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ВОЗДЕЙСТВИЕ ВОЛН ЦУНАМИ НА ПОБЕРЕЖЬЕ И СООРУЖЕНИЯ

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Цунами оказывает высокое воздействие, приводит к долгосрочным бедствиям, о которых в большинстве случаев возможно заранее дать предупреждение только за несколько минут. Количество энергии после прохождения огромных волн цунами может вызвать серьезное разрушение, когда это поражает землю и следовательно вызывает крупные человеческие жертвы. Воздействие цунами можно рассмотреть в социальных, экологических и экономических аспектах. Социальное воздействие может быть рассмотрено в разрушении жизни и собственности, эпидемическом кризисе и заболеваниях. Цунами может вызвать крупное экологическое воздействие разрушительными эффектами. В данной статье воздействие цунами 2004 и 2011 гг. на побережья и сооружения оценено с инженерной точки зрения. Представлены обсуждения и даны предложения. Надежный и обоснованный план уменьшения воздействия цунами должен быть разработан в прибрежных районах. В развитии этого плана и системы прогноза должны быть учтены структурные и неструктурные меры. Проблему цунами необходимо учитывать во время любого строительства, необходимо применять стойкие к землетрясению структуры, дамбы, волнорезы, а также строения для эвакуации. Также необходимо применять неструктурные меры, например законы о планировании землепользования, обучение и образование, чтобы повысить осведомленность общественности.

Ключевые слова: цунами, воздействие, разрушения, прибрежная инженерия, полевые исследования.

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TSUNAMI ACTION ON COASTS AND CONSTRUCTIONS

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Tsunamis are high-impact, long-lasting disasters, which in most cases allow for only a few minutes of warning before impact. The amount of energy behind huge tsunami waves can cause severe destruction when it hits land and consequently causes massive loss of human life. The impact of tsunami can be considered in social, environmental, and economic dimensions. The social impact can be seen in destruction of life and property, health crisis and disease. Tsunamis may cause massive environmentally impact by devastating effects. In this paper, the impact of 2004 and 2011 tsunamis on coasts and constructions are evaluated from the engineering perspective. Discussions with suggestions are presented.

Key words: tsunami, impact, destructions, coastal engineering, field observations.

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It is an obvious fact that the tsunamis have devastating effects on coastal areas. One of the main components of tsunami hazard mitigation is to achieve structural resilience against tsunamis. Preparation and tsunami hazard mitigation strategies need better understanding of tsunami impact on coasts and constructions. However, damages after recent tsunamis also showed the importance of the design codes for sea defence structures. The improvement of those documents is essential for the further development and preparation of coastal communities. This paper summarizes the Deliverable «on recommendations to guide and engineering codes» of ASTARTE Project [1] and presents two recent tsunami events and their destructive results within the engineering perspective and design considerations. This is especially required to enable the determination of the deficiencies in design codes and their improvements. The importance of the improvement of the design codes is discussed and conclusions are underlined.

Coastal impacts of recent tsunamis. December 26, 2004 Indian Ocean earthquake and tsunami was one of the worst natural disasters in the history affecting 18 countries (Indonesia, India, Thailand, Bangladesh, Malaysia, Sri Lanka, Myanmar, Maldives, Mauritius, Madagascar, Reunion Island, Seychelles, Oman, Comoros islands, Somalia, Kenya, Tanzania, Mozambique, South Africa, South Africa) in Southeast Asia and Eastern Africa, killing more than 250,000 people in a single day, and leaving more than 1.7 million people homeless. The impacts of this tsunami is summarized in [2] as;

— humanitarian toll: it affected more than 18 countries from Southeast Asia to Southern Africa, killing more than 250,000 people in a single day and leaving more than one million homeless,

— economic toll: it left several millions of dollars of economic loss affecting fishing and tourist industries,

— environmental and medical threats including water pollution and flooding and endemic diseases.

