From Observatory Messages to Initial Tsunami Bulletin Parameters: Does the Central Limit Theorem still apply?

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As part of its daily operations the Pacific Tsunami Warning Center (PTWC) in Honolulu, Hawaii, routinely analyses most earthquakes with a 5.5 or larger magnitude occurring around the globe. Although not officially required, the PTWC scientists on duty will usually issue an observatory (obs) message that contains the first set of preliminary source parameters for these events. If the magnitude of the earthquake under analysis crosses the 6.5 magnitude threshold, however, the protocol requires the issuance of at least a tsunami information bulletin. For many years, scientists at the PTWC assumed that the ubiquitous central limit theorem guaranteed that the inclusion of a larger number of seismic stations in the initial analyses would automatically improve the quality of the source parameters, particularly a more accurate hypocenter location and Mwp magnitude estimate. In this study we assess the validity of these assumptions and their impact on the message delays based on the actual messages' data and statistics. We matched 577 observatory messages issued by the PTWC between 2003 and 2016 with the corresponding official tsunami message products that followed them. We then computed the corresponding epicentral offsets, magnitude residuals, and message latencies against the source parameters listed in the International Seismological Centre (ISCGEM), the Global Centroid Moment Tensor (GCMT) Project, and the National Earthquake Information Center (NEIC) online catalogs. Analysis of these statistics reveals that 53% of the reported magnitudes did not change despite up to 20 additional minutes of processing time since issuing the observatory message. Paradoxically, for 17% of the dataset the median magnitude residual increases from zero in the obs messages to 0.2 magnitude units in the matching bulletins that followed. In the remaining 30% of the events the initial magnitude estimates see a reduction of the median magnitude residual from 0.3 in the obs messages to 0.1 magnitude units in the corresponding bulletins. These results indicate that for the majority (70%) of the earthquakes analyzed by the PTWC during the last 12 years the quality of the preliminary earthquake parameters does not benefit from the additional message delays. Moreover, the data statistics reveal that from 2003 to 2016 in most cases the initial source parameters included in the obs messages had an accuracy matching or exceeding those included in the initial tsunami messages that followed them. Such results suggest that within this context the central limit theorem has a limited operational applicability. This appears to stem from the rather short analysis times and limited data availability typical for most initial earthquake source characterizations conducted by the PTWC scientists for tsunami warning purposes. Notwithstanding, additional message delays seem justified when dealing with earthquakes characterized by either a complex rupture or large magnitudes. For the majority of the earthquakes processed at the PTWC, however, the results do not justify additional time delays to add more seismic stations in the initial hypocenter location analyses, or to manually review individual magnitude estimates before issuing the first official message product. Moreover, we can conclude that as often as not additional processing times turn into a waste of otherwise precious warning time, something particularly important in the near field.

Keywords: tsunami bulletins, central limit theorem, source parameters accuracy, observatory messages, magnitude residuals, tsunami message delays

Tsunami fragility functions for buildings and their applications in New Zealand

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The use of fragility functions for buildings to assess the risk to the built environment from tsunamis has become increasingly important over the last decade. Fragility functions express the conditional probability that a particular building structural damage state (e.g. low, moderate, complete damage) will be reached or exceeded for a given tsunami intensity parameter such as flow depth, velocity and/or debris strike. Results can then be used to estimate impacts and losses for various tsunami hazard scenarios in order to better inform hazard or risk planning and mitigation. In this poster, we report on the application of tsunami fragility functions for buildings to estimate tsunami impacts and losses in New Zealand using the RiskScape loss modelling tool. RiskScape is a multiple hazards loss modelling software tool that has the capability of correlating hazard models (e.g. tsunami inundation model) with asset inventories (e.g. buildings, lifelines) using fragility functions to determine risk exposures and potential losses. In the absence of major historical damaging tsunamis in New Zealand, estimating tsunami risks via RiskScape has traditionally been carried out using analogous flood depth-damage functions. However, we demonstrate here that the application of tsunami fragility functions for buildings developed in Japan following the recent 2011 Tohoku-oki tsunami provides a more realistic estimation of tsunami impacts to buildings via RiskScape. Furthermore, presenting the results as damage probabilities permits the identification of risk hotspots for a given tsunami inundation model, allowing for a more strategic approach to mitigation planning. Our findings suggest that global tsunami fragility functions can be used to improve tsunami risk assessment in other countries given the availability of country-specific tsunami hazard models and asset inventory data.

