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The analysis of tsunami arrival time during the event from 11.03.2011 (Japan)

Analiza czasu rozchodzenia się fali tsunami podczas zdarzenia z 11.03.2011 r. (Japonia)

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Key words: tsunami arrival time, the safety of the shipping and ports

Abstract

The paper presents an analysis of the tsunami arrival time as a result of the earthquake on 11.03.2011 on the Pacific Ocean. For 91 ports arranged along coasts of Pacific, one counted theoretical arrival times of the tsunami and compared it with data real noted on water level gauges of West Coast / Alaska Tsunami Warning Center. Change of the coefficient in the formula for the wave arrival time from 5.0 to 4.72 as the average factor for the ports lying directly on the open ocean waters was proposed. This is of practical importance for the possible procedures to improve forecasting and warning system for tsunami, which are important in maintaining the safety of navigation in the coastal zone of the ocean.

Słowa kluczowe: czas przybycia tsunami, bezpieczeństwo żeglugi i portów

Abstrakt

W pracy dokonano analizy czasu przemieszczania się fal tsunami na Oceanie Spokojnym w efekcie trzęsienia ziemi w dniu 11.03.2011 r. Dla 91 portów rozmieszczonych wzdłuż wybrzeży Pacyfiku obliczono teoretyczne czasy dotarcia fal tsunami i porównano je z danymi rzeczywistymi zanotowanymi na wodowskazach West Coast / Alaska Tsunami Warning Center. Zaproponowano zmianę współczynnika we wzorze na czas rozchodzenia się fali $T_{TS} = 5x$ na $4{,}72x$ jako uśredniony współczynnik dla portów otwartych na ocean. Ma to znaczenie praktyczne dla ewentualnego poprawienia procedur prognozowania i ostrzegania przed tsunami, które są istotne w zachowaniu bezpieczeństwa żeglugi w strefie brzegowej oceanu.

Introduction

The coasts of the Pacific Ocean, the so called Fire Ring (areas of plate tectonics), are the areas which are most threatened by tsunami. The phenomenon also, but less frequently, occurs on the coastline of the Indian Ocean, Mediterranean Basin and Caribbean Basin. According to the information from NOAA [1] there have been over 2,400 registered tsunami occurrences since 2000 BC. 63% of all tsunami waves occurred on the Pacific Ocean, 21% on the Mediterranean Sea, 5% on the Atlantic Ocean, 4% on the Caribbean Sea, 6% on the Indian Ocean and 1% on the Black Sea. One of the most catastrophic tsunami occurred on 26 December 2004, when a very strong earthquake (9.1°R) generated a tsunami which killed about 230,000 people on the coast of the Indian Ocean. The most recent tragic tsunami occurred in Japan (the island of Honsiu) and the coasts of the Pacific on 11 March 2011 (9.0ºR). The tsunami killed over 15,800 people and caused great destruction of cities, port infrastructure and the coastal zone of North-Eastern Japan.

The aim of this work is to analyze the time of the arrival of tsunami towards particular coasts of the Pacific Ocean on 11 March 2011. The analytical part of the work compares the actual times and theoretically calculated times of reaching by the tsunami the chosen 91 ports situated on the coasts of the Pacific Ocean. This comparison gives a possibility to improve the procedures of predicting and warning against tsunami, including the possibility of implementing formulas by ship captains who would then be able to estimate the time of arrival of the tsunami wave at the place and position of the ship.

The physical description of the phenomenon of tsunami was included in the authors' earlier publications [2, 3, 4, 5].

The Course of Tsunami of 11 March 2011 on the Pacific Ocean and Japanese Islands

On 11 March 2011 at 5:46:23 UTC, (14:46:23 local time) the North-Eastern part of Japan was struck by an earthquake with a force of 9.0ºR. The hypocenter (the focus of the earthquake) was located below the sea bottom, about 130 km east from the Oshika peninsula on the island of Honsiu, at the depth of 24.4 km. The force of the magnitude made it the biggest earthquake in Japan in the last 140 years (that is since seismic activity in Japan started to be registered) and the fourth biggest earthquake in the world. The main quake was preceded by a series of smaller ones reaching the maximum of 7.2ºR on 9 March. On 11 March, after the main quake, subsequent quakes reaching from 6.0ºR to 7.4ºR were registered (Fig. 1) [6].

