S-net project: Deployment and its seismic and tsunami observation system

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Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench (S-net) has 150 real-time monitoring observatories that cover the area about 1000km x 300 km from off-Hokkaido to off-Kanto. It is expected that early tsunami and earthquake warnings and earthquake researches will be enhanced. S-net consists of six segment networks of about 25 observatories and 800 km fiber optic cable (1,500 km fiber optic cable for the Japan Trench outer rise segment network). Each observatory has four sets of three-component seismometers for earthquake observation and two sets of pressure gauge for tsunami observation. Fiber-optic cable connects to landing station, and the data is transmitted from landing station to the data center via IP-VPN network.

S-net project has started in 2011. We have already finished deployment of all of the observatories and fiber-optic cables in 2016. Observatories and cables are installed by cable ship which conducts laying and installation of submarine fiber optic communication cables. We carried out installation by C/S Subaru (9,557 ton), C/S KDDI Pacific Link (7,960 ton), and C/S SEGERO (8,323 ton). In order to avoid influence of with fishery activity (for example, the trawling with using otter board), we buried the cables and observatories one meter or deeper below the seabed in the sea area where water depth is shallower than 1,500 meters using the plough and/or ROV (Remotely Operated Vehicle).
We have also constructed five landing stations; Minamiboso station in Minamiboso City, Chiba Pref., Kashima station in Kashima City, Ibaraki Pref., Watari station in Watari Town, Miyagi Pref., Miyako station in Miyako City, Iwate Pref., and Hachinohe station in Hachinohe City, Aomori Pref.. The Watari station is located on the third floor of reinforced concrete building, and other stations are container-type data centers. The S-net (except outer-rise segment) started to operate in May 2016, and the pressure gauge and accelerometer data have been transmit to Japan Metrological Agency (JMA) for monitoring purpose. The S-net detected many earthquakes. S-net also observed tsunamis like with the earthquake of the November 22, 2016 off Fukushuma (M7.4).

Keywords: S-net

Offshore tsunami observation array suitable for coastal tsunami prediction using multiple linear regression with L1 regularization

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In recent years, tsunami prediction methods using the offshore tsunami data are investigated while high-density offshore tsunami observation networks have been deployed around Japan. We proposed methods to predict the coastal tsunami height by regression from offshore tsunami heights in the previous studies (Baba et al., 2014; Igarashi et al. 2016). These aimed to utilize the tsunami data observed by previously installed offshore gauges to improve the accuracy of tsunami prediction at the coast as possible. On the other hand, considering a development of a similar system including construction of a new offshore observation network in other area, we have to answer a question where we should install observation points to make the prediction accuracy the best. Therefore, in this study, the importance of each offshore observation point was evaluated by introducing L1 regularization term (LASSO) in the regression analysis. This study was carried out by the following procedure. We assumed 2622 rectangular fault models in total in the Nankai trough subduction zone. Uniform sliding was assigned for 1506 models. The remaining 1116 models have heterogeneity of slip distribution by assuming a large slip patch on the fault plane. The tsunamis caused by the 2622 fault models were repeatedly calculated by solving the nonlinear long wave theory. We performed a multiple linear regression analysis with L1 regularization term to the maximum tsunami heights at a point in the Asakawa bay, Tokushima, and these recorded at the 57 offshore points of GPS wave meters and the DONET water pressure gauges. The analysis showed that it is possible to predict the coastal tsunami height with the accuracy of RMS residual less than 1 m by using only 12 offshore points which are located in the Kii Channel between the Cape Shiono and the Cape Muroto.

Keywords: tsunami prediction, offshore observation, L1 regularization term

Countermeasures against various types of tsunami earthquakes

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Tsunami earthquakes are those which generate tsunami greater than that expected from its magnitude determined from seismic amplitude. It is considered that there are two types of tsunami earthquake. One is a slow earthquake, in which radiation of short period seismic wave is relatively small. In those earthquake, the slip is usually small compared with its fault size. It is considered that tsunami generation is not different very much from that expected from the moment magnitude in those slow earthquakes. On the other hand, the amplitude of seismic wave is smaller than those of regular earthquakes of the same moment magnitude. Since conventional magnitudes based on seismic wave amplitude are often used for the first tsunami warning to be issued within three minutes after occurrence of the earthquake, the first tsunami warning may underestimate the tsunami height for slow earthquakes. Not to underestimate the tsunami height even for slow earthquakes, magnitude determination with more longer seismic wave or integrated displacement such as Mwp would be effective. Mwp is determined from teleseismic data. Other methods should be developed to determine appropriate magnitude from local seismic data of slow earthquakes.

On the other hand, there is another type of tsunami source such as submarine land slide or collapse of volcanoes. In 1792, Mt Mayuyama collapsed, and its volcanic debris avalanche caused high tsunami. Prediction of the collapse would be very difficult. However, it is possible to estimate the tsunami height and affected areas before the event by introducing some assumptions. In 1998, very high tsunami estimated to be caused by a submarine landslide attacked the shore of Papua New Guinea. We investigated the possibility of landslide detection by seismic waves, and got negative conclusions. Offshore tsunami gauges are considered to be effective countermeasure for such submarine landslides. Tsunami radar and microbarogram may be effective to detect offshore tsunami in addition to the GPS wave gauge and the submarine tsunami gauge.

Keywords: tsunami earthquake, slow earthquake, submarine landslide, volcanic debris avalanche

Retrieval of tsunamis by the interferometry of deep ocean pressure records

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Over the last 10 years, seismic waveform interferometry became a popular technique for studies of earth's subsurface. It enables to retrieve virtual seismic waveforms propagating between two stations without earthquake sources by stacking of the cross-correlation of continuous records of ground motions. We applied waveform interferometry to the records from deep ocean pressure gauges to retrieve tsunami waveforms without tsunamis sources.

Continuous pressure records for the year 2011-2015 from three DART stations (21418, 21413, 52401), located along the western boundary of the Pacific at the depth of 5500-5900 m were used for the tsunami interferometry. Distance between stations ranges from 956 to 2265 km. De-tided data in a common four or eight hour-long data window were pre-processed: removal of the long-period trend by 6th-order polynomial fit, time domain one-bit amplitude normalization, and frequency domain amplitude spectrum whitening. Cross-correlated waveforms of multiple time windows with a half timewindow overlap for three years were stacked. The stacked waveforms showed gradual amplitude increase toward the arrival time of virtual tsunami propagating between two stations. A sharp transition from positive to negative amplitude was observed at the expected arrival time.

