"DETERMINATION OF ACCURATE TSUNAMI EARLY WARNING THROUGH ASSIMILATION METHOD BY USING LLW & DSP MODEL" – A CASE STUDY OF NANKAI & KII EARTHQUAKES (M=7.4).

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Abstract: We have an inclination to gift a technique of wave knowledge assimilation employing a linear dispersive model so as to source a correct wave early warning. To hurry up the assimilation method, we have a leaning to use the Green's function-based wave knowledge assimilation, during which the Green's functions are calculated before with linear dispersive wave propagation models. We have a propensity to demonstrate a legal action within the Nankai Trough off southwest Japan, with a source model just like the most shock of the 2004 off the Kii dry land earthquake (M=7.4) that generated tsunamis with dispersive characteristics. We have a tendency to show that assimilation of existing seabed gage knowledge will speedily forecast the wave point & also the most height of the primary wave peak on the coast of Shikoku & island. each the linear long-wave model & also the linear dispersive model will accurately forecast the wave height, however the linear dispersive model will predict the wave point a lot of accurately for the tested earthquake.

Index Terms - wave statement, knowledge assimilation, linear dispersive model, and linear long-wave model

I. Introduction

Wave knowledge assimilation could be a promising approach for wave statement. It predicts the wave undulation by absorbent offshore discovered knowledge into a numerical simulation. An optimum interpolation methodology (Kalnay 2003) is adopted in knowledge assimilation to cypher the wave field & to forecast the wave point & most amplitude on the coast. This methodology has been with success applied to discovered wave waveforms of the 2012 Haida Gwaii Earthquake (Gusman et.al. 2016) mistreatment bottom gage array knowledge within the Cascadian geologic process zone & a hypothetical wave within the Tohoku region (Maeda et.al. 2015) mistreatment artificial knowledge supported the Seafloor Observation Network for Earthquakes & Tsunamis (S-net). If the observations are placed in source regions, a brand new assimilation methodology developed by Tanioka (2018) is wont to solve the matter of non-hydrostatic effects & reproduce wave height distribution accurately. In previous applications of the wave knowledge assimilation methodology, the linear long-wave (LLW) wave propagation model was used (Maeda et.al. 2015; Gusman et.al. 2016; Wang et.al. 2017). The LLW model is predicated on the long-wave approximation (Satake 2015). After the horizontal scale of motion, or the wavelength of the wave is far larger than the water depth, the vertical acceleration of water is negligible compared with gravity. The horizontal motion of the water mass could be a smart approximation uniform from the seabed to the surface. Then, the part rate solely depends on the depth of the ocean. However, the long-wave approximation breaks down after the wavelength of the water height distribution isn't a lot of bigger than the water depth (Saito et.al. 2010). Therefore, a dispersive (DSP) wave model supported the Boussinesq equations ought to be wont to cypher wave waveforms with dispersive characteristics. The DSP wave model has been with success employed in forward wave simulation (Furumura & Saito 2009; Chou et.al. 2012) & wave undulation inversion analysis to estimate the initial water height distribution (Saito et.al. 2010, 2011). Until now, there has been no application of the DSP model in wave knowledge assimilation. as a result of the wave knowledge assimilation methodology planned by Maeda et.al. (2015) calculates the wave field at each time step, An application of the DSP model with this methodology would cause a particularly high procedure price & so fail to source timely wave early warnings. To hurry up the info assimilation method, Green's function based wave knowledge assimilation (GFTDA) was planned to scale back the procedure time for wave early warning (Wang et.al. 2017). Such nice earthquakes of recent years embrace the 1946 Tonankai (M=7.9) & 1944 Nankai (M=8.0) earthquakes. Additionally, an oversized (M =7.4) earthquake occurred off the Kii dry land among the subducting Philippine Sea Plate in 2004. The wave generated by the 2004 off the Kii dry land earthquake exhibited evident dispersion characteristics at offshore stations like MPG1 & MPG2 (Saito et.al. 2010). One in every of the vital options of wave generation is that the dispersive waves have a powerful directional dependence with reference to the fault strike (Saito et.al. 2010). Therefore, the dispersive wave developed expeditiously toward the direction of the on top of offshore stations. So as to watch the earthquakes & tsunamis within the Nankai region, Japan Agency for Marine-Earth Science & Technology (JAMSTEC) founded the Dense Ocean floor Network System for Earthquakes & Tsunamis (DONET). It an elaborate system of cables & numerous devices & consists of fifty two observation points in DONET1 &