The consequence of the earthquake were massive tsunami waves reaching the height of over 8 meters (the maximum height of an accumulated incoming wave reached almost 24 metres at the port of Ōfunato), which struck almost the entire eastern coast of Japan, flooding sea ports, industrial zones, cities, villages, farms, arable fields and coastal forests of the Tōhoku region. On plains the sea water forced its way 10 km into the land [7].

The most dangerous consequence of the earthquake and tsunami in Japan was a series of accidents at the Fukushima 1 nuclear power plant connected with the reactor cooling system.

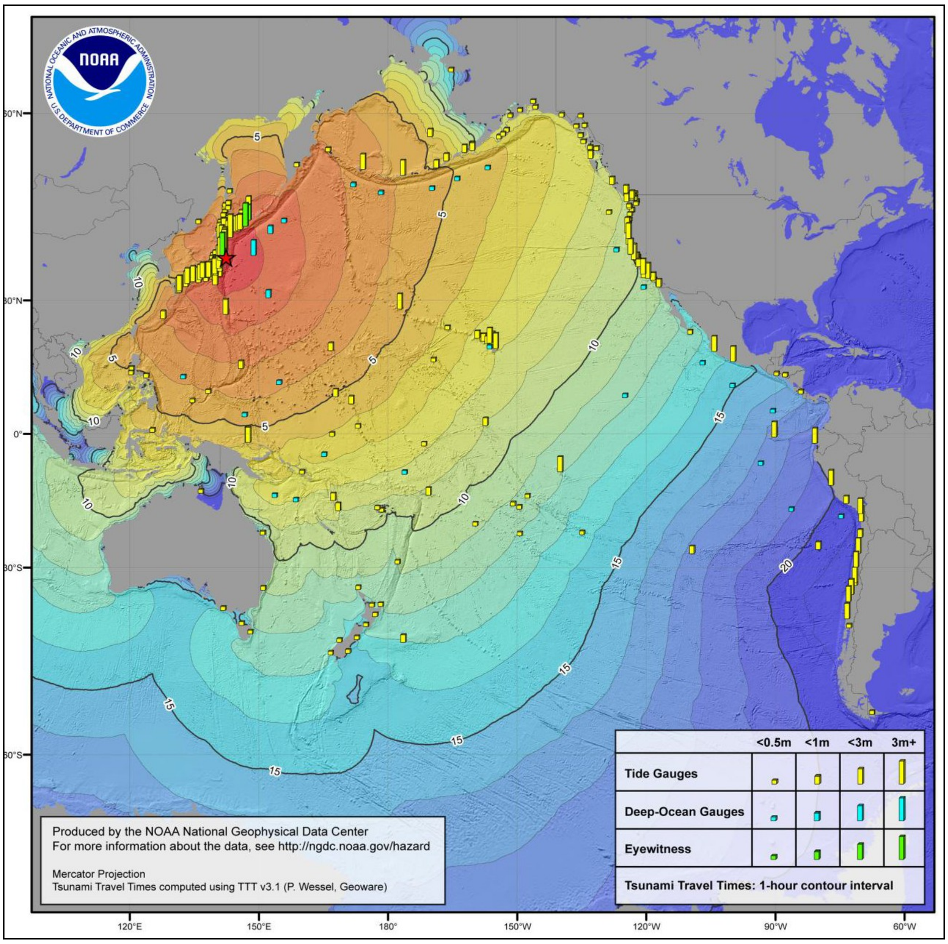

Fig. 1. Wave height and tsunami arrival time by the Pacific [9]
Rys. 1. Wysokość i czas przejścia fal tsunami (godziny) przez Pacyfik [9]

According to the latest statistics (December 2011), as a result of the tsunami 15,800 people were killed, 3,500 were found missing and over 1,000,000 flats and buildings were partly or entirely damaged [8].

The announcement warning against the tsunami was issued for all islands and coasts of the Pacific, including Russia, the Philippines, Australia, Hawaii and South America. Evacuation was ordered in coastal areas of the Kuril Islands, Kamchatka and Sakhalin. However, the concerns were not confirmed – the tsunami wave spread mainly in the South-East direction and that is why the wave on the above coasts was much smaller than expected and did not cause significant damage. The wave exceeded 2 m only in few places on the coast of Hawaii, Oregon, California and Chile. The tsunami wave went across the Pacific Ocean in less than one day. After about 21 hours it reached the west coast of South America (Fig. 1).