This characteristic waveform reflects the fact that the long-wave tsunami at the deep ocean is nearly non-dispersive for a broad wave-period range. In theory the cross-correlation of 2D isotropic non-dispersive wavefield coming from large distance shows gradual increase of amplitude before the expected arrival time of the virtual waves traveling between two points because; the time lag of an incoming plane wave to the two points with a slant angle is less than the traveltime between the two points, and interference of plane waves coming from all azimuth will result in the maximum amplitude of the cross-correlation in the azimuth connecting two points. No plane wave arrives at two points with a time lag larger than the traveltime between the two points, corresponding to the abrupt amplitude decrease of cross-correlated waveforms. In reality dispersive surface gravity waves propagate at the speed slower than the long-wave and appear later than the virtual tsunami.

The extracted virtual tsunami waveforms were then analyzed for the phase velocities of tsunamis between two points. Subtracting the initial phase from the measured phase by assuming cylindrical 2D waves, we succeeded to measure the phase velocity of virtual tsunamis for the period range from 300 to 3000 s. The measurements were in good agreement with the tsunami phase velocities expected from the ocean depth. A clear reduction of phase velocity from long-wave speed, as predicted from the surface gravity wave theory, was detected for wave periods toward 300 s.

Keywords: tsunami waveform interferometry, DART, tsunami waveform, phase velocity of tsunami, dispersive tsunami, cross-correlation of ocean bottom pressure

Integrated Probabilistic Tsunami Hazard Assessment contributed from possible tsunami sources along Nankai Trough, Sagami Trough, and Japan Trench

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Last years, we presented regional Probabilistic Tsunami Hazard Assessments (PTHAs) for three coastal zones along Nankai Trough, Sagami Trough, and Japan Trench (Hirata et al., 2014, 2015, AGU; Hirata et al., 2016, SSJ). In three PTHAs, our procedures are follows; (i) we consider all possible earthquakes in the future, including those that Earthquake Research Committee (ERC), the Headquarters for Earthquake Research Promotion (HERP) of Japanese Government already assessed. (ii) We construct a set of Characterized Earthquake Fault Models (CEFMs), for all the possible earthquakes(Toyama et al., 2014, 2015, JpGU; Kito et al., 2016, JpGU). (iii) For all the CEFMs, we compute tsunamis by solving a nonlinear long wave equation, using FDM, including runup calculation, over a nesting grid system with a minimum grid size of 50 meters.(Saito et al., 2014, 2015, JpGU; Takayama et al., 2017, JpGU) (iv) Finally, we gather excess probabilities for variable tsunami heights, calculated from all the CEFMs, at every observation point along the coastal zone to get PTHA. We incorporated aleatory uncertainties inherent in tsunami simulation and earthquake fault slip heterogeneity in the integration process(Korenaga et al., 2014, JpGU; Abe et al., 2014, JpGU).

In this study, we integrate three of the regional PTHAs calculated from all possible earthquakes along Nankai Trough, Sagami Trough, and Japan Trench to get a nationwide PTHA. We will make two kind of the probabilistic tsunami hazard maps ; one is “Present-time hazard map” under an assumption that earthquake occurrence basically follows a renewal process based on BPT (Brownian Passage Time) distribution. The other is “Long-time averaged hazard map” under an assumption that earthquake occurrence follows a stationary Poisson process. The former is based on long-term assessments for the forthcoming large earthquakes in three subduction-zones. So it offers a probabilistic tsunami hazard map that naturally corresponds to a set of the long-term assessments of the forthcoming earthquakes, for three subduction-zones above, published by ERC/HERP. On the other hand, the latter is effective for us to make social/infrastructural preparations over hundreds year long.

A Present-time hazard map, showing the probability that the tsunami height will exceed 3 meters at coastal points in next 30 years (starting at 1st January, 2016), suggests high possibility over 60% in several coastal zones along the southern coasts of Shikoku to Tokai region, perhaps due to contribution from the next Nankai earthquake. Since the occurrence probability for the next 30 years, starting from 2013/01/01, is assessed 60% to 70% by ERC, this high possibility of 60% means that almost all the tsunami heights in the several coastal zones will tend to be greater than 3 meters. However, a long-time averaged hazard map, showing the probability that the tsunami height will exceed 3 meters at coastal points in next 30 years, suggests a not-so high possibility less than 20-30% for coastal zones along the Pacific coast. This is because long-time averaged hazard maps do not present an impending danger but do give a long-term perspective over hundreds to thousands years.

Keywords: probabilistic tsunami hazard assessment, probability, tsunami, Nankai Trough, Sagami Trough, Japan Trench

Examination of tsunami fault model for the 17th century great earthquake in eastern part of Hokkaido.

