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DETERMINISTIC ANALYSIS OF THE TSUNAMI HAZARD IN CHINA

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ABSTRACT

Seismic hazard analysis has reached a level of maturity in China. Such work has contributed significantly towards improvements of the national infrastructure in effecting programs of disaster preparedness and mitigation. However, the work on tsunami risk assessment is still in a preliminary stage. The present study proposes a deterministic method of tsunami hazard analysis based on coastal bathymetry and morphology, as well as on mathematical simulations, and evaluates the potential tsunami risk to China's coastal areas.

KEYWORDS: Earthquake; Tsunami; Hazard; Deterministic analysis method

1. INTRODUCTION

Presently, Probabilistic Seismic Hazard Analysis (PSHA) has been widely applied to seismic zonation and the evaluation of ground motions at specific sites. PDHA is necessary for normal seismic design of structures. The determination of ground motions is a key design factor for special construction projects, such as construction of nuclear power plants (Hu, 1988). Seismic hazard analysis has reached a level of maturity in China. It has provided needed technical support for urban planning and major engineering projects by giving technical references that can be used for vital policy decisions of the government in the establishment of the national system on disaster prevention and mitigation. However, no similar attention has been given to the analysis of the tsunami hazard. The importance of having such analysis performed, became evident after the catastrophic tsunami of December 26, 2004 in Sumatra and the Indian Ocean. The methodology on how to carry out work on tsunami hazard analysis in China is still a challenge. To help solve this problem, the present study provides and discusses a deterministic method of tsunami hazard analysis. First it delineates potential tsunami source regions that could affect China's coastline, based on historical earthquake and tsunami data, and sea bathymetry. Secondly, potential tsunami source regions are identified. Thirdly, based on numerical modeling, each tsunami source is evaluated and the potential coastal run-up heights are estimated. Finally, these wave heights are normalized and the extent of the tsunami hazard in China coastal areas is evaluated. Such methodology has been used in evaluating the tsunami hazard in the east coasts of Korea and Russia (Kurkin et al., 2004; Ho and Sung, 2001).

Research on tsunami hazard analysis begun in Japan and the United States of America in the 1980s. Japan's coast was divided into eight potential tsunami source regions (Rikitake and Aida, 1988). Based on the characteristic earthquake model, the annual exceeding probability of Japan assaulted by near-field tsunami was given. Annaka and Satake et al. (2007) used the logic-tree method to obtain the tsunami hazard curves (relationship between wave heights and annual exceeding probabilities) of Japan coast. Other scholars used a deterministic method based on numerical simulation, by assessing the hazards in coastal areas of Korea and Russia resulting from tsunamis generated along Japan's west coast (Kurkin and Pelinovskii et al., 2004; Ho and Sung, 2001). The tsunami hazards in the eastern Mediterranean region were evaluated through the use of historical tsunami database and by numerical simulation (Salamon and Rockwell et al., 2007). The probability of tsunami generation by landslides along southern California was evaluated by means of the Monte Carlo method (Watts, 2004). Also, GIS technology has being used in analyzing the tsunami hazard and in compiling tsunami hazard maps and flood inundation maps (Florence et al., 2005; Priest, 1995; Priest et al., 1997). Geist and Parsons (2006) applied the method of probabilistic tsunami hazard analysis in their work. Based on tsunami numerical simulation, the use of historical tsunami data and the Monte Carlo method separately, the tsunami hazard curves for Acapulco in Mexico and Cascadia on the U.S. West coast were evaluated. The studies pointed out two issues on the tsunami hazard analysis. The first issue is the difficulty on assigning specific earthquake probabilities to circum-Pacific subduction zones, and second issue is the limited amplitude range of tsunami measurements.

