TRANSPORT PROBLEMS 2008
PROBLEMY TRANSPORTU Tom 3 Zeszyt 2

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THREATS TO THE SAFETY OF NAVIGATION RESULTING FROM THE TSUNAMI

Summary. The tsunami traveling times were examined in connection to the earthquake that took place on 26 December 2004 in the Indian Ocean, changing the sea level as far as the Atlantic. For 17 ports located on the coasts of the two oceans theoretical times of wave arrival at the ports were calculated and compared with the real data recorded by mareographs. It has been found that the theoretical and real times differed, which can be explained by the effect of shallow water. Furthermore, as regards to the earthquake itself, instead of a single point epicenter as it was reported, it should have been considered as a zone of continental plates subduction extending 1200 km. The tsunami speed averaged for 17 ports amounted to 682 km/h, which necessitates an alteration of the coefficient in the formula (2) from the existing 5.0 to 4.38.

ZAGROŻENIE BEZPIECZEŃSTWA ŻEGLUGI W WYNIKU WYSTĄPIENIA TSUNAMI

Streszczenie. W pracy dokonano analizy czasu przemieszczania się fal tsunami na Oceanie Indyjskim i Atlantyku w efekcie trzęsienia ziemi w dniu 26.12.2004. Dla 17 portów rozmieszczonych wzdłuż ich wybrzeży, obliczono teoretyczne czasy dotarcia fal tsunami i porównano je z danymi rzeczywistymi zanotowanymi na wodowskazach (mareografach). Stwierdzono odpowiednie ich różnice, co uzasadnia się oddziaływaniem efektów płytkowodnych i uwzględnieniem faktu, że miejsce trzęsienia ziemi nie zaistniało jako punkt epicentrum podawany w komunikatach a jako strefa subdukcji płyt kontynentalnych na długości około 1200 km. Dla 17 portów uśredniona prędkość fali tsunami wyniosła 682 km/h co w tym przypadku zmienia współczynnik we wzorze (2), z 5,0 na 4,38.

1. INTRODUCTION

The term tsunami has been adopted directly from the Japanese language, a combination of the words *tsu* and *nami*, which mean, respectively, port and wave, that is a port wave. The tsunami is most often the effect of seismic phenomena occurring on the Earth. It is formed as an effect of an earthquake that takes place on the ocean or sea bottom or earthquakes in the coastal area. It can also be generated by an underwater explosion of a volcano, slip of a steep slope on the coast, landslide phenomena in ocean trenches or underwater canyons. It is also assumed that the tsunami may be caused as a result of a huge meteor hitting the surface of the ocean or sea.

Areas mostly endangered by tsunami waves are the coasts of the Pacific Ocean and the Indian Ocean, and less likely, other regions of the Earth, such as the coasts of the Mediterranean Sea and the Caribbean. It often happens that densely populated, well developed and tourist-attracting areas are struck.

The tragedy that happened on 26 December 2004 was a great shock to people all over the world. After an undersea earthquake with a magnitude > 9˚ in Richter scale, whose epicenter was located about 30 km under the ocean floor near the Northwest coast Sumatra, a tsunami wave was generated on the surface of the Indian Ocean, devastating the land areas off the shore. The tsunami caused enormous destruction on the coast of Indonesia - Aceh Province, Sri Lanka and India - states Tamil Nadu and Andhra Pradesh, the Andaman and Nicobar archipelagos) and in Thailand – Phuket Island and other areas. Damage to the structures also occurred in Malaysia, Burma, the Maldives, the Seychelles and Somalia. The number of casualties will never be exactly estimated. The human toll included about 230 thousand inhabitants of 13 Asian and East African countries as well as more than two thousand tourists. It is estimated that about 1.7 million inhabitants have lost their homes and property [1,2].

This work aims at examining the impact of the tsunami wave in several ports located along the rim of the Indian Ocean. Comparison of observed times when the tsunami reached the places selected for the survey with the theoretically calculated times creates grounds for possible improvement of tsunami forecasting and warning procedures, which are of importance for the safety of shipping in the offshore regions of the ocean.