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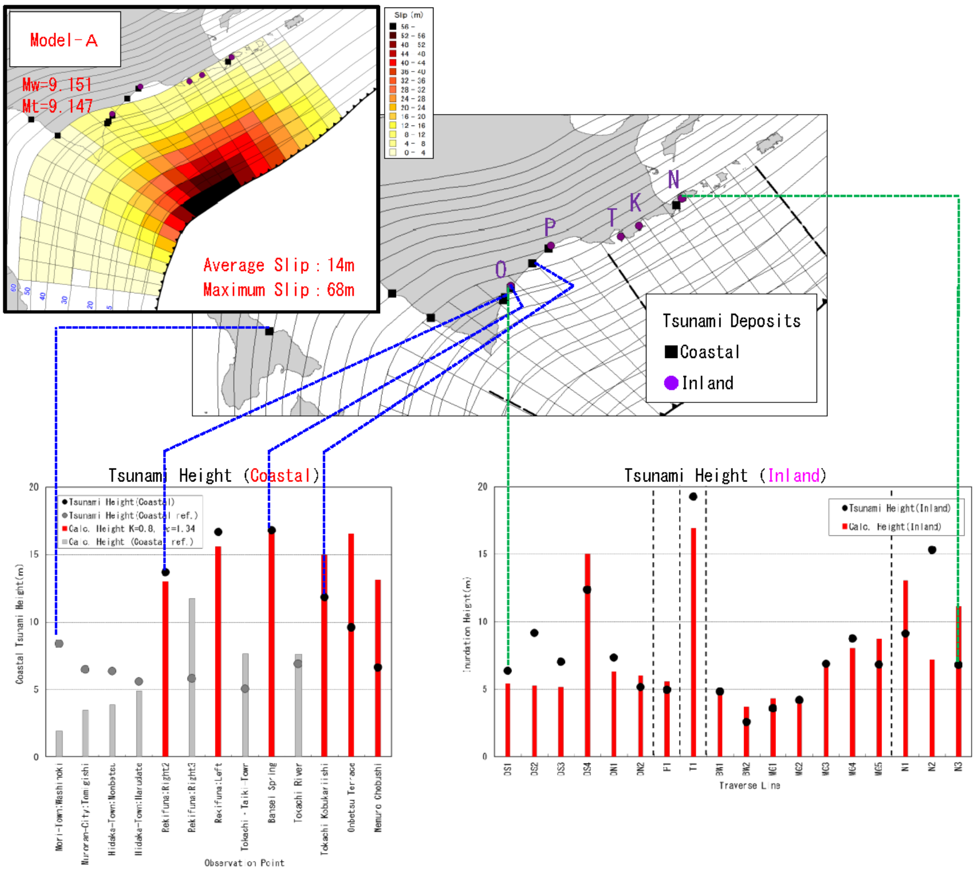
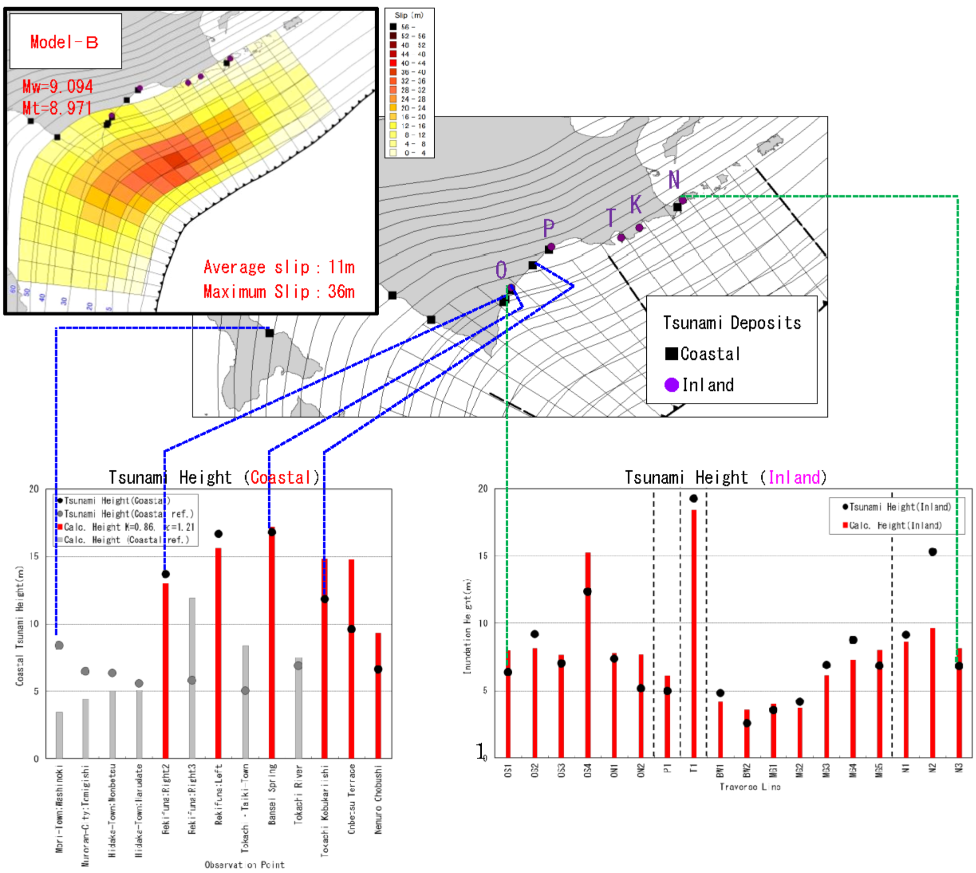
The Cabinet Office is conducting examination of the largest class earthquakes occurring in the Japan Trench and the Kuril Trench in the “Council for studying megaquake models in the Japan trench and the Kuril trench (established in February 2015)". As a part of the council, Yokota et al. (2015) re-examined tsunami fault model for the 2011 off the Pacific coast of Tohoku Earthquake and currently construct tsunami fault model for the 17th century great earthquake in eastern part of Hokkaido.
Compared with Nankai Trough, there is a small amount of historical data for the 17th century great earthquake. However, investigation of the tsunami deposits for the 17th century great earthquake has been actively carried out not only near the coast but also in inland areas (e.g. Nanayama et al. (2003); Hirakawa et al. (2005)). Some researchers (e.g. Satake et al. (2008); Ioki and Tanioka (2016)) reported the tsunami fault model that explained inundation and coastal tsunami heights estimated by the deposits data. They tried to estimate the tsunami fault model with a few rectangle fault planes that explained inundation and coastal tsunami heights using tsunami forward simulations.
In this study we estimated the fault slip distribution on the Kuril plate using tsunami inversion analysis with inundation and coastal tsunami height data. To solve the inversion, it is crucial whether the fault slip reaches to the Kuril Trench or not. Therefore we assumed two models, i.e. Model-A and Model-B. The slip of Model-A reaches to the Kuril Trench, but that of Model-B does not reach to the Kuril Trench.
Characteristics of Model-A and Model-B are as follows:
1) Model-A : Mw=9.2, Mt=9.1
Maximum slip is 68 meters and average one is 14 meters.
2) Model-B : Mw=9.1, Mt=9.0
Maximum slip is 36 meters and average one is 11 meters.
Although the two models equally reproduce inundation and coastal tsunami heights, the obtained slip near the Kuril Trench of Model-A is much larger than that of Model-B. One of the reasons for this is that the dip angle of the plate near the Kuril Trench is smaller than that of the plate at the deeper region of the fault and the slip near the Kuril Trench of Model-A must be larger to generate powerful tsunami.