DONET2 (Kaneda 2010). Such a dense observation network permits America to forecast a wave on the Nankai coast by the strategy of wave knowledge assimilation. During this paper, we have a tendency to propose to use GFTDA to forecast the wave supported the linear DSP model. We have a tendency to cypher artificial wave observations within the Nankai region mistreatment the source parameters of the 2004 earthquake & forecast the wave on the Coast of Shikoku Island. We have a tendency to conjointly compare the forecasted results of point & most height by assimilation mistreatment the LLW & DSP models.

II. Methodology

2.1. Linear DSP wave model

Numerical simulations of 2-D DSP wave equations are conducted on superior computers & private computers to simulate dispersive waves (Saito et.al. 2010). The equations are derived from the continuity equation & also the equation of motion for water waves. In coordinate, they're.

$$\frac{\partial h}{\partial t} = - \frac{\partial M}{\partial x} - \frac{\partial N}{\partial y},$$
$$\frac{\partial M}{\partial t} + gd\left(\frac{\partial h}{\partial x}\right) = \frac{1}{3} h^2 \frac{\partial^2}{\partial x\, \partial t}\left(\frac{\partial M}{\partial x} + \frac{\partial N}{\partial y}\right),$$
$$\frac{\partial N}{\partial t} + gd\left(\frac{\partial h}{\partial y}\right) = \frac{1}{3} h^2 \frac{\partial^2}{\partial y\, \partial t}\left(\frac{\partial M}{\partial x} + \frac{\partial N}{\partial y}\right),$$

wherever M & N is that the x & y elements of flux, or rate integrated on the vertical direction from the ocean bottom to the ocean surface, h is that the wave height at the ocean surface, d is that the water depth, & g is that the attractive force acceleration. The right-hand sides of the second & third equations are linear dispersive terms, which cause the dispersion result (Saito & Furumura 2009; Saito et.al. 2010; Maeda et.al. 2016). Within the LLW model, we have a tendency to neglect the dispersion terms, therefore the right-hand sides of those 2 equations become zero. Though the linear DSP model is a lot of difficult, the one-dimensionality still permits America to use GFTDA in our analysis.

2.2. Optimum interpolation methodology

We have a tendency to adopt the optimum interpolation methodology for wave knowledge assimilation, as within the previous studies of Kalnay (2003) & Maeda et.al. (2015). the main points of the strategy are delineating in these papers. During this methodology, we have a tendency to assume the full variety of procedure grid points is L, & also the total observation variety is m. The wave field at the ordinal time step is described as a (3L × 1) column vector.

$$x_n = (h(n\Delta t,x,y),M(n\Delta t,x,y),N(n\Delta t,x,y))^T.$$

The info assimilation method consists of 2 steps: a propagation step & an assimilation step. The propagation step is expressed as

$$x_n^f = Fx_{n-1}^a,$$

This suggests that at each step, the forecasted wave field x_n^f is simulated by finding the wave propagation equations mistreatment the assimilated wave field within the last time step x_{n-1}^a. Here, F refers to the wave propagation matrix (3L × 3L) that corresponds to the wave propagation model. The assimilation step is expressed as.

$$x_n^a = x_n^f + W(y_n - Hx_n^f),$$

Wherever the observation matrix H (m × 3L) could be a thin matrix that extracts the forecasted wave heights at the m points from the complete simulated wave field. The residual is calculated by scrutiny it with the important discovered wave height y_n. The load matrix W (3L × m) is a crucial dominant issue for the standard of wave assimilation (Maeda et.al. 2015). It's calculated by minimizing the variance matrix as an answer of the linear system.

$$W(R + HP^f + H^T) = P^f H^T,$$

Where $P^f = \varepsilon^f \varepsilon^{fT}$ & $R = \varepsilon^O \varepsilon^{OT}$ are the variance matrices of the forward numerical simulation & also the observations, severally. Here, ε^f represents the errors in numerical forecasts between 2 procedure grids & ε^O represents the data-based errors (Kalnay 2003; Maeda et.al. 2015). The burden matrix is then increased by the residual to bring the assimilated wave field nearer to the discovered wave field. By or else continuance the propagation & assimilation steps, the wave field is assimilated.

