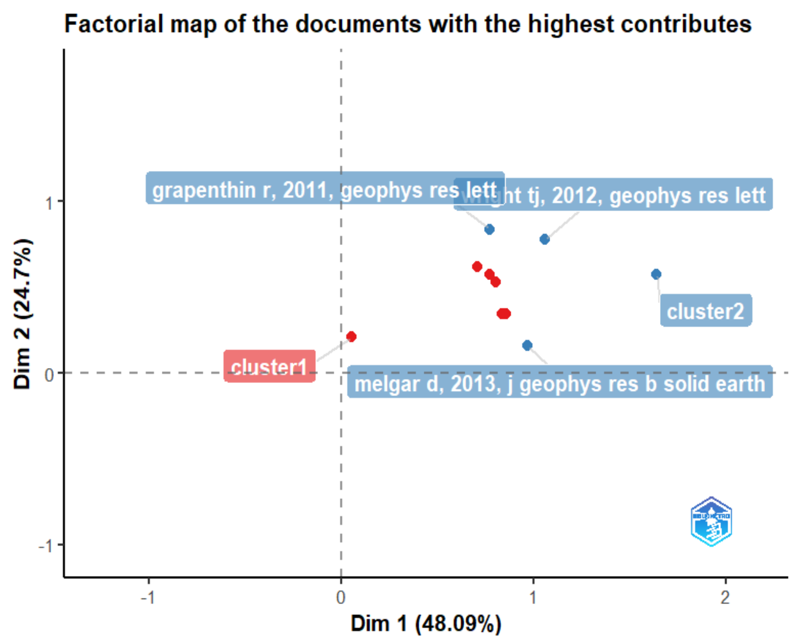


Figure 12. Factorial map using multiple corresponding analysis approach by highest contributions related to TEWS during 2002-2022.

In addition, MCA presents a visualization that shows similar data on a researched field that can be attention-specific to the field being studied (Parchomenko et al., 2019; Florence et al., 2022). That way, a researcher can find out in the TEWS field the most widely referenced data distribution as seen in Figures 11 and 12.

3.13 Analysis Topic Dendrogram

One form of good data representation used is in the form of a dendrogram. This is because it refers to clusters on the field analyzed so that grouping for better research results. The results chart of TEWS can be seen in Figure 13, which shows a dendrogram visualization model based on hierarchical analysis. Analysis results of the group data is based on clusters with the most closely related relationships between one with another. In essence, the analysis assists researchers in connecting or looking for a relationship between one field of science to another. It is equalized to a tree consisting of roots, and branches, as shown in Figure 13 (Eissa et al., 2022; Öztürk et al., 2022).

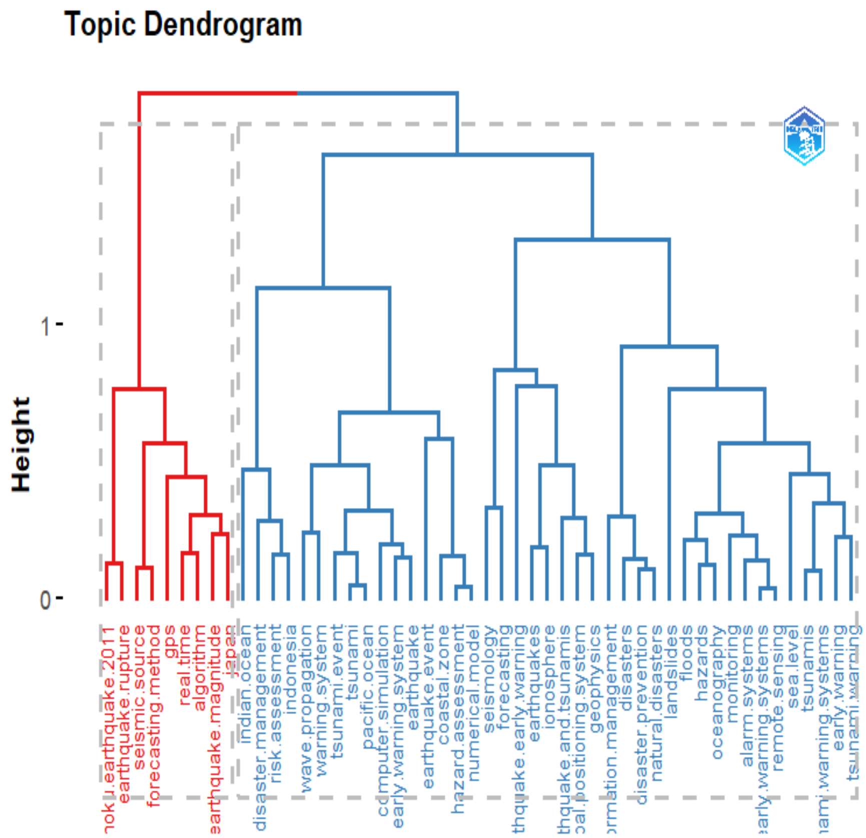


Figure 13. Dendrogram Analysis.

CONCLUSION

This article discusses research trends in the TEWS field during the years 2002-2022. In addition, the thematic map section discusses the basic emerging or declining themes, which consists of related words. From the presented discussions, it becomes evident that the TEWS field consists of various roots or branches that can be identified from the existing clusters. In addition, research in the TEWS field is predominated by the USA, Japan, and Germany, the most relevant countries in this field, which have contributed to most authors. In addition, the most contributing authors over the last twenty years are from the USA (with 108 docs). The most influential journal in the field of TEWS is Pure and Applied Geophysics, with a frequency of 40. This article is expected to impact future research related to existing information. It has the potential finding to be used as a starting art for further research. On the other hand, suggestions for writers and readers are made to compare with TEWS researches so that they can find a new line of discovery in predicting and anticipating and preparing for future earthquakes and tsunamis.

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EVALUATION OF EARTHQUAKE RECURRENCE ON THE NORTHERN ANATOLIAN FAULT OF ASIA MINOR AND OF TSUNAMI GENERATION IN THE SEA OF MARMARA – Review of the 17 August 1999 Earthquake and Tsunami.

George Pararas-Carayannis

Tsunami Society International

ABSTRACT

The North Anatolian Fault Zone (NAFZ) is the most prominent active fault system in Northwestern Turkey. It is a major fracture that traverses the Northern part of Asia Minor and marks the boundary between the Anatolian tectonic plate and the larger Eurasian continental block, and has been the source of numerous large earthquakes throughout history. The NAFZ splits into three strands at the eastern part of the Marmara Sea. The northern strand passes through Izmit Bay, traverses the Marmara Sea and reaches to the Saros Gulf. The central fault zone passes through Izmit Bay, traverses the Sea of Marmara and reaches the Saros Gulf to the southeast. Earthquakes on this zone involve primarily horizontal ground motions (strike-slip type of faulting). Because of this unstable tectonic system, the area is considered to be as one of the most seismically active zones of the world. In the last hundred years, numerous large earthquakes have also occurred along the NAFZ, in the western part of Turkey. Beginning with an earthquake in 1939, several more quakes - with Richter magnitudes greater than 6.7 - struck in progression along adjacent segments of the great fault. The August 17, 1999 Izmit earthquake was the eleventh of such a series that have broken segments of the NAFZ, in both eastward and westward direction. The epicenter of the 1999 earthquake was near Izmit, as well as the location of previous events. The sequence of historic events indicates that the next destructive tsunamigenic earthquake could occur west of the 1999 event in the Sea of Marmara. The present study incorporates the results of a subsequent 2001 study which uses standardized remote sensing techniques and GIS-methods – based on Digital Elevation Model (DEM) data, and on geo-morph metric parameters that influenced local site conditions in the Sea of Marmara, as determined with Digital elevation data of the Shuttle Radar Topography Mission (SRTM), and with high resolution ASTER-data. With such remote sensing methods, areas that are potentially vulnerable areas in the Sea of Marmara were detected, so that disaster mitigation strategies can be implemented more effectively in the future. Based on such technology, local site conditions, which exacerbated earthquake intensities and collateral disaster destruction in the Marmara Sea region, were identified. Also reviewed by the present study are the similarities of NAFZ with the San Andreas fault in California in the USA, for the formation of an active transform boundary of the strike-slip type, with the two sides moving horizontally and continuously past each other. Finally examined is the tectonic and continuing geodynamic evolution and collision between the Arabian Plate and Eurasia, which places in danger many cities in southeastern Turkey and NorthWest Syria - which is are located on the boundary with the Arabian tectonic plate, as evidenced by the recent disastrous earthquake of 8 February 2023 along the Eastern Anatolian Fault Zone (EAFZ).

Keywords: *1999 Izmit earthquake, tsunami, landslides, Bosporus, Sea of Marmara, Dardanelles, GIS methods, Digital Elevation Model, Shuttle Radar Topography.*

1. INTRODUCTION

On August 17, 1999, a very destructive earthquake on the Northern Anatolian fault struck northwest Turkey and generated a local tsunami within the enclosed Sea of Marmara. Both the earthquake and the tsunami were particularly destructive at Golcuk in the Gulf of Izmit and at other coastal cities in the eastern portion of the Sea of Marmara. The earthquake was also responsible for extensive damage from collateral hazards such as subsidence, landslides, ground liquefaction, soil amplifications, compaction and underwater slumping of unconsolidated sediments. This was the strongest tsunamigenic earthquake to strike Northern Turkey since 1967, and it was recorded by many seismic stations around the world (Pararas-Carayannis, 1999, 1999a, 2000; Yalçiner EtAl, 1999; Altinok EtAl, 1999; Erdik, 2000; Altinok EtAl, 2001; Armijo EtAl. 2002, Taymaz EtAl, 2004; Herbert EtAl, 2005; Soirensen EtAl, 2006; Pararas-Carayannis EtAl, 2011).

Official estimates indicated that about 17,000 people lost their lives and thousands more were injured. However, it is believed that the death toll may have been much higher**.** On 31 August, a strong aftershock killed one person, injured about 166 others and knocked down some of the buildings that were already weakened by the main quake. Surprisingly the aftershocks caused a great deal of damage, which indicated that local conditions, exacerbated earthquake intensities of even weaker events to have secondary collateral destructive impacts. Most of the destruction and deaths resulted from such secondary collateral impacts at locations along coastal area of the Sea of Marmara that were particularly vulnerable because local geologic site conditions, exacerbated earthquake intensities. Therefore, it was determined that there was a need to identify and map such vulnerable sites, based on technology not previously available.

Thus, and as briefly stated in the abstract, the present study incorporated the results of a subsequent study in 2001 which used standardized remote sensing techniques and GIS-methods – based on Digital Elevation Model (DEM) data, and on geomorphometric parameters that influenced local site conditions in the Sea of Marmara, as determined with Digital elevation data of the Shuttle Radar Topography Mission (SRTM), and with high resolution ASTER- data. With such recent remote sensing methods and technology, areas that are potentially vulnerable in the Sea of Marmara were detected, so that disaster mitigation strategies can be implemented more effectively in the future. The use of such methods was documented by the author in collaboration with Professor Theilen-Willige of the University o f Berlin and Professor Wenzel in Austria (Pararas-Carayannis EtAl., 2011). More of these findings are discussed in greater detail in a subsequent section of this report. Figure 1 below is a map of the Sea of Marmara and of the Gulf of Izmit.