Keywords: Tsunami, Fragility functions, RiskScape, New Zealand

Key features of the real-time forecast system for tsunami inundation developed by NIED

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We are developing a real-time forecast system for tsunami inundation as well as coastal tsunami heights for the Pacific coast of Chiba prefecture (Aoi et al., 2017), using the real-time ocean bottom pressure data observed by the Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench (S-net; Kanazawa et al., 2012). The main purpose of the system is to provide the tsunami information that would help the local governments promote the evacuation and react the tsunami disaster. The information of tsunami inundation is highly important because the risk of the tsunami could be intuitively recognized. Therefore, we employ the database-driven system in order to forecast the inundation for relatively broad region, which requires a large cost for real-time computation.
The database is called as “Tsunami Scenario Bank (TSB)” and includes “tsunami scenario” composed of the possible tsunami source model, and the simulation results of the ocean bottom pressure data at S-net observation stations, coastal tsunami heights, tsunami arrival times, and flow depths for each source model. TSB is constructed considering interplate earthquakes along the Japan Trench, Sagami Trough, Nankai Trough, and outer-rise earthquakes along the Japan Trench. The ocean-bottom pressure data and coastal tsunami height data are pre-calculated for more than 10,000 source models. Among them, the inundation data are calculated for the source models with the maximum coastal tsunami height of 1 m or greater using the 10-m mesh terrain model with sea walls. Tsunami scenarios are created by appropriately associating these information in consideration of the resemblance of the simulation results.
The forecast system continuously searches for the tsunami scenarios whose pre-calculated pressure data reasonably explain the real-time observation data based on the multi-index method (Yamamoto et al., 2016). The method uses the correlation coefficient and two kinds of the variance reductions for the spatial distribution of the ocean-bottom pressure data to evaluate the degree of the matching. If all of the three indexes meet the criterion values, the tsunami scenarios are selected as candidates to generate the forecast information. The selection methodology is less sensitive to the perturbation of the timing because these indexes are calculated from the peak-hold value of the absolute value of the pressure change. In addition, the methodology could evaluate the scale of the tsunami appropriately using two kinds of the variance reductions that are sensitive to overestimation and underestimation respectively. Several kind of the tsunami forecast information can be created in this system from the selected tsunami scenarios according to the needs of users. The tsunami information related to the best-fit scenario for ocean-bottom pressure data is one of the useful forecast information. In order to prevent the system from the underestimation, the maximum values of all the selected scenarios is the possible forecast information.
The system is in trial operation using the real-time observation data to see the stability and performance.
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Keywords: Real-time tsunami forcast, S-net

