Localization of the tsunami source area for effective warning with the given sensor position

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***Abstract*— In case of strong earthquake offshore Japan, tsunami wave approaches the nearest coast in approximately 20 minutes. So, time required for evaluation of tsunami danger is the key parameter for any warning system. The authors propose to determine the parameters of initial sea surface displacement at tsunami source (initial data to simulate numerically wave propagation) by only a part of the measured tsunami wave time series. The necessary part of wave profile is determined by tracking the relative changes of source parameters. Determination of the tsunami source parameters is conducted by the orthogonal decomposition of synthetic time series, calculated in advance. By a number of numerical experiments mutual position of the initial disturbance zone (as well as the earthquake epicenter) and the sensor are determined. It is expected that the proposed approach will save time (up to few minutes) for security and evacuation measures.**

***Keywords*—initial sea surface displacement, tsunami source, orthogonal decomposition**

I. INTRODUCTION

As is noticed by many researchers, timely warning about the real danger of a particular near field tsunami is among the core problems in natural hazards mitigation. There are a number of software tools to calculate tsunami wave propagation and inundation of a dry land. The MOST (Method of Splitting Tsunami) software package [1, 2] allows real time tsunami inundation zones forecasting by incorporating real-time data from tsunameter's network. The MOST software is used most often in the United States for developing inundation maps. TUNAMI N2 [3] was originally authored by Imamura in 1993 for the Tsunami Inundation Modeling Exchange (TIME) program [4]. It is a registered copyright of Professors Imamura, Yalciner and Synolakis and has been applied to several tsunami events [5,6]. Any of such tool requires an information about initial sea bed (or rather sea surface) displacement at tsunami source. In this paper we provide quantitative analysis of mutual position of the earthquake epicenter and sensor (tsunameter), when the source parameters could be sufficiently determined by a part of the wave profile until the first maximum.

For the source parameters determination we use the so-called orthogonalization algorithm which operates with the measured wave profile. Earlier the authors found numerically which part of the wave profile is enough for a robust determination of the Initial Sea Surface Displacement (ISSD) at tsunami source [7]. Several numerical tests have been conducted to find value of the Necessary Part of Wave Profile (NPWP), which may depend both on the wave shape and on a mutual localization of the source and sensor.

Having the calculated values of NPWP it is possible to reduce the operating time to determine ISSD. Namely, one does not need to wait while the whole wave train will pass over the sensor, bottom pressure recorder, e.g. Depending of the wave length, it is possible to save tens of seconds or even a few minutes. We determine numerically [7] such NPWP for the cases of special form (linear combination of the so-called unit sources) and mutual location of sensor and tsunami source. However, in practice the real tsunami source differs from the synthetic one we use in numerical experiments and its exact position is known only approximately. So, we do not know which NPWP it is possible to use. Also, while the wave is passing over the sensor, one does not know the length of the entire wave profile and, therefore, knowledge of NPWP in percentage of the full profile is also useless. To use the proposed approach in practice it is necessary to develop the robust stop criteria – the time instance in which one can start the algorithm to determine ISSD at tsunami source.

In the present paper we propose such a stop criteria and test numerically. That is the simple calculation algorithm is proposed to determine of a time moment during the wave passing over the sensor, when we are already able to found the correct parameters of tsunami source using only the currently available part of the wave profile.

Rest of the paper is arranged as follows. First, we briefly remind the orthogonal decomposition approach to find the tsunami source parameters by processing a single wave profile or even its part. Second, we describe digital bathymetry in use, introduce the proposed stop criteria, and design of numerical experiments. Then, the obtained results are given and discussed.

II. PROBLEM STATEMENT

A. Orthogonal Decomposition Approach

In this paper we treat the wave profiles, both measured and computed, as time series – time-dependent functions, given in a number of time moments. On the other hand, such functions could be regarded as the traces of functions, defined at segment $t_0<t<T$. Concerning these functions we refer to the Fourier decomposition theory, very well developed in mathematics.