After the 2004 Boxing Day tsunami there have been considerable improvement in warning methodology and pre-disaster preparedness but, destruction of 11 March 2011 Tohoku earthquake (magnitude 9.0 M_w) and tsunami still proved not only need to advancements in implementing applied hazard mitigation but also necessity to improve design codes for sea defence structures [3].

The Great East Japan Earthquake (GEJE) was the fourth most powerful earthquake recorded in the past 100 years. The quake shock last for six minutes. A half hour later, a massive tsunami penetrated over 650 km of coastline (Fig. 1, see the insert), overtopping sea walls and other coastal defence structures, flooding through more than 500 km² of land causing entire towns and villages to be washed away. Japan was simply not as prepared as they estimated they were for such a disaster, e.g., causing 15,883 fatalities and 2,654 missing in northeastern Japan [4] and damage costs of \$150 billion. The Fukushima, Iwate, and Miyagi prefectures were the worst hit areas.

In 2011, it was estimated that Japan prepared well and reached to adequate level of capabilities to withstand a huge tsunami hazard on its coastal zones, with sea defence infrastructures, e.g., seawalls, sea dikes, and breakwaters. Seawalls with height of 10 m or more were constructed to protect busy settlement coastal areas; sea dikes were built along the coastal zones to defend low-lying towns and agricultural lands; and massive detached breakwaters were constructed to protect industrial ports. The wave height turned out by the magnitude 9.0 M_w 2011 Great East Japan Earthquake and Tsunami led to submerging of coastal defence structures where in many cases they were completely or partially devastated. Seawall overtopping at the Fukushima Daiichi nuclear power plant (NPP) resulted in loss of seawater pump facilities for the reactor cooling water led to a major release of radioactive material. The Fukushima Daiichi NPP accident was the third most severe accident in a NPP ever. Synolakis and Kanoğlu (2015) demonstrated and explained what cascade of engineering and regulatory failures led to the Fukushima disaster and they stated that the NPP accident was preventable.

The Japan was well prepared in the case of non-structural measures. They established robust and comprehensive tsunami forecast system and strong evacuation and hazard-resistance plan. It is seen by the Great East Japan Earthquake and Tsunami (2011) that although the counter-measures were well-prepared, severe damage was observed along the Pacific coastline of Japan. The main reason behind it is underestimation of design tsunami properties. Furthermore, it is seen that estimating the design tsunami properties accurate enough as the process involves many uncertainties. Therefore, Japanese understanding has changed from «withstanding tsunamis with tremendous coastal structure» to «live with tsunamis with the help of soft counter-measures».

As a result, Japan conducted a research to illustrate the failure mechanisms of coastal defence structures, describes the different levels which have to be considered in construction of coastal defence structures and prepared the detailed disaster scenario document that now can be used for design considerations.

Field observations following the 2011 Japan tsunami. Being the most recent major tsunami in the last decade, the Great East Japan Earthquake and Tsunami (2011) caused severe damages to ports and harbors along the Pacific coast. Two Earthquake Engineering Field Investigation Team (EEFIT) operated missions to depict the damage amount of coastal defence structures. They, also, illustrated the reconstruction of damaged structures in some locations. The two EEFIT consist of researchers from various civil engineering disciplines including coastal engineers. The first EEFIT investigation to Japan was back to 11 weeks after the 11 March 2011 earthquake and tsunami.

Taking a brief survey in Japan's reputation for coastal engineering, it can be seen that they constructed more than 1300 breakwaters between 1965 and 1985 [5]. Following the 2004 Boxing Day tsunami they also prepared training to tsunami-prone communities under the auspices of UNESCO (ICHARM). Consequently, field survey and visual observation of Japan's coastal defence structures were important to understand the stability level of the infrastructures. The investigation was performed and comprehensive details were prepared in the EEFIT reports 2011 and 2013 and by Fraser et al. [6]. Fig. 2 shows the key observation locations in the Tohoku region.