Fig. 1. Map of the Sea of Marmara and of the Gulf of Izmit.

The source mechanism and impact of the August 17, 1999 earthquake and tsunami, as well as those of other numerous historical events along the North Anatolian Fault Zone (NAFZ), have been studied extensively and reports have been published by numerous researchers, in addition to the ones mentioned above for events before and after 1999. These included the following: Altinok & Ersoy, 1998; Ansal EtAl., 2004; Barka & Kadinsky-Cade, 1988; Barka, 1992; Crampin & Evans,1986; Erdik, 2000; the Kandilli Observatory and Research Institute; the U.S, National Earthquake Information Center; Heidbach EtAl., 2008; Kuran & Yalciner, 1993; Ross EtAl, 1996; Toksoz EtAl.,1979; Spence (ed 2007). 2007.

1A. Earthquake Epicenter, Origin Time, Magnitude and Aftershocks

The epicenter of the 17 August 1999 earthquake was at 40.702 N, 29.987 E (USGS) near the town of Gölcük on the western segment of the North Anatolian Fault. The earthquake occurred at 00:01:39.80(UTC), 03:01:37 am local time, and its focal depth was shallow at 17 km. (USGS). The Izmit earthquake – as it was named - was measured widely by seismic stations around the world. However, there were small differences in magnitude determinations. The surface wave magnitude was given as 7.8 by the USGS, and its Moment Magnitude was given as Mw=7.4 by the USGS and by the Kandilli Observatory and Earthquake Research Institute (Kandilli). The Duration Magnitude was given as 6.7

(Kandilli), the Body Wave Magnitude as 6.3 (USGS), and as 6.8 (British Geological Survey). The earthquake resulted from right-lateral strike-slip movement on the Northern Anatolian fault, as many other seismic events in the past.

Numerous aftershocks with magnitude above 4 were recorded after the main earthquake. The first of the aftershocks (magnitude of 4.6) occurred 20 minutes later. Several others followed in subsequent days. According to the USGS and Kandilli most of the aftershock activity was confined to the region bounded by 40.5-40.8N and 29.8-30.0E, which covers the area between Izmit and Adapazari to the east of the epicenter (Pararas-Carayannis, 1999). However there was a cluster of aftershocks near Akyazi and Izmit.

Several days later, on 31 August, a strong aftershock killed one person, injured about 166 others and knocked down some of the buildings that were already weakened by the 17 August main quake. According to the USGS and Kandilli most of the aftershock activity was confined to the region bounded by 40.5-40.8N and 29.8-30.0E, which covers the area between Izmit and Adapazari to the east of the epicenter. However there was a cluster of aftershocks near Akyazi and near Izmit. Figure 2 shows the epicenter of the 1999 earthquake and the distribution of the larger aftershocks.

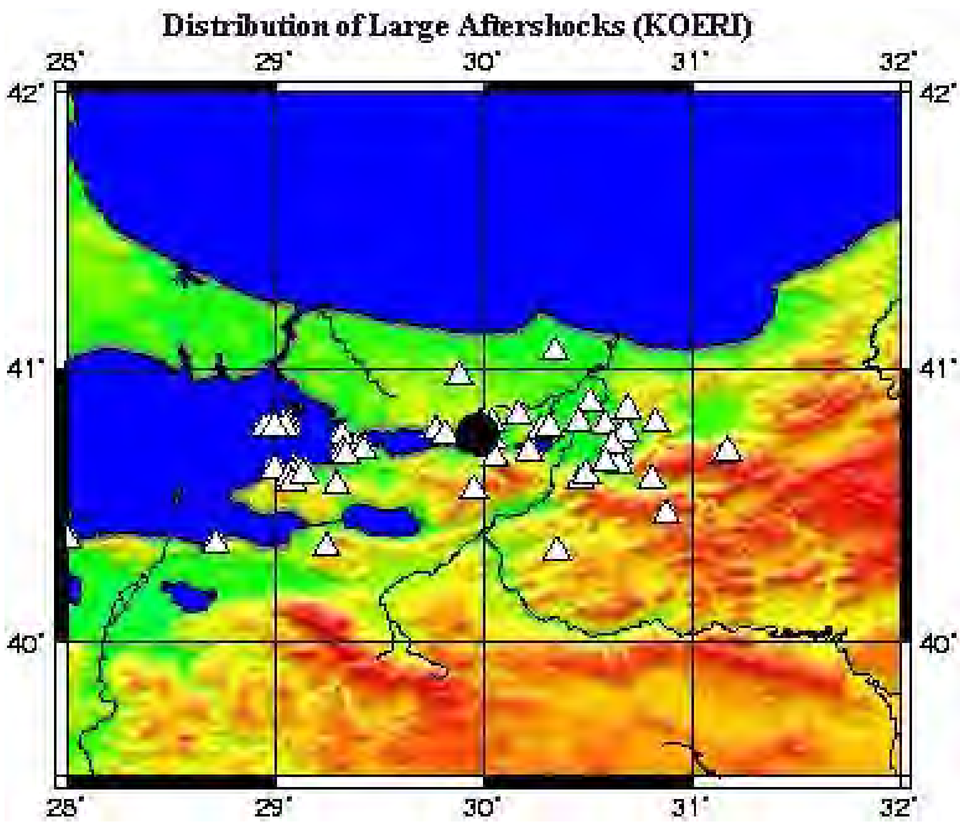

Fig. 2. Epicenter of the 1999 earthquake and distribution of the larger aftershocks

1B. Earthquake Destruction and Death Toll

The early historic record shows that in 1754, an earthquake near Izmit killed about 2,000 people. The earthquake struck a densely populated residential and industrial area, which included the major cities of Istanbul and Izmit. The more recent 17 August 1999 earthquake struck a densely populated residential and industrial area, which included the major cities of Istanbul and Izmit. The quake caused immense destruction to homes, apartment buildings, and oil refineries, to power and communication facilities. According to official reports the earthquake killed thousands of people and injured more than 16,000 others. The exact death toll for this event will never be accurately known as thousands were reported as missing.

Izmit - The earthquake in Izmit also caused immense destruction to homes, apartment buildings, and oil refineries. Many apartment buildings in the poorer section of Izmit collapsed burying thousands. Improper building construction was primarily responsible for the high death toll. Also, a huge fire at Turkey's largest oil refinery outside Izmit, destroyed several storage tanks.

Golcuk - At Golcuk about 500 buildings collapsed leaving about 20,000 people homeless. A Turkish naval base in the port of Golcuk sustained major damage. Reportedly, the collapse of the barracks killed 248 sailors.

2. TECTONIC AND GEODYNAMIC EVOLUTION - INSTABILITY OF THE NORTH ANATOLIAN AND OF THE EAST ANATOLIAN FAULT REGIONS

The source mechanism and impact of the August 17, 1999 earthquake and tsunami, as well as those of other numerous historical events along the North Anatolian Fault Zone (NAFZ), have been studied extensively and reports have been published by numerous researchers (Altinok & Ersoy, 1998; Altinok, et al., 1999, 2001; Armijo, et al. 2002; Ansal et. Al 2004; Barka & Kadinsky-Cade, 1988; Barka, 1992; Crampin & Evans,1986; Erdik, 2000; Kandilli Observatory and Research Institute; the U.S, National Earthquake Information Center; Hebert et.al,, 2005; Heidbach et.al,, 2008, Kuran & Yalciner, 1993; Pararas-Carayannis, 1999, 1999a, 2000; Pararas-Carayannis et.al. 2011; Ross et.al, 1996; Soìrensen, et.al, 2006; Taymaz et.al, 2004; Toksoz et.al 1979, Yalçiner et.al, 1999; Spence (ed 2007). 2007.

The excessive seismicity of this particular region can be explained by current geophysical knowledge of its structural development. The North Anatolian fault is a major fracture that transverses the Northern part of Asia Minor and marks the boundary between the Anatolian tectonic plate and the larger Eurasian continental block (Fig. 3). Because of this unstable tectonic system, the area is considered as one of the most seismically active zones of the world. Turkey is being squeezed sideways to the west as the Arabian plate pushes into the Eurasian plate. The north Anatolian fault forms the edge of this Turkish (Anatolian) crustal block so that destructive earthquakes happen regularly along it as different sections break. The Sea of Marmara is an inland sea separating Asia Minor from Europe. It is 280 km (175 miles) long and almost 80 km (50 miles) wide at its greatest width. On its northeast connects with the Black Sea through the Bosporus Strait. On its southwest end it connects with the Aegean Sea through the Dardanelles (Fig. 3). Although its total area is only 11,350 square km (4,382 square miles), its average depth is about 494 m (1,620 feet), reaching a maximum of 1,355 m (4,446 feet) in the center. The sea was formed as a result of tectonic movements that occurred about 2.5 million years ago, in the Late Pliocene. The region is characterized by frequent earthquakes.

Fig. 3. Tectonic map of the Anatolian Plate bounded by the African, Eurasian and Arabian plates - Modified After Nafi Toksoz of MIT/ERL

The Sea of Marmara is an inland sea separating Asia Minor from Europe. It is 280 km (175 miles) long and almost 80 km (50 miles) wide at its greatest width. On its northeast connects with the Black Sea through the Bosporus Strait. On its southwest end it connects with the Aegean Sea through the Dardanelles. Although its total area is only 11,350 square km (4,382 square miles), its average depth is about 494 m (1,620 feet), reaching a maximum of 1,355 m (4,446 feet) in the center. The sea was formed as a result of tectonic movements that occurred about 2.5 million years ago, in the Late Pliocene. The region is characterized by frequent earthquakes.

The earthquake of August 17, 1999 occurred along the long, East-West trending, great North Anatolian Fault Zone (NAFZ) - known to be the most prominent active fault system in Northwestern Turkey. NAFZ passes through Izmit Bay, traverses the Marmara Sea and reaches the Saros Gulf to the southeast. This great fault system has many similarities to the San Andreas Fault system in California. Earthquakes involve primarily horizontal ground motions (strike-slip type of faulting). Numerous large earthquakes have occurred throughout history. Figure 4 below, shows the epicenter of the 17 August 1999 earthquake and the chronological earthquake activity and sequence of major earthquakes along the Northern Anatolian Fault.