2.3. Green's function primarily based wave knowledge assimilation (GFTDA)

So as to hurry up the info assimilation method & use the linear DSP model, we have a tendency to use the GFTDA planned by Wang et.al. (2017). The Green's operate $G_{i,j}$ is outlined because the undulation at the j^{th} grid purpose ensuing from the propagation of the i^{th} station's assimilation response. We have a tendency to cypher the Green's functions between the mounted observation stations & Pols with each the LLW model & also the linear DSP model. The computation of Green's functions can be quite long; however this can be exhausted advance. Moreover, this cannot have an effect on the potency of the info assimilation method. Then, throughout the assimilation method, we will directly synthesize the forecasted wave waveforms by multiplying the residual by the corresponding Green's function

2.4. Green's function

The mensuration & topography dataset are derived from the overall measurement Chart of the Ocean (GEBCO). The grid knowledge discharged in 2014 (GEBCO 2014) with a grid spacing of 30arcs (Weather all et.al. 2015) are used. The finite distinction methodology (FDM) with the implicit theme is employed for numerical simulation. We have a tendency to use a grid spacing of 30arcs & a time step of 1s. The topographic point is 30°N–35°N, 130°E–140°E; therefore the total grid variety is 600 × 1200 = 720,000. The JAGURS wave code (Baba et.al. 2015) is employed to cypher the Green's functions between the observation points & conjointly n totally different observation points. We have a tendency to use fifteen observation stations, as delineate within the next section. Hence, the full variety of Green's functions is (9 + 15) ×15 = 360. The parameters for optimum interpolation are similar as those employed in a study by Maeda et.al. (2015).

III. Application & results

Observation stations & forecast points we have a tendency to use the planned methodology to simulated knowledge for the Nankai Trough. DONET has thirteen science nodes, & every node is connected with many bottom pressure observation points. So as to make an equally distributed observation network for knowledge assimilation, we have a tendency to take one purpose for every node aside from Node C, that we have a tendency to take 2 observation points. Additionally, we have a tendency to use the submarine cable stations PG1 & PG2, conjointly maintained by JAMSTEC. In total, fifteen observation stations are used for knowledge assimilation (Fig. 1). However, as a result of DONET1 was completed in 2011 & DONET2 started operation in 2015, we have a tendency to lack a true wave record for the 2004 off the Kii dry land earthquake. To assess the power of our knowledge assimilation approach, we have a tendency to use artificial wave knowledge from the 2004 earthquake source model. In real apply; wave knowledge can be obtained by removing the tide signal & high-frequency seismal signal from the observation record. The strategy of Tanioka (2018) may also be applied to the stations in or round the source space. The 9 points of interest (PoIs) are designated close to population centers on the Coast of Shikoku Island & Kyushu Island (Fig 1) that are below the potential threat of wave disaster. They're wont to compare simulated waveforms & waveforms expected by knowledge assimilation's.

3.1. Source models

In our numerical simulation, we have a tendency to use the most shock source model of the 2004 off the Kii dry land earthquake. The fault parameters are set in keeping with the unpublished results of Yamanaka (data offered at http:// wwweic.eri.u-tokyo .ac.jp/sanch u/SeismoNote/2004/ EIC15 three.html) by analysis of the telic seismal body waves. The geographic point is 137.142°E, 33.143°N, & also the depth is ten km. The fault direction is perpendicular to the trough axis with a strike of 135°. The dip angle is 40°, & also the rake angle is 123°.