Comparison of Theoretical and Observed (Actual) Time of Reaching the Ports of the Pacific by the Tsunami

Methods of Calculation and Sources of Data

Since we are not able to predict an earthquake, earlier prediction of tsunami is not possible. However, we know that a tsunami wave spreads with a finite speed and thus, if we know the place where an earthquake struck, we know its force and the shape of the bottom of the water area, we can evaluate the speed with which a tsunami wave is going to spread and its initial energy.

Determining the arrival time of the wave in the event that the place where waves originate are known is essential for shipping and the coasts. The work determines the theoretical time of the tsunami wave arriving from the epicentre to 91 ports located on the coast of the Pacific.

For the purpose of predicting the arrival of tsunami we use dependence determined on the basis of numerous empirical data from former earthquakes and occurrences of tsunami is used as followes [10]:

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

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

The distances between the hypocenter of the earthquake and a chosen port were calculated along the orthodrome, that is the shortest distance between two points on the surface of a globe. The calculations are based on the shortest distance, because that is how any liquid behaves – it travels the most simple and fastest way. The length of the orthodrome between two points on the surface of the Globe (zenithal distance between two points) was calculated according to a cosine formula commonly used in navigation:

$$D = \arccos((\sin\varphi_1 \sin\varphi_2) + (\cos\varphi_1 \cos\varphi_2 \cos\Delta\lambda))\cdot 6371$$

where: D – the distance among the epicentre and with the chosen port [km]; φ_1, φ_2 – geographical latitudes of both points [°]; $\Delta\lambda$ — the difference of geographical longitudes of both points; 6371 – the average ray of Earth [km].

Additionally, the work determines:

- actual time of the travel of the wave (difference between the time of arrival and the time of the occurrence of the earthquake at the epicentre) on the basis of observation data (observed time) [hours: minutes: seconds];
- actual speed of the wave [km/h];
- wave speed determined on the basis of the theoretical time of the tsunami [km/h];
- difference between actual time of the arrival of the wave (observed time) and theoretical tsunami time [minutes].

All calculations were performed in Excel.

Sources of data

Observation data, i.e. geographical coordinates of 91 ports of the Pacific (west coasts of both Americas and islands of the Pacific), the time of arrival of the wave and the maximum height of the wave registered at a given port, was taken from the following website: West Coast / Alaska Tsunami Warning Center, NOAA/NWS. Information on the time of the occurrence of the earthquake at the epicentre and its location (05:46:23 UTC 11 March 2011, 38.322N, 142.369E) was taken from the U.S. Geological Survey. The analysed time was indicated in UTC [11].

Results of Calculations and Discussion

The results of calculations regarding the theoretical time of tsunami and additional, observed parameters of the wave for chosen ports are shown in table 1.

The longest observed and theoretical time of the tsunami wave was determined at Valparaiso, a port in Chile (observed time: 22:16, theoretical time: 23:30). That is because the port is the furthest from the epicentre of the earthquake out of all analysed stations. The shortest observed and theoretical time of the tsunami wave was determined in the port situated the closest to the epicentre, that is the Japanese port of Boso (00:17 and 00:35, respectively). The average observed time (of the wave travel), taking into account all analysed ports was

Table 1. Comparison between observed time of the tsunami wave and theoretical time determined using the $t = 5x$ formula, as well as additional, observed parameters of the wave at 91 ports of the Pacific (own study on the basis of [11], NOAA/NWS)
Tabela 1. Porównanie zaobserwowanego czasu tsunami i czasu teoretycznego określonego przy użyciu formuły $t = 5x$, jak również zaobserwowanych parametrów fali w 91 portach na Pacyfiku (oprac. własne na podst. [11], NOAA/NWS)