2. SOURCE MATERIALS AND METHODOLOGY

Professional publications recommend that a ship's captain, having received information on an earthquake ≥ 6° Richter scale, should estimate the traveling time of the tsunami from the earthquake epicenter to the ship's position and to assess possible range of sea level fluctuations. In this case the captain should take into account data on the distance to the epicenter, the Richter magnitude of the earthquake, ocean depths on the predicted path of the tsunami wave and the depth of the waters the ship is sailing in. It is also recommended that ships should proceed in areas where depths exceed 50 meters [6].

It goes without saying that the estimation of tsunami arrival time is essential for ships at sea and coastal areas, possible when the place of wave generation is known. Theoretically, the propagation speed of transverse circular waves is determined from this equation:

$$C = \sqrt{gH} \tag{1}$$

where: g – 9.81 [m/s^2], H – sea depth [m]

The relationship used for forecasting tsunami arrival time has been worked out from many empirical data obtained from previous earthquakes and tsunami waves. Practitioners are recommended to use averaged tsunami characteristics [6]

$$T_{TS} = 5x \text{ [s]} \tag{2}$$

where: T_{TS} – time of tsunami arrival in seconds, x – distance from the epicenter in kilometers

This study is a post factum analysis focusing on computations of theoretical times of tsunami arrival in various locations along the Indian Ocean and selected ports of the Atlantic Ocean and the comparison of the theoretical times with real observations as of 26 December 2004. As there is no warning/monitoring system on the coast of the Indian Ocean that would register the formation and propagation of the tsunami the information from monitoring is the one transmitted at the time of disaster by the Pacific Tsunami Warning Center (PTWC).

Information on the earthquake on Sumatra substantially facilitated precise analysis of the phenomenon. The places for which the calculations were made include ports on Sumatra, Sri Lanka, Maldives, Mauritius, the Seychelles and ports in Africa, Europe and the port of Halifax, the latter being a location on the coast of North America where tsunami was observed.

In the analysis of the events of 26 December 2004 additional information was used. This was obtained from data bases of the University of Washington, data collected by Tokyo University, information from the National Oceanic and Atmospheric Administration (NOAA), Northwestern University, U.S. Geological Survey (USGS), University of Hawaii, Fisheries and Oceans Canada [3,7,8,9,10,11] on real fluctuations of the sea level.

More precisely, calculations were made for 14 locations on the coasts of the Indian Ocean (Fig.1) and three ports of the Atlantic Ocean. The ports selected to illustrate the effect of the tsunami wave on the coast are situated at various distances from the earthquake epicenter. This allows to estimate the time when wave occurrence in various places of the Indian Ocean Basin. The analysis was based on data on harbor water level changes observed in the ports included in Table 1.

The earthquake focus was assumed to have been a point with these geographical coordinates $\varphi = 3.4^o$ N and $\lambda = 95.7^o$ E, reported as the epicenter of the earthquake.

The times of tsunami occurrence are given as the Universal Time Co-ordinated - UTC. This will allow to estimate the difference in the arrival of waves in particular ports as well as to calculate the actual speed of the "port wave" propagation. The distances are the values of the shortest track between the points passing around islands and mainland.

The analysis has shown that many places located by the Indian Ocean were differently affected by the tsunami waves. Ports situated close to the epicenter were devastated so the losses caused by the high wave were heavy. Several minutes that passed from the earthquake to the moment the wave struck Sumatra (01:15 UTC) was too short to warn the residents and evacuate them. The ordinates of the runup height ranging from +5 m to + 30 m occurred in various localities on the coast of Banda Aceh, as shown in Fig. 2.