Development of GPU Tsunami Simulator for Expanding Tsunami Scenario Bank

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In the development of database driven tsunami real-time forecasting system using real-time observation data from pressure gauge, adequate and cyclopedic tsunami scenarios should be taken into consideration and tsunami simulations should be done before tsunami occurrence to improve the accuracy of forecast. Rack of variety of tsunami scenario in disaster preparedness such as pre-disaster damage estimation or database driven early warning system reads to unexpected situation in emergency and increase casualties because that limits prevention effort and drops emergency response performance.
However, current commonly used tsunami simulation technique needs 30 hours to finish 1 case of the calculation which simulates 6 hours from earthquake in 10km square area at 10m spatial resolution, which is needed for estimation, using 1 CPU core. Under this condition, we need vast amount of time and computation resources to execute a lot of tsunami simulations that cover various tsunami scenarios. Resource saving and speeding up of tsunami simulation is necessary for building tsunami scenario bank effectively and efficiently.
From this perspective, we are developing the simulator that can compute tsunami faster and at low cost using graphic processing unit (GPU). GPU’s massive parallel computation capability is now used for a lot of purpose. The area of tsunami simulation we focused is Sotobo coastal area Chiba prefecture. This area is divided to 13 regions whose minimum spatial resolution is 10m square and total number of spatial grids is 82 million, or 6.4 million grids on average for each region. We ported the commonly used tsunami simulation program which uses non-linear long wave theory and leap-flog scheme and considers run-up to GPU. And then, we tuned the ported program according to the characteristics of GPU’s way of execution, using memory, and so on.
Firstly, using concurrent kernel execution API (Application Programming Interface) of NVIDIA CUDA, we changed the program to be able to execute calculation asynchronously in the part where there is no need to synchronize each nested region. Or connecting data between nested regions with appropriate timing, computation of rougher grid region and that of finer grid region are executed simultaneously by 1 GPU. This can extract more GPU power and speed up the simulation.
Next, we reduced “if” branch to avoid performance degradation due to warp divergence. A lot of conditional branching exist in tsunami simulation program, such as upwind difference scheme, run-up boundary processing. CPU can process these if-else clauses in an efficient way, but GPU processes if-clause and else-clause separately and take time. So, we improved the program reducing if-else clause as far as possible.
Thirdly, we tuned global memory access. When we compute tsunami with GPU, we must use global memory to store 100 million grids of data. And the access to global memory consumes time. So, we changed the program to increase coalesced global memory access, avoid frequent access to certain variable by copying it to registers.
And various tunings are applied, such as reduction of divisional operation, replacement of power function to other functions, reduction of automatic cast from double to float, reduction of kernel calls.
By these improvements on the program, execution of tsunami simulation is accelerated to a large degree, and the simulator becomes to be able to finish the calculation of 1 region within 1 hour with 1 GPU. Furthermore, we enabled concurrent execution using multi GPUs and multi nodes, and created the environment to process massive tsunami simulations.

Keywords: Tsunami simulation, High Performance Computing, Tsunami Scenario Bank

Estimation of the Characterized Tsunami Source Model by Using the observed waveforms of GPS Buoys in the Nankai Trough

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In the 2011 Tohoku earthquake tsunami disaster, the delay of understanding damages state increased the human damage. To solve this problem, it is important to develop the method to estimate the area with severe damage. Koshimura (2007) showed the method to estimate the regional impact of a tsunami using a numerical model and the world population database. In this method, the accuracy of the external force conditions in the calculation of tsunami greatly affected the result of the estimation. Therefore, it is important to estimate the tsunami source quickly and precisely after the earthquake. Satake (1987) showed the method for estimating fault heterogeneity by an inversion of tsunami waveforms. Recently, many researches based on this inversion method have been reported (e.g. Tsushima et al., 2009; Takagawa and Tomita, 2012; Fuji et al., 2013; Tsushima et al., 2014). The previous studies needed a lot of data of tsunami observation, such as GPS Buoys, DART stations, DONET and tidal gauges, to estimate the distribution of dislocation on tsunami source. The reason is that the tsunami source is segmented by small faults.

In this study, we examined the new method to estimate the characterized tsunami source model. The model consists of three zones. They are Large slip zone (LSZ), Super large slip zone (SLSZ) and background rupture zone (BZ) as the Cabinet Office, Government of Japan (2012) reported after the Tohoku tsunami. The characteristic of the proposed method is that the tsunami fault is segmented by the three zones and this segmentation reduces the amount of observed data required estimating the characterized tsunami source model. The targeted fault parameters to estimate are fault length, fault width, dislocation and forming location in each zone. At the beginning of this method, the rectangular fault model is assumed based on the seismic magnitude and hypocenter reported right after an earthquake. By using the fault model, tsunami propagation is simulated numerically, and the fault model is improved after comparing the computed data with the observed data repeatedly. In the comparison, correlation coefficient and regression coefficient are used as indexes. They are calculated with the observed and the computed tsunami wave profiles. This repetition is conducted to get the two coefficients close to 1.0, which makes the precise of the fault model higher.