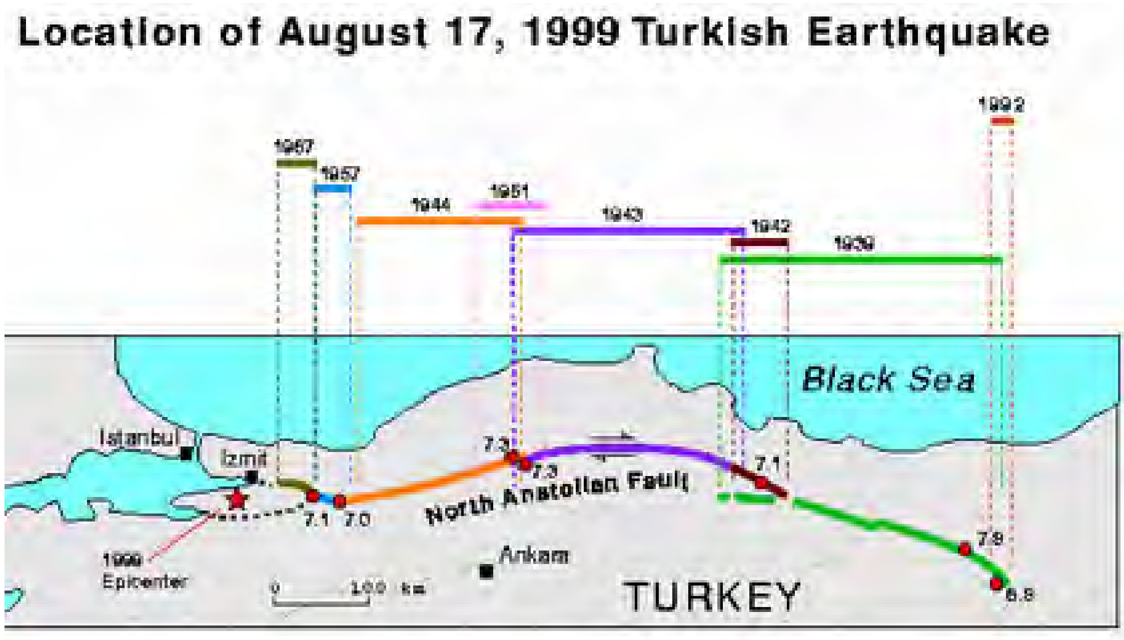

Fig. 4. Epicenter of the 17 August 1999 Earthquake. Historical Seismic Activity Along the Northern Anatolian Fault (Source: Kandilli Observatory and Research Institute)

2A. Earthquake's Surface Rupture and Ground Displacements

As stated, and shown in Figure 5 below, the 17 August 1999 Earthquake occurred along a known seismic gap on the North Anatolian Fault Zone. The earthquake's surface rupture extended for about 100 km east of Golcuk, but did not continue southeast and did not join the rupture of the 1967 earthquake - the last event in this region. Instead, the rupture turned northeast near Akyazi, where a cluster of aftershocks subsequently occurred. Ground displacements of about 1.5 m were measured in this area. Subsequent field studies indicated right lateral ground displacements ranging from 2.5-3 m up to 4 m, with a maximum of 4.2 m east of Lake Sapanca. Ground displacements between Lake Sapanca and the Gulf of Izmit were about 2.60 m. Additionally, there was evidence of about 2 meters subsidence along the north side of the fault's block - which was particularly evident along the coastline at Golcuk, where tsunami waves and major flooding occurred. Such tectonic ground displacements are characteristic of major earthquakes along the North Anatolian Fault and, possibly, have been responsible for tsunami generation in the past.

Fig. 5. Historical Earthquakes and Crustal Movements along the North Anatolian Fault (from Stein et al., 1996)

2B. Historical Earthquakes on the North Anatolian Zone of Turkey

Turkey is seismically very active on both the North Anatolian Fault Zone (NAFZ) and the Eastern Anatolian Fault Zone (EAFZ). The early historic record shows that in 1754, an earthquake near Izmit killed about 2,000 people. In the last hundred years, numerous large earthquakes have occurred along the Northern Anatolian Fault (NAF), on the western part of Turkey. Beginning with an earthquake in 1939, several more quakes - with Richter magnitudes greater than 6.7 struck in progression along adjacent segments of the great NAFZ fault zone. The 17 August 1999 Izmit earthquake was the eleventh of such series that have broken segments of the NAF, in both eastward and westward direction.

There has been an interesting pattern to this seismic activity. Historic seismic records indicate that between 1939 and 1944 there was an active westward trend in seismic activity on the NAF, with a resulting surface rupture of about 600 km. Subsequently, the westward trend of earthquakes slowed down. Figure 6 shows the epicenter of the 17 August 1999 earthquake on the northern strand of the NAF fault in the Sea of Marmara and the Saros Gulf, and its diverging central and southern strands in both the Sea of Marmara and on Turkey's north–west mainland.

Fig. 6. Branching of the NAF fault on its western segment.

Previous earthquakes that occurred in 1957 and 1967 ruptured an additional adjacent 100 km of the NAF, but there was separate activity further west during 1963 and 1964. The 1963 event (Richter magnitude 6.3) in the Sea of Marmara, to the west of Izmit, broke a section of the fault and killed only one person. The last strong earthquake (magnitude 7.1) to strike Northern Turkey occurred in 1967. It killed 173 people.

A long seismic gap separated the location of the 1967 quake and those of the 1963 and 1964 quakes. Quite predictably, the August 17, 1999 earthquake occurred on this gap, where apparently seismic stress had build up. The earthquake filled in the 100 to 150 km long gap, which existed. As early as 1979, numerous scientists had readily identified this gap as a potential site for a future earthquake. A subsequent evaluation in 1997 estimated a 12% statistical probability of an earthquake occurring in the 30-year period, from 1996 to 2026, in this region. Obviously, the statistical probability was underestimated as the earthquake occurred much sooner than statistical studies had anticipated.

Elsewhere in Turkey, a major earthquake (Richter magnitude 7.1) in 1970 near Gediz - about 160 km (100 miles) on the southern strand of NAF killed over 1,000 people. Its aftershocks continued for several years. In 1998, a less severe earthquake on the same southern strand killed 140 people.

2C. Strain and Seismic Gap Release of the North Anatolian Fault by the August 17, 1999 Earthquake. Effects of Seismic Stress Transference into the Aegean Sea.

It appears that most of the seismic strain along this section of the North Anatolian fault was released by the August 17, 1999 earthquake. However, given the measurements of 1.5 meter ground displacements in the Akyazi area, versus the larger displacements elsewhere, it is quite possible that not all of the seismic strain was released by this event and that some future seismic event will release the remaining strain. This may not happen for many years. Also, it appears that there was seismic stress transference to the west on the northern strand of the North Anatolian fault, as several earthquakes occurred subsequently in the Northern Aegean Sea (see Fig. 7).

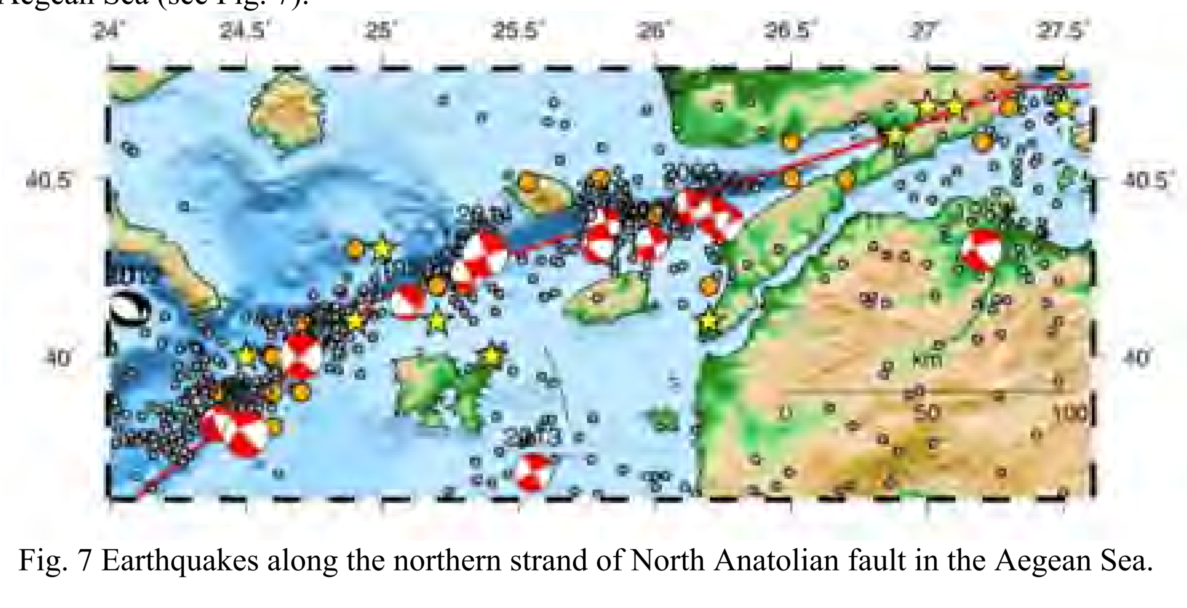

Fig. 7 Earthquakes along the northern strand of North Anatolian fault in the Aegean Sea.

A detailed analysis and measurements of the extension of the North Aegean Fault as it enters into the North Aegean Trough, provided evidence of change from a tectonically controlled simple strike-slip fault deformation, to dextral displacement within the eastern part of the trough and the Gulf of Saros, in the form of oblique en-echelon fractures (McNeil EtAl., 2004)

2D. Counter clockwise crustal block rotation of the Asia Minor Microplate. Effects of Stress Transference on the East Anatolian plate by northward movement and collision of the Arabian Tectonic plate resulting in the 8 February 2023 two earthquakes in Southeast Turkey and Northwest Syria.

Also indicated by the August 17, 1999 earthquake on the North Anatolian Fault are the effects of stress transference along a sinistral NW striking fault separating two sub-basins, which indicates counter clockwise crustal block rotation of the entire tectonic subplate of Asia Minor, as it is pushed northward at 16 mm/year by the Arabian tectonic plate (see Figure 8 below). In fact, based on this continuing collision and resulting stress, a prediction was made as early as 2013, that one or more significant earthquakes were overdue and expected along the East Anatolian plate, which would strike both Southeast Turkey and Northwest Syria (Pararas-Carayannis, 2013) - as indeed they occurred on 6 February 2023.

The counter clockwise rotation of the Asia Minor sub-plate is the result of a continuing geodynamic evolution that began long ago, when the Arabian plate was part of the African plate during much of the Phanerozoic Eon (Paleozoic – Cenozoic) and until the Oligocene Epoch of the Cenozoic Era. Because of the Arabian Plate and Eurasian plate collision, many cities in southeastern Turkey and Northwest Syria - which are along these boundaries - had major earthquakes.

Fig. 8. Collision of the Arabian tectonic plate with the Anatolian plate resulting in Stress Transference and in its counterclockwise rotation.

Figure 9 below shows in greater detail the effects of seismic stress transference along the East Anatolia Fault Zone (EAF) on the North Anatolia Fault Zone NAF by earthquakes such as that of 1999, and of its East-Southeast counterclockwise stress and branching of NAF into the Aegean Archipelago.

Fig. 9. Seismic stress transference on the North Anatolia Fault Zone (NAF) by earthquakes such as that of 1999, and of its East-Southeast counterclockwise stress and branching into the Aegean Archipelago.

2E. Possibility of Near Future Earthquake Recurrence in the Sea of Marmara.

Nearly 24 years have elapsed since the disastrous earthquake of 19 August 1999 on Turkey's North Fault Zone (NFZ) in the Sea of Marmara region. Based on an assessment of seismic stress transference, and the geodynamic complexity of the fault in this western region, it is very possible that not all such stress has been expended, and that another disastrous earthquake could strike and impact more populated areas along the Eastern Sea of Marmara, including Istanbul. Such an earthquake could affect critical structures on both sides of the Bosporus Strait, such as a connecting bridge, or even change the bathymetry of this significant navigable shipping waterway that links the Black Sea with the Dardanelles Straight and the Mediterranean Sea.