Keywords: tsunami fault model, tsunami deposit, inversion, earthquake hazard assessment



Model-A
Mw=9.151
Mt=9.147
Average Slip : 14m
Maximum Slip : 68m
Slip (m)
O
P
T
K
N
Tsunami Deposits
Coastal
Inland
Tsunami Height (Coastal)
Tsunami Height (Inland)
Coastal Tsunami Height(m)
Observation Point
Traverse Line



Model-B
Mw=9.094
Mt=8.971
Average slip : 11m
Maximum Slip : 36m
Slip (m)
O
P
T
K
N
Tsunami Deposits
Coastal
Inland
Tsunami Height (Coastal)
Tsunami Height (Inland)
Coastal Tsunami Height(m)
Observation Point
Traverse Line

Developmental status of real-time tsunami inundation forecast system using S-net

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We designed a database-driven real-time tsunami inundation forecast system based on the multi-index method with correlation coefficient and two kinds of variance reductions. And we implemented a prototype system for the Pacific coast of Chiba prefecture (Kujukuri-Sotobo region), Japan using the Seafloor Observation Network for Earthquakes and Tsunamis (S-net). To evaluate the propriety of our developed system, we investigated whether it is possible to select appropriate tsunami scenarios from Tsunami Scenario Bank (TSB) for the 1677 Enpo Boso-oki earthquake as “pseudo observation” and the November 22, 2016 Mw 7.0 earthquake off Fukushima prefecture, Japan. This work was partially supported by the Council for Science, Technology and Innovation (CSTI) through the Cross-ministerial Strategic Innovation Promotion Program (SIP), titled “Enhancement of societal resiliency against natural disasters” (Funding agency: JST).

Keywords: S-net, Seafloor observation network, Tsunami, Real-time forecast

Nonlinear parametric model based on power law for tsunami height prediction

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Dense Ocean-floor Network system for Earthquakes and Tsunamis (DONET) was constructed in offshore Wakayama prefecture to cope with the damage of the Nankai Trough earthquakes accompanied by a large-scale disaster. In DONET1, ocean-bottom pressure gauges are installed at 20 points, and it is possible to detect the pressure change caused by tsunami immediately. Moreover, by using a super computer it has become possible to simulate tsunami in various scenarios precisely and get the observation value of ocean-bottom pressure gauges in DONET1 and the tsunami height along the coast (Baba et al. 2014).
Methods of predicting tsunami have been proposed in previous studies. These methods predict the tsunami height by learning the relation between the ocean-bottom pressure and the tsunami height. A method using linear regression (Baba et al. 2014) and a method using Gaussian process (Igarashi et al. 2016) were proposed. However, the former method is impossible to learn the nonlinear relationship and to predict with high accuracy. On the other hand, the latter method is based on nonparametric model which is difficult to correspond to the physical model.
In this study, we propose a nonlinear parametric model based on the assumption that there is a nonlinear relation based on power law between the ocean-bottom pressure and the tsunami height. In this model, the relationship is expressed by the formula d = a1x1^b1 + a2x2^b2 + ... + a20x20^b20 + c, where d is the tsunami height, xi is the observation value of ocean-bottom pressure gauge, and ai, bi, and c are parameters.
An experiment to compare the accuracy of tsunami height predicting methods was carried out. As a result, we observe that the prediction error of the proposed method is 0.81m, where that of the linear regression is 1.28m. It decreased by 37%. Moreover, the prediction error of the proposed method is as low as that of the Gaussian process, 0.77m. According to the proposed method, it is possible to create an interpretable and highly accurate model that predict the tsunami height by learning the relation between the observation value of ocean-bottom pressure gauge and the maximum value of the tsunami height.

Keywords: Tsunami height prediction, Nonlinear parametric model, DONET

Extraction of tsunami response functions at small islands by averaging four tsunami spectra

*Kuniaki Abe[1]

1. none

Tsunami power spectra obtained from the tide gauge records of four Pacific tsunamis, 1952 Kamchatka, 1960 Chile, 1964 Alaska and 2011 Tohoku, were used to extract response function of small islands. The extractions were applied to three small islands, Wake, Johnston and Midway, being located in north-west Pacific. Response function is defined as logarithm of spectral component averaged to the four tsunamis. It was derived for Wake, Johnston and Midway. The power spectra showed wavy ramp function in a log-log expression. The corner frequency is approximated to be 0.1 cycle/min (10 min in period) for Wake and Midway, and 0.032 cycle/min (30 min in period) for Johnston. Difference spectra defined as difference of the averaged spectrum to each tsunami spectrum were obtained to each tsunami. The difference spectra, being approximated as that of tsunami incident to the tide station, were compared with tsunami power spectra obtained at open ocean (DART21413) in the 2011 Tohoku tsunami and at Japanese coast (Ishinomaki, Sendai, Soma, Onahama and Ooarai) in the 2016 Off-Fukushima tsunami on Nov. 21,2016. The difference spectrum of 2011 Tohoku tsunami at Wake is shown with tsunami spectrum and average spectrum in Fig. 1. At the same time spectrum of DART 21413 by NOAA is shown in the same figure. DART 21413 (30.55N,152.13E) is located near the source and in the direction of N132E . On the other hand tide station of Wake is distant from the source and has an azimuth of N126E. Both the points have an almost same azimuth angle. The fact that main peaks in difference spectrum reproduce those of DART spectrum supports the response function. A part of tide gauge data is cited from webcites of NOAA and JMA. Author acknowledges the citation to NOAA and JMA.