Research on tsunami hazard analysis in China begun in 1988, while Zhou Qinghai published a paper named “Tsunami Risk Analysis for China” in *Natural Hazards* (Zhou and Adams, 1988). In this paper, China tsunami historical database was used. By combining the geology and earthquake characteristics of China's continental shelf, the relative ratio of tsunami hazard in China coastal areas was evaluated. It suggested that the tsunami hazard ratio of Eastern Taiwan Coast, Continental Shelf and Bo Hai Bay is 16:4:1 and a zoning map of the tsunami hazard along China’s coast was provided. Although the results were ambiguous, it was an important first step for tsunami research in China. After that there was a period of inactivity. However, after the 2004 Sumatra tsunami, the interest was revived. Limited to utilizing historical data, geology and geophysical characteristics of the continental shelf, the vulnerability of China coast to tsunamis was assessed (Wen and Ren, 2007; Yang, 2005; Yang and Wei, 2005). In 2007, Liu Yingchun, of the South China Sea Institute of Oceanology, (SCSIO, Chinese Academy of Sciences), used numerical modeling to analyze the probabilistic tsunami hazard for China’s southeast coastal areas (Liu and Santos et al., 2007). Five major coastal cities of southeast China were specifically identified (Shantou, Xiamen, Xianggang, Aomen, and Tainan) as having probabilities of being struck by tsunami with amplitudes of 1-2m and above 2m separately. These results were more substantive and contributed to enhancing China tsunami research. In addition, Ren Yefei and Wen Ruizhi, scholars of IEM (Institute of Engineering Mechanics, China Earthquake Administration), following similarities with the seismic hazard analysis method, guidelines were provided (Ren, 2007) for a probabilistic tsunami hazard analysis, by suggesting the methodology on which this present work is based. Thus, this work can provide a theoretical basis and a technical reference for doing further research on tsunami hazard analysis in China.

2. DELINEATING POTENTIAL TSUNAMI SOURCE REGIONS

Tsunamis in the region are mostly generated by earthquakes with magnitudes above 6.5. There is no established recurrence frequency for tsunamigenic earthquakes in the Bohai and the Yellow Seas (Gao and Min, 1994), as there are in the East and South China Seas (Yang and Wei, 2005; Wei and Chen, 2005). In delineating potential tsunami sources that can affect China’s coasts, regions of infrequent earthquakes are not included. Potential tsunami sources are selected along the Korean peninsula, the Sea of Japan, Ryukyu Islands, Taiwan and the Philippines. Plate tectonics, local geology, bathymetry, paleoseismological evidence, as well as historical earthquake and tsunami data, were the main parameters in delineating potentially tsunamigenic regions. Another criterion for selecting each source region was the depth of the sea, which must be deep enough to satisfy the condition for tsunami generation, generally believed to be more than 200m.

The historical database documents a total of 1470 significant earthquake events (listed by the Novosibirsk Tsunami Laboratory, in Russia), from 2150 B.C to 2002 A.D., in the area between 0°N to 45°N and 105°E to 150°E. (Figure 1). The historical database of the National Geophysical Data Center (U.S. NGDC), documents that 471 tsunami events occurred from 173 A.D. to 2007 A.D, between 0°N to 45°N and 105°E to 150°E. (Figure 2). By using global bathymetric data supplied by NGDC, the isobaths of China coast are drawn. The 200 m sea depth was selected as one of necessary conditions for tsunami generation, as shown in Figure 3. Based on such data, China potential tsunami source regions were reasonably delineated, as shown in Figure 4.