«Many dock warehouses and loading machines were inundated and destroyed. Containers and cars were washed away to the sea» [7] — all these contributed to increased and extensive damage in harbors and ports. The Great East Japan Earthquake and Tsunami (2011) caused severe damages to ports and harbors along the Pacific coast. Fig. 3 clearly shows the extent of damage to the Sendai Port, Japan. In the Kamaishi Port the GEJE tsunami dumped a cargo ship of 175,000 tons on top of a pier (Fig. 4, *a*) and eroded ground around the concrete building is also shown in Fig. 4, *b*. The reader is advised to refer to [7] for a detailed coverage of damages to Japanese ports due to the Great East Japan Earthquake and Tsunami (2011).

8500 m of breakwaters including dedicated tsunami breakwaters like the World record breakwater at Kamaishi collapsed during the 2011 tsunami [8]. It was constructed in a maximum water depth of 63 m consisting of two sections: one, 670 m length and the other 770 m length. A cross-section is indicated in Fig. 5.

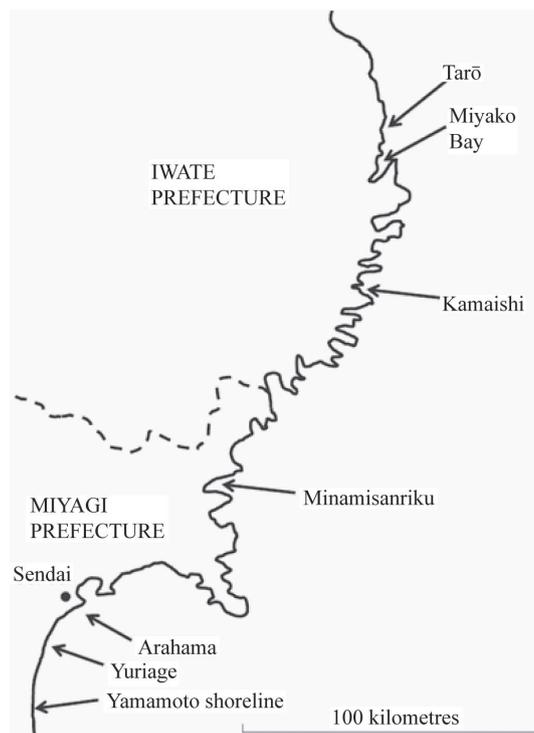


Fig. 2. Outline map of the EEFIT observation region, showing locations of key coastal structures [3].

Рис. 2. Карта схемы региона наблюдения EEFIT, показывая местоположения ключевых прибрежных структур [3].



Fig. 3. The damage to the Port of Sendai caused by the Great Tohoku, Japan Earthquake and Tsunami in March 2011.

Рис. 3. Повреждение Порта Сендая, вызванного Большим Землетрясением и Цунами в марте 2011.