Keywords: responce function, island, tsunami spectra

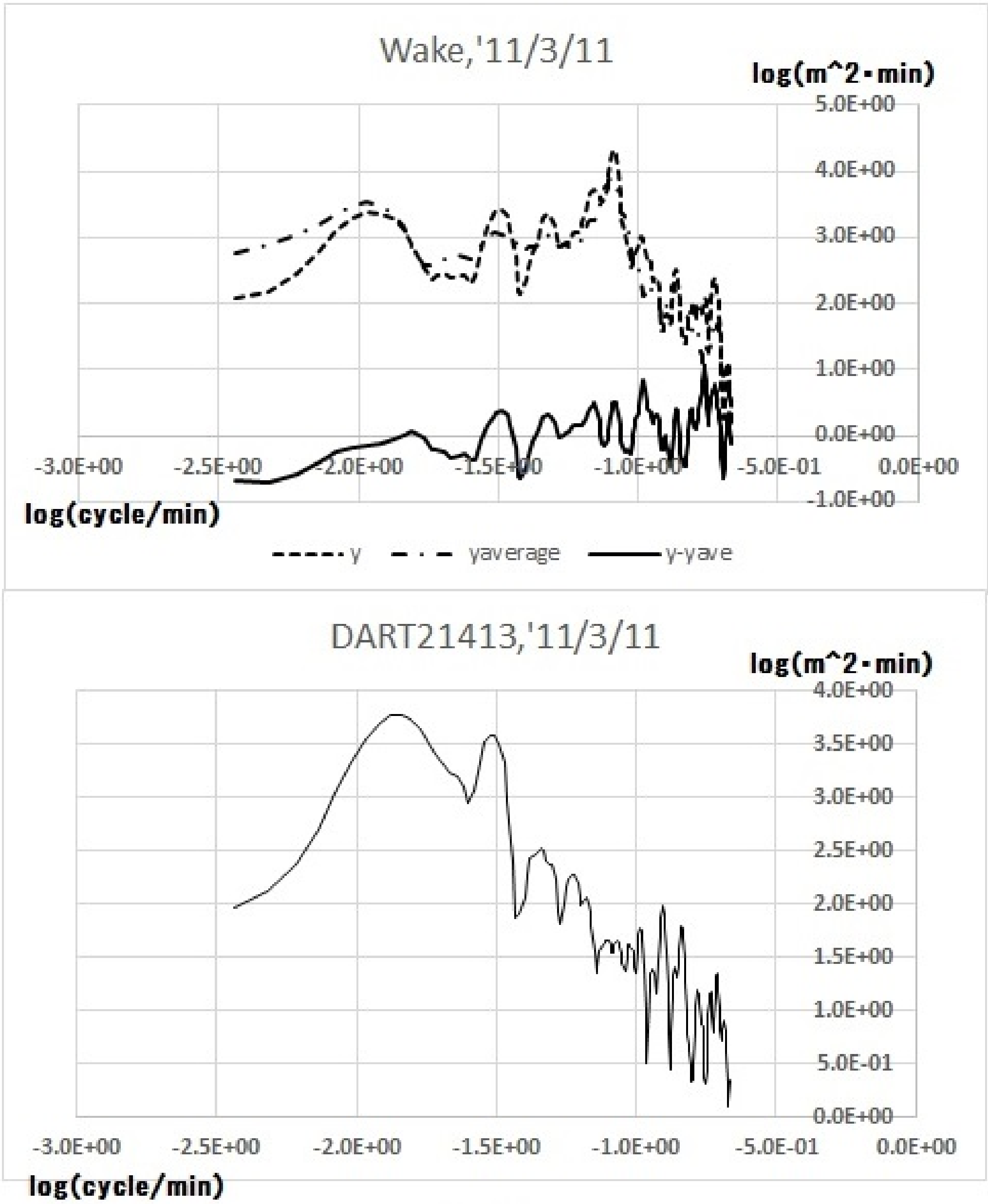
Wake,'11/3/11
log(m^2・min)
5.0E+00
4.0E+00
3.0E+00
2.0E+00
1.0E+00
0.0E+00
-1.0E+00
-3.0E+00
-2.5E+00
-2.0E+00
-1.5E+00
-1.0E+00
-5.0E-01
0.0E+00
log(cycle/min)
y
yaverage
y-yave
DART21413,'11/3/11
log(m^2・min)
4.0E+00
3.5E+00
3.0E+00
2.5E+00
2.0E+00
1.5E+00
1.0E+00
5.0E-01
0.0E+00
-3.0E+00
-2.5E+00
-2.0E+00
-1.5E+00
-1.0E+00
-5.0E-01
0.0E+00
log(cycle/min)

Fig.1

Fault model of the 1611 Keicho Tsunami earthquake (Mw9.0) estimated from historical documents using tsunami inundation simulation

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The 1611 Keicho Tsunami earthquake generated huge tsunamis and caused a disaster along the Pacific coast of Tohoku area from Fukushima to Miyako. There are several historical documents, but some of them were controversial. Recently, Ebina and Imai (2014) checked historical documents in detail and made the most reliable data set of the tsunami inundation of the 1611 Keicho Tsunami. We compared the data set with the tsunami inundation of the 2011 Tohoku tsunami and found that the tsunami from the 1611 tsunami earthquake inundated larger distance than the 2011 Tohoku tsunami at many places.
The numerical tsunami inundation computations with various fault models were carried out along the Pacific coast of Tohoku. The computed inundation were compared with reliable tsunami evidences of historical documents in Ebina and Imai (2014 in Japanese), such as tsunami evidence about 30 m height at Koyadori in Iwate or tsunami evidence at Suwa in the Sendai plain about 7 km away from the coast. Results indicate that the tsunami generated from the combination of two rectangular fault models, north fault with the length of 100 km, the width of 100 km, and the slip amount of 80 m and south fault with the length of 150km, the width of 100 km, and the slip amount of 40 m, explains all reliable evidences very well. The moment magnitude of the 1611 tsunami earthquake is calculated to be 9.0 by assuming that the rigidity is 3 x 10**11 N/m**2. The moment magnitude of the 1611 Keicho tsunami earthquake is the same as that of the 2011 Tohoku-oki earthquake.
The northern part of the fault with a slip amount of 80 m was not ruptured by the 2011 Tohoku-oki earthquake but located at north of the rupture area. The southern part of the fault, where 40 m slip was estimated, is located at the almost same area of the large slip area of the 2011 Tohoku-oki earthquake. This suggested that the 2011 Tohoku-oki earthquake re-ruptured the southern part of fault area ruptured by the 1611 Keicho tsunami earthquake. This southern part was also ruptured by the 869 Jogan earthquake previously. Because the plate convergence rate of Pacific plate along the Japan Trench is about 9 cm/year, a large slip of 40 m by the 1611 Keicho tsunami earthquake is slightly smaller than 65 m accumulated after 869 Jogan earthquake. But a large slip of about 45 m estimated for the 2011 Tohoku-oki earthquake is slightly larger than 36 m accumulated after the 1611 Keicho tsunami earthquake. Because the above differences are not so large, it can be caused by the different slip distributions of three earthquakes.