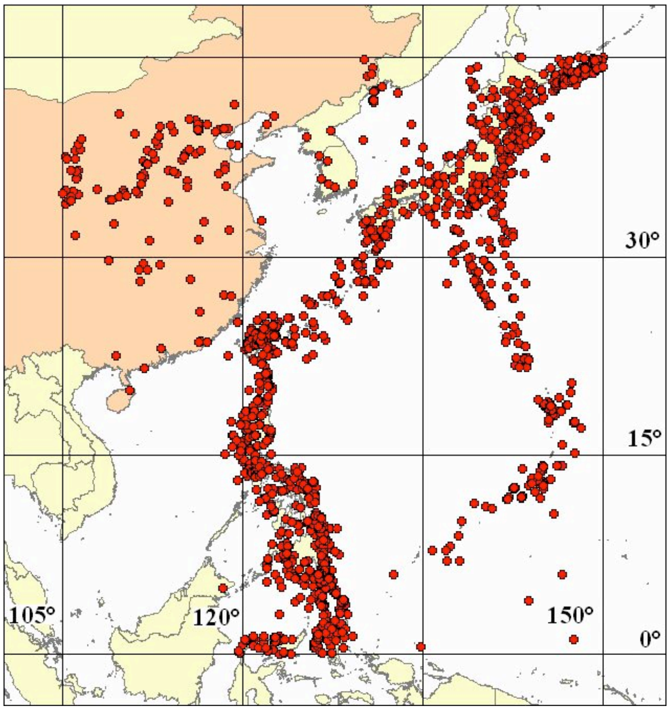

Fig. 1. Regional historical earthquakes

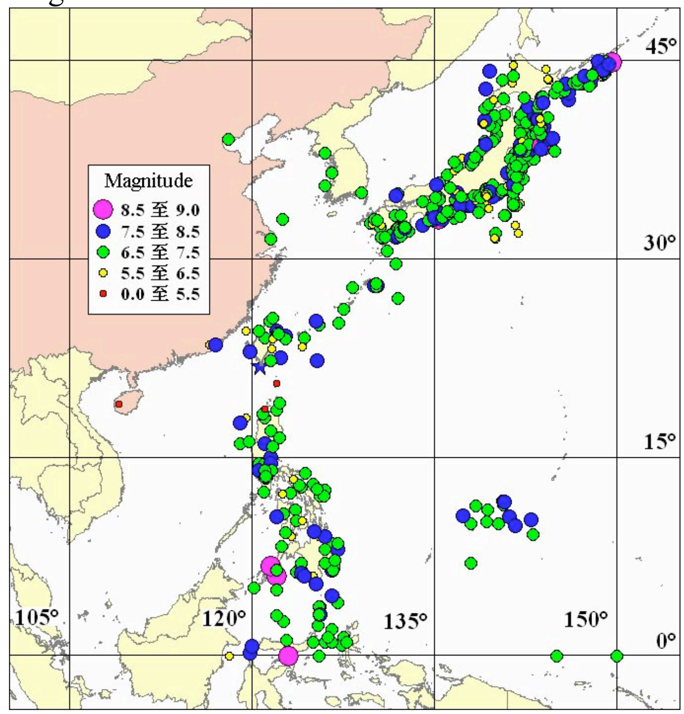

Fig. 2. Regional historical tsunami generation

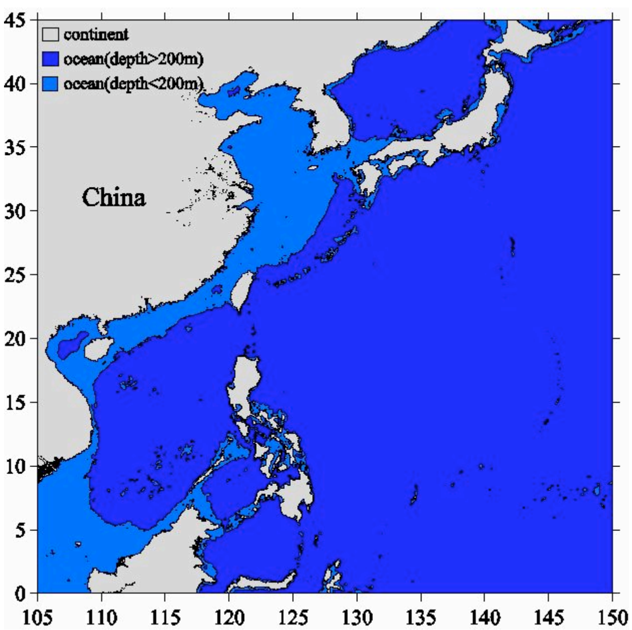

Fig. 3. Bathymetry of China coast (200m depth

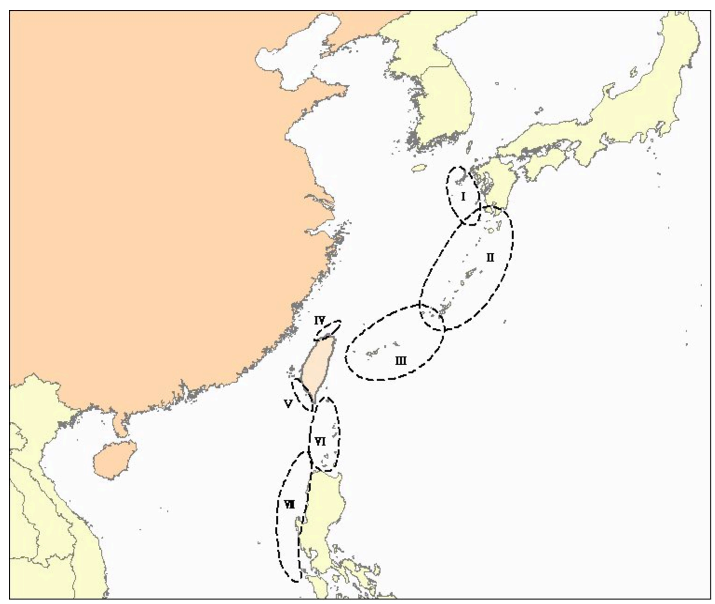

Fig. 4. Source regions of tsunamis that could potentially impact China's coasts.