Another such earthquake on the NSF could reach a magnitude between 7.2 to 7.8, and could have devastating consequences for Turkey even worse than those of the 1999 event and could cause as many as 100,000 deaths. The timing of such an earthquake, however, is impossible to predict, as well as that of another similar to the 7 February 2023 on the East Anatolian fault (EAF). With these two major faults in North Anatolia and East Anatolia, Turkey is one of the most earthquake-prone regions in the world.

2F. Brief Review of Past Work on the 27 August 1999 Earthquake in the Sea of Marmara.

A brief description of the 27 August 1999 earthquake and tsunami in the Gulf of Izmit and elsewhere in the Sea of Marmara was published in 2011 (Pararas-Carayannis Et.Al., 2011). Accordingly, the tsunami was also responsible for extensive damage caused from collateral hazards such as subsidence, landslides, ground liquefaction, soil amplifications, compaction and underwater slumping of unconsolidated sediment.

As stated and although the earthquake involved primarily horizontal ground displacements, slumping and landslides triggered tsunami waves which were particularly damaging in the Gulf of Izmit, perhaps because of convergence and funneling effects. The long duration of the earthquake's ground motions for 45 seconds, the directivity of the surface seismic waves, the proximity of the epicenter to the Sea of Marmara and the Gulf of Izmit, and the overall orientation of the affected area, strongly supported that the tsunami was generated in the Gulf of Izmit, in the eastern portion of the Sea of Marmara. The tsunami waves from this earthquake had an extremely short period of less than a minute, which also supports the premise that the source was localized subsidence of coastal areas and underwater slumping of unconsolidated sediments, rather than larger scale tectonic movements, which involved primarily lateral motions. Figure 10 shows the destruction of buildings due to subsidence, as well as the effect of waves on boats.

An initial recession of the water, which was observed at both sides of Izmit Bay immediately after the quake, was followed by tsunami waves, which had an average run-up of 2.5 m. along the coast. Maximum run-up was 4 m in Golcuk, where there was considerable damage to the naval base facilities. In fact, Golcuk and several coastal areas are now flooded permanently as a result of the tectonic subsidence and landslides. Also, large coastal portions of the town of Degirmendere remained flooded as a result of subsidence - with sea level reaching the second floors of apartment buildings. Similar permanent flooding, but to a lesser extent, occurred also at Karamursel.

3. THE TSUNAMI OF 27 AUGUST 1999 IN THE SEA OF MARMARA

The lesson learned from this event is that tsunamis can occur in any body of water since a variety of mechanisms can generate them. Even earthquakes involving primarily horizontal ground motions (strike-slip type of faulting) can generate tsunamis by triggering slope failures and underwater landslides. Obviously the tsunami risk for the Sea of Marmara needs to be carefully evaluated. Measures must be taken to mitigate the effects of future tsunamis in the area. Better construction and building codes will definitely help.

Numerous large destructive earthquakes and tsunamis have occurred from antiquity to the present in the Ionian Sea, Greece, the Aegean Archipelago, Turkey and the Sea of Marmara - which separates Asia Minor from Europe. Large earthquakes with intensity greater than VIII on the Modified Mercalli scale have caused damaging or disastrous tsunamis - particularly along the Southern Aegean Sea. Most of the destructive tsunamis in the past originated from a region of the Hellenic arc where normal faulting within the southern part of the Anatolian Tectonic Plate (the Aegean plate) is consistent with a NE-SW trending graben along which the Santorin volcanic field has also developed. (Pararas-Carayannis, 1992).

3.1 Assessment of the Tsunami Potential in the Sea of Marmara and the Aegean Archipelago

Numerous large destructive earthquakes and tsunamis have occurred from antiquity to the present in the Ionian Sea, Greece, the Aegean Archipelago, Turkey and the Sea of Marmara - which separates Asia Minor from Europe. Fig.10 below is a photo of the tsunami-like impact of short period waves caused by land subsidence and not of tectonic origin.

Large earthquakes with intensity greater than VIII on the Modified Mercalli scale have caused damaging or disastrous tsunamis - particularly along the Southern Aegean Sea. Most of the destructive tsunamis in the past originated from a region of the Hellenic arc where normal faulting within the southern part of the Anatolian Tectonic Plate (the Aegean plate) is consistent with a NE-SW trending graben along which the Santorin volcanic field has also developed. (Pararas-Carayannis, 1992).

Fig. 10. Damage from the earthquake, tectonic subsidence, ground liquefaction and the tsunami. Ship in the foreground thrown onshore by tsunami wave action. Source: Kandilli Observatory and Research Institute (modified))

To a lesser extent, tsunamis have been also generated along the northeast portion of the Aegean Sea, and the Sea of Marmara. Although most of the earthquakes along the great North Anatolian fault involve primarily horizontal ground displacements - and such tectonic movements do not ordinarily generate tsunamis - some of the earthquakes along the western segment of the fault have triggered major slumps that have generated tsunamis. At least 9 major tsunamis have been reported to have occurred in the Marmara Sea in the past (Kuran and Yalciner, 1993). The most recent tsunami in the Eastern Marmara Sea was associated with the 18 September 1963 earthquake.

Strike-slip ground movement with a very small vertical component; can indeed generate a tsunami in a closed body of water. A combination of disturbances can be triggered by a large magnitude earthquake and several secondary mechanisms for the generation of tsunami waves are possible. Generative causes may include a combination of tectonic movements associated with the earthquake or major sub-aerial or underwater slides. Such secondary phenomena associated with a large earthquake can contribute to the generation of destructive waves particularly in an enclosed body of water like the Sea of Marmara. Tsunami generation will depend on the earthquake's energy release, the proximity of the body of water to the epicenter, the physical rupture along the fault, the propagation path of surface seismic waves, and the magnitude and duration of the dynamic, near-field, strong motions. Earthquake ground motions of high intensity could result in strong ground accelerations and the generation of waves in the immediate area of the earthquake (Pararas-Carayannis, 1999). Ground liquefaction can also trigger landslides, which in turn could generate destructive waves.

CONCLUSIONS

Based on the present analysis, it is believed that earthquakes occurring along the Western portion of the Northern Anatolian fault zone can generate destructive tsunami waves in the Sea of Marmara. A number of grabbens, fault offsets and other structural topo-morphological features at the bottom of the Sea of Marmara indicate that seismic activity and movements of branches of the North Anatolian fault extend under the sea.

Even an earthquake on land or a large aftershock could trigger a landslide in unconsolidated deposits or sediments along the coast. The tsunami danger is more pronounced in the eastern region of the Sea of Marmara and particularly in the Gulf of Izmit. Another significant earthquake further east close to Istanbul and the Bosporus is very possible in the near future and could be extremely destructive and result in great loss of lives. Thus the earthquake and tsunami risk for the Sea of Marmara needs to be carefully reevaluated. Obviously, government authorities will have to do some serious reviews of what measures must be taken to mitigate the effects of future earthquakes and possible tsunamis in the area. Better construction and building codes will definitely help. The potential for tsunami generation in the Sea of Marmara is substantial.

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TSUNAMI DESTRUCTION IN JAPAN CANNOT BE PREVENTED WITH USE OF EXISTING SEAWALLS – Case Study: The Great Tsunami of 11 March 2011

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ABSTRACT

A megathurst magnitude 9.0–9.1 (M_w), undersea earthquake on 11 March 2011 off Japan's Tohoku region on the Pacific coast, generated massive tsunami waves. Extremely high waves and the resultant debris flow overtopped and destroyed the existing seawalls which offered little or no protection, thus resulting in thousands of deaths and causing extensive destruction of coastal facilities, including the Fukushima Daiichi nuclear plant. The tsunami destroyed easily the tidal gates on the roads connecting the port to the town, and since there was no seawall protection on the tsunami's path on rivers, there was also extensive inland damage upstream, as the waves striking over river banks reverted river flows, thus causing the water to rise and form even higher waves with greater inland inundation. Even weak tsunamis striking a river outlet on a coast can generate a high-volume river water flow reversal and potentially cause substantial damage upstream. The present government tsunami countermeasures in Japan for such river areas are unable to prevent such enhancement of tsunami damage and to provide adequate protection for inland areas.

Keywords: *river tsunami; tsunami countermeasures; Earthquake & tsunami; seawall protection; river flow reversal; upstream tsunami inundation enhancement*

1. INTRODUCTION

To use seawalls for protecting the mainland regions of Japan from locally or distantly generated tsunamis, it is necessary for the responsible civil defense authorities to have the ability to take into consideration and evaluate the height of a potential tsunami on populated coastlines and issue appropriate timely warnings. This is not always possible to do because of unpredictable factors contributing to unknown secondary tsunami height enhancement effects. Historically, many destructive local and distant earthquakes have generated tsunamis that struck Japan. Most of the locally generated tsunamis are from oceanic regions surrounded by oceanic trenches and characterized by tectonic subduction. The Japanese archipelago is surrounded by oceanic trenches - including the Chishima-Kamchatka Trench, the Japan Trench, the Izu-Ogasawara trench, and the Philippine Trench, where extensive subduction is taking place. However, besides earthquakes near trenches, destructive local tsunamis have been generated by a variety of other events, such as volcanic eruptions and landslides.

According to reports from Japan and elsewhere (Pararas-Carayannis, 2011; Aydan, 2011; Arikawa EtAl, 2012; Shigeo Takahashi EtAl., 2011, In Japanese; Arikawa & Shimosako, 2013; Raby EtAl. 2015), the 11 March 2011 off Japan's Tohoku region on the Pacific coast occurred at 14:46 JST on Friday, 11 March 2011 and had a moment magnitude of 9.0, and epicenter about 129 km east of Sendai off the coast of northern Japan. The coasts of Iwate, Miyagi, and Fukushima Prefectures were severely damaged and Hokkaido, Aomori, Ibaragi, Chiba Prefectures were also damaged, particularly due to the extreme tsunami generated by this earthquake. Immediately following the disaster extensive field surveys were carried out by the Japanese authorities and research organizations (Shigeo Takahashi EtAl., 2011 in Japanese) which included analyses of seismic and tidal records as well as of GPS wave meters, as reported in the scientific literature (Pararas-Carayannis, 2011).

The following sections describes briefly this 2011 disaster and some of the historical tsunamis that have impacted Japan, which originated from a variety of local or distant earthquakes or other local sources, with special emphasis given on the extensive inland damage upstream over river banks by reverted river flows.

2. EXAMPLES OF MISCELLANEOUS HISTORICAL TSUNAMI EVENTS THAT IMPACTED JAPAN

Historically, Japan has been struck by destructive tsunami waves generated from local and distant earthquakes, from volcanic eruptions and collapses of lava domes and of resulting coastal cliffs. The following sections describe briefly some of these mechanisms.