Consider the problem of optimal approximation of a given function, *f(t),* by the linear combination of the finite subset of functions from the system $\{f_k(t)\}$. As is well known, in case the system is orthogonal and normalized, the coefficients of such optimal approximation are nothing but the Fourier coefficients of expansion of $f(t)$ in a series with respect to $\{f_k(t)\}$ (see, for example, [11]). Based on the statement above, the corresponding algorithm for orthogonalization was proposed and tested by the authors, see [8-10].

The so-called "Calculation in Advance" inversion strategy is used [12]. It has been proposed to cover the subduction zone (area of possible tsunami sources) with the system of 50x100 km rectangles (typical size of the seabed displacement zone for tsunamigenic 7.5 M earthquake). In case of Alaska-Aleutian subduction zone there are 50 of such Unit Sources (UnSs), composed in two alongshore lines. Then a typical (for this region) shape of the initial sea-bed displacement, normalized with an amplitude of 0.57 m, is used at each UnS as tsunami wave source, Fig. 1. Propagation of such wave from all the UnSs were numerically calculated (in advance) over the entire Pacific Ocean according to the linear approximation of shallow water system. As a result, a database of the calculated tsunami wave profiles, generated by the source of the same initial shape at all UnSs, is available for all grid points of the Pacific Ocean.

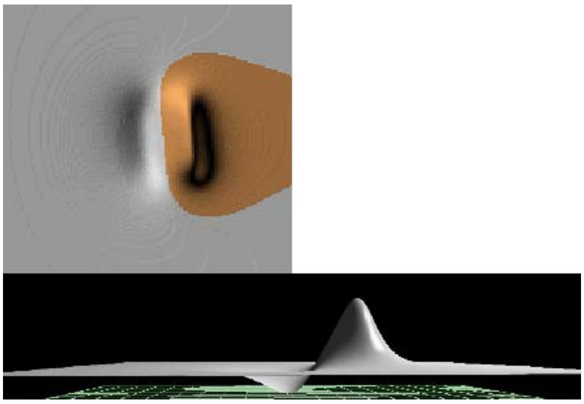

Fig. 1. 2D shaded and 3D images of the initial displacement at tsunami source used for numerical modeling.

Now, having the measured (real) wave profile at certain sensor location, one can approximate this curve with the help of linear combination of calculated wave profiles from a number of UnSs, picking up at the same point of sensor location. In the other words, the problem is to determine the amplification coefficients for the UnSs such that the corresponding linear combination of UnSs (say, a Combined Source – CS) provides a good approximation of the initial sea-bed displacement.

The following shape of CS (initial sea surface displacement at tsunami source), composed from the 4 UnSs, were used in numerical experiments, Fig. 2. Coefficients (to be reconstructed by the orthogonal decomposition algorithm) for the linear combination of 4 UnSs are as follows: 1.2, 1.3, 0.7, 0.8.

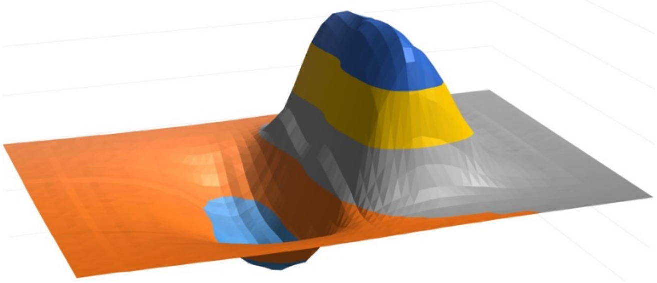

Fig. 2. Visualization of the ocean surface displacement in CS used for numerical experiments.

B. Digital Bathymetry

Numerical experiments were arranged at the gridded bathymetry around Kanto area (east of Honshu Island, Japan). The array of depths was created on a base of data distributed by the Japan Oceanographic Data Center (JODC) [13]. This bathymetry and the computational grid have the following characteristics: (1) Size is 2000x2500 knots; Mesh size: 0.003x0.002 arc degrees (approximately 223x273 m); (3) Array covers the area between 137° and 143° East longitude and between 32° and 37° North latitude; (4) Time step is equal to 0.5 sec.

C. Criteria description

To determine the moment of stopping the calculation during the registration process of the wave passing, we will iteratively calculate the value of the ISSD (that is, remind, the set of amplification coefficients multiplying the unit sources) with the same frequency (for example, once a second). As a criteria for stopping the calculation, it is proposed to use a function of the difference between the sets of coefficients obtained at adjacent iterations. In this case, the absolute value of the coefficients should not affect the process.