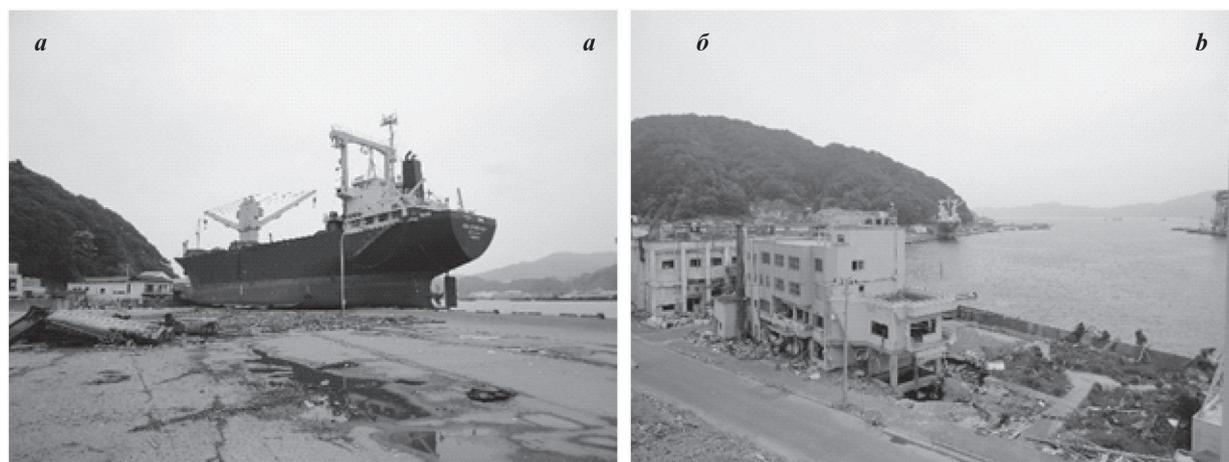


Fig. 4. A cargo ship dumped to a pier in the Kamaishi Port, Japan (a) and the scour around concrete building in Kamaishi by the Great East Japan Earthquake and Tsunami (b) (photos by Ahmet Cevdet Yalciner).

Рис. 4. Грузовое судно, сваленное к пирсу в Порту Камаиши, Япония (a) и разрушения вокруг бетонного здания в Камаиши Большим Восточным Землетрясением Японии и Цунами (b) (фотографии Ахмета Ялченира).

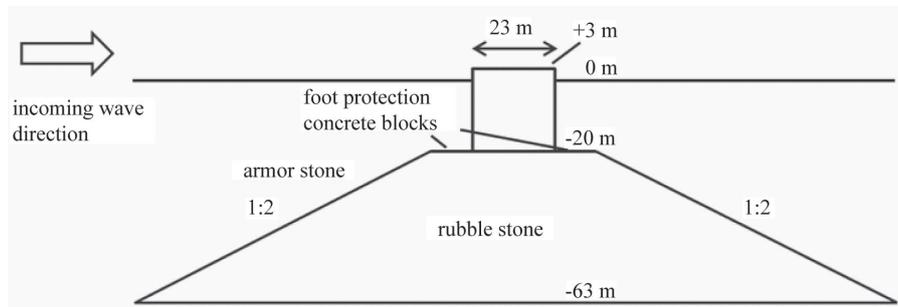


Fig. 5. Cross-section through the Kamaishi South breakwater [10].

Рис. 5. Поперечное сечение через волнорез Юга Камаиши [10].

The failure of the breakwater has been investigated using physical and numerical modelling performed by the Port and Airport Research Institute (PARI).

The investigation showed that the failure of breakwater was due to three effects caused by the tsunami overflow. One, water level difference between the two sides of the breakwater resulted in a rise in the lateral force, two, the overflow scouring causing a decline in friction between the caisson and mound leading to sliding [9], and three the seepage between the blocks (50 cm distance) causing additional scouring of the back fill materials.

Fig. 6 shows a variety of concrete debris which were the parts of breakwater and seawall in the bay of Tarō. The picture was taken during the 2011 EEFIT survey. Clear effects of scour on the sea dikes is indicated in Fig. 7 where effects of scour on the lee side causing to insufficient cracking of reinforced concrete lattice work.

Seawall failures of both gravity seawalls and compacted sand core structures were also observed (Fig. 8). Failure mechanisms of the Tarō seawall included the removal of rear slope protection blocks due to the tsunami overflow, the collapse of the crest parapet due to impulsive fluid forces, the collapse of the front protection blocks due to draw-down and there was also evidence of shear failure between blocks [11].



Fig. 6. A variety of concrete debris from breakwater and seawalls offshore of Tarō which observed during the 2011 EEFIT mission [3].

Рис. 6. Множество бетонных обломков от волнореза и дамб на расстоянии от берега Tarō, которые обследовались во время полевых исследований 2011 г. [3].

