THE ASIAN TSUNAMI OF 2004: OBSERVATIONS AND NUMERICAL SIMULATION

K. Satake [kenji.satake@aist.go.jp] and Y. Fujii
National Institute of Advanced Industrial Science and Technology (AIST)
Tsukuba, Ibaraki, 305-8567 Japan

ABSTRACT: The December 26, 2004, Sumatra-Andaman earthquake generated tsunamis that propagated across the Indian Ocean and caused the worst tsunami disaster in history. The tsunami was recorded in various ways; many scientists and engineers visited the affected coasts to survey the tsunami heights and to document the damage, the tsunami waveforms were instrumentally recorded by coastal tide gauges, and sea surface heights during the tsunami propagation in Indian Ocean were detected by altimeters on several satellites. The tsunami source can be modeled from earthquake fault parameters, and its propagation can be simulated by numerically solving shallow water (long wave) equations on actual bathymetry. The tsunami source can be also estimated by inverse modeling of tsunami data, by comparing the observed data with the simulated tsunamis.

1. INTRODUCTION

A giant earthquake occurred off Sumatra Island on December 26, 2004. This earthquake generated tsunami which devastated the shores of Indian Ocean (Fig. 1); more than 200,000 people lost their lives. The number of victims, death and missing together, is the largest in Indonesia (160,000), followed by Sri Lanka (36,000), India (16,000) and Thailand (8,300) [1]. Within minutes of the earthquake, the tsunami devastated Banda Aceh and other coastal villages of Sumatra Island. The tsunami arrived at Thai, Sri Lankan and Indian coasts in about two hours after the earthquake. The tsunami further propagated and arrived at the eastern coast of Africa several hours after the earthquake to cause 300 fatalities in Somalia.

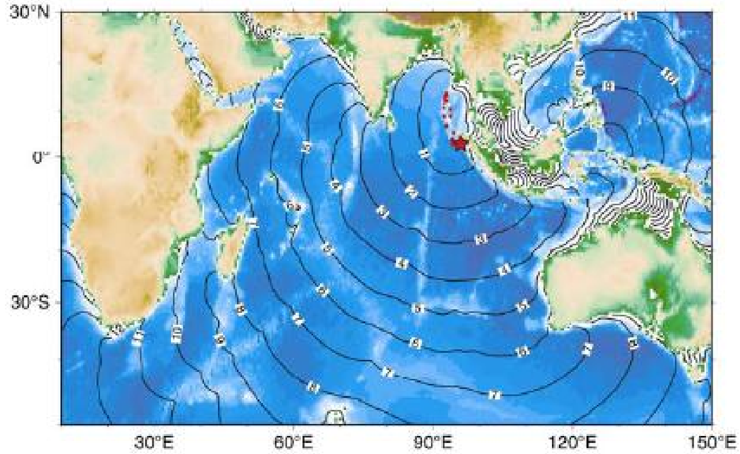

Fig. 1: Tsunami propagation in the Indian Ocean. Each curve indicates wavefront at each hour. Red star and circles indicate the mainshock and aftershocks within one day, respectively (data by U.S. Geological Survey).

2. TSUNAMI GENERATION AND PROPAGATION

Tsunamis are generated by submarine earthquakes, volcanic eruptions or landslides. Such submarine geological process produces water surface disturbance, or the tsunami source, which propagates toward coasts. "Tsunami" is a Japanese term, meaning "harbor wave". Tsunami is usually small in deep ocean, but becomes larger and more dangerous toward shallow water and causes coastal damage. Tsunami propagation in deep ocean is rather simple; the velocity depends only on water depth. Once the initial condition, or the tsunami source, is known, the propagation and coastal behavior can be modeled by computer simulation. Such an approach is called forward modeling, and used for engineering and hazard assessment purposes (Fig. 2).

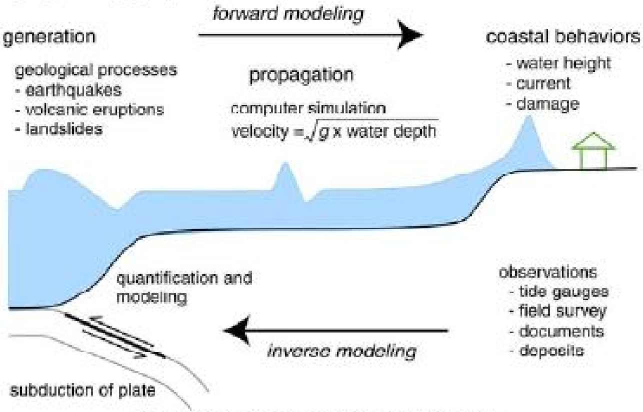

Fig. 2: Tsunami generation and propagation.

