Kütahya Dumlupınar University
Institute of Graduate Studies

Journal of Scientific
Reports-A
E-ISSN: 2687-6167
Number 47, June 2021

RESEARCH ARTICLE

OVERESTIMATION of DISPLACEMENT DUE to MISINTERPRETATION of EARTHQUAKE RUPTURE PARAMETERS

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Received Date:15.09.2020 *Accepted Date:26.08.2021*

ABSTRACT

Tsunamis that killed hundreds of thousands of people, especially in the last two decades, are one of the most devastating natural hazards. Throughout history, tsunamis caused by devastating earthquakes have resulted in the loss of life, property, and environmental damage on the coasts. Recently, however, extreme hazard possibilities have been suggested due to misinterpretation of earthquake parameters and the overestimation of displacements. The structure of the seismic moment equation commonly used by scientists allows some manipulation on the rupture area of the fault and the displacement. Because of this gap, scientists produce different displacement amounts for an earthquake of the same magnitude and therefore, different tsunami wave heights are estimated by decreasing the rupture area and also, increasing the displacement under the sea. In this study, earthquake parameters are calculated based on a comprehensive literature review and compared with previous studies. The difference between the displacements calculated using regression analysis in the study and other studies reveals that the assumptions and estimations regarding the rupture parameters differs according to expert knowledge. The article aims to shed light on a reliable method of rupture parameter calculation to avoid misinterpretation and randomness.

Keywords: *Misinterpretation of rupture parameters, displacement, historical earthquakes, overestimation of tsunami wave heights*

1. INTRODUCTION

The Mediterranean Sea coastlines have been densely populated in recent years. The utilization of the coastal regions has also been increased with critical infrastructures such as international ports, airports, industrial structures, and power plants. Therefore, reliable estimation of potential hazards is vital for the maximization of risk reduction along these coastlines. The reliable analysis of historical earthquakes and tsunamis is a method that has been used to determine the destructive effects of possible future hazards [1-4]. Ambraseys [5] stated that the 365 Crete earthquake and tsunami, which uplifted the western coast of the Crete island about 9 m and affecting almost all of the coastal cities of the Mediterranean, is the largest natural disaster recorded in the Mediterranean. Papadapoulos et al. [6] compiled evidence of the 365 Crete earthquake and tsunami. It has been recorded that up to 7 m tsunami waves hit the coasts of the Mediterranean Sea and resulted in nearly 5000 drowned people in Alexandria, countless affected people in Sicily, Crete, and other towns located along the

Mediterranean coastline. However, Papadopoulos et al. [6] also noted that the geological documentation of the 365 Crete earthquake and tsunami has still questionable. Yolsal et al. [7] also conducted a numerical investigation on the 365 Crete, the 1222 Paphos earthquake, and the 1303 Crete earthquake. Yolsal-Cevikbilen and Taymaz [8] conducted a study on earthquake source parameters along the Hellenic subduction zone and estimated the rupture parameters and displacement amounts for the same historical earthquakes in the Eastern Mediterranean Sea. Detailed rupture parameters were revealed, both historical earthquakes and tsunamis (Table 1).

Table 1. Rupture parameters the most known megathrust earthquakes in the Mediterranean Sea [7-8].

Rupture Parameters	365 Crete Earthquake	1222 Paphos Earthquake	1303 Crete Earthquake
Moment magnitude (M_w)	>8.0	7.0- 7.5	≈ 8.0
Focal Depth (km)	20	15	20
Displacement (D) (m)	15	3	8
Fault length (L) (km)	200	50	≈100
Fault width (W) (km)	50	25	≈30
Strike angle (°)	295	305	115
Dip angle (°)	15	35	45
Rake angle (°)	90	110	110

Shaw et al. [9] estimated 20 m vertical displacement occurred in the 365 Crete earthquake. Necmioglu [10] also conducted a wide-ranging study on tsunami hazards in Turkey and connected seas. The study concluded by examining 2415 different tsunami scenarios that especially for the Aegean and Eastern Mediterranean regions. It was concluded that earthquakes with moment magnitude, $M_w \approx 6.5$-6.9, and focal depth ≤ 100 km generate 0.5 m tsunami wave height along the coastlines of Aegean Sea, South-East Cyprus, and around the Hellenic Arc. For the earthquakes with a focal depth greater than 100 km, the Richter magnitude of the earthquake should be greater than $M_w 7.0$ for the same tsunami wave height along the coastline. In order to obtain a 0.5 tsunami wave height around the Levantine coasts, the northern parts of Egypt, the northeastern part of Libya, and the southern coasts of Turkey, the moment magnitude of the earthquake should be $M_w \approx 7.0$ to 7.4.