We analyzed sensitivity of the indexes to fault length, fault width and dislocation. Further, we examined influences of LSZ and SLSZ on the indexes, and the following two results are obtained. (1) The correlation coefficient corresponds to fault length and fault width. On the other hand, the regression coefficient corresponds to fault length, fault width and dislocation. (2) The two coefficients decrease at close to LSZ and SLSZ when estimation of BZ. Therefore, the estimation of BZ is carried out as a first step, and LSZ and SLSZ are estimated next. The proposed method by using GPS buoy was applied for a tsunami scenario in the Nankai Trough. LSZ and SLSZ in BZ could be estimated well.

Keywords: Tsunami fault, Tsunami inversion, Tsunami observed information, Heterogeneous tsunami sources, Correlation coefficient, Regression coefficient

A fast tsunami data assimilation approach on 2012 Haida Gwaii earthquake: based on the employment of Green’s function

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Tsunami data assimilation has been proposed for tsunami hazard forecasting. It estimates the tsunami wave field by assimilating tsunami data observed offshore into a numerical simulation, without calculating initial sea surface height at the source. The Optimum Interpolation (OI) method is widely adopted in assimilating observed data. However, the traditional data assimilation approach requires quite large calculating time, because the forecasted waveforms are still calculated with tsunami propagation model for the entire region.

In this study, we present a new approach based on the employment of Green’s function to improve the speed of tsunami data assimilation. For the OI method, if the residual between observed and calculated tsunami height is not zero, there will be an assimilation response around the station. We consider the occurrence and linear propagation of such tsunami-height response as the ‘Green’s function’ of a station. Then the forecasted tsunami wave field can be calculated as the superposition of the Green’s functions corresponding to different stations. Similarly, the observed tsunami data is repeatedly assimilated during the time window, and more Green’s functions are superposed to the forecasted waveforms at Points of Interest (PoI).

This approach greatly reduces the time cost for tsunami forecasting because it no longer needs to run the tsunami propagation model, as long as the Green’s functions are calculated in advance. The forecasted waveforms at PoIs can be obtained by simple matrix manipulation. This method requires additional computer memory space for pre-calculated Green’s function from stations to PoIs, but it does not have a significant impact on computational efficiency for regional scale tsunami data assimilation.

We apply our method to synthetic and real-time tsunami of the 2012 Haida Gwaii earthquake. The comparison with traditional data assimilation method reveals that this approach could achieve an equivalent high accuracy while saving much time. And this approach is also helpful for studying different lengths of assimilating time windows.

Keywords: Tsunami, Data assimilation, Green's function

A reduced rank data assimilation for airborne measurements of a tsunami

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Our experiments have suggested that a large tsunami can possibly be observed by airborne platforms equipped with a high precision nadir pointing radar altimeter. However, the use of multiple airborne radars is necessary to ensure the applicability of the proposed tsunami observing system for a real-time tsunami forecasting. This can be achieved by attaching the radar on commercial airplanes, considering the viable spatiotemporal coverage of commercial airplane routes in our study area that is located around the Nankai Trough, south of Japan. Assuming that the tsunami signal has been successfully isolated from other oceanic phenomena, a data assimilation is needed to bridge the observation with a model, so that we can numerically spread the observed information throughout the areas of interest. With a considerable number of airplanes, this possible new type of tsunami observation should provide high-resolution data, which is desired but may raise some complexities as well. The large dataset due to the moving observation and the vast number of airplanes requires an efficient data assimilation method to satisfy operational constraints of a typical tsunami forecasting system.