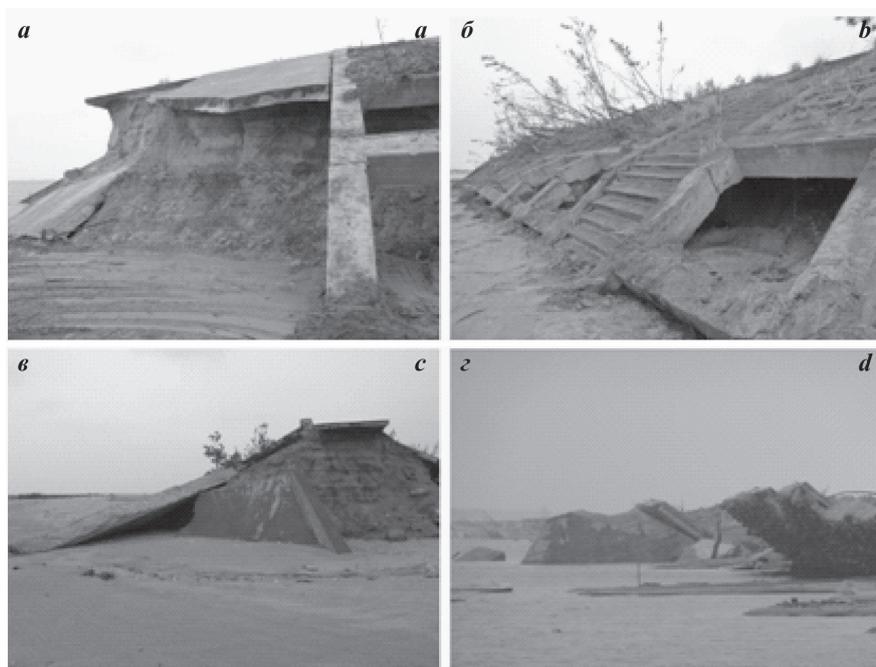


Fig. 7. Failure of Yamamoto sea dikes, captured during the 2011 EEFIT mission.
a — exposed sand core on the lee side; *б* — proof of sand core having been washed out;
в — exposed section through the sea dike; *г* — debris of the dike at the distance, lying in pools of seawater to the lee side of the structure having not subsequently drained away [3].

Рис. 7. Фото прорыва морских плотин Ямамото, обнаруженных во время полевых исследований EEFIT 2011 г.

a — размывте песковой основы; *б* — размывте песковой основы с другой стороны;
в — разрушение секции морской дамбы; *г* — разрушение плотины [3].