2.1 Tsunami Generation by Earthquakes

The earth's surface is divided into a dozen of tectonic plates which move each other. In the source area of Sumatra-Andaman earthquake, the Indian plate is sinking beneath the Burma microplate at a rate of about 5 cm per year. This subduction causes upper plate to be dragged and deformed up to a certain limit. When the strain reaches the limit, the two plates are rebound to cause an earthquake. This motion, called faulting, is the mechanism of an interplate earthquake, and most large earthquakes in the world occur at subduction zones. While the epicenter of the December event was located west off Sumatra Island, the aftershock zone extended through Nicobar to Andaman Islands; the total length of the fault is more than 1,000 km.

The fault parameters can be estimated from seismological analysis. The product of fault length, width and slip, as well as rigidity near the fault, is known as seismic moment, and indicates the physical size of earthquake source. The moment magnitude (M_W), calculated from seismic moment, of the 2004 Sumatra-Andaman earthquake has been estimated as 9.1-9.3, largest in the world in the last 40 years [2, 3].

Once the fault parameters are known, seafloor displacement, which becomes the tsunami source, can be computed by using the elastic theory of dislocation. Recent seismological developments, both in theory and observation, make it possible to estimate the earthquake source parameters within minutes after large earthquakes and utilize it for the tsunami warning purposes. In addition, tsunami data, such as waveforms recorded on tide gauges, run-up heights measured by field surveys, damage data described in historical documents and tsunami deposits, are used to study the tsunami sources. Such inverse modeling has been made to study modern, historical and prehistoric tsunamis (Fig. 2).

2.2 Tsunami Propagation

Tsunamis are considered as a shallow water, or long, waves. Depending on the relation between wavelength and water depth, water waves can be classified as shallow water (or long) wave or deep water (short) wave. The Indian Ocean or Andaman Sea is deep, up to 4,000 m or 4 km, but the wavelength of seafloor deformation is an order of 100 km, much larger than the water depth. Hence we can use the shallow water approximation for tsunamis generated from earthquakes.

One of the characteristics of the shallow water is that the wave velocity is given as a square root of g times d, where g is gravitational acceleration, 9.8 m/s^2, and d is water depth in meters. If d is 4,000m, the velocity is about 700 km/h. For shallow water, at 40 m, the velocity is about 70 km/h.

Including the bottom friction and the Coriolis force, the momentum equation for shallow water waves can be written as

$$\begin{aligned} \frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y} &= -fV - g\frac{\partial h}{\partial x} - C_f\frac{U\sqrt{U^2+V^2}}{d+h} \\ \frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y} &= fU - g\frac{\partial h}{\partial y} - C_f\frac{V\sqrt{U^2+V^2}}{d+h} \end{aligned} \tag{1}$$

and the mass equation is

$$\frac{\partial h}{\partial t}+\frac{\partial}{\partial x}\{U(h+d)\}+\frac{\partial}{\partial y}\{V(h+d)\}=0 \tag{2}$$

where the coordinate system is x=East and y=South, f is the Coriolis parameter, C_f is a non-dimensional frictional coefficient, and U and V are the average velocities in x and y directions, respectively. The horizontal velocities are averaged from the bottom to the surface,

$$\begin{aligned} U &= \frac{1}{(h+d)}\int_{-d}^{h} u\, dz \\ V &= \frac{1}{(h+d)}\int_{-d}^{h} v\, dz \end{aligned} \tag{3}$$

A typical value of a non-dimensional frictional coefficient C_f is 10^{-3} in for coastal water and 10^{-2} for run-up on land, but negligible in deep ocean. In addition, the advection terms, second and third terms of left hand side of (1), can be also omitted in deep ocean. In the deep ocean, equations (1) and (2) become simple, linear form.

3. TSUNAMI OBSERVATIONS

To document the 2004 tsunami, many scientists and engineers from all over the world visited the affected coasts [4-6]. The measured tsunami heights in Sumatra Island, particularly around Banda Aceh, were mostly larger than 20 m with the maximum of 30 m. The tsunami heights along the Andaman Sea coast were highly variable; 5 to 15 m in Thailand but less than 3 m in Myanmar. The tsunami heights were up to 5 m on India's Andaman Islands. In Sri Lanka, the tsunami heights were 5 to 15 m. The tsunami height distribution is consistent with the damage distribution, and indicates that the source of the large and damaging tsunami was concentrated in the southern 700 km section of the aftershock zone.