However, there are some recent studies mentioning misinterpretation and overestimation of historical earthquakes and tsunamis in the Mediterranean Sea. Underestimation of rupture parameters are comprehensively investigated for tsunami risk assessment and implementation of tsunami early warning issues considering the 2011 Tohoku Earthquake [11]. A specified Probabilistic Tsunami Hazard Analysis (PTHA) and risk assessment method was developed for the coastal urban areas [11]. Marriner et al. [12] mentioned that 90% of the inundation events observed throughout history along the Mediterranean coastlines might be due to storm activities instead of tsunamis. Therefore, it is claimed that scientists misinterpreted the evidence found in inland regions [12]. The support of this claim comes from the analysis of tsunami and storm data compiled in the EM-DAT (Emergency Events Database), which is an international data repository of disasters for the period 1900–2015. However, Papadopoulos et al. [13] stated that storm surge action does not explain the typical characteristics of tsunami deposition. Considering the literature survey, it is obvious that there is no consensus among scientists for a reliable calculation method of the earthquake rupture parameters. This difference of opinion creates a gap about the unreliable calculation of rapture parameters that can be the reason for overestimation of displacement and tsunami waves. Since the risk analyses are conducted to estimate the most probable consequences of a natural hazard, a kind of misinterpretation of any data may have resulted in extraordinary risk evaluations and unnecessary precautions against an impossible hazard.

In this study, a comprehensive investigation has been conducted on the reliable estimation of earthquake rupture parameters, especially rupture area and displacement. Rupture parameters for the megathrust earthquakes are compiled from different scientific studies and compared with calculated ones. The source parameters (i.e. fault length (L), fault width (W), and displacement (D)) of 365 Crete, 1222 Paphos, and 1303 Crete earthquakes are re-evaluated using a specific calculation mean contrary to the revealed rupture parameters by some of the scientists (Figure 1).

Figure 1. Locations of the historical earthquakes.

A comprehensive investigation on empirical calculation means of rupture parameters is made and the most reliable empirical equations are revealed to end the debate on the vital issue. The performances of the selected equations are tested by calculating the rupture parameters of the megathrust historical earthquakes that occurred in the Mediterranean Sea. The difference between the results released by the previous studies and by this research is extremely erratic and presented in the results and discussion section.

2. MATERIALS AND METHODS

2.1. Calculation of Rupture Parameters

Commonly used seismic moment (M_0) equation was developed by Hanks and Kanamori [14]. The equation is derived as a function of the shear modulus of the crust (μ), L, W, and D to reveal the relationship between the source parameters and the magnitude of the earthquake. M_0 is calculated for crustal faults as [14]:

$$M_0 = \mu LWD \qquad (1)$$

where μ is taken as $3*10^{11}$ dyne/cm^2.

Hanks and Kanamori [14] also developed a well-known relationship between M_0 and M_w of a crustal earthquake as follows:

$$M_w = {}^{2}/_{3} * \log(M_0) - 10.7 \qquad (2)$$

In this study, earthquake rupture parameters are calculated using Eq. 2 and Eq. 1, respectively. However, especially Eq.1 can easily be manipulated due to the proportional relationship between the essential parameters used in the equation. Therefore, some other empirical relationships are revealed by the scientists dealing with seismic analysis. [11,15-17]. Since the constituent parameters of the seismic moment equation are reversely proportional, an infinitesimal change of fault length or fault width value might end up within an extremely high displacement of the crust determines the size of tsunami wave height for the same moment magnitude. For instance, 2 m and 10 m displacement values can be obtained for M_w7.0 by just manipulating the fault length or fault width value in M_0 equation. Thus, the correct determination of rupture parameters is significant to abstain from the overestimation of displacement of the earthquake.

The regression analysis proposed by some researchers are compared using the same historical earthquake data set (EDS) and shown as M_w-W, and M_w-L relationship in Figure 2 (a) and (b), respectively.

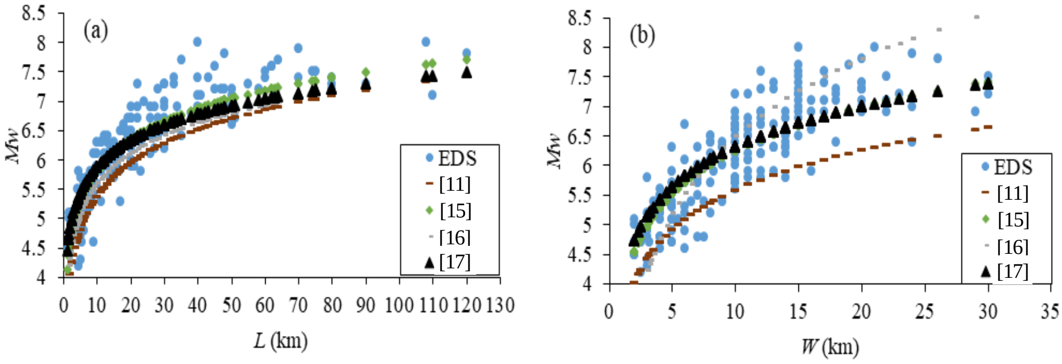

Figure 2. Comparison of (a) fault length and (b) fault width calculation from different sources.