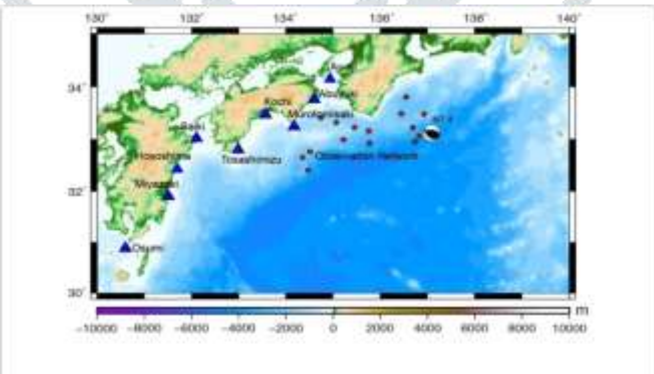

Fig. 1 The observation network for data assimilation & near-shore PoIs. The observation points contain 13 DONET stations, PG1 & PG2, which are marked with red circles. Nine PoIs near Shikoku Island & Kyushu Island are marked with blue triangles. The focal mechanism is plotted according to Yamanaka (2004)

The length & breadth of the oblong fault are 50 km & 30 km, severally. The fault slip is 6.4 meters that is per the magnitude of the most shock (M=7.4). We have a tendency to use Okada's model to calculate the initial ocean surface elevation in an elastic half-space (Okada 1985), which might be used because the initial condition for numerical simulation. Here, we have a tendency to solely contemplate the vertical displacement. If the wave source is on a steep sea floor & also the horizontal motion is far larger than the vertical motion, horizontal displacement can become vital for wave generation (Tanioka & Satake 1996)

3.2. Assimilation setting

We have a tendency to use the JAGURS wave code to calculate the wave propagation. We have a tendency to contemplate solely linear terms & assume reflective boundary at the outline. to form the wave propagation nearer to the important state of affairs, we have a tendency to apply the linear DSP model, just like that wont to cypher the dispersive Green's functions we have a tendency to set the earthquake origin time as t =0s. The observation stations of the assimilation network aren't aloof from the geographic point of the Kii dry land earthquakes. Hence, the wave arrives at the close stations of KMC09, KMC21, & KMD13 before long after the earthquake (Fig 2). We have a tendency to set that the info assimilation method to start at t =0s. The assimilation time window is outlined because the amount throughout that we have a tendency to use artificial observation for assimilation. Throughout the assimilation time window, the waveforms at PoIs are synthesized with the Green's functions & also the simulated observation. We have a tendency to apply the GFTDA algorithmic program with each the LLW & linear DSP models. The length of the time windows is about to vary from a pair of to 24min, with an interval of 2min. The calculation time for the info assimilation method is a smaller amount than 10s, nearly negligible on the EIC system at the Earthquake research Institute, the University of Tokyo.

3.3. Wave comparison

Figure 3 demonstrates the comparison between simulated waveforms & waveforms expected with an assimilation time window of 20min. The waveforms expected mistreatment each the LLW model & also the linear DSP model agree well with the simulated waveforms. This proves the validity of information assimilation supported the observation network of DONET, PG1 & PG2. For the statement the primary wave peak amplitude, the LLW model & also the linear DSP model have similar performances. Within the coastal PoIs of Murotomisaki, Awaji, & Abuyuki, the utmost amplitude forecasted by the linear DSP model tends to be nearer to the simulation than that forecasted by the LLW model, though the variations are quite little. The most distinction between the 2 models lies within the point. In nearly each PoIs, particularly Tosashimizu & Murotomisaki, the expected undulation mistreatment the linear DSP model features a lot of correct point of the primary wave peak.

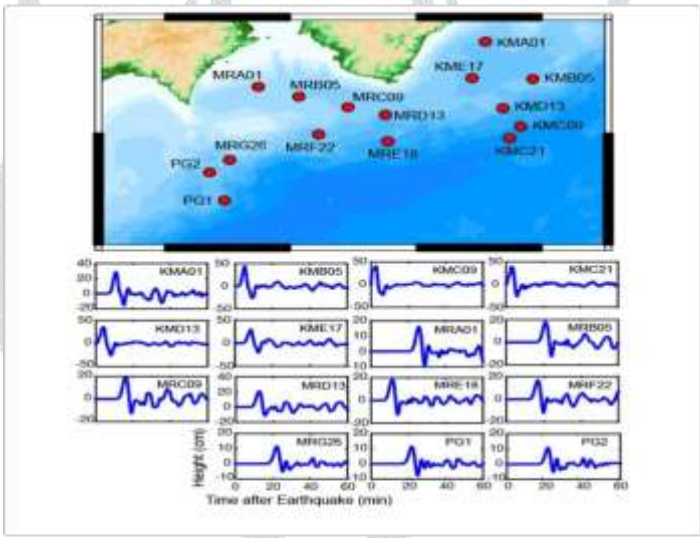

Fig. 2 Distribution of 15 observation points & the waveforms of synthetic tsunamis at each point. The tsunami arrives at the stations of KMC09, KMC21, & KMD13 soon after the earthquake. The data assimilation process begins at the time of earthquake