Lp.	Port	φ	λ	Distance [km]	Observed time [h:m:s]	Theoretical time [h:m:s]	Difference between observed and theoretical time [h:m:s]	Actual speed of the wave [km/h]	Wave hight [cm]
1	Adak, AK	51,863	–176,632	3493,8	04:31:37	4:51:09	–0:19:32	771,8	110
2	Alitak, AK	56,85	–154,3	4962,1	07:37:37	6:53:31	0:44:06	650,6	18
3	Craig, AK	60,558	–145,753	5415,7	08:29:37	7:31:18	0:58:19	637,6	31
4	Dutch Harbor, AK	53,888	–166,538	4190,8	05:49:37	5:49:14	0:00:23	719,2	51
5	Elfin Cove, AK	58,193	–136,343	5990,3	07:57:37	8:19:11	–0:21:34	752,5	21
6	Juneau, AK	58,289	–134,412	6095,3	09:30:37	8:27:56	1:02:41	640,9	21
7	Ketchikan, AK	55,333	–131,625	6365,1	09:09:37	8:50:26	0:19:11	694,9	11
8	King Cove, AK	55,059	–162,324	4467,5	06:19:37	6:12:17	0:07:20	706,1	54
9	Kodiak, AK	57,74	–152,483	5064,3	07:12:37	7:02:02	0:10:35	702,4	35
10	Nikolski, AK	52,941	–168,872	4030,1	05:21:37	5:35:51	–0:14:14	751,9	84
11	Old Harbor, AK	57,22	–153,306	5019,4	07:19:37	6:58:17	0:21:20	685,1	38
12	Port Alexander, AK	56,246	–134,647	6152,8	08:10:37	8:32:44	0:22:07	752,5	42
13	Sand Point, AK	55,333	–160,502	4583,3	06:35:37	6:21:57	0:13:40	695,1	61
14	Saint Paul, AK	57,125	–170,275	4000,3	05:56:37	5:33:21	0:23:16	673,0	61
15	Seward, AK	60,119	–149,427	5219,4	08:06:37	7:14:57	0:51:40	643,6	29
16	Shemya, AK	52,730	174,103	2909,5	03:38:37	4:02:28	–0:23:51	798,5	157
17	Sitka, AK	57,052	–135,342	6084,4	08:10:37	8:27:02	–0:16:25	744,1	40
18	Langara Point, BC	54,2	–133,1	6322,7	08:15:37	8:46:54	–0:31:17	765,4	54
19	Winter Harbor, BC	50,7	–128,3	6776,8	08:59:37	9:24:44	–0:25:07	753,5	83
20	La Push, WA	47,544	–124,388	7193,0	09:33:37	9:59:25	–0:25:48	752,4	71
21	Neah Bay, WA	48,368	–124,617	7132,8	09:47:37	9:54:24	–0:06:47	728,3	43
22	Port Angeles, WA	48,125	–123,44	7221,9	10:20:37	10:01:49	0:18:48	698,2	59
23	Seattle, WA	47,602	–122,335	7322,4	11:34:37	10:10:12	1:24:25	632,5	4
24	Westport, WA	46,908	–124,11	7246,7	09:52:37	10:03:54	–0:11:17	733,7	46
25	Astoria, OR	46,208	–123,767	7308,9	10:27:37	10:09:05	0:18:32	698,7	18
26	Charleston, OR	43,345	–124,322	7436,5	09:42:37	10:19:43	–0:37:06	765,8	71
27	Garibaldi, OR	45,555	–123,912	7336,6	09:46:37	10:11:23	–0:24:46	750,4	35
28	Port Orford, OR	42,737	–124,497	7459,9	09:28:37	10:21:40	–0:53:03	787,2	202
29	South Beach, OR	44,625	–124,043	7381,3	09:55:37	10:15:07	–0:19:30	743,6	43
30	Arena Cove, CA	38,913	–123,705	7745,1	09:42:37	10:45:25	–1:02:48	797,6	174
31	Crescent City, CA	41,745	–124,183	7540,3	09:47:37	10:28:21	–0:40:44	769,9	247
32	La Jolla, CA	32,867	–117,258	8608,3	11:00:37	11:57:22	–0:56:45	781,8	39
33	Los Angeles, CA	33,719	–118,272	8475,9	10:53:37	11:46:19	–0:52:42	778,1	49
34	Monterey, CA	36,605	–121,888	8021,4	10:01:37	11:08:27	–1:06:50	800,0	70
35	North Spit, CA	40,767	–124,217	7596,2	09:47:37	10:33:01	–0:45:24	775,6	97
36	Point Reyes, CA	37,997	–122,975	7854,5	09:59:37	10:54:32	–0:54:55	786,0	135
37	Port San Luis, CA	35,168	–120,753	8197,2	10:23:37	11:23:06	–0:59:29	788,7	202
38	San Francisco, CA	37,807	–122,465	7903,4	10:25:37	10:58:37	–0:33:00	758,0	62
39	Santa Barbara, CA	34,408	–119,69	8325,4	10:40:37	11:33:47	–0:53:10	779,8	102
40	Santa Monica, CA	34,008	–118,5	8439,7	10:56:37	11:43:19	–0:46:42	771,2	84
41	Boso, Japan	34,75	140,76	422,4	00:17:37	0:35:12	–0:17:35	1438,57	74
42	Hanasaki, Japan	43,28	145,57	613,5	00:51:37	0:51:07	0:00:30	713,1	282
43	Ishigakijima, Japan	24,3	124,2	2317,8	03:37:37	3:13:09	0:24:28	639,0	23
44	Minamitorish. Japan	24,3	153,97	1905,7	02:00:37	2:38:48	–0:38:11	948,0	48
45	Naha, Japan	26,22	127,67	1924,1	03:15:37	2:40:20	0:35:17	590,2	61
46	Omaezaki, Japan	34,6	138,23	555,1	01:00:37	0:46:16	0:14:21	549,5	157