2A. Tsunami Generated from Distant and Local Earthquakes

More recently, the main generation of tsunamis that hit Japan was from distant sources such as that of the 1960 Chile earthquake, or from local earthquakes such as that of 2011 off the Island of Honshu (Pararas-Carayannis, 2012). For tsunamis generated from distant sources, such as that of the 1960 Chile earthquake which caused extensive damage in Japan, at least there was sufficient time for the Japanese authorities to issue a timely warning and take measures for preparation. However, this was not possible for the great magnitude M9.0 earthquake of 11 March 2011 off Honshu in northern Japan. This earthquake occurred off the coast at 4:46 JST on Friday, 11 March 2011. Its epicenter was 129 km east of Sendai (Pararas-Carayannis, 2011; Shigeo Takahashi EtAl., 2011 In Japanese).

Tsunami waves from this 2011 earthquake, not only were extremely high along the coasts but also reversed the flow of local rivers, causing the water to rise and form higher waves that traveled much further inland, and resulting in extensive damage to structures on river banks. Historically, even weak tsunamis striking a coast have often generated high-volume river water flow reversal and have caused substantial damage upstream. However, and until recent times, there was low awareness as to how tsunami waves propagate on rivers and on how destructive they can be.

2A. Tsunamis of Volcanic Origin and of Coastal Collapse of Cliffs

There have been many destructive tsunami events from such sources in Japan. For example, a 1792 collapse of a lava dome of Mt. Mayuyama of the Unzen volcano triggered an avalanche that resulted in a 20-meter tsunami which surged across the Ariake Sea and killed 14,524 people.

Large earthquakes near Japan can also cause coastal cliffs to collapse into the sea and also generate large waves. In 1958, a magnitude 7.7 earthquake in Araskaritsuya Bay resulted in the collapse of cliffs of a narrow fjord causing an avalanche into the sea which generated huge waves that inundated up to 524 meters inland across the adjacent shore.

2B. Inland Tsunami Destruction Caused by River Flooding of Embankments

Nearly all of Japan's rivers feature high-volumes of water flow because of melting snows and of heavy typhoon related rains. As a consequence, this large amount of water often overflows the edges of river embankments causing extensive flooding and destruction. Japan's tsunami-related countermeasures – at least until 2011 - ignored this vulnerability due to river flooding, which is also exacerbated by the earthquake-generated tsunami inundation. Often, existing seawalls did not provide adequate protection. For example, approximately 190 kms of an existing 300 kms seawall along the coast of Sanriku was destroyed by the massive tsunami generated by the great 2011 earthquake, resulting in great indirect losses, as well to the deaths of many people of vulnerable coastal communities (Raby EtAl. 2015). Approximately 190 km of the 300 km seawall along the Sanriku coast was destroyed by this massive tsunami. The above article "Consideration of Structure of Coastal Conservation Facilities", and the included photographs below as in figures 1 and 2 in the following section, document the extent of coastal damage to three Tohoku prefectures.

2C. Seawall Destruction by the 11 March 2011 off Japan's Tohoku region

The 2011 tsunami caused immense damage to seawalls and other protective structures along the coastal Tohoku region. Specifically, about 190 km of the coast's 300-km seawall was completely or partially destroyed. Also, the waves of the tsunami resulted in the inland deposition of sediments of up to 50 centimeters in thickness. The force of the tsunami wave impact and the flow of the debris contributed in the whole or to the partial destruction of the seawalls which had been designed to only withstand seawater hydraulic pressures. As shown in Fig. 1, a seawall on the coast of Yamamoto Town in the Miyagi Prefecture and the base of the levee were shredded by the force of the waves of the 2011 tsunami (Mano et al. 2013).

Fig. 1. Seawall destroyed by a tsunami (Mano et al. 2013)

Subsequent studies examined the failure mechanism of coastal levees on the Sendai Bay Coast hit by this 2011 gigantic tsunami, and determined that almost eighty percent of these intended to protect the land from storm surges were broken in various degrees of damage by the tsunami (Mano et al. 2013). However, following this disaster, both national and local governments decided to rebuild these levees to be durable to withstand even the force of mega tsunamis.

The height of the levee was high on the beach, and was designed to only withstand seawater pressure and to offer protection to storm generated surges, but of not of sufficient strength to protect from changes in the seabed topography due to tsunami flooding and subsidence of its foundation – in spite of the embankment's reinforcement with concrete (Fig. 2). In brief, tsunami waves containing large amounts of sludge and sediments are much more destructive. For example, the great Meiwa Tsunami of 1771 carried a 1000-ton rock to a point 35 m above sea level and 100 m from the coast on Ishigaki Island (Travel JP, Okinawa travel guide). Since this tsunami had a run-up height of 85 m, seawalls would offer no protection from its damaging effects. Additionally, ports have shipping routes that lead to the open sea. Therefore tsunami wave can impact ports through these shipping route openings. Figure 2 depicts a port's seawall, completely destroyed by a tsunami.

Fig. 2. Seawall of a harbor in Yamada completely destroyed by a tsunami.

The sturdy doors that blocked the road between the port and town were also easily destroyed. Simply, increasing a coastal seawall height will not mitigate sufficiently the damaging effects of tsunamis. Furthermore if a river flows through a town, a tsunami can strike and breach the river embankment.

The statement above is supported by the author's own experience with the 2011 tsunami, whose house is located about 20 km away from the sea in close proximity to the Sasame River. Soon after the earthquake, there was 1 meter fluctuation in the level of the river, relative to the tidal shift. Therefore, and based on what happened, the potential damage spreading upstream via rivers must be examined, as even weak tsunami can create a damaging wave of significant height, if the affected river is large and has a high-volume of water flow.

Based on the field observations of significantly high waves on rivers even at great distance from the shoreline, it must be evident that the present analysis of the Japanese government's tsunami and flood hazard maps for such region must be re-evaluated and appropriate countermeasures of worst-case scenarios must be adopted.

3. TSUNAMI DAMAGE PREVENTION MEASURES

The Japanese government has built a 400-km seawall on the Sanriku coast at the cost of 1 trillion yen and the coast is blocked by a long and high embankment. In urban areas with limited land, embankments are thin and can be easily destroyed by a tsunami. Seawalls are very expensive to build (2.5 billion yen/km) and are useless as they can only provide protection for smaller tsunamis. Moreover, failing seawalls can actually exacerbate the damages. Additionally, some residents trusting protection from seawalls, remain in their homes even after tsunami warnings are issued. Every few decades, a huge tsunami breaches the sea walls, threatens inhabitants, and causes numerous deaths. The 1896 Meiji Tsunami Tsunami killed 22,000 people along the Sanriku Coast. The 1933 Showa Tsunami, resulted in 3,000 people deaths, another 142 people died from the 1960 Chile Tsunami, and 22,000 more people died by the Heisei Tsunami in 2011.

This loss of human life has been happening on the Sanriku coast for decades, specifically four times in just 115 years, and has had adverse effects on other natural life. Lastly, even seawalls deprive young fish of their habitat, block nutrients flowing from land to sea and destroy natural landscapes.

In brief, past tsunamis and their resultant debris flows easily have destroyed seawalls. Additionally, tidal gates on the roads connecting the ports to the towns were also destroyed. Therefore, until 2011 there has been no really effective seawall protection in blocking a tsunami's inland inundation as the existing seawalls are inadequate as the rivers' embankments can be easily breached.

CONCLUSIONS

In addition to other measures, Japanese Civil Defense Authorities must also prepare for inevitable river tsunamis, as these can be generated from even weaker earthquake events. Unfortunately, the current administration's tsunami countermeasures must be revised in order to become more effective and prevent worse damage from future tsunamis

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BRIDGE ACROSS THE KERCH STRAIT - HISTORY AND MODERNITY

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ABSTRACT

The present study provides a brief description of the geological conditions in the Kerch Strait, as well as a historical aspects on the complexity of building a bridge across it. The bridge consists of a four-lane road and of another double-track railaway spanning the extensive Staight. The paper provides estimates of expected maximum heights of tsunami waves for the pillars of the Crimean bridge if a significant catastrophic earthquakes occurs in the northwest of the Crimean Peninsula and in the localization of the earthquake source in the basin of the Black and Azov Seas in front of the entrance to the Kerch Strait. The main purpose of this work is to provide estimates of the tsunami mhazard for the area of the Crimean bridge in the Kerch Strait during earthquakes with sources in the nearest basin areas of the Black and Azov Seas, with magnitudes M = 7, 7.5 and 8. Comparative histograms of possible maximum wave heights near the bridge pillars are given. It is shown that in the area of the western pillars of the Crimean Bridge, the tsunami wave heights for all scenarios do not exceed 0.3–0.5 m, and in the area of the eastern pillars, the range of possible wave heights lies in the range of 0.6–1.95 m.

Keywords: Kerch Strait Bridge; Crimean Peninsula; Black Sea; Sea of Azov; Bridge tsunami impact

1. INTRODUCTION

The Kerch Strait is the most important water artery connecting the basins of the Black and Azov Seas [1,2]. According to hydrogeologists, the Kerch Strait is actually the site of a tectonic fault. The bottom relief of the Kerch Strait has a rather complex structure. The geological conditions in the strait are quite complex: seismicity, tectonic fault, soft soils. The area of the Kerch Strait is located in close proximity to the South Azov source zone, which runs sublatitudinally near the coast of the Kerch Peninsula [3,4]. The Kerch Strait coincides with the East Crimean (Kerch) source area. This area corresponds to the fault-shear zone of the strait [4-6]. The seismic potential of the mentioned zones is determined by the possibility of occurrence of crustal earthquakes with M ≥ 7.0 with an average frequency of one earthquake every several hundred years. The magnitudes of these earthquakes can reach $M \geq 8$ [6-8]. However, in addition to taking into account the possibility of an earthquake in the very water area of the Kerch Strait, it is necessary to take into account the possibility of a repetition of the earthquakes of 1927 in the Black Sea and the probability of the passage of tsunami waves into the strait.

2. THE KERCH STRAIT

The Kerch Strait, which separates the Kerch Peninsula of Crimea and the Taman Peninsula of continental Russia, is the most important water artery connecting the basins of the Black and Azov Seas [1,2]. The length of the Kerch Strait in a straight line is about 43 km, along the fairway - 48 km. The width of the strait varies widely: from 3.7 to 42 km. The strait is shallow: the greatest depths at the entrance to the strait from the Sea of Azov do not exceed 10.5 m, from the Black side - 18 m. Towards the middle of the strait, the depths gradually decrease and over a larger area are about 5.5 m. The total area of the Kerch Strait is approximately equal to 805 km^2, water volume – 4.56 km^3.

The strait plays a significant role in the formation of the features of the hydrological and hydrochemical regime of the Azov-Black Sea basin and is the most important fishing area and navigable highway [1,2,4] form the variability of coastlines and shoals dangerous for the navigation service. The transverse profile of the bed of the strait is asymmetric, and the strait itself is delimited by two sandbars into three parts [1-3]. A characteristic feature of the geological structure of the site in the transition area is the relatively high occurrence of the roof of bedrock clay near the Crimean coast of the strait and their sharp decrease to a depth of 50 m in the eastern part of the strait. Very weak silty soils lie above bedrock. The shores of the Kerch Strait are partially low-lying and marshy with sandy spits (Chushka, Tuzla), in some places steep and rocky [1-3].