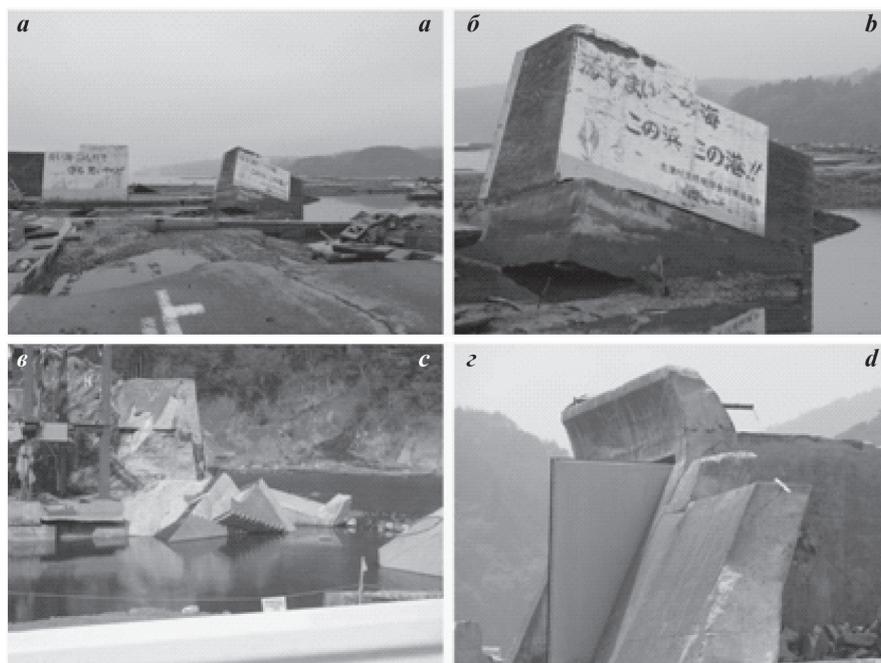


Fig. 8. Damage to the seawall observed during the 2011 EEFIT Mission.
a — failure of seawall and quay at Minamisanriku; *б* — close-up of seawall block at Minamisanriku indicating no interlinkages;
в — restoration of the seawall at Miyako Bay; *г* — remaining seawall buttress at Tarō [3].

Рис. 8. Повреждение дамбы, наблюдаемой во время полевых обследований 2011 г.

a — дамба и причал в Минамисанрику; *б* — дамба в Минамисанрику;
в — дамба в заливе Мияко; *г* — оставшаяся часть дамбы в Тарō [3].

Discussion and conclusions. Tsunamis are high-impact, long-lasting disasters, which in most cases allow for only minutes of warning before impact. The amount of energy behind huge tsunami waves can cause severe destruction when it hits land and consequently causes massive loss of human life. The impact of tsunami can be considered in social, environmental, and economic dimensions. The social impact can be seen in destruction of life and property, health crisis and disease. Tsunamis may cause massive environmental impact by devastating effect on insects, animals, plants, also, damage on natural resources, e.g., contamination of soil and water, a permanent change to the landscape, massive amount of disaster debris, and hazardous materials (toxic substances, and industrial raw materials and chemicals). The March 11, 2011 Japan earthquake and tsunami economic damage costs was \$150 billion.

The nearshore plantation in Rikuzentakata Japan with 78000 pine trees with 40 cm diameter each could not resist against 2011 Japan earthquake and tsunami. Mangroves and other coastal trees were uprooted and snapped off at mid trunk level and caused extensive damage when swept inland by tsunami in PNG in 1998. However, mangroves resisted against the tsunami in Malaysia. The role of mangroves in providing coastal protection against marine hazards is known. Mangrove green belts contribute to saving lives against tsunamis, such as the recent one in Asia, depends on a number of factors including the height and velocity of the tsunami, the topography and orientation of the coastline, the width of the forest and — to a lesser extent — the height, density and species composition of the forest.

As widely reported, extensive areas of mangroves can reduce the loss of life and damage caused by tsunamis by taking the first brunt of the impact and by dissipating the energy of the wave as it passes through the mangrove area. On the other hand, narrow strips of mangroves, when uprooted or snapped off at mid-trunk and swept inland, can cause extensive property damage and loss of life.

Examples of the positive effects of mangroves and other coastal forests (Casuarina, Pandanus, coconuts etc.) in absorbing or reducing the strength of the recent tsunami include the following:

- In Tamil Nadu, India, the trees standing in the front lines were damaged but well established forests such as the Pichavaram mangrove forest acted as a protective belt slowing down the waves and protecting around 1,700 people living in hamlets built inland between 100 to 1,000 meters from the mangroves.

- In Malaysia, in areas where the mangrove forests were intact, there was reduced damage, as reported by the Penang Inshore Fishermen Welfare Association.

- In Indonesia, the death toll in the island of Simeuleu, located close to the epicentre was relatively low, partly due to mangrove forests that surrounded the island.

- Large mangrove forests mitigated the force of the tsunami in Phang Nga province (Thailand) where the inland territories were only slightly damaged.

- Low impact was observed behind a 100m mangrove strip in Medilla (Sri Lanka, RUK area), behind an elevated beach with coconuts and behind a tall sand dune stabilized by a Casuarina plantation.

Similar examples exist of the positive role played by mangroves and coastal forests as buffer zones during past marine hazards, such as the 1999 cyclone in the eastern coastal state of Orissa (India); the 1991 cyclone and tidal wave in Bangladesh; and the typhoon Wukong in Viet Nam in 2000.