The tsunami was also recorded on coastal tide gauges throughout the Indian Ocean (Fig. 3). The tide gauges in Indonesia and Thailand started to record the tsunami in about two hours after the earthquake, followed by those on Indian Coasts and Maldive Islands (Fig. 4 *left*). The tsunami amplitudes are several tens of cm to 2 m. The initial motion was upward at tide gauges located to the west of the source (India, Sri Lanka and Maldives), while it was downward at the stations located to the east (Indonesia and Thailand). An international program called GLOSS (Global Sea Level Observation System) has been formed to establish high-quality global sea level network for climate change, oceanography and coastal research. Many GLOSS data are available in real-time through internet [7]. The tsunami was also observed in the Atlantic and Pacific Oceans [8].

The tsunami propagation across the Indian Ocean was captured by altimeters on three satellites, Jason-1, TOPEX/Poseidon and Envisat (Fig.3) [9]. This is the first time that tsunami traveling in deep ocean was detected by satellites. The maximum Sea Surface Height (SSH) was about 0.8 m (Fig. 4 *right*). The accuracy of satellite altimetry is better than 5 cm and its spatial resolution is approximately 15 minutes of the arc (~27 km).

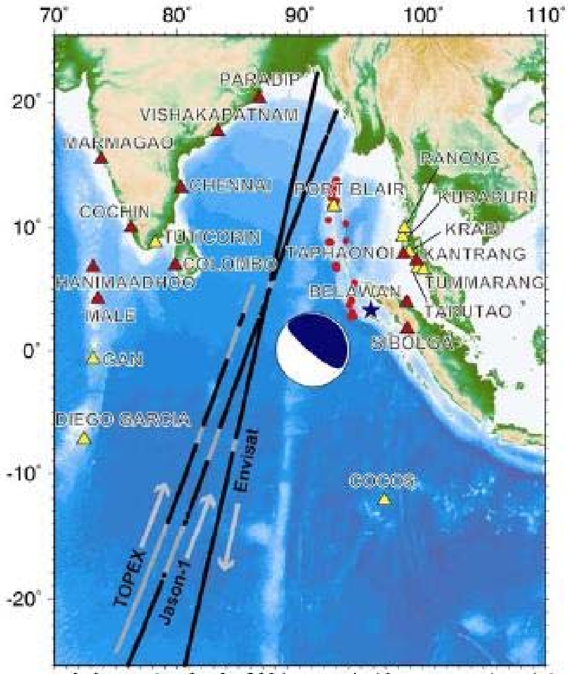

Fig. 3: Locations of instrumental observation for the 2004 tsunami: tide gauge stations (triangles) and satellite paths (solid line). The epicenter (blue star) and aftershocks (red circles) are also shown.

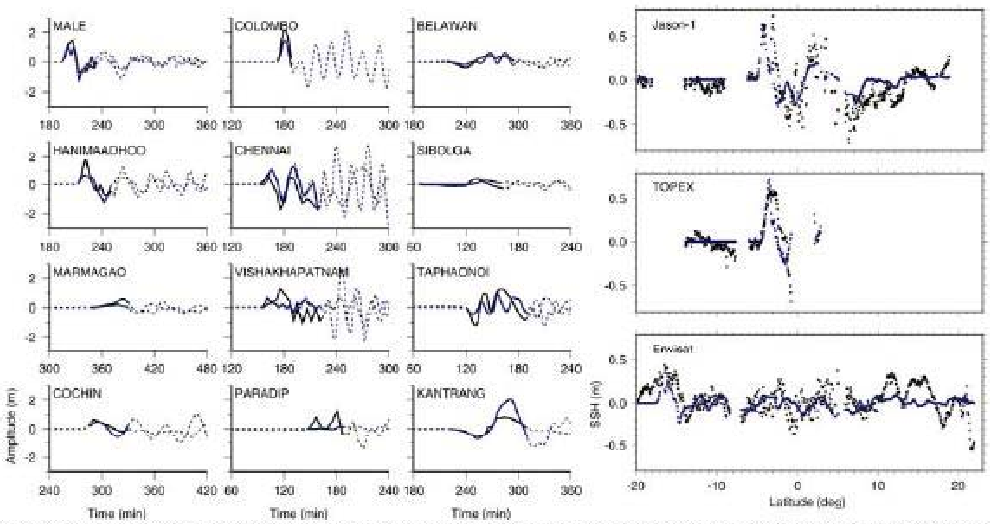

Fig. 4: Instrumental records of the 2004 tsunami. (*left*) Tsunami waveforms recorded at tide gauge stations. (*right*) Sea Surface Height (SSH) data along the satellite tracks. In both cases, the black symbols indicate the observed record and the blue symbols are computed from the estimated source model by inverse modeling (see section 5). Dashed part was not used for the analysis.