At each step (say, *n*-th iteration) the orthogonal decomposition algorithm [8] determines the set of coefficients, $C_n=\{c_{1,n};\ c_{2,n};\ \ldots\ c_{M,n}\}$, such that the corresponding linear combination of the UnSs is a current approximation of the tsunami source. Consider the following quantity to measure the "relative distance" between the coefficients, obtained at *n*-th and *(n-1)*-th iterations:

$$D_n = \max_i \left(\frac{|c_{i,n} - c_{i,n-1}|}{|c_{i,n}|} \right) \tag{1}$$

Let us choose the threshold value Δ and stop the calculations then at the *n*-th iteration the inequality holds:

$D_n \leq \Delta.$

D. Description of numerical experiments

The proposed algorithm operates with the measured wave profile. So, we simulate numerically the wave propagation from the several locations CS (given in Fig. 2) to the artificial sensor. Then, the NPWP can be calculated using the procedure, detailed description of which is given in [7,11]. Having the calculated wave profile at sensor position, we start to use the proposed algorithm to determine ISSD from the sequential parts of the wave profile with the time discretization equal to 1

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sec of the wave propagation. These are the iterations to calculate the values of coefficients $C_n=\{c_{1,n};\ c_{2,n};\ \ldots\ c_{4,n}\}$ and then to determine the value of our criteria D_n (1).

An area off the coast of central Honshu Island has been taken for computational experiments, where the Japan deep-sea trough directed along the coast transits into the Izu-Osagawara deep-water trench directed strictly south. Numerous sources of historical tsunami were located in the area. The tsunamigenic earthquake epicenters are drawn in Fig. 3 as circles of different colors. Ellipses of large size show the approximate position of tsunami sources according to expert’s estimation.

It is assumed that tsunami sources are located on the western slope of the deep-sea trough in the Izu-Bonin subduction zone.

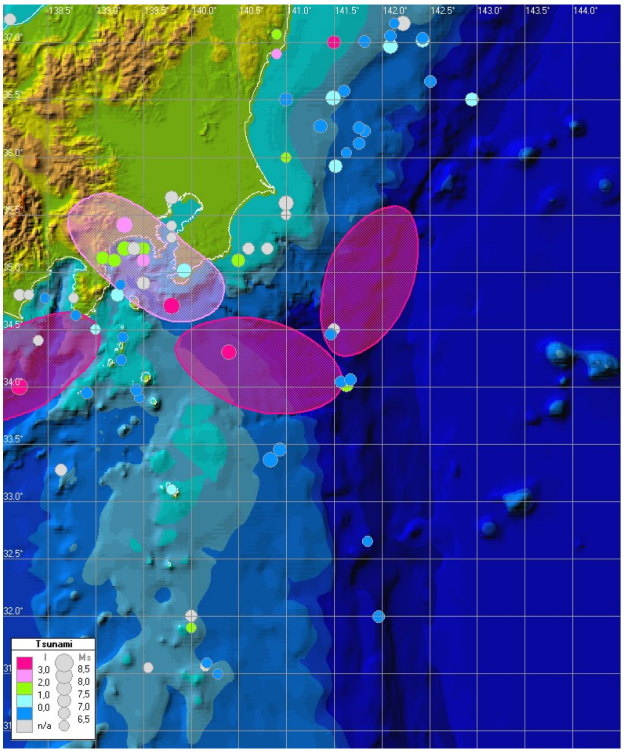

Fig. 3. Digital bathymetry of the water area under study. Small circles indicate epicenters of historical earthquakes, ellipses correspond to evaluation of tsunami sources.

The MOST software package [6] has been used for numerical modeling of tsunami generation and propagation in this area. Every composed source (CS) (the initial water surface displacement) used in numerical experiments is nothing but linear combinations of 4 so-called Unit Sources. Unit Source (UnS) is the surface (ocean bottom) displacement as the result of the typical for subduction zone submarine earthquake of Magnitude 7.5. The set of such UnSs is used by NOAA for approximation of the initial tsunami source. Positions of CSs along the Izu-Ogasawara deep-ocean trench are shown in Fig. 4.