Keywords: 1611 Keicho Tsunami Earthquake, Tsunami inundation simulation, 2011 Tohoku-oki Earthquake

Tsunami and landslide model due to the 1741 Oshima-Oshima eruption in Hokkaido, Japan

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The 1741 tsunami was generated by the Oshima-Oshima sector collapse in the southwestern Hokkaido, Japan. The tsunami caused great damage along the coast of Japan Sea in Oshima and Tsugaru peninsula. By the survey of tsunami deposits, at the coast of Okushiri Island and Hiyama in Hokkaido, tsunami deposits of this tsunami were found. In this study, the landslide and tsunami by the Oshima-Oshima eruption were modeled to explain distribution of debris deposits, tsunami heights by historical records, and distribution of tsunami deposits. First, region of landslide and debris deposits were made out from the bathymetry based on the bathymetry survey data (Satake and Kato, 2001) in the north part of Oshima-Oshima. In addition, topography before the sector collapse and landslide volume were re-estimated. The volume of landslide was estimated at 2.2 km^3. Based on those data, the landslide and tsunami were simulated using the integrated model of landslide and tsunami considered soil mass and water mass (Yanagisawa et al., 2014). As the results, soil mass slid slowly submarine slope and stopped after about 15 minutes. On the other hand, the first wave of tsunami were generated during 1 minute that soil mass slide. Distribution of computed debris deposits agree relatively well with region of debris deposits made out from the bathymetry. Calculated tsunami heights match with historical records along the coast of Okushiri and Hiyama in Hokkaido. Calculated inundation area of tsunami cover distribution of tsunami deposits found by tsunami deposits survey in Okushiri and Hiyama coast.

Keywords: tsunami, landslide, Hokkaido

Ray tracing for dispersive tsunamis and estimation of initial sea-surface displacement: Application to the 2015 Smith Caldera earthquake

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Ray tracing method based on the optics theory has been applied to tsunamis in order to calculate travel times and refractions due to bathymetry variations. Previous methods are applicable to linear long-waves [e.g. *Satake*, 1988, PAGEOPH; *Woods and Okal*, 1987, GRL]. However, real tsunamis are dispersive, that is, have frequency-dependent propagation speeds so that the method needs to be extended to dispersive tsunamis.

The method is also used for estimation of the initial sea-surface displacement in combination of Green's law, that is based on the conservation law of the potential energy of linear long-waves [e.g. *Abe*, 1973, PEPI; *Satake*, 1988, PAGEOPH]. By using the law, previous studies estimated the height of the initial sea-surface displacement assuming that the peak amplitudes of the initial displacement and outgoing waves from a source region are the same. However, this assumption might lead to an underestimation of the initial wave height, because tsunami waves behave differently inside the source region.

In this study, we first propose a new ray-tracing method extended to dispersive tsunamis. We create frequency-dependent velocity maps from 2-D bathymetry data by solving iteratively the formula of dispersion relation of the linear gravity wave by a recursive algorithm. Then ray paths at different fixed frequencies are traced on the frequency-dependent velocity fields by integrating ray equations for seismic surface waves [e.g. *Yomogida and Aki*, 1985, JGR].

For more precise modeling of the initial sea-surface displacement, we investigate tsunami behaviors near the source region by waveform simulations to confirm that outgoing waves from the source region have a wave height less than a half of the height for various initial sea-surface displacement models. We propose an alternative way to estimate the initial sea-surface displacement. First, the source region is estimated by means of the back-projection using arrival times of tsunami signals at stations. Secondly, the wave height of outgoing waves from the source region is derived from an observed height by using Green's law. Finally, we obtain the height of the initial sea-surface displacement by using the ratio of the peak amplitudes of the initial static displacement models and simulated outgoing waves from the source region.

These two methods are applied to a real tsunami event that was caused by an abnormal volcanic earthquake near Smith Caldera with a diameter of about 7 km on the Izu-Bonin arc. The earthquake had a CLVD-type focal mechanism and generated larger tsunami waves compared to its magnitude (M5.7), and therefore the earthquake may be regarded as a "volcanic tsunami earthquake." Dispersive tsunamis were recorded by a dense array of ocean bottom pressure (OBP) gauges, 100 km to the NNE from the epicenter [*Fukao et al.*, 2016, JpGU]. It is notable that the measured slowness direction of wavefront deviates from the great circle path and varies as a function of frequency.

Our new ray tracing for dispersive tsunamis shows that ray paths are significantly dependent on its frequency, particularly at deep oceans. Simulated slowness direction and arrival time at the array change as a function of frequency, which is consistent with the observations by *Fukao et al.* [2016, JpGU]. By minimizing the misfit between observation and ray tracing, the peak point of the tsunami source can be constrained within Smith Caldera. In addition, we model the initial sea-surface displacement using our new method with the tsunami data at the OBP array. The boundary of the source region is located close to the inner-wall of Smith Caldera. By assuming a column-shaped displacement with the size of Smith Caldera, we obtain the initial wave height of at least 30 cm. Although some uncertainties remain, these results imply that these methods are very powerful to preliminarily estimate the initial sea-surface displacement.