Depending on the calculation results in Figure 2, the regressions provided by Wells and Coppersmith [17] are found as the most convenient equations and applied to calculate L and W of the historical earthquake's rupture parameters. Displacement occurred on the earth's crust due to earthquake can then be easily extracted from the seismic moment equation (Eq. 1) proposed by Hanks and Kanamori [14].

The empirical equation proposed by Wells and Coppersmith [17] shows the regression of L, on M_w as follows;

$$\mathrm{M_w} = 4.38 + 1.49 * \log(\mathrm{L}) \tag{3}$$

The following equation shows the regression of W, on $\mathrm{M_w}$ [17].

$$\mathrm{M_w} = 4.06 + 2.25 * \log(\mathrm{W}) \tag{4}$$

To preserve the similarity and ease of the comparison, the rest of the rupture parameters such as the location of the historical earthquake and the rupture angels are directly compiled from the literature [7-10]. This study shows that even making a small change among the rupture parameters in Eq. 1 by remaining the seismic moment value similar can be resulted in a high difference for the D value.

Misinterpretations of rupture parameters, especially for the rupture area, always resulted in high level of displacement estimation underneath the sea. That can cause extraordinary tsunami wave heights, which can be caused overestimated hazard assessments and unnecessary precautions against a hypothetical tsunami event throughout a coastline. If rapture area is correctly calculated, the overestimation of tsunami hazards might be prevented.

3. RESULTS

The assumed and estimated fault length, fault width, and displacement values revealed by the scientists are shown for the historical earthquakes are given in Table 2 with their references. To do this, L and W of the historical earthquakes are calculated using the equations proposed by Wells and Coppersmith [17]. Then displacement values can then be calculated using Eq. (1) and compared with the published studies. Displacement values are also calculated using the proposed method in this study, and given in Table 2, to show the misinterpretation of rupture parameters and their effects on the calculation of displacement.

Table 2. Comparison of the estimated and calculated displacement values for 365 Crete, 1222 Paphos and 1303 Crete Earthquakes.

Earthquake ID	L (km)	W (km)	D (m)	Reference
365 Crete	100	90	20	[18]
	200	50	15.00	[7,8]
	100	No data	9.00	[5], [19]
	100	No data	10	[20,21]
	255	**55**	**5.04**	**Calculated data**
1222 Paphos	50	25	3.00	[7,8], [22,23]
			3.00±1.00	[24]
	75	**25**	**1.40**	**Calculated data**
1303 Crete	100	30	8.00	[7,8]
	60	30	4.00	[25]
	No data	No data	1.00-3.60	[26]
	230	**50**	**3.75**	**Calculated data**

All these data show that the displacement values released by the previous studies differ dramatically. This is because of the misinterpretation or manipulation of the commonly used seismic moment equation proposed by Hanks and Kanamori [14]. Calculated rupture area using the Eqs. (3) and (4) gives lower displacement values comparing with the literature. Especially, Yolsal et al. [7] and Yolsal-Cevikbilen and Taymaz [8] misinterpreted the rupture areas and overestimated the tsunami risk for all three case studies in their research. Considering the 2004 Indian Ocean, 2011 Tohoku, and similar earthquakes and tsunami disasters experienced in the last two decades, the displacement values and tsunami wave heights coincide with the calculation mean proposed in this study.

4. CONCLUSION

Contrary to the magnitude of an earthquake, earthquake rupture area beneath the sea or ocean cannot be precisely recorded due to lack of scientific and technological deficiency. Because of this gap in the recorded data, fault length and fault width parameters are generally either estimated by the local authorities or based on expert options. Misinterpretation of the rupture area can generate a fatal error for the local authorities to take extraordinary precautions against a hypothetical tsunami event along the coastline. This can be resulted in wasting huge amounts of money and investment along the coastline. The structure of the seismic moment equation, commonly used by scientists, allows some manipulations on the rupture area and displacement. Due to this problem, scientists may generate different displacement values for the same magnitude of an earthquake by lowering the rupture area and increasing the displacement amount underneath the sea. Therefore, a reliable estimation of rupture area and displacement are vital for a pointed tsunami risk assessment not only for the Mediterranean coastline but also throughout the world. This study shows that the calculation characteristics of rupture parameters should be reconsidered and well-founded to obtain a good tsunami risk assessment.

ACKNOWLEDGEMENTS

The author of the paper would like to thank the authorities of Kutahya Dumlupinar University Technical Sciences Vocational School Department of Construction Technology for providing their understanding and support during the research.

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