Water level oscillations in the Kerch Strait are of different nature, the most significant in magnitude are surge oscillations, seasonal and climatic level oscillations have a significantly lower amplitude. The range of seasonal oscillations reaches approximately 25 cm. The main cause of mesoscale sea level oscillations in the Kerch Strait is the wind. The surge oscillations caused by it are superimposed on smooth seasonal level oscillations and, on average, exceed them in amplitude by 5–6 times, and in very strong storms by 8–10 times. Most often, surge phenomena occur in the northern part of the strait with a northeast wind, which is characterized by the greatest frequency, strength and duration [4,7-9]. For almost two centuries, the climate of the Sea of Azov and the Caspian Sea has been characterized by intra-secular cyclicity - the alternation of warm and extremely cold winters with snowfalls. The duration of freeze-up in the Sea of Azov during cold periods reached 50–80 days. In this regard, there were delays in shipping (for two to three months). At the end of winter, ice jams and hummocks, as well as blocks of ice drifting at high speed, became a common occurrence in the Sea of Azov. The drift of the Azov ice into the Kerch Strait under the pressure of hurricane northeast winds seems to be extremely dangerous. In addition to drifting ice, hurricane-force southwesterly and southerly winds, reaching a speed of 38 m/s, which cause waves over 3–4 meters high in the Kerch Strait [7, 10], present a danger.

In addition, the area is characterized by high seismic activity, accompanied by strong underwater tremors. The ability to bypass the tectonic fault zones is rather problematic [1-5]. When erecting any hydraulic structures in the Kerch Strait, it is necessary to take into account the existing dangers and threats: a) Azov Sea ice drift through the strait; b) Hurricane surge winds up to 37 m/s; c) Unpredictable lithodynamics (erosion and collapse of coasts and islands); d) Underwater earthquakes. The most powerful of them can cause sea gravity waves (including tsunamis) [10]. The passage of the tsunami on September 11–12, 1927, December 28, 1939, and July 12, 1966 from the Black Sea to the Sea of Azov through the Kerch Strait was noted: the echoes of these tsunamis were recorded at Opasnoe or Mariupol of the Sea of Azov [10].

3. BRIDGE ACROSS THE KERCH STRAIT

3.1. Brief historical tour of the construction of the bridge

It was planned to communicate the western shore of the strait, namely the Kerch Peninsula of Crimea, and the eastern one - the Taman Peninsula of the Krasnodar Territory of Russia - more than a thousand years ago [11-12]. Projects for the construction of a bridge across the Kerch Strait arose repeatedly, but all attempts were unsuccessful [11-12] (see also [13-15]). Starting from the 7th century BC, there was communication between the western and eastern shores of the Bosporan kingdom, which was located on two peninsulas - Kerch and Taman. The width of the Kerch Strait allowed merchants and fishermen to cross in boats. In 1068, historians recall, the henchman of Kyiv, Prince Gleb Tmutarakansky, measured the sea on ice to Korchevo. A message about this action was inscribed on the famous Tmutarakan stone. In 1903, it was decided to build a bridge across the Kerch Strait. The best Russian engineers were involved in the design, who by 1910 had developed a project for the Kerch crossing, the implementation of which was prevented by the First World War, then the October revolution and the Civil War. In the Soviet years, along with the bridge, the reconstruction of railways was also conceived, along which trains were supposed to drive up to the structure. In the 1930s, Soviet engineers designed a large-scale construction - a railway line from Kherson to Poti through the Kerch Strait. Large-tonnage parts of the bridge structures could not be manufactured by domestic factories, and they were ordered in Germany. The project was not implemented due to the outbreak of World War II [11-12]. The war began, and in 1942 German troops captured the Crimea, there were battles for the Caucasus. German military engineers began to develop their own project for a bridge across the Kerch Strait, which would make it possible to build a railway and a highway from Kerch to the Novorossiysk region. However, after a change in the situation on the Caucasian front, the construction of the bridge was stopped. And already in the summer of 1943, German military engineers were forced to design and build an aerial cableway across the Kerch Strait for the transfer of military cargo as soon as possible, which was partially blown up during the retreat.

After the liberation of Crimea from German troops, Soviet engineers began to connect the two banks of the Kerch Strait. In February 1944, the cable crossing over the Kerch Strait began to operate again. In the same 1944, the Kerch railway bridge was built in 7 months. The length of the bridge was 4.5 km, the width was 22 meters, it had 115 spans of 27.1 m each and a 110-meter turning device in the middle part to ensure the passage of large-capacity vessels [11-12]. At the end of February 1945, the ice, blown up by the wind from the Sea of Azov, destroyed 42 out of 115 pillars and they collapsed, dragging the spans with them. The bridge operated in this way for only a little over three months.

3.2. The state of the problem since the end of the last XX and the beginning of this XXI century

The Kerch Bridge is a transport crossing over the Kerch Strait. It was planned to build a bridge with railway and road passages [11-12]. The bridge was supposed to pass between the Kerch and Taman Peninsulas through the island of Tuzla and the Tuzla Spit. The road junction of the bridge from the side of Taman was to be built simultaneously for the bridge and for the largest Russian port on the Black Sea, the port of Taman, which was under construction [11-12]. It was planned that the bridge should be part of the ring road being created around the Black Sea for the needs of the Black Sea states by 450 km, shortening the road without the need for a detour through Rostov-on-Don [11-12]. In the early 1990s, a competition was announced for participation in the implementation of a transport crossing project across the Kerch Strait; at that time there were 4 crossing projects (two bridges and two tunnels). The Crimean authorities believed that the implementation of this project would facilitate contacts with Russia and consolidate the “intermediate” position of Crimea between neighboring states. In addition, for a long time the bridge was put forward as one of the elements of the ring road along the Black Sea coast. The issue of building a bridge was discussed in the Ukrainian government in 2006, which believed that such construction would be "a plus for Crimea." In the same year, the design and construction of the bridge was included in the "Transport Strategy of the Russian Federation until 2030", which included, as one of the main directions for the development of transport infrastructure in the Southern Federal District, the design of a bridge across the Kerch Strait and the reconstruction of road approaches and entrances to the sea port of the Caucasus.

Fig. 1. Model of the bridge across the Kerch Strait.

On December 17, 2013, an agreement was signed between the Government of the Russian Federation and the Cabinet of Ministers of Ukraine on joint actions to organize the construction of a transport passage through the Kerch Strait. In March 2014, preparations for the construction of the bridge intensified significantly. In June 2014, the project for the construction of a bridge in the alignment of the Tuzla Spit was recognized as optimal (see, for example, [2,12,13]. During the construction of the bridge, complex tectonic conditions in the zone of possible earthquakes and a layer of plastic sedimentary rocks of silt at the bottom of the strait required the creation of a very long pile foundation to semi-hard clays at a depth of up to 58 meters, which required the use of piles up to 94 meters long [13,14]. The large-scale project was planned to be implemented in a short time. The bridge does not create obstacles for the movement of ships because the height of the bridge is 35 m. The length of the bridge is 19 km (see also [15-17]. On December 18, 2019, the construction of the Crimean railway bridge was officially completed - an acceptance certificate was signed allowing the commissioning of the railway bridge. Freight traffic opened on June 30, 2020. On January 20, 2020, the first 100 trains passed through the Crimean bridge.

Fig. 2. Top view of the Crimean bridge

4. FORECAST OF TSUNAMI HAZARD FOR THE CRIMEAN BRIDGE.

Tsunami prediction in the Black and Azov seas was carried out by a number of authors (see, for example, [15-27]). So, in the work by Dotsenko and Ingerov [22], a numerical analysis of the propagation of tsunami waves in the Sea of Azov was carried out. As they write, "the question of the efficiency of tsunami generation in the Sea of Azov by seismic sources remains relevant and little studied".

4.1. Numerical modeling of tsunamis during strong and catastrophic earthquakes

For numerical modeling of tsunami waves, the northeastern part of the Black Sea, the Kerch Strait and the southern part of the Sea of Azov were considered (Fig.3, Fig.8). For numerical simulation of tsunami wave generation by a seismic source, we used a keyboard model of an earthquake (see, for example, [15–17]) and a nonlinear system of shallow water equations in a two-dimensional formulation, taking into account dissipative effects and bottom friction (see, for example, [28]). Displacement wave fields were obtained and histograms of maximum wave heights were constructed along the northwestern coast of the Black Sea and along the coasts of the Kerch Strait.

4.1.1. Tsunami hazard of the Crimean bridge during the localization of the seismic source in the northwest of the Crimean Peninsula

To describe the process of generation and propagation of a wave caused by the movements of keyboard blocks in a seismic source, a nonlinear system of shallow water equations in a two-dimensional formulation was used (see, for example, [17,28]). In the numerical description of the generation and propagation of a tsunami wave over the water area, a scheme was used that was constructed in analogy with the Sielecki difference scheme [29]. A computational grid is introduced with spatial intervals , and with a time integration step of 1 sec. (see, for example, [15-17]). The calculations presented in this paper used the bathymetry of the Black Sea, the spatial step in which was approximately 900 m. The simulation was carried out with a time step of 1 s. At the last seaward point at a depth of 3 m, the condition of total reflection (vertical wall) is set, which makes it possible to fix the maximum and minimum values of the wave level shift at this depth.

For the first stage of modeling the tsunami source, an elliptical seismic source was chosen, located, in accordance with the historical data of the earthquake on September 12, 1927, south of Yalta and extended along the coast with approximate coordinates of the epicenter: 34.5 ° E, 44.4 ° N (Scenario 1) (Fig. 3 purple). An earthquake with magnitude M = 7 was considered. With the source localized on the same fault, a hypothetical earthquake with a magnitude M = 7.5 was considered, with a source consisting of two semi-elliptical blocks, and the block separation line intersects with the fault line of the Earth's crust (Scenario 2) (Fig. 3 black line). In addition, two hypothetical earthquake sources were selected. They were located in possible zones of active faults of the Earth's crust near the Crimean Peninsula. The sources have close localization, both are blocky, the division line into blocks coincides with the major axis of the ellipse and passes along the fault line of the Earth's crust (2). The first of them has a magnitude of M = 7.2 (Scenario 3), for the second M = 8 (Scenario 4). The localization of the sources for Scenario 3 and Scenario 4 is shown in Fig. 3 in yellow and blue, respectively.