4. COMPUTER SIMULATION OF TSUNAMI

The tsunami propagation can be computed for actual water depth. The ocean depth has been globally mapped from bathymetry soundings or satellite gravity data and can be used for numerical computation of tsunamis [10]. Tsunami arrival times can be computed by using Huygens principle for actual bathymetry. For the 2004 tsunami, computed travel time to Thailand and Sri Lanka are similar, despite the distance is different, because the Andaman Sea is shallower than Bay of Bengal (Fig.1). In order to estimate the tsunami amplitudes or waveforms, the linear long wave (shallow water) equations are numerically solved by using the finite-difference method [11, 12].

When an earthquake, or fault motion, occurred, the elastic dislocation theory shows such deformation that seafloor just above the fault is uplifted while above the deeper end of the fault is subsided. The water above is also vertically moved in a similar way and becomes the source of tsunami. Because the tsunami wave propagates in both directions, those in the east would first observe the receding wave, whereas those in the west would observe sudden rise in water. Such a feature of tsunami propagation was reproduced by computer simulation (Fig. 5). It shows that the water depression, or receding wave, propagate toward Thailand, whereas to the west, say toward Sri Lanka, high water is traveling. This feature is consistent with the initial motions recorded in tide gauges (Fig. 4 *left*). The tsunami heights are larger to the east and west of the source, in directions perpendicular to the fault.

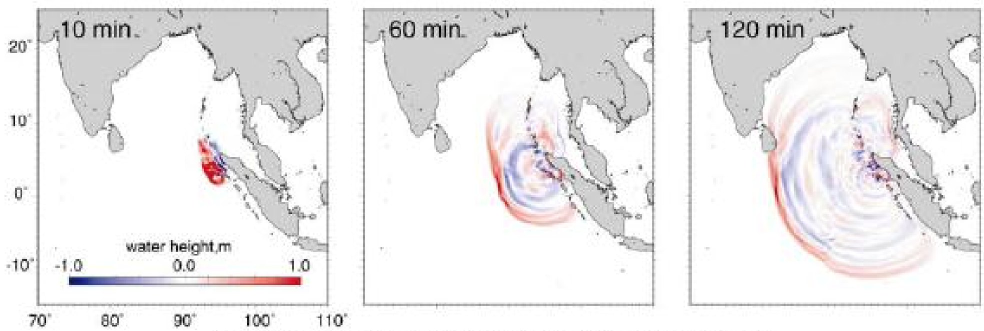

Fig. 5: Snapshots of computer simulation for tsunami propagation.

5. INVERSE MODELING TO ESTIMATE THE TSUNAMI SOURCE

Numerical simulation of tsunami has been carried out from many fault models around Japan [13]. The best fault models are obtained by trial and error comparisons of observed and computed tsunami waveforms or coastal tsunami heights. Tsunami waveforms recorded on tide gauges were then inverted to estimate the slip distribution on the fault [14]. In this method, the fault plane is first divided into several subfaults and the deformation on the ocean bottom is computed for each subfault with a unit amount of slip. Using this as an initial condition, tsunami waveforms are numerically computed on actual bathymetry. The observed tsunami waveforms are expressed as a superposition of the computed waveforms as follows,

$$A_{ij}(t) \cdot x_j = b_i(t) \qquad (4)$$

where A_{ij} is the computed waveform, or Green function, at the i-th station from the j-th subfault; x_j is the amount of slip on the j-th subfault; and b_i is the observed tsunami waveform at the i-th station. The slip x_j on each subfault can be estimated by a least-squares inversion of the above set of equations.

An inversion of tide gauge records and sea surface heights of the 2004 tsunami indicates that the slip on fault was the largest (~25 m) in the southern part of the source, off Sumatra. These large slip produces large sea floor deformation (up to 12 m), which became the source of the tsunami.

Dashed part was not used for the analysis.