One important observation that can be made while analyzing the events of 26/27 December 2004 is that the time of tsunami arrival at various measurement points differs from that calculated theoretically. In such places as Male on the Maldives or Port Blair, Vishakapatnam on the eastern Indian coast the observed time the wave hit the land turned out less than the theoretical time from calculations. Although the differences can be due to varying depths of the ocean along the tsunami path, the main reason is that the earthquake occurred in a rupture zone approximately 1200 km in length (Sumatra – Andaman Islands) not just a point with specifically defined epicenter latitude $\varphi = 3.4^o$ N and longitude $\lambda = 95.7^o$ E. On the way to the ports of Male and Vishakapatnam the wave traveled meeting no natural obstacles, such as shallow waters or islands. The depth of the ocean between the epicenter and Male and Vishakapatnam, 1500 metres on the average. Therefore, the tsunami moved forward with slight loss of speed and energy.

3. THE RESULTS AND COMMENTS

The results of calculations are presented in tab. 1.

Tab. 1

Data and calculated results for the surveyed ports
(authors' study based on reports of PTWC, NOAA, USGS)[2,4,5,11]

	PORT	COUNTRY	GEOGRAPHICAL COORDINATES		TIME OF TSUNAMI OCCURRENCE		TIME DIFFERENCE FROM EARTHQUAKE		DIST.	ACTUAL SPEED
					LT	UTC	ACTUAL	THEORETICAL		
			Φ	λ	h:m	h:m	h:m	h:m	Km	km/h
1	Banda Aceh	Indonesia	05°31,00' N	095°25,00' E	07:59	00:59	-		-	-
2	Panjang	Indonesia	05°27,00' S	105°17,00' E	10:35	03:35	02:36	01:59	1430	550
3	Ta Phao Noi	Thailand	07°49,00' N	098°18,00' E	09:55	02:55	01:56	00:48	578	300
4	Port Blair	India	11°40,00' N	092°44,00' E	07:14	01:44	00:45	01:23	994	1325
5	Vishakapatnam	India	17°42,00' N	083°15,00' E	09:05	03:35	02:36	02:55	2108	811
6	Colombo	Sri Lanka	06°59,00' N	079°51,00' E	09:25	03:55	02:56	02:31	1812	619
7	Male	Maldives	04°11,00' N	073°31,00' E	09:15	04:15	03:16	03:43	2472	756
8	Kochj	India	09°59,00' N	076°16,00' E	11:10	05:40	04:41	03:10	2280	487
9	Salalah	Oman	15°56,00' N	054°00,00' E	12:06	08:06	07:07	06:38	4778	671
10	Pt La Rue	Seychelles	04°40,00' S	055°32,00' E	12:09	08:09	07:10	06:19	4555	635
11	Port Louis	Mauritius	20°09,00' S	057°30,00' E	12:15	08:15	07:16	06:50	4919	678
12	Lamu	Kenya	02°16,00' S	040°54,00' E	12:44	09:44	08:45	08:30	6128	700
13	Zanzibar	Tanzania	06°09,00' S	039°11,00' E	13:38	10:38	09:39	08:50	6368	670
14	Port Elizabeth	RSA	33°58,00 S	025°28,00 E	15:12	13:12	12:13	11:52	8519	697
15	East London	RSA	33°01,00 S	027°55,00 E	14:28	12:28	11:29	11:27	8269	720
16	Cape Town	RSA	33°04,00 S	018°26,00 E	17:01	15:01	14:02	12:50	9265	660
17	Brest	France	48°24,00 N	004°28,00 W	9:00 (27.12)	8:00 (27.12)	31:00	27:51	19937	643
18	Halifax	Canada	44°39,00 N	063°34,00 W	4:30 (27.12)	8:30 (27.12)	31:30	29:32	21317	677