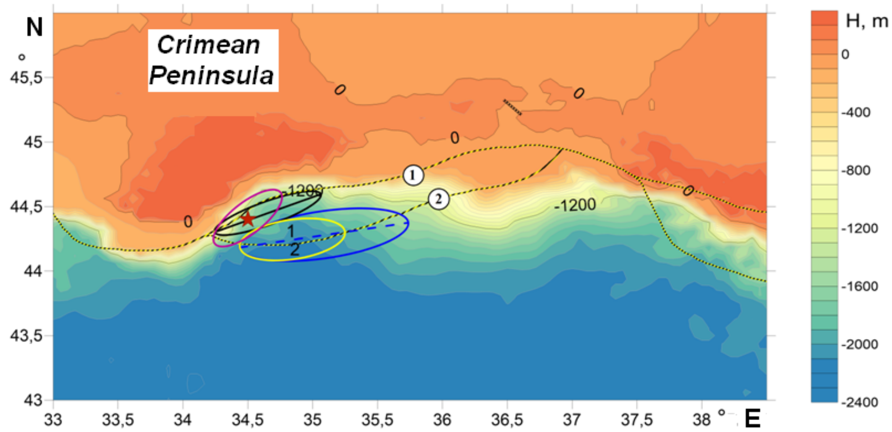
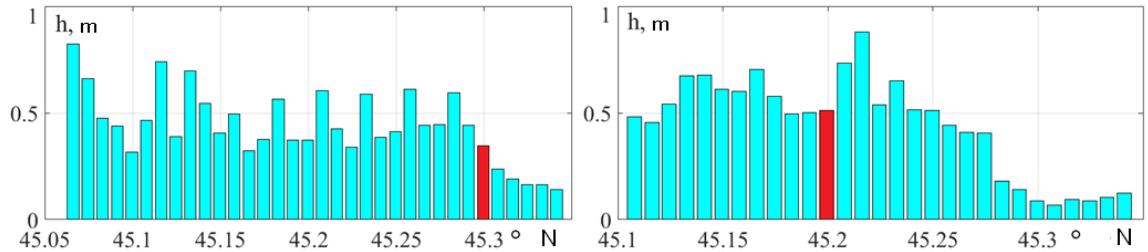


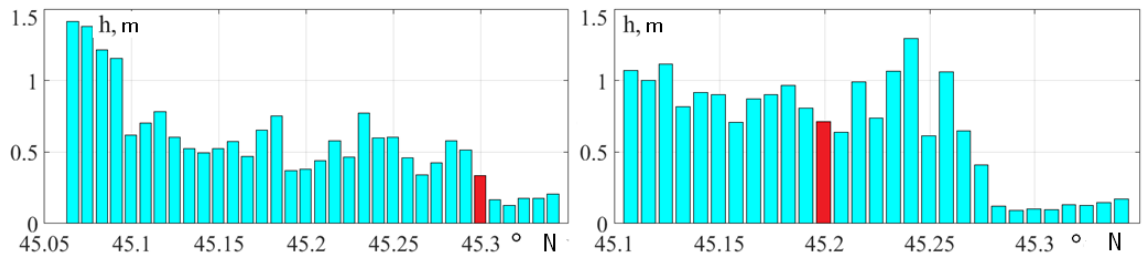
Fig. 3. Bathymetric map of the Black Sea in the region of the Crimean Peninsula and the Kerch Strait. In the figure: black-yellow line - shows the fault lines in the northeastern part of the Black Sea, ellipses - localization of simulated earthquake sources, red asterisk - localization of the epicenter of the historical earthquake of 1927.

When tsunami waves propagate from the considered sources (Scenarios 1-4), the waves reach the Kerch Strait and propagate along it. Figure 4 shows histograms for the maximum tsunami wave heights for the eastern and western coasts of the Kerch Strait. The geographic location of the pillars of the Crimean bridge in the projection is marked in red on them (slice in longitude). It should be noted that for the considered scenarios of the occurrence and propagation of a tsunami, with an increase in the magnitude of the seismic source, the level of water rise on 3-meter isobaths in the Kerch Strait also increases.



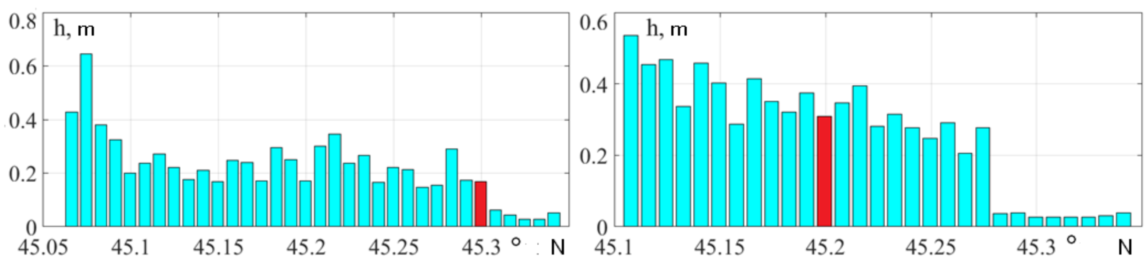
a) Western shore of the strait b) eastern shore of the strait

Fig. 4. Histograms of maximum tsunami wave heights on the 3-m isobath for the coast of the Kerch Strait for Scenario 1 ($M = 7$)



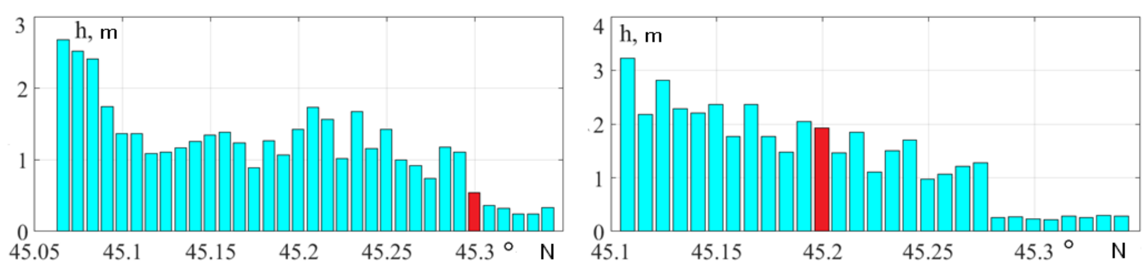
a) Western shore of the strait b) eastern shore of the strait

Fig. 5. Histograms of maximum tsunami wave heights on the 3-m isobath for the coast of the Kerch Strait for Scenario 2 ($M = 7.2$)



a) Western shore of the strait b) eastern shore of the strait

Fig. 6. Histograms of maximum tsunami wave heights on the 3-m isobath for the coast of the Kerch Strait for Scenario 3 ($M = 7.5$)



a) Western shore of the strait b) eastern shore of the straiT

Fig. 7. Histograms of maximum tsunami wave heights on the 3-m isobath for the coast of the Kerch Strait for Scenario 4 ($M = 8$)

As can be seen from Figure 4, for Scenario 1, the maximum water level rise was 0.32 m and 0.51 m for the western and eastern pillars, respectively. In general, in the water area of the strait, the height was slightly less than 1 m. For Scenario 2, the maximum height of sea level rise for the area of the western bridge pillars was 35 cm (Fig. 5), and for the area of the eastern pillars it was 0.53m. It can be also noticed that at the entrance to the Kerch Strait from the Black Sea, the wave heights on the 3-meter isobath reached 1.5 meters. On average, for both coasts of the Kerch Strait under this scenario, the height of the tsunami waves on the 3-meter isobath did not exceed 40 cm. Under Scenario 3 (Fig. 6), with a block source with a magnitude of M = 7.5, the maximum wave height at the western pillars was 18 cm, and in the eastern ones it is about 32 cm. For the case of a hypothetical block source with M = 8 (Fig. 7), the maximum heights near the pillars were: at the western pillars of the bridge 0.5 m, at the eastern ones 1.95 m; the highest height for this scenario for the area of the western bridge pillars was 3.2m. All these data on the maximum values of the wave rise height on the 3-meter isobath near the pillars of the Crimean bridge are given in Table 1.

Table 1. Data on the maximum values of the wave height at the pillars of the Crimean bridge (Localization of the source near the Crimean peninsula)

Scenario №	Max. water level rise (western pillars)	Max. water level rise (eastern pillars)
1	0,32 m	0,51 m
2	0,35 m	0,53 m
3	0,18 m	0,32 m
4	0,5 m	1,95 m

4.1.2. Tsunami hazard of the Crimean bridge during the localization of the seismic source near the Kerch Strait in the Black Sea and in the Sea of Azov

We also performed numerical simulation for two hypothetical earthquake sources located in front of the entrance to the Kerch Strait (Fig. 8) below.

It should be noted that for the scenarios considered in this paper, for the corresponding magnitudes of earthquakes, the wave heights in the strait, and, in particular, in the area of the Crimean bridge, have lower values. Thus, the maximum wave height at the eastern pillars of the Crimean bridge (see also [16,17]) was 1.5-2 m. the height of the tsunami waves at the eastern pillars of the bridge is 0.5 - 1.9 m. For these areas of the sea area, three scenarios of possible strong earthquakes with magnitude M = 7 from two hypothetical ellipsoidal earthquake sources located in front of the Kerch Strait to the northeast of the Crimean Peninsula in the Black Sea at magnitudes M = 7 (Scenario 1) and M=7.6 (Scenario 2) and the earthquake source localized in the Sea of Azov in front of the Kerch Strait (Scenario 3) were considered.

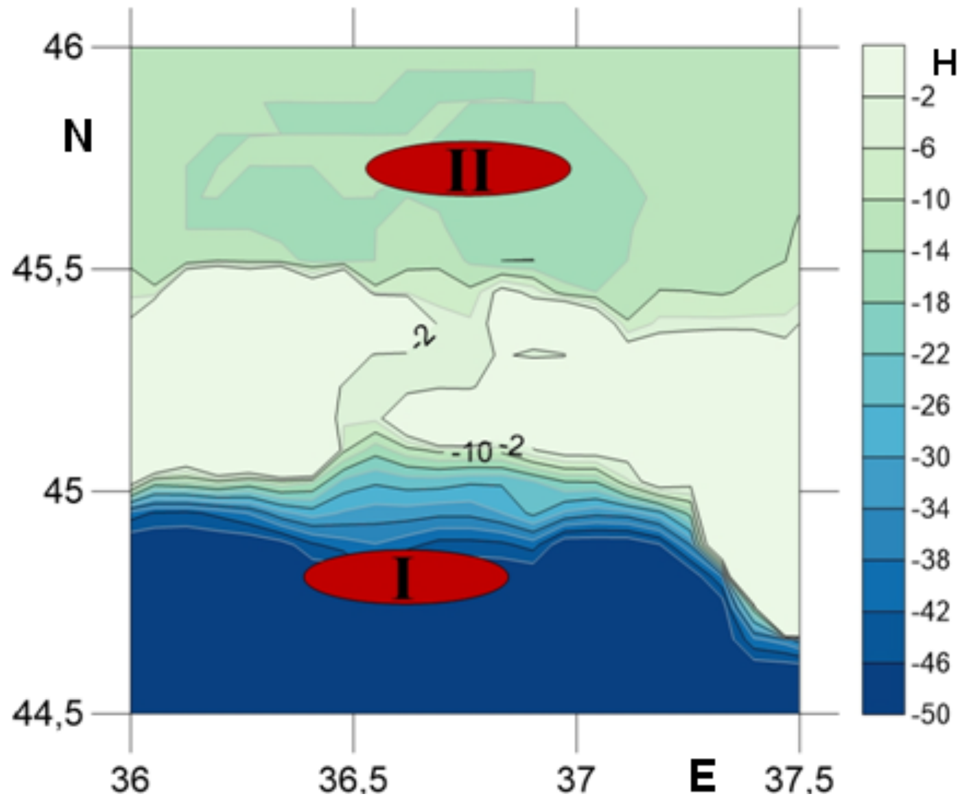
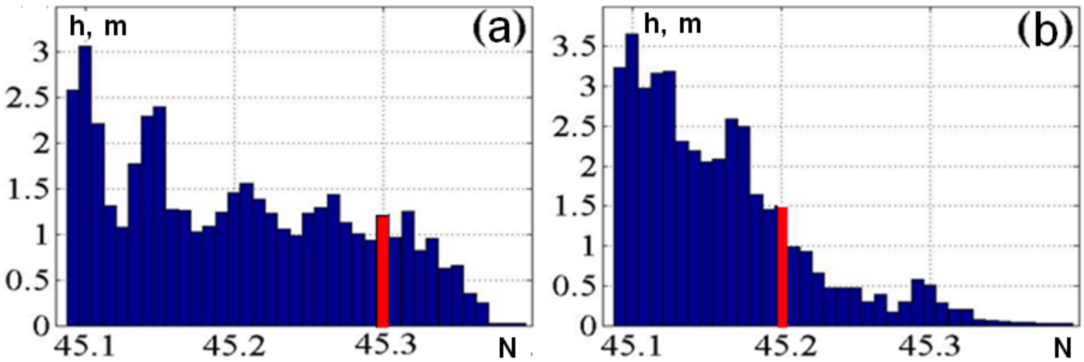