Table 1 (cont.)

1	2	3	4	5	6	7	8	9	10
47	Tokai, Japan	33,77	137,59	663,7	00:49:37	0:55:19	–0:05:42	802,6	24
48	Hilo, Hawaii, HI	19,73	–155,057	6301,3	07:56:37	8:45:06	–0:48:29	793,3	117
49	Honolulu, Oahu, HI	21,307	–157,867	5960,4	07:28:37	8:16:42	–0:48:05	797,2	71
50	Johnston Island	16,739	–169,523	5241,4	06:24:37	7:16:47	–0:52:10	817,6	17
51	Kahului, Maui, HI	20,898	–156,472	6106,7	07:42:37	8:28:53	–0:46:16	792,0	250
52	Kawaihae, Hawaii,	20,036	–155,832	6214,9	07:36:37	8:37:55	–1:01:18	816,6	103
53	Midway Is. USA	28,211	–177,356	3875,8	04:41:37	5:22:59	–0:41:22	825,8	156
54	Nawiliwili, Kauai, HI	21,957	–159,36	5791,4	07:13:37	8:02:37	–0:49:00	801,4	87
55	Gisborn, NZ	–38,675	178,023	9304,1	13:17:37	12:55:21	0:22:16	699,9	72
56	North Cape, NZ	–34,415	173,049	8684,5	12:01:37	12:03:43	–0:02:06	722,1	46
57	Davao, Philippines	7,0733	125,633	3860,7	05:24:37	5:21:43	0:02:54	713,6	40
58	Legaspi, Philippines	13,161	123,758	3346,7	04:32:37	4:38:54	–0:06:17	736,6	27
59	Rikitea, Fr. Polynes.	–23,12	–134,969	10975,4	14:09:37	15:14:37	–1:05:00	775,1	37
60	Betio, Tarawa, Kiribati	1,362	172,93	5155,2	06:16:37	7:09:36	–0:52:59	821,3	25
61	Christmas Is, Kiribati	1,589	–157,283	7349,7	08:58:37	10:12:29	–1:13:52	818,7	59
62	Funafuti, Tuvalu	–8,5	179,2	6453,2	07:56:37	8:57:46	–1:01:09	812,4	26
63	Honiara, Solomon Isl.	–9,4288	159,987	5615,5	07:50:37	7:47:58	0:02:39	715,9	22
64	Kawajalein, Marshall	8,735	167,736	4154,2	05:00:37	5:46:11	–0:45:34	829,1	67
65	Malakal, Palau	7,198	134,278	3555,2	04:45:37	4:56:16	–0:10:39	746,8	14
66	Manus, PNG	–2,03	147,367	4516,2	05:54:37	6:16:21	–0:21:44	764,1	109
67	Nauru, Nauru	0,05	166,9	4939,0	05:56:37	6:51:35	–0:54:58	831,0	26
68	Nukualofa, Tonga	–21,133	–175,17	7957,2	10:37:37	11:03:06	–0:25:29	748,8	60
69	Pago Pago, A.Samoa	–14,274	–170,676	7619,7	09:21:37	10:34:58	–1:13:21	814,0	62