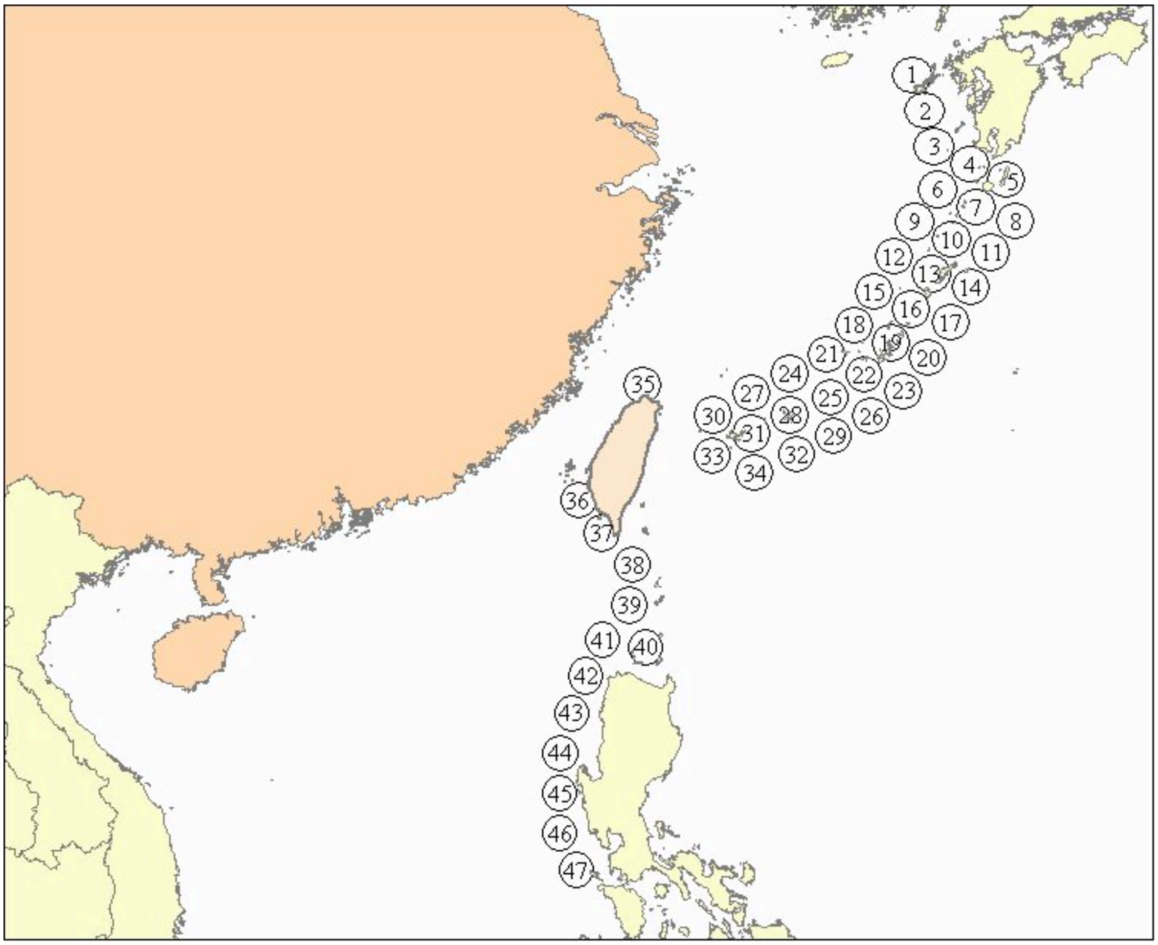

Fig. 5. Distribution of potential tsunami sources that can potentially impact China's coastlines.

3. DETERMINING POTENTIAL TSUNAMI SOURCES

For modeling purposes, 47 potential tsunami sources with 50km radius were selected, as shown in Figure 5 to apply initial water displacements. Each tsunami source was depicted as a cone-shaped area with maximum height of 5m, as shown in figure 6. It should be noted that the initial displacement field for each source in the numerical tsunami simulation was estimated on the basis of fault dislocation in elastic half-space. However, point sources were depicted due to the lack of fundamental information on active faults. Tsunami wave heights were normalized first, as not to result in erroneous assessment results that would unduly elevate the tsunami hazard along China's coasts.