Considering the positive role of the mangroves in Asia, the use of pine or palm trees as coastal protection in Europe can be a soft measure, which also improve environmental quality.

A reliable and sustainable tsunami mitigation plan should be prepared to reduce hazardous impacts of tsunami in coastal areas. In developing a reliable tsunami mitigation and forecast system both structural and non-structural measures have to be strengthened. Tsunami structural measures refer to any physical construction, e.g., earthquake-resistant structures, seawalls, breakwaters, and also evacuation shelters to mitigate or avoid hazardous impacts of tsunami waves. Moreover, it includes application of engineering techniques, e.g., using validated and verified tsunami numerical models and vulnerability assessment methods to achieve hazard-resistance plan. On the other hand, non-structural measures may be considered as any measure not involving physical construction to reduce risks and impacts, e.g., land use planning laws, training and education to raise public awareness.

Consequently, it is necessary to approach some advancements in implementing applied hazard mitigation and also it is important to improve design codes for sea defence structures.

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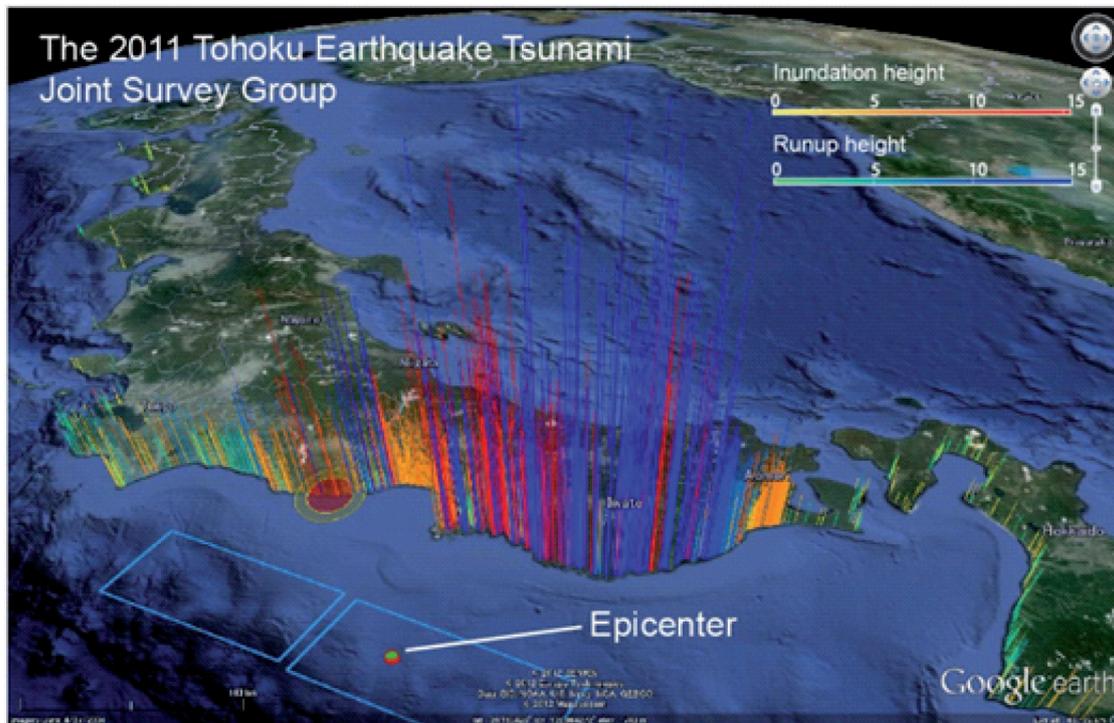


Fig. 1. 11 March 2011 Tohoku earthquake and tsunami.
After the 2011 Tohoku Earthquake Tsunami Joint Survey (TTJS) Group.

Рис. 1. 11 марта 2011 г. Тохоку землетрясение и цунами.
Полевые обследования Цунами Землетрясения Тохоку 2011 г. (TTJS).