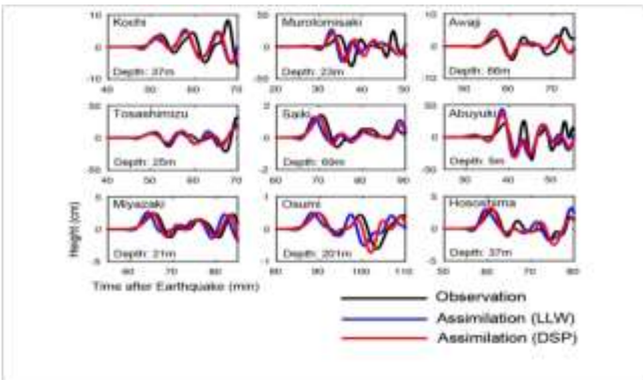

Fig. 3 Simulated waveforms (black lines) & waveforms forecasted by data assimilation at nine near-shore PoIs. The water depth of each PoIs is provided. The forecasted waveforms are calculated by GFTDA using the LLW model (blue lines) & the linear DSP model (red lines). The time window of data assimilation is 20 min

3.4. Quantitative analysis

To quantitatively assess the performance of 2 models in knowledge assimilation, we have a tendency to calculate the wave forecast accuracy (Gusman et.al. 2016) for various assimilation time windows. It's supported the mean quantitative relation (K) of the discovered (O_i) & simulated (S_i) most amplitude of the primary wave peak for the i^{th} station (Aida 1978),

$$\log(K) = \frac{1}{N}\sum_{i=0}^{n}\log(O_i/S_i),$$

$$\text{Accuracy (\%)} = \frac{1}{k}\times 100\,\%(K \geq 1) \text{ or } K \times 100\,\%(K < 1),$$

The accuracy for numerous assimilation time windows is shown in Fig 4a. The shapes of the statement accuracy curves for each the LLW model & also the linear DSP model are quite similar. Within the starting, the time window is merely 2min, & shortly after the earthquake, the accuracy of each model is incredibly low. As a result of the primary wave peak has not knowledgeable any observation stations of our network, the info length used for assimilation is simply too short to source correct forecasts. Then, at 4min, there's a pointy increase within the accuracy for each models, with the forecast accuracy surpassing 85% (Fig 4). After that, the forecast accuracy varies slightly however exhibits a rising trend generally. Though there's not an oversized distinction in forecast accuracy between the LLW model & also the linear DSP model, the forecast accuracy of the LLW model is slightly higher. After the time window of 20min the primary wave peak has already passed all of the observation stations. The forecast accuracy becomes saturated & stops increasing. Here, the values of statement accuracy calculated by each models also are similar, however the linear DSP model performs slightly higher. The distinction in point of the primary wave peak between the 2 models is a lot of evident. To quantitatively analyze the accuracy of the forecasted point, we have a tendency to use the strategy of scheming pause planned by Tsushima et.al. (2012). the pause of the i^{th} coastal station is outlined as $\Delta T_i = t_i^s - t_i^o$,

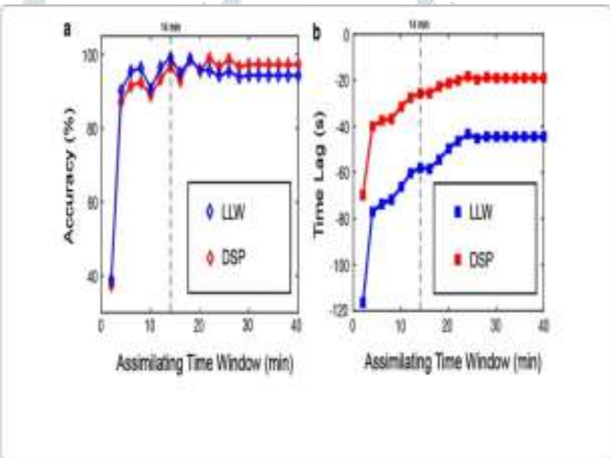

Fig. 4 Forecast accuracy & time lag b of the two models for various assimilation time windows. The forecast accuracy is used to evaluate the forecasted maximum amplitude of the first tsunami peak (Aida 1978). The time lag is used to examine the forecasted arrival time (Tsushima et al. 2012)