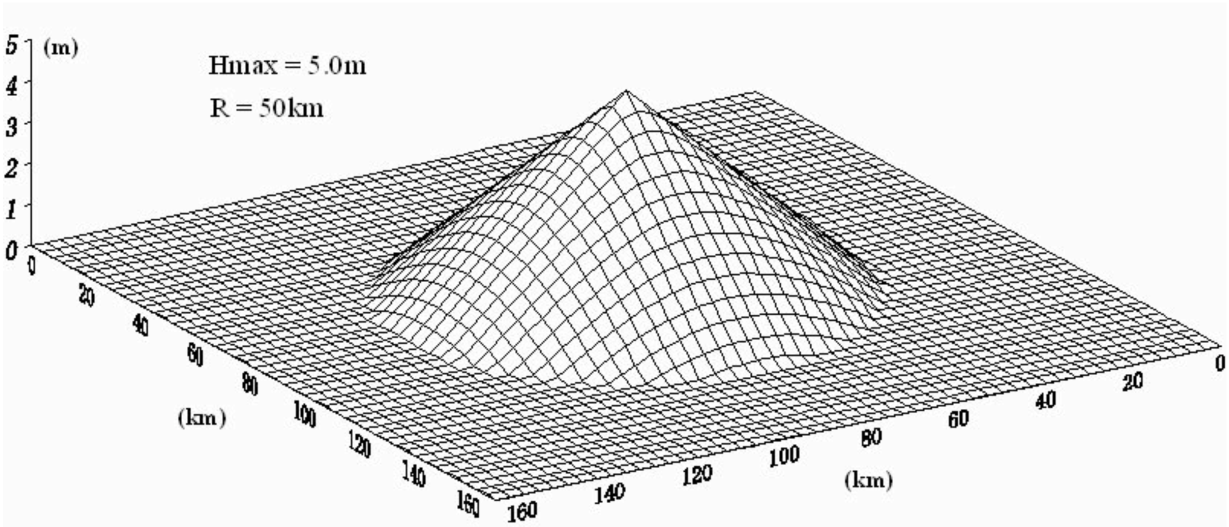

Fig. 6. The postulated shape of each potential tsunami source

4. MATHEMATIC CALCULATION

After the initial displacement fields were determined, waves were propagated from each tsunami source using a near-field tsunami numerical mode (Wai and Chau et al., 2005; Ren, 2007; Wen and Ren et al., 2007). The governing, nonlinear, shallow water equations were solved by means of finite difference methods.

$$\frac{\partial \eta}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0 \tag{4.1}$$

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{D}\right)+\frac{\partial}{\partial y}\left(\frac{MN}{D}\right)+gD\frac{\partial \eta}{\partial x}+\tau_x D=0 \tag{4.2}$$

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{MN}{D}\right)+\frac{\partial}{\partial y}\left(\frac{N^2}{D}\right)+gD\frac{\partial \eta}{\partial y}+\tau_y D=0 \tag{4.3}$$

Where, η is the vertical displacement of the water surface; $D = h+\eta$ is the total water depth; g is the gravity acceleration constant; $M = u\ (h+\eta)$ and $N = v\ (h+\eta)$ are the x and y-directional discharges, where u and v are the x and y-directional averaged particle velocities; x τ and y τ are the x and y-direction values of bottom frictions, which can be expressed by:

$$\tau_x=\frac{gn^2}{D^{10/3}}M\sqrt{M^2+N^2}\ ,\quad \tau_y=\frac{gn^2}{D^{10/3}}N\sqrt{M^2+N^2} \tag{4.4}$$

Figure 7 below shows the tsunami heights along China's coasts resulting from the mathematical simulation of waves originating from the No.18 tsunami source. A maximum height of 2.67m occurred near the area with latitude 30°N., indicating that this was the region of the highest tsunami risk. Perhaps the high run-up value results from the short distance to the No.18 tsunami source.