Here we develop a reduced rank approach applied to the standard tsunami data assimilation based on the optimal interpolation. The rank reduction scheme works by decomposing the background error covariance matrix using the Eigen decomposition. The assimilation is then performed using the reduced covariance matrix obtained from a reconstruction of leading eigenvalues with the corresponding eigenvectors. Note that the background error covariance matrix does not depend on measurements, and therefore can be computed and decomposed in advance and stored. Together with the observation error covariance matrix, the background error covariance matrix will characterize the spread of information through the resulted gain matrix. In the standard optimal interpolation, the gain matrix is dependent on observations-to-grids and observations-to-observations distance using a normalized Gaussian kernel and is assumed to be constant. This assumption is no longer valid for the moving observations, as the said distances vary over time. Therefore, the rank reduction approach is necessary to minimize the computational burden, because we have to compute the gain matrix at every assimilation cycle.

In this study, we demonstrate that the rank reduction scheme for the background error covariance matrix can lead to a substantial reduction of computing times without a significant loss of accuracy. Using 200 airplanes, the computing time and accuracy of the full rank matrix are 4.4 min and 98%, respectively. For the same number of airplanes, the reduced rank approach requires only 0.8 min of computing time with a slightly reduced accuracy of 94%.

Keywords: Tsunami forecasting, Airborne observations, Reduced rank data assimilation

Correction for applying equations on tsunami heights between offshore and coastal tsunami height

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The way of multiplying estimated tsunami amplification to tsunami height obtained at a corresponding offshore point is widely used for forecasting onshore tsunami heights. For examples, scenario-based tsunami databases are often prepared by outputs at a set of offshore sampling points, instead of performing costly tsunami calculations to obtain accurate onshore tsunami heights. In addition, this way is used for updating tsunami forecast based on real-time rapid evaluation of after detection of tsunamis at offshore observatories.
There are several equations on coastal tsunami heights between offshore and onshore points. Among previous equations, there are some practical ones for above-mentioned purposes: Green's law neglecting effects by width of waterway, empirical relations derived from observed tsunami heights by pairs of offshore and onshore observatories (e.g. Hayashi(2016, JpGU)), and experimental relations derived from calculated tsunami heights at off- and onshore sampling points.
However, sampling points are often affected by overlapping waves such as a direct wave and reflected one at a shore, and refraction of ray paths caused heterogeneous water depth. If an offshore tsunami height is sampled near a loop of overlapped wave, it tends to be larger than the spatial average near sampling points. And tsunami heights obtained near nodes tends to be smaller than spatial average of the area of concern.
From the theoretical consideration on superposition of a long wave and its imperfect reflected wave, we defined the corrected offshore maximum tsunami height as $H^*=((H_{max}{}^2+(h/g)*V_{max}{}^2)/2)^{1/2}$, where H_{max}, V_{max} , h, and g are the maximum tsunami height, maximum velocity, water depth at a sampling point, and gravity acceleration, respectively. In applying to equations on coastal tsunami heights between offshore and onshore points, using H^* instead of H_{max} can reduce influences by the location of a sampling point, because H^* has been defined so that it is equal to the root mean square of H_{max} through one wave length.

Keywords: Green's law, offshore tsunami, tsunami amplification factor, tsunami forecast

Tsunami source of the Mw7 2016 Fukushima Earthquake inferred from tide gauge and GPS buoy records