Wherever t_i^o is that the point of initial wave peak discovered at the station & t_i^s is that the point forecasted by knowledge assimilation? A negative pause indicates that the forecasted point is prior the observation. A little definite quantity of your time lag indicates correct statement of the point. We have a tendency to calculate the pause in the slightest degree PoIs & calculate the common price. Fig 4b clearly shows that the time lags calculated by the 2 models are clearly negative, which suggests that each the LLW model & also the linear DSP model forecast the wave arrival times prior discovered. Moreover, because the assimilation time window will increase, the pause becomes nearer to zero. The tendency of the variation of your time lag is that the same as that of statement accuracy. As a lot of discovered knowledge is employed in knowledge assimilation, absolutely the price of your time lag decreases quickly from the top of the two min time window to the four min time window. Then, it decreases slowly. After the time window of 20min, the variation finally becomes terribly little. It's vital to notice that the distinction between the LLW model & also the linear DSP model is noticeable within the figure. The linear DSP model results in a far smaller pause than the LLW model, indicating that the linear DSP model performs higher in statement wave point.

IV. Discussion & conclusion

In our application, we have a tendency to use 2 linear models, the LLW model & also the linear DSP model. The accuracy of the forecasted most amplitude & point depends on the length of the assimilation time window. It's vital to settle on a correct assimilation time window for each model. In our application to the 2004 off the Kii dry land earthquake, a time window of 14min could be a sensible alternative so as to provide a reliable & early wave forecast. At now, the forecast accuracy of each the LLW & linear DSP models exceeds 96%, & also the average pause of wave point is − 58.1s (LLW) & − 25.7s (DSP). Figure 2 shows that the primary wave peak reaches the closest dish (Murotomisaki) around 35min after the earthquake & reaches alternative PoIs over 40min after the earthquake. Mistreatment the wave height & point of PoIs as input parameters, the bound wave height or sea forecasts are doable by applying the wave run-up models (Liu et.al. 2009). As a result of the calculation time within the GFTDA method is negligible; the wave forecast is created 14min after the earthquake supported the information assimilation. On the opposite hand, it's not sensible to use a time window of over 20min. though the statement accuracy becomes even higher & also the pause becomes even smaller, the wave forecast might not be helpful if it's created shortly before the wave arrival. The results conjointly counsel that the wave propagation model might have an effect on the accuracy of wave statement by knowledge assimilation. For the utmost amplitude of the primary wave peak, 2 models perform equally. However, with reference to the point, the linear DSP model features a higher accuracy than the LLW model. The common pause calculated by the linear DSP model is plainly smaller. For individual stations, if the station is found close to Shikoku Island, that's near the observation network, the distinction in lag time isn't thus massive. However, if the station is found close to island that is close to 200km from the observation network, the distinction in lag time becomes noticeable. This can be caused by the limitation of the long-wave approximation. The constraints of the long-wave approximation might not be thus evident after the wavelength of wave is sufficiently long. However, for the Kii dry land earthquake thought-about during this paper, the big dip leads to short-wavelength elements of the wave, & such an approximation would overestimate the speed of wave propagation (Saito et.al. 2010). Thus, the point forecasted by the LLW model becomes quite prior the DSP model results, particularly for PoIs aloof from the observation network, as a result of an extended propagation distance can increase such errors. Compared with the previous knowledge assimilation methodology, the straightforward assimilation method of GFTDA permits America to use a lot of difficult models, other than the LLW model. As long as one-dimensionality is assumed, the GFTDA is tested to be mathematically admire the previous knowledge assimilation approach (Wang et.al. 2017). For potential tsunamis with a lot of dispersion characteristics, or tsunamis that propagate over a extended distance from the observation network, the distinction between dispersive & non-dispersive models is a lot of vital. Therefore, the linear DSP model would be ready to create a lot of enhancements in statement the point accurately & to mitigate the disasters of potential harmful tsunamis generated by outer-rise earthquakes.

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