70	Port Villa, Vanuatu	–17,75	168,3	6796,6	08:48:37	9:26:23	–0:37:46	771,4	81
71	Saipan, N Marianas	15,226	145,742	2589,3	03:17:37	3:35:47	–0:18:10	786,2	74
72	Suva Viti Levu, Fiji	–18,134	178,424	7317,8	09:45:37	10:09:49	–0:24:12	749,7	21
73	Wake Island	19,29	166,618	3153,2	03:31:37	4:22:46	–0:51:09	894,0	49
74	Yap, Micronesia	9,305	138,077	3254,9	04:08:37	4:31:15	–0:22:38	785,5	16
75	Acajutla, El Salvador	13,573	–89,8383	12094,9	16:48:37	16:47:55	0:00:42	719,5	51
76	Acapulco, Mexico	16,833	–99,9166	11093,7	14:33:37	15:24:28	–0:50:51	761,9	105
77	Cabo S.Lucas,Mexico	22,528	–109,545	9927,2	12:32:37	13:47:16	–1:14:39	791,4	29
78	Manzanillo, Mexico	19,03	–104,2	10599,2	13:45:37	14:43:16	–0:57:39	770,3	163
79	Quepos, Costa Rica	9,4	–84,1666	12847,6	17:36:37	17:50:38	–0:14:01	729,6	55
80	Baltra Is, Ecuador	–0,433	–90,283	13201,7	17:30:37	18:20:08	–0:49:31	753,9	88
81	Easter Island, Chile	–27,09	–109,269	13361,1	17:29:37	18:33:26	–1:03:49	763,8	74
82	Iquique, Chile	–20,22	–70,17	16302,3	21:12:37	22:38:31	–1:25:54	768,6	99
83	Juan Fernandez, Chile	–33,617	–78,825	16302,0	21:18:37	22:38:30	–1:19:53	765,0	59
84	Valparaiso, Chile	–33,02	–71,38	16927,8	22:16:37	23:30:39	–1:14:02	759,9	155
85	La Libertad, Ecuador	–2,209	–80,902	14065,3	19:32:37	19:32:06	0:00:31	719,7	176
86	Atico, Peru	–16,233	–73,6666	15732,6	20:37:37	21:51:03	–1:13:26	762,7	67
87	Callao La Punta, Peru	–12,071	–77,174	15140,4	20:19:37	21:01:42	–0:42:05	744,8	173
88	Antofagasta, Chile	–23,32	–70,428	16493,4	21:32:37	22:54:27	–1:21:50	765,6	95
89	Arica, Chile	–18,472	–70,335	16162,0	21:17:37	22:26:50	–1:09:13	759,0	250
90	Caldera, Chile	–27,058	–70,834	16687,5	21:40:37	23:10:37	–1:30:00	769,8	201
91	Coquimbo, Chile	–29,93	–71,35	16794,3	22:10:37	23:19:31	–1:08:54	757,3	220