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On November 22, 2016, at 05:59 local time (UTC+9), an earthquake occurred off the coast of Fukushima Prefecture, Japan (epicenter 37.392°N, 141.403°E and M_w7.0 according to the National Research Institute for Earth Science and Disaster Resilience, NIED). The fault mechanism of this event was a normal faulting with shallow focal depth of 11 km [1]. The subsequent tsunami was recorded at several tide gauge station along the east coast of Japan. Them maximum tsunami wave amplitude was 1.4 m at Sendai port located more that away 100 km from the epicenter [2].
This study aims to investigate the tsunami source of the 2016 Fukushima Earthquake using inversion of recorded tsunami waveform signals. The Japan Meteorological Agency (JMA) provided the tide records from Ofunato, Ayukawa, Sendai port, Soma, and Onahama stations. In addition, we manually digitized the tsunami waveforms recorded at Miyagi Central and Sendai offshore GPS buoys that were published by the Nationwide Ocean Wave information Network for Ports and Harbors (NOPHAS). These waveform records usually include ocean tides, which we removed by applying a high-pass filter.
To estimate the extent of the tsunami source and the slip distribution, we divide the tsunami source into 8 subfaults that covers the aftershock area during one week after the mainshock. The subfault size is 10 km x 10 km with a top depth of 7 km. The focal mechanisms for all the subfaults were taken form the USGS solution of the mainshock.
The preliminary inversion result showed that the largest slip was located around the epicenter with a maximum value of 6.0 m. The estimated moment magnitude was calculated as M_w=7.1 (5.78E+19 N-m), which is slightly bigger than the estimated by NIED (M_w7.0, moment 3.47E+19 N-m). The estimated slip distribution suggested that the fault rupture started near the epicenter and propagated from south to north. This evidence is supported by the aftershock distribution.

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Keywords: 2016 Fukushima Earthquake, Tsunami Source, Tsunami Modeling

Artificial Underwater Object’ s Protection Properties Study using Numerical Modeling

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The important part of the tsunami research is focused on studying the considerable influence of natural geographical objects, like islands and near-coastal bathymetry, on tsunami waves. Complementing the physical modeling, we are designing a system for computer simulations at crucial coastal areas. The Bathymetry and Tsunami Source Data Editor is a basic system tool for editing bathymetric and tsunami source data by including/removing artificial seawalls and submerged barriers having different shapes and sizes. Accordingly, an artificial object is specified by special features/parameters including latitude and longitude of the object central point, height and width of the object as well as its rotation angle relative to north, and elevation/depth. The user can also work with composite objects creating them as a combination of atomic shapes. It makes possible forming complicated shapes as well as designing many of artificial objects/barriers. Current version of the Editor uses the NOAA Bathymetry data format. The editor also allows to specify an initial water surface elevation ‘specified parameters. It operates with ellipsoidal source shapes having the smooth water height distribution along the ellipse axis. This approach gives the possibility of the numerical simulation of the tsunami waves generated by combination of such sources with a specified location and an initial height.

Results of numerical experiments are presented for the gridded hybrid bathymetry for several coastal areas of Japan. Calculations were provided with a hybrid bathymetry formed by barriers with a parallelepiped shape using the grid-switching algorithm for the tsunami propagation computation from the initial source to the coastline. Accordingly, the 2148x1074 knots gridded bathymetry was created for the Oppa Bay and the neighboring harbors. The grid resolution is approximately 17 m. These data cover the geographical area from 141.41659 o *E* to 141.75 o *E* and from 38.5 o *N* up to 38.6666 o *N*.

The new method for numerical modeling of partial reflection of the long wave off the submerged vertical barrier was developed and tested. This method is based on the inner boundary condition, which takes into account the wave energy loss due to such kind of reflection. This system can help to issue recommendations for better protection of some crucial objects on a coastline. A number of numerical experiments with submerged barrier located at the entrance of the Oppa harbor were carried out. Barrier size, placement and depth were changed during experiments. All along the barrier its height is equal to the half of the local depth. After analyzing results, we can resume that wave heights in the northern part of the Oppa harbor within half a depth high barrier were reduced (suppressed) by 0,8 as compared to the wave height distribution without any barrier. In case of the barrier height be equal to 0,75 of a local depth the tsunami height reduction ratio decreases down to approximately 0,65. In order to protect some crucial coastal objects we can vary the position, width or the height of virtual submerged barriers choosing the desired mitigation effect.

Keywords: Tsunami Modeling, Hybrid Bathymetry, Coastline Crucial Objects Protection