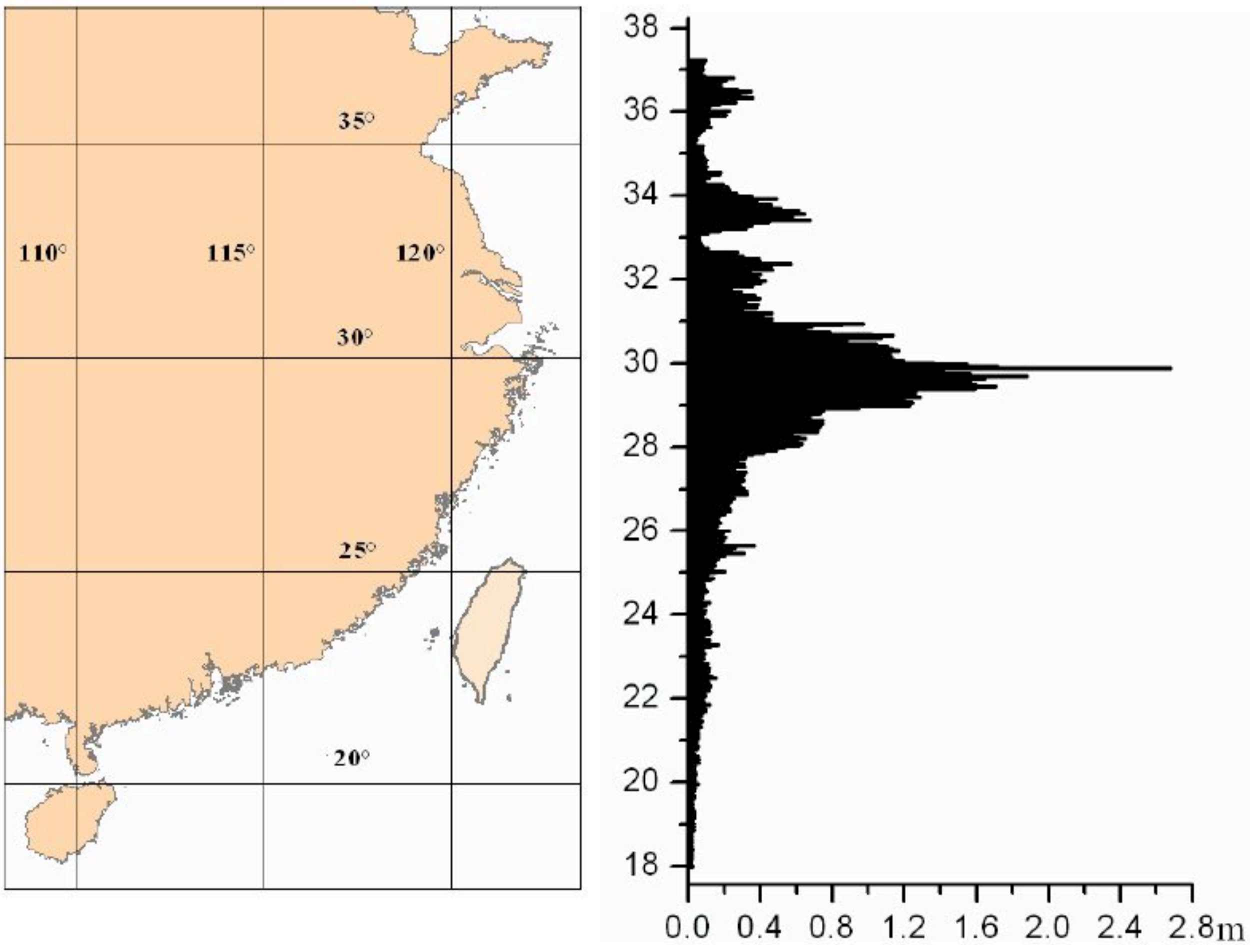

Fig. 7. Tsunami run-up heights along China coast from the No.18 tsunami source.

However, for a complete tsunami risk evaluation along China's coastlines, all the results from all potential sources must be comprehensively analyzed and integrated. Figure 8 summarizes the tsunami run-up heights from the mathematical modeling of all 47 potential sources.