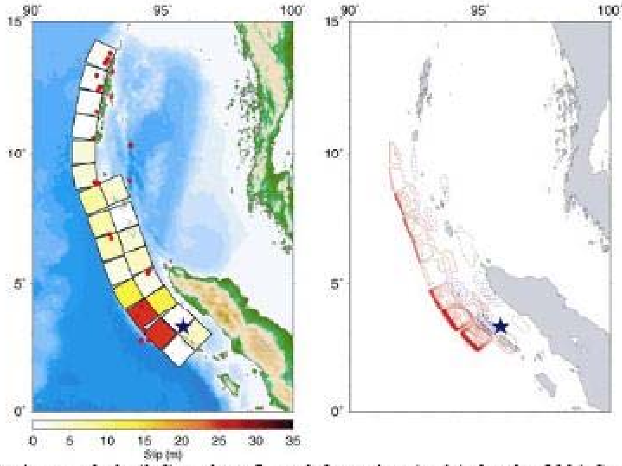

Fig.6: Slip distribution on fault (*left*) and seafloor deformation (*right*) for the 2004 Sumatra-Andaman earthquake by an inversion of tsunami waveforms recorded on tide gauges and Sea Surface Height measured by satellite. For the seafloor deformation, red and blue contours indicate uplift and subsidence, respectively, with a contour interval of 0.5 m.

REFERENCES

[1] International Federation of Red Cross and Red Crescent Societies. ***World Disasters Report***, Kumarian Press, 2005.

[2] Lay T, Kanamori H, Ammon CJ, Nettles M, Ward SN, Aster RC, Beck SL, Bilek SL, Brudzinski MR, Butler R, DeShon HR, Ekstrom G, Satake K, and Sipkin S: The great Sumatra-Andaman earthquake of 26 December 2004, *Science* 2005, **308**, 1127-1133.

[3] Stein S and Okal EA: Speed and size of the Sumatra earthquake, *Nature* 2005, **434**, 581-582.

[4] Borrero JC: Field survey of Northern Sumatra and Banda Aceh, Indonesia after the tsunami and earthquake of 26 December 2004, *Seism. Res. Lett.* 2005, **76**, 312-320.

[5] Satake K, Than Tin Aung, Sawai Y, Okamura Y, Kyaw Soe Wing, Win Swe, Chit Swe, Tint Lwin Swe, Soe Thura Tun, Maung Maung Soe, Thant Zin Oo, and Saw Htwe Zaw: Tsunami heights and damage along the Myanmar coast from the December 2004 Sumatra-Andaman earthquake, *Earth Planets Space* 2005, **58**, in press.

[6] Liu PLF, Lynett P, Fernando H, Jaffe BE, Fritz H, Higman B, Morton R, Goff J, and Synolakis C: Observations by the International Tsunami Survey Team in Sri Lanka, *Science* 2005, **308**, 1595-1595.

[7] Merrifield MA, Firing YL, Aarup T, Agricole W, Brundrit G, Chang-Seng D, Farre R, Kilonsky B, Knight W, Kong L, Magori C, Manurung P, McCreery C, Mitchell W, Pillay S, Schindele F, Shillington F, Testut L, Wijeratne EMS, Caldwell P, Jardin J, Nakahara S, Porter FY, and Turetsky N: Tide gauge observations of the Indian Ocean tsunami, December 26, 2004, *Geophys. Res. Lett.* 2005, **32**, doi: 10.1029/2005GL022610.

[8] Titov V, Rabinovich AB, Mofjeld HO, Thomson RE, and Gonzalez FI: The global reach of the 26 December 2004 Sumatra tsunami, *Science* 2005, **309**, 2045-2048.

[9] Gower J: Jason 1 detects the 26 December 2004 tsunami, *Eos, Trans. Am. Geophys.l Union* 2005, **86**, 37-38.

[10] Smith WHF and Sandwell DT: Global sea floor topography from satellite altimetry and ship depth soundings, *Science* 1997, **277**, 1956-1962.

[11] Satake K. Tsunamis, In Lee WHK, Kanamori H, Jennings PC, and Kisslinger C, eds. *International Handbook of Earthquake and Engineering Seismology*, Academic Press, 2002, 437-451.

[12] Satake K: Linear and Nonlinear Computations of the 1992 Nicaragua Earthquake Tsunami, *Pure Appl. Geophys.* 1995, **144**, 455-470.

[13] Aida I: Reliability of a tsunami source model derived from fault parameters, *J. Phys. Earth* 1978, **26**, 57-73.

[14] Satake K: Inversion of Tsunami Waveforms for the Estimation of Heterogeneous Fault Motion of Large Submarine Earthquakes - the 1968 Tokachi-Oki and 1983 Japan Sea Earthquakes, *J. Geophys. Res.* 1989, **94**, 5627-5636.