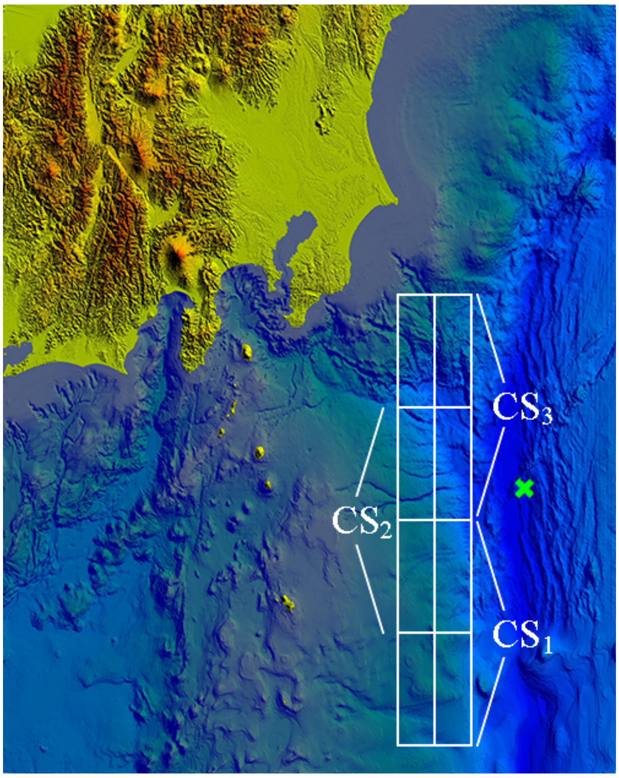

Fig. 4. Visualization of the digital bathymetry for the water area under study. White rectangles show locations of 3 unit sources covering the subduction area, artificial sensor position is indicated by green cross.

III. NUMERICAL RESULTS

First numerical test was arranged using a model depth profile, reflecting the main features of depth variation from the coast through subduction zone, see Fig. 5. This have been done for criteria preliminary verification.

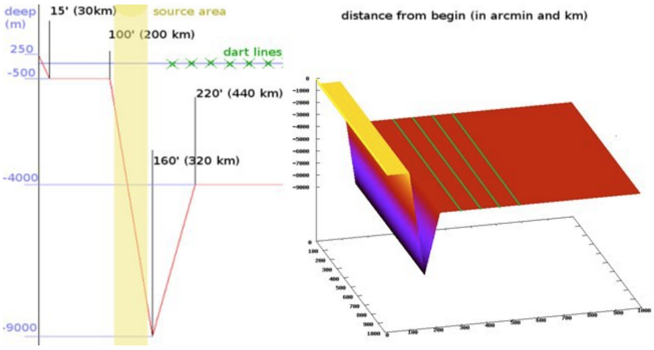

Fig. 5. Artificial depth profile and its 3D visualization.

The upper part of Fig. 6 shows the calculated wave profile. In the bottom part one can see the values of criteria D_n (1) obtained from the corresponding part of the wave profile. It is clear from Fig. 6, that after the first wave maxima values of criteria D_n (1) become negligible. It means that the values of coefficients $c_{i,n}$ does not change any more. In the other words, we have already determined the parameters of our CS by just the quarter of the entire wave period.

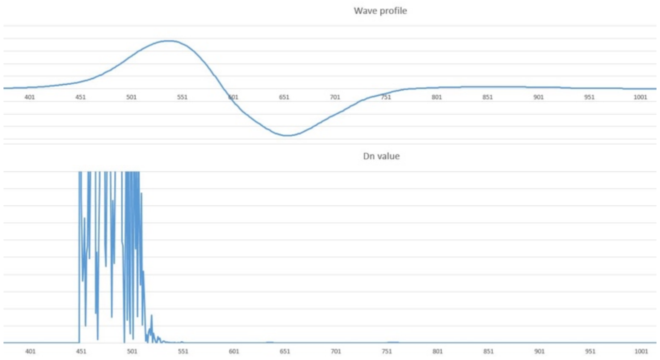

Fig. 6. Artificial bathymetry (Fig. 5). Calculated wave profile (above) and the values of the proposed stop criteria (1).