Keywords: ray tracing, dispersive tsunamis, tsunami analysis, volcanic earthquake, tsunami earthquake

Oceanfloor network system and real-time tsunami prediction system

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Very severe damages were brought by huge tsunami accompanied with the 2011 off Tohoku earthquake. It is important to take measures for tsunami to reduce the damages using real disaster scenarios. To use their scenarios on actual implementation, it is indispensable to detect tsunami, and to understand the situation from propagation of tsunami to its inundation.
Around the Nankai Trough area, which is concerned about future large earthquake, the dense ocean-floor network system for earthquakes and tsunamis (DONET) was constructed and implemented. A real-time tsunami prediction system using DONET was developed by JAMSTEC and is revised in collaboration among NIED, JAMSTEC and NTT data CCS to introduce DONET2 data in the Nankai area. The system predicts tsunami arrival time and the height with an inundation map based on amplification of the tsunami during the propagation using the database with fault models of over 1500 cases. In other words, it uses correlation between maximum average values of absolute pressure gauge data and maximum tsunami height of the predicted points. To develop it to improve the prediction, fault models to be used for the prediction are sorted out using differences of trigger times for the earthquake and tsunami between DONET observatories. In addition, the used DONET observatories are also sorted out based on the direction of the tsunami propagation for each predicted point. The system using DONET1 data in the Tonankai area is already implemented by prefectures of Wakayama and Mie, Chubu electronic power, and Owase city, and the new version is under verification. This system does not determine one best fault model, and selects some worse cases to be satisfied some conditions for the predicted point. Therefore, it reflects heterogeneous slip distribution and local effects like landslide on the sea bottom.
It is indispensable for the implementation to evaluate the quality of the input data. Knowing the data quality and considering the implementation by local governments, the system should have flexibility to be able to prevent issues like lack of data and comprehensibility for the implementation. The visualization and prediction method depend on the purposes and the locality of the target. I point hybrid system adopting some prediction method and the visualization considering user’s confusion by multiple prediction data.

Keywords: Tsunami, real-time prediction, DONET

Application of Tsunami Information to Disaster Mitigation in Chiba Pref.

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We engage in educational activities on the disaster management staff in local government and local residents in the Chiba Prefecture for the tsunami disaster mitigation, To put over the important of the evacuation during Tsunami disaster, we promote the activity based on the AIDMA that is the marketing framework. We report the activity during 3 years supported by the SIP Project.
I wish this English abstract would help for the disaster mitigation.

Keywords: Tsunami Information, Education for Disaster Mitigation, AIDMA

Height Distribution of the tsunami of the Keicho Earthquake of February 3, 1605 on the coast of the Boso Peninsula

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The tsunami of the Keicho Earthquake of February 3, 1605 was recorded at the points on the Pacific coast of the western part of the Japanese Islands, and is sometimes regarded as one of the Tokai Gigantic earthquakes. In the present study we made clear the detailed distribution of heights of the tsunami of this earthquake on the open coast of the Boso Peninsula, Chiba Prefecture. The basic document of the present study is called "The Boso Chiran-ki" (Chronology of inner battle in Boso Peninsula), in which the names of 35 tsunami damaged villages were listed and the locations of these villages are shown by small circles in the Figure. There is a no damage coast of the lenghth of about 12 kilometers between Katsuura town and Uchiura village, which is presumable that only a slight damage took place in this coastal section. The Text of "Toudai-ki (The Chronology of the years under the rule of the first Shogun Ieyasu Tokugawa)" also recorded this tsunami, and seven villages in the territory of Ootaki clan were swept away and nothing left on the ground. The locations of these seven villages are shown by black diamonds in Figure. A temple called Saitokuji in Amatsura village in Kamogawa city, handed down an old document in which it is recorded that all houses were swept away in this village. We made a field measurement in those villages. We obtained the tsunami height distribution is shown as the figure. The tsunami height exceeded 10 meters at sixteen points. Considering this tsunami height distribution, the 1605 Keicho earthquake is not considered as one of the series of the Off-Tokai gigantic earthquakes.
Acknowledgement: This study was achieved as a part of the commissioned research named "Study on the historical tsunamis in the Pacific coast of Japan (2016)" on disaster prevention for nuclear facilities proposed by the Nuclear Regulation Authority, Japan.

Keywords: the 1605 Keicho Earthquake-Tsunami, Historical Earthquake, Historical Tsunami, Boso Peninsula, Japan Trench

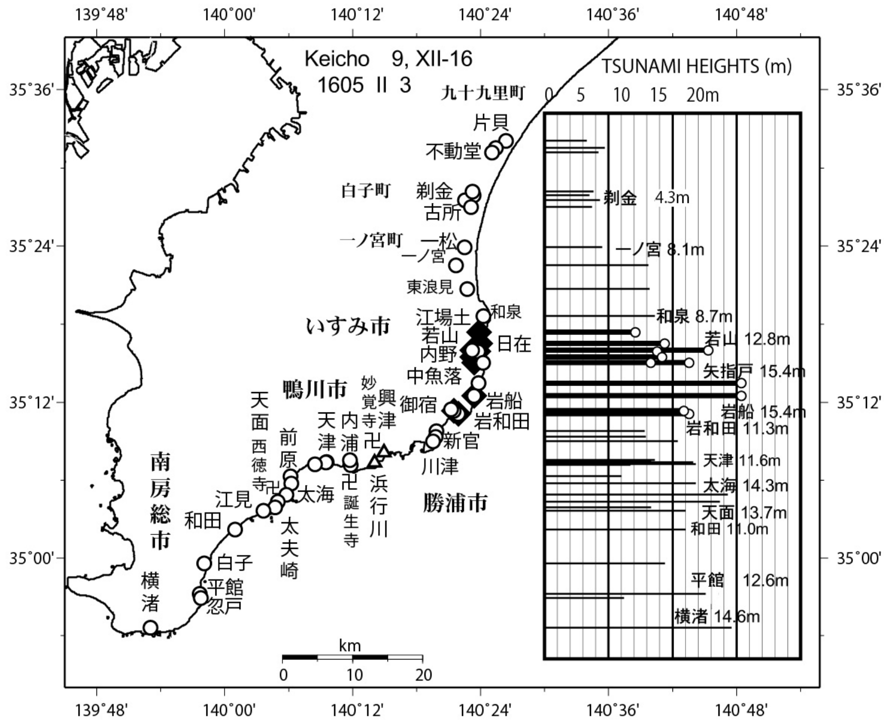

図　慶長9年12月16日（1605年2月3日）関東南方沖地震による房総半島の津波高さ

◆　『当代記』によって、小多喜領七ケ村が「中ニモ七村は跡形モナシ」と記された集落。

○　『房総治乱記』に「先潮災ニ逢シハ」で始まる文章で記された35ケ村。4ケ村は『当代記』に「あとかたもなし」と記された村と重複している。勝浦市川津以西、鴨川市内浦までの約13kmの間にある集落は被災した村が無く、この間は無事であったらしい。

Maximum initial tsunami height estimation 10 min after large earthquake using initial total electron content pulse observation

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Ionospheric plasma disturbances after a large tsunami can be detected by measurement of the total electron content (TEC) between a Global Positioning System (GPS) satellite and its ground-based receivers. Nine minutes after initial sea surface enhancement in tsunami, TEC pulse enhancement equatorialward from the tsunami source area clearly appeared. In this study, we show the relationship between the TEC change and the initial tsunami height, which implies that the detection of the initial TEC pulse might contribute to tentative information of initial tsunami height.