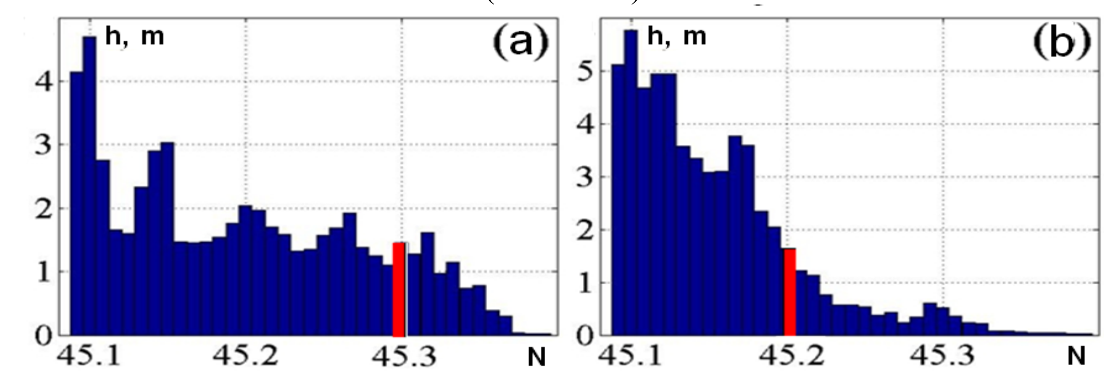
Fig. 8. Location of the tsunami sources considered: I - Scenarios 1, 3; II - Scenario 2

It should be noted that for the scenarios considered in this paper, for the corresponding magnitudes of earthquakes, the wave heights in the strait, and, in particular, in the area of the Crimean bridge, have lower values. Thus, the maximum wave height at the eastern pillars of the Crimean bridge (see also [16,17]) was 1.5-2 m. the height of the tsunami waves at the eastern pillars of the bridge is 0.5 - 1.9 m. For these areas of the sea area, three scenarios of possible strong earthquakes with magnitude $M = 7$ from two hypothetical ellipsoidal earthquake sources located in front of the Kerch Strait to the northeast of the Crimean Peninsula in the Black Sea at magnitudes $M = 7$ (Scenario 1) and M=7.6 (Scenario 2) and the earthquake source localized in the Sea of Azov in front of the Kerch Strait (Scenario 3) were considered. A sign-positive vertical displacement in the source up to 2.1 m was considered. Sea of Azov (Fig. 8). The computational domain in this problem was chosen in the square of 35–38^0 E, 44.5–47.5^0 N with a grid including the number of nodes $345 \times 361 = 124545$. Bathymetry of the Black Sea with a resolution of 500 m was used for modeling. When considering Scenario 1 (Scenario 2), hypothetical tsunami sources of an elliptical shape of magnitude $M = 7.0$ ($M = 7.6$, respectively) with the center in the point 36.6°E, 44.735°N were modeled. (Fig. 8). Wave fields of displacements and fields of velocities were obtained along the northwestern coast of the Black Sea, the coasts of the Sea of Azov and along the coasts of the Kerch Strait, histograms of maximum wave heights were constructed (Fig. 9, Fig. 10, Fig. 11). The geographic location of the pillars of the Crimean bridge in the projection is marked in red on them (slice in longitude).



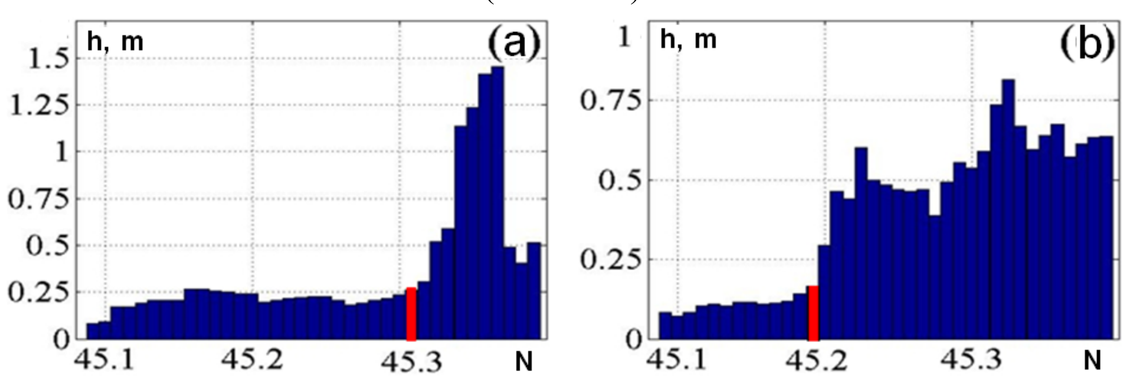
a) Western shore of the strait; b) eastern shore of the strait

Fig. 9. Histograms of the maximum heights of tsunami waves on the 3-meter isobath for the coast of the Kerch Strait near the Crimean bridge from the Black Sea for M=7 (Scenario 1)



a) western shore of the strait; b) eastern shore of the strait

Fig. 10. Histograms of the maximum heights of tsunami waves on the 3-meter isobath for the coast of the Kerch Strait near the Crimean bridge from the Black Sea for M = 7,6 (Scenario 2)



a) western shore of the strait; b) eastern shore of the strait

Fig. 11. Histograms of the maximum heights of tsunami waves on the 3-meter isobath for the coast of the Kerch Strait near the Crimean bridge from the Sea of Azov for M = 7 (Scenario 3)

As follows from the data of the histograms (Fig. 9 and Fig. 10), for sources similar in localization (the Black Sea at the entrance to the Kerch Strait) and different in magnitude (M = 7 and M = 7.6), corresponding to scenarios 1 and 2, the maximum heights of sea level rise at the same points on the coast differ significantly. At the entrance to the strait, the maximum difference was 1.7 m, at the bridge pillars up to 0.25 m. The time of the movement of the front from the source to the coasts coincides, because the wave velocity in the shallow water approximation depends only on the depth of the considered basin. When implementing Scenario 3, if the potential tsunami source is located in the Sea of Azov, the wave heights in the Kerch Strait are noticeably lower - up to half a meter. The main impact of the wave falls on the southern coast of the Taman Bay, so that when part of the wave front approaches the bridge line, its energy has already been substantially extinguished. A characteristic feature of tsunami propagation along the strait is the flat shape of the wave front, both when moving along the Chushka Spit and when approaching the bridge directly. In contrast to the case of the localization of the source in the Black Sea considered above, the elevation wave attacks the bridge along the entire width of the bridge from the Tuzla Spit in the east to Ak-Burun Cape in the west [15-17]. Note that the wave height here is significantly less than in the first case, however, the entire bridge structure is immediately attacked. Of course, in this case, the bend of the bridge near Ak-Burun Cape experiences a compressive load, in contrast to the capsizing load in the case of a source in the Black Sea. All this data on the maximum values of the wave rise height on the 3-meter isobath near the pillars of the Crimean bridge are given in Table 2.

Table 2. Data on the maximum values of the wave height at the pillars of the Crimean bridge (localization of the source near the Kerch Strait)

Scenario №	Max. water level rise (western pillars)	Max. water level rise (eastern pillars)
1	**1.3 м**	**1,5 м**
2	**1,4 м**	**1,8 м**
3	**0,26 м**	**0,15 м**

CONCLUSIONS

It is shown that under scenarios when a seismic source with magnitudes M = 7 and M = 7.6 is located in the Black Sea at the entrance to the Kerch Strait, the height of the sea rise on the 3-meter isobath near the western pillars of the Crimean bridge can reach 1.3 m, in the eastern ones 1.5 m. With a source with a magnitude of M = 7, located in the Sea of Azov at the exit from the Kerch Strait, the maximum heights of water rise were 0.4 and 0.5 m for the western and eastern pillars of the bridge, respectively. For the M = 7.6 source located in the Black Sea at the southern entrance to the Kerch Strait, these values were 1.5 and 2m. The speed of the water flow in the vicinity of the western pillars of the bridge that goes around Ak-Burun Cape can reach 50 km/h, which can lead to damage to the bridge pillars and erosion of their base. It is shown that if the localization of the earthquake source is much further from the Kerch Strait, for example, near the southwestern coast of the Crimean Peninsula, then the maximum possible heights both at the western and eastern pillars of the bridge are about half a meter and lower. And only with a hypothetical earthquake with magnitude M = 8, which has not historically been observed in the basin of the Black and Azov Seas, and statistical estimates do not give such a significant natural event in the coming decades [27,30], wave heights near the rear and eastern pillars of the bridge can reach 1, 5 and 2m, respectively. When the bridge pillars are buried to a depth of 90m, such wave heights will not be able to cause significant damage to the bridge state.

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Best Wishes to Dr. Raissa Mazova for her birthday of 6 April 2023.

Wishing Dr. Raissa Mazova Happy Birthday and **a**cknowledging her numerous research projects and remarkable contributions over the years to our journal Science of Tsunami Hazards, with novel new approaches of numerical modeling methods and simulations. Dr. Mazova's research has been broadly centered on natural hazards and risk, with the goal of understanding the response of the environment to natural disasters in order to better prepare for, respond to, and recover from them. She has provided technical assistance and support to experts' panels, emergency management (for planning/preparedness) and has participated in community preparedness, training, exercises, evaluations/assessments, and post-disaster field surveys with scientists in her own country (Russia) and with other scientists from countries around the world. See her latest contribution in this April 2023 issue of the journal, entitled "BRIDGE ACROSS THE KERCH STRAIT - HISTORY AND MODERNITY", coauthored by Dr. E.A Baranova, Dr. R.Kh. Mazova, and Dr. A.A Kurkin.

Thank you Raissa, and again Happy Birthday with Good Health and Continuing Productivity.

George Pararas-Carayannis,
President, Tsunami Society International,
Editor, SCIENCE OF TSUNAMI HAZARDS

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