The, three different positions of CSs, indicated in Fig. 4 as CS_i, $i=1,2,3$, were used. For all the cases reconstruction of the source parameters were done by processing the wave profile at the same tsunameter (sensor), indicated in Fig. 4 by the green cross.

The obtained results, given in Fig.s 7-9, are qualitatively similar. The values of criteria (1) become negligible around the first wave maxima, slightly later for CS_1 (Fig. 7) and slightly earlier for CS_3 (Fig. 9).

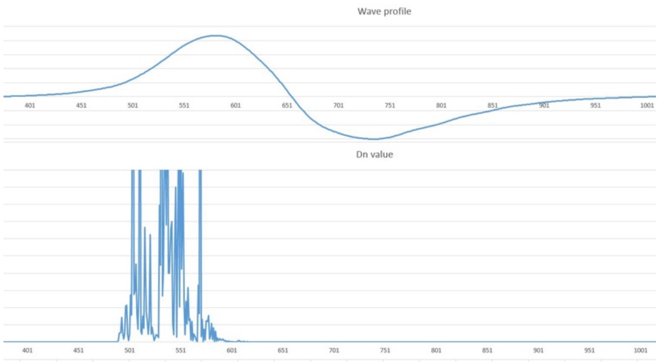

Fig. 7. Calculated wave profile from CS_1 (upper part) and values of criteria (1) for the same time moments, given in seconds.

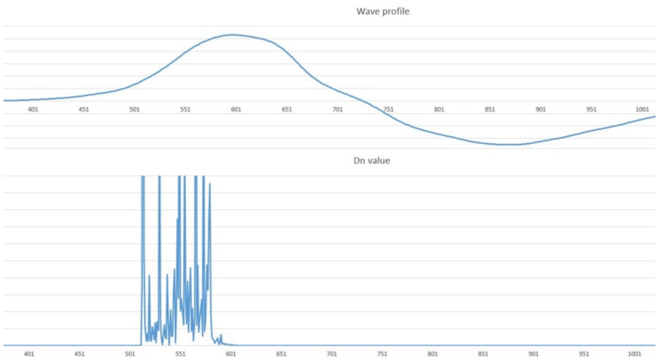

Fig. 8. Calculated wave profile from CS_2 (upper part) and values of criteria (1) for the same time moments, given in seconds.

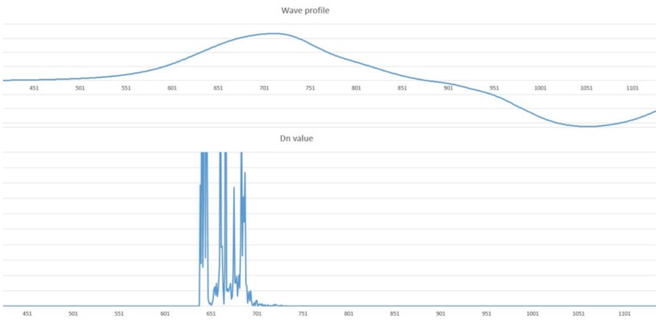

Fig. 9. Calculated wave profile from CS_3 (upper part) and values of criteria (1) for the same time moments, given in seconds.

All the Fig.s 7-9 are arranged in a similar way. In the upper part the calculated wave profile is displaced. The wave is generated by one of the sources CS_i and is "measured" by the same sensor (see Fig. 4). Horizontal scale shows time, in seconds, from the initial moment of wave generation. The lower part provide the values of criteria (1), calculated with the time step 1 sec.

IV. DISCUSSION

The performed series of calculations showed that with the considered (see Fig. 4) relative positions of the recorder (tsunameter) and composite sources, the criterion for trimming the "tail" of the ocean level record here proposed gives the correct form of the initial displacement (a set of four amplification coefficients in the linear combination of UnSs) gives the NPWP, which is only slightly longer then the distance until the first maximum. In contrast to the considered CSs composed of UnSs, in the case of a real source, the target value of the error Δ and the required record length is expected to be larger than in the numerical experiments performed. However, it could be compensated by an optimization of the sensor system. Justification of the proposed criteria for an arbitrary shape of tsunami source should be revealed by additional research.

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