Keywords: Ionospheric disturbance, Total electron content, Tsunami

Inversion of the perturbation GPS-TEC data induced by tsunamis in order to estimate the sea level anomaly.

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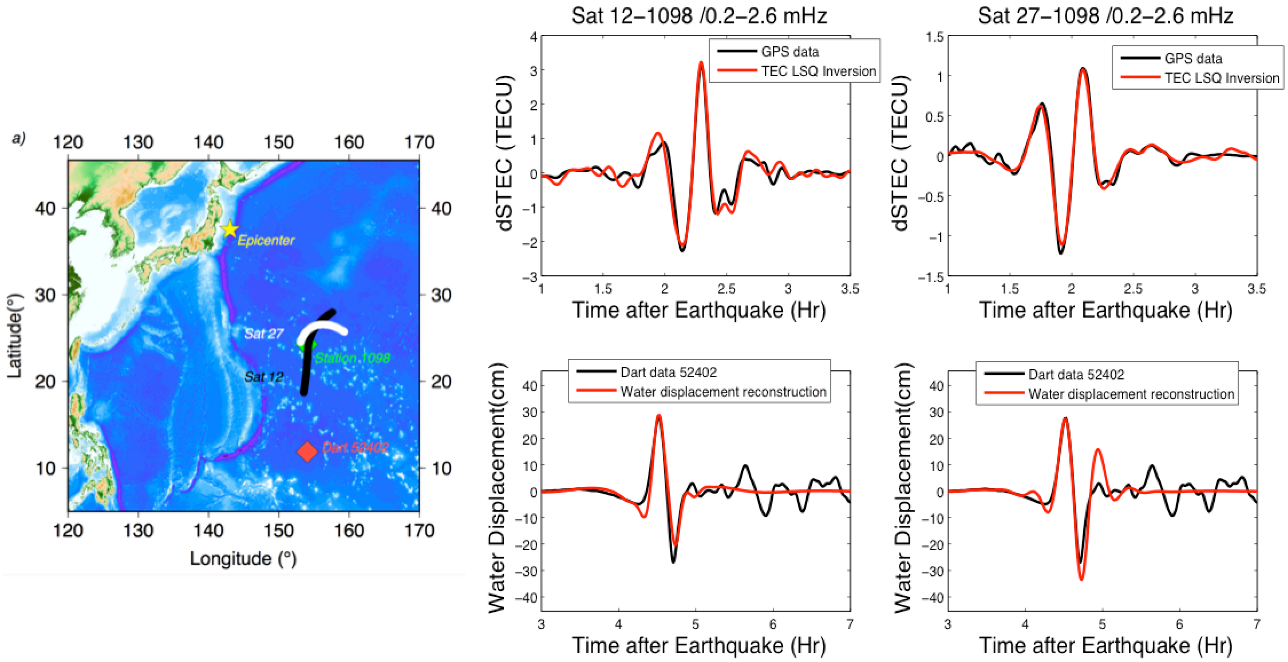
Large underwater earthquakes (Mw > 7) can transmit part of their energy to the surrounding ocean through large sea-floor motions, generating tsunamis that propagate over long distances. The forcing effect of tsunami waves on the atmosphere generate internal gravity waves which produce detectable ionospheric perturbations when they reach the upper atmosphere. Theses perturbations are frequently observed in the total electron content (TEC) measured by the multi-frequency Global navigation Satellite systems (GNSS) data (e.g., GPS,GLONASS). In this paper, we performed for the first time an inversion of the sea level anomaly using the GPS TEC data using a least square inversion (LSQ) through a normal modes summation modeling technique. Using the tsunami of the 2012 Haida Gwaii in far field as a test case, we showed that the amplitude peak to peak of the sea level anomaly inverted using this method is below 10 % error. Nevertheless, we cannot invert the second wave arriving 20 minutes later. This second wave is generaly explain by the coastal reflection which the normal modeling does not take into account. Our technique is then applied to two other tsunamis : the 2006 Kuril Islands tsunami in far field, and the 2011 Tohoku tsunami in closer field. This demonstrates that the inversion using a normal mode approach is able to estimate fairly well the amplitude of the first arrivals of the tsunami.

Keywords: tsunami modes, gravity waves, inversion, Total Electron Content (TEC)

Tohoku Earthquake and tsunami occured the 11/03/2011



-15.4 min. shift applied

Error on max. tsunami height estimation: 12.5%

The effectiveness of Green's Function based Time Reverse Imaging method for tsunami source estimate

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We developed a Green's Function based Time Reverse Imaging (GFTRI) method in order to recover the initial sea surface displacement associated with tsunami generated by undersea earthquake, submarine landslide etc. This method has the same source representation as the least square (LSQ) source inversion method. In GFTRI method, the source region is divided into a number of source patches and Green's functions (GF) are computed using a unit point source located over each source patch. Instead of using LSQ method, this method uses time reverse imaging method to estimate tsunami source by convolving GFs with time-reversed observed waveforms. This method was implemented in the 2011 Tohoku-Oki earthquake tsunami. In this work, we implemented the method to the 2009 Samoa tsunami whose source mechanism is believed to be complex. For this event, only few observations are available and many of them are located quite far way from the source and contain reflected, refracted, or even scattered waves. So, it is an ideal event to examine whether the method is capable of reconstructing a source model associated with earthquake source having double-couple feature using only the first wave (FW) or the first wave with later arrivals (FL). We carried out several experiments with synthetic waveforms and results indicate that the method is able to extract complex features of the earthquake. We, then, applied this method with actual tsunami waveforms of the Samoa 2009 tsunami (both FW and FL) and our results suggest that this tsunami occurs due to both normal and thrust faulting. Our finding is very consistent with previous studies of seismic waveforms for this earthquake that have suggested the event is a doublet, consisting of both an outer rise normal fault and megathrust rupture.

Keywords: Tsunami , time reverse imaging, source inversion