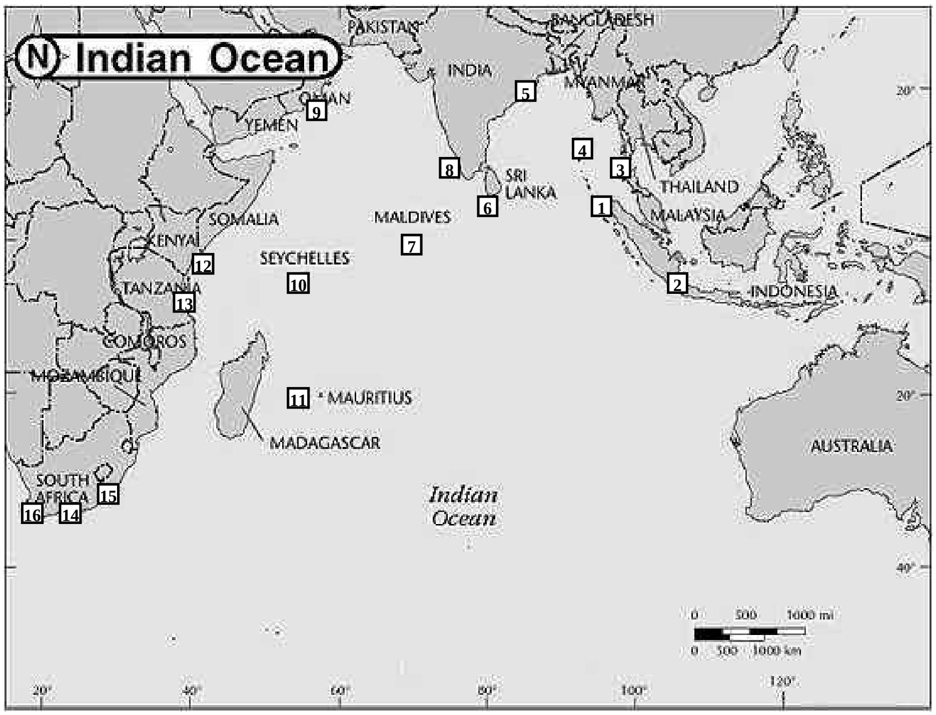

Fig. 1. Places in the Indian Ocean chosen for the tsunami survey
Rys. 1. Miejsca analizy fali tsunami na Oceanie Indyjskim

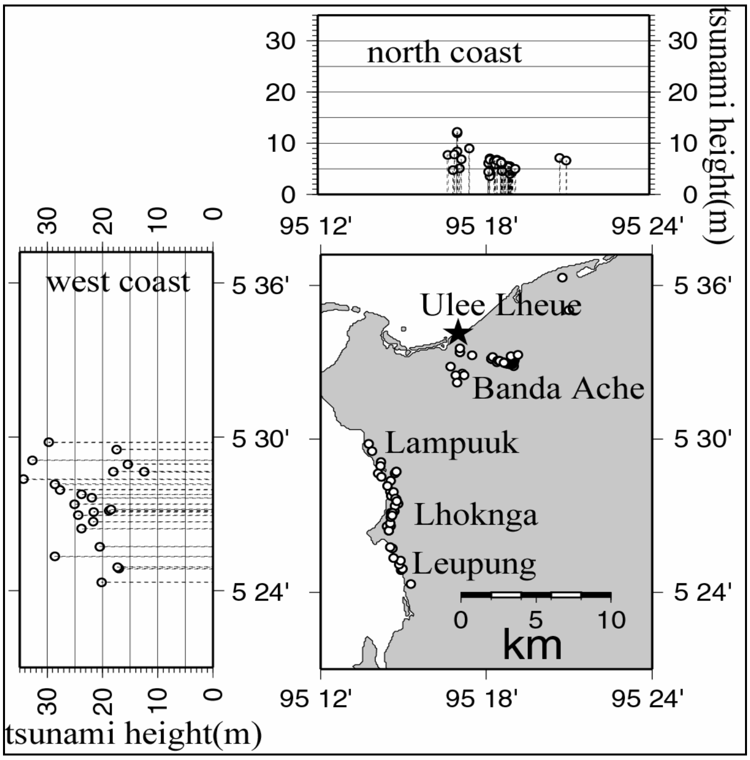

Fig. 2. Maximum recorded runup caused by the tsunami wave on 26.12.2004 on the coast of Sumatra [3]
Rys. 2. Maksymalne odnotowane wzniesienie poziomu morza (Runup) wywołane falą tsunami 26.12.2004 r. na wybrzeżu Sumatry [3]

These three ports witnessed the wave arrival earlier than the assumed tsunami speed of 800 km/h (222 m/s), which proves that the distances of those ports from the location where the tsunami was generated were shorter than the distance to the epicenter given in reports.