* instances where the difference between observed and theoretical time is negative are marked blue.

9 h and 44 min., whereas theoretical time was 10 h and 10 min. Thus, the average difference came to 26 minutes (Table 2).

Table 2. Extreme and average values of calculated and observed tsunami wave parameters at analyzed 91 ports [own study]
Tabela 2. Ekstremalne i średnie wartości wyliczonych i obserwowanych parametrów fali tsunami w 91 analizowanych portach [opracowanie własne]

Parameter		Maximum		Average	Minimum	
Distance	[km]	Valparaiso, Chile	16927,8	7331,0	Boso, Japonia	422,4
Observed time	[hour:min]	Valparaiso, Chile	22:16	09:44	Boso, Japonia	00:17
Theoretical time	[hour:min]	Valparaiso, Chile	23:30	10:10	Boso, Japonia	00:35
Difference time(o.-t.)	[hour:min]	Caldera, Chile	01:30	–00:26	Dutch Harbor, USA	00:00,3
Speed wave	[km/h]	Boso, Japonia	1438,6	759,8	Omaezaki, Japonia	549,5
Hight wave	[m]	Hanasaki, Japonia	2,82	0,80	Seattle, USA	0,04

A curious fact regarding the minimum speed of the wave in Japan – Oemazaki port (549.5 km/h) results from a small distance calculated along the orthodrome (only 555 km) and relatively long time of travel of the wave (1:37). This is connected with the location of the port, which is partly shielded by 2 peninsulas of the central part of Honsiu, which forces the wave to travel a distance much longer than calculated. On the other hand, the Japanese port of Boso – the port with the largest speed of the wave (1438.6 km/h) is a port situated directly by the Pacific, the closest to the epicentre. The highest wave, among ports that are distant from the epicentre and analysed in the table 2, reached 2.82 m at the port of Hanasaki (ports that are located the closest to the epicentre and directly subject to tsunami are not included in Table 1). Relatively high waves were registered on the other side of the Pacific in Arica, Chile – 2.5 m, or Crescent City in California – 2.47 m (Fig. 1). The wave that struck both of the ports did not have a chance to lose any energy on shallows, coral reefs or archipelagos. The lowest tsunami wave (4 cm) was registered in the USA, in Seattle, which is located inland by Puget Sound, over 100 km from the open ocean (Fig. 2).

Fig. 2. Seattle port location in the hinterland [12]
Rys. 2. Położenie portu w Seattle w głębi lądu [12]

The most important result of the undertaken analysis is the fact that in almost 75% of cases (68 out of 91 ports) the theoretical time of travel of the wave was shorter than observed time (the wave came faster than it had been calculated). The average total theoretical time of the wave (data from all 91 ports) was longer than observed time by 26 minutes. This can prove the lack of preciseness and unsuitability of the used $t = 5x$ formula to the conditions of the Pacific Ocean. In 75% of cases the formula overestimates the arrival time of the wave according to the distances calculated along the orthodrome. The formula should be modified in order to be practically used in navigation. Obtaining time of the arrival of the wave which is longer than the actual arrival time can cause a threat to ships and their crew.

There was an attempt to verify and improve the $t = 5x$ formula using a solver tool. Solver is an Excel add-on – an optimizing function that uses a program of non-linear optimization called Generalized Reduced Gradient (GRG2).

When verifying the $t = 5x$ formula in this consideration, we need to establish that coefficient 5 should be modified in a way that would minimize the differences between observed and calculated time. Putting the assumption into the solver, a different result for the coefficient in the formula was obtained [4.72 ($t = 4.72x$)]. New theoretical time of wave travel was calculated for all 91 ports using the new coefficient. The results summarizing optimization of the formula for theoretical time of tsunami wave travel are shown in Table 3.

On the basis of data from table 3 the optimized formula verified the results calculated with the use of new theoretical time ($t = 4.72x$) can be seen. The difference between total average observed (actual) time from all 91 ports and total average theoretical

Table 3. Results regarding theoretical time of tsunami wave calculated as an average from 91 ports of the Pacific [own study]
Tabela 3. Wyniki pokazujące teoretyczny czas fali tsunami obliczony jako średni z 91 portów na Pacyfiku [opracowanie własne]

	Average observed time of tsunami wave [hours:min]	Average theoretical time of tsunami wave [hours:min]	Difference between observed and theoretical time [hours:min]	Number of cases in which observed time < theoretical time	Average speed of observed tsunami wave [km/h]	Average speed calculated from theoretical time of tsunami [km/h]
Calculations by the formula $t = 5x$	09:44	10:10	–00:26	74.7% (68 / 91)	759,8	720
Calculations by the formula $t = 4.72x$		9:37	+ 00:07	49.5% (45 /91)		761.9

time decreased from 26 minutes to 7 minutes. Consequently, the average speed of a tsunami wave determined on the basis of theoretical time increased from 720 to 762 km/h.

The new formula reduced the number of instances in which the time difference was negative (because the wave arrives sooner than it comes out of former calculations). The number of such cases decreased from 74.7% to 49.5%.

Conclusions

The above results of optimizing the formula for calculating the time of tsunami arrival cannot be recognised as satisfactory. The formula should determine theoretical time so that in every case it was shorter than the actual time of tsunami arrival. Otherwise, it can cause danger to the lives of people in seaside towns, as well as shipping in the coastal zone. Another drawback of the formula is that it causes problems in the case of shielded ports, located far from the coast, where calculating the distance along the orthodrome significantly lowers the actual travel time of the spreading of a tsunami. A good example of this is the port of Seattle in the USA, for which the difference between the observed time and theoretical time determined according to the improved formula reached as much as +1 h 58 min, which results from the inland location of the port. That is why it is necessary to conduct further studies on optimizing formulas used for predicting tsunami arrival time. The comparison between theoretical and actual (observed) time gives us a chance to introduce possible improvements to tsunami-related forecasting and warning procedures, which are significant as regards the safety of shipping in the ocean coastal zone.

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