Ports sheltered from the direct impact of the tsunami noted a lower wave and much later time of its arrival than the calculated time. One example of such place is the port of Kochi on the southwest coast of Indian Peninsula and Salalah in Oman. The differences noted at the measurement point in India showed that the tsunami reached that place one hour and a half later, while the port in Oman was reached over half an hour later than the relevant calculations suggest. Wave heights in those places, according to tide gauge (mareograph) recordings, did not exceed 1.5 meters. These differences result from the fact that those places are sheltered by land. Before the tsunami reached the port of Kochi, it had changed its direction due to refraction and moved around the island of Sri Lanka, which extended its track and reduced its speed at south-eastern and southern coast of the island. Additionally, shallow waters near Sri Lankan coast weakened the wave due to increased friction against the bottom. In calculations of the tsunami arrival one should take into account the distance the wave covered, which is difficult to determine accurately in the case of refraction. To sum up, the main factor which delayed the wave traveling time was shallow waters in the proximity of Sri Lanka and India. The tsunami behaved similarly near the port of Salalah in Oman.

The analysis has also shown that archipelagos such as the Seychelles, Maldives or Mauritius significantly interact with the tsunami by reducing its energy, and consequently, its height. The tsunami, having passed such natural obstacles as an island, is characterized by weak force, therefore its impact on the coasts is slight or in some cases the wave completely disappears. For instance, the wave was completely stopped on the eastern coast of Africa in the vicinity of the ports of Lamu and Zanzibar. After passing the Seychelles the wave height substantially decreased. Lamu, a port situated about 1500 km west of the archipelago, recorded a wave runup of about 0.4 m, while in Zanzibar tsunami waves changed the sea level by 0.15 m.

The tsunami waves were higher in more distant ports where the wave had easier access from the open ocean. For example, Port Elizabeth noted +2.73m rise, East London +1.35m, Cape Town +0.96 m, even Halifax in the North Atlantic recorded a noticeable change of + 0.43 m.

4. SUMMARY

This study includes an analysis of the time the tsunami waves traveled in the Indian and Atlantic Oceans after they had been generated by the earthquake that occurred on 26 December 2004. For 17 ports on the ocean coasts theoretical times the tsunami took to reach them were calculated and compared with real data recorded by mareographs. Differences were found between the theoretical times calculated using the formula (2) and the actually recorded times. Three ports were reached by the tsunami earlier than theoretically calculated times with differences varying from 19 to 38 minutes; in the other 11 ports by the Indian Ocean, due to shallow water effects, the tsunami came later than in theory, the difference ranging from 15 minutes to 1.5 hours. For the same reason the tsunami arrived later at the examined ports of the Atlantic Ocean: Cape Town - 1 hour 12 minutes, Halifax – 1 hour 58 minutes and Brest - 3 hours 9 minutes. The averaged wave speed for the 17 ports was 682 km/h, which may suggest that the coefficient 5 in the formula (2) should be changed to 4.38.

As there is no earthquake/tsunami warning system in the Indian Ocean, ships in the affected area could not receive any information, navigational warnings or weather reports. The Pacific Tsunami Warning Center in Hawaii (PTWC) took but limited attempts to inform about the earthquake. It received messages from the stations on the Pacific Ocean, but naturally had no data on tsunami from the Indian Ocean. This situation is going to change when under the auspices of NOAA and the governments of Thailand and Indonesia a network of stations recording tsunami waves (DART) will be established, the same as are in operation in the Pacific and the Atlantic. With two such stations already installed by November 2007, the system will include 20 stations located along the coasts of the Indian Ocean [12].

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Received 28.04.2008; accepted in revised form 17.06.2008