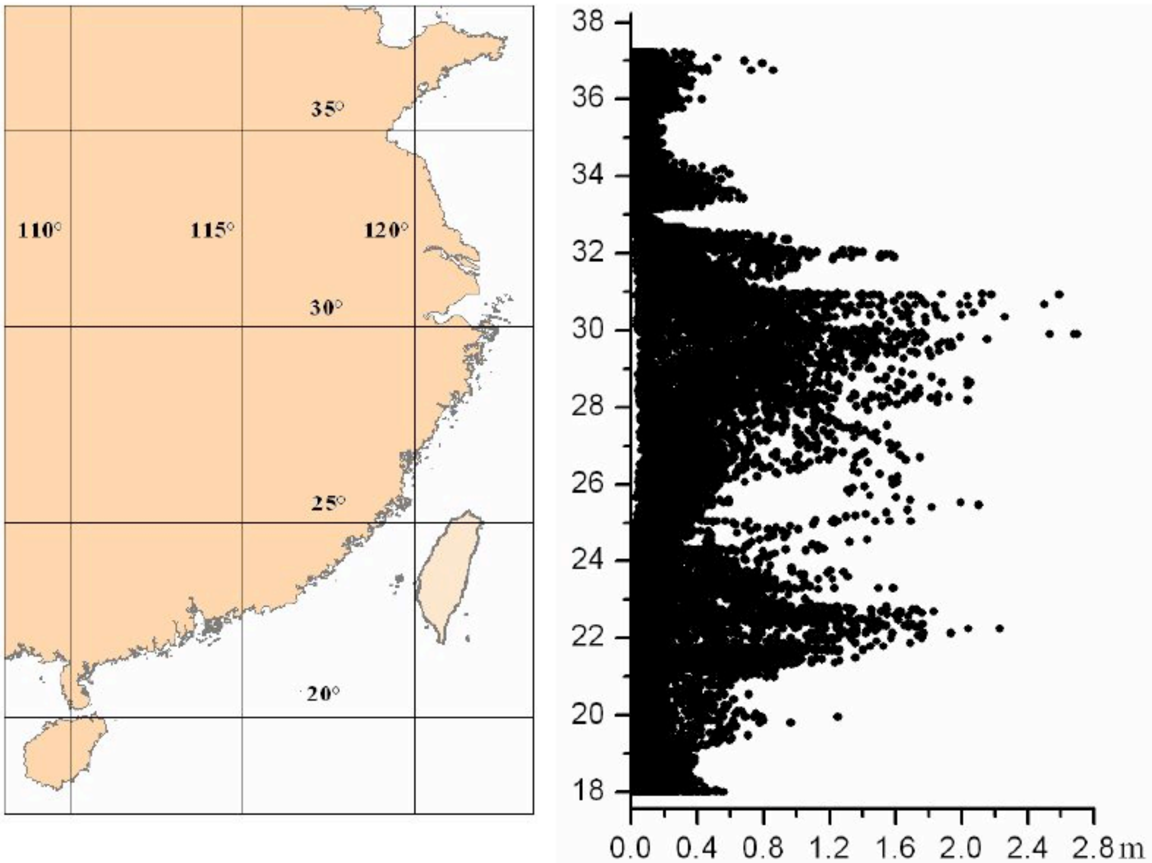

Fig. 8. Tsunami run-up heights along China's coast line from all 47 potential tsunami sources.

5. NORMALIZING TSUNAMI WAVE HEIGHTS

All tsunami wave heights were normalized by selecting from each group the maximum run-up heights. As a result, a series of ratios, which are less than 1, were obtained. Figure 9 shows the values resulting by the process of normalizing all tsunami run-up heights.

6. CONCLUSIONS

The tsunami run-up heights along China's coastlines will depend on earthquake parameters such as magnitude and type of faulting, as well as on the source's distance from the coast and coastal bathymetry and morphology, among other factors. In the present study, conical tsunami sources were used in order to eliminate the influence of some of the unknown earthquake source parameters such as magnitude and directionality due to faulting and angle of strike. All wave heights were normalized in order to eliminate the effects of that distance may have on tsunami propagation. As a result, the differences in the degree of tsunami hazard vulnerability along China's coastlines were determined primarily on the basis of coastal bathymetry and configuration. On the basis of such probabilistic tsunami hazard analysis as illustrated by Figure 9, it is concluded that:

1. The degree of tsunami hazard in Bohai Bay is considerably low, since it is a semi-enclosed basin that restricts the entry of tsunami energy from distant sources. Additionally, Bohai Bay does not have known sources that can generate tsunamis.

(2) From the Yellow Sea to Hainan Island and in three areas near the deltas of the Yangtze, Qiantang and Pearl river, the potential tsunami hazard is higher than in other coastal areas. On the basis of the proximity of earthquake sources, coastal areas along the East China Sea are more vulnerable, while coastal areas along the South China Sea are less vulnerable. The lowest tsunami hazard vulnerability is assigned to coastal areas fronting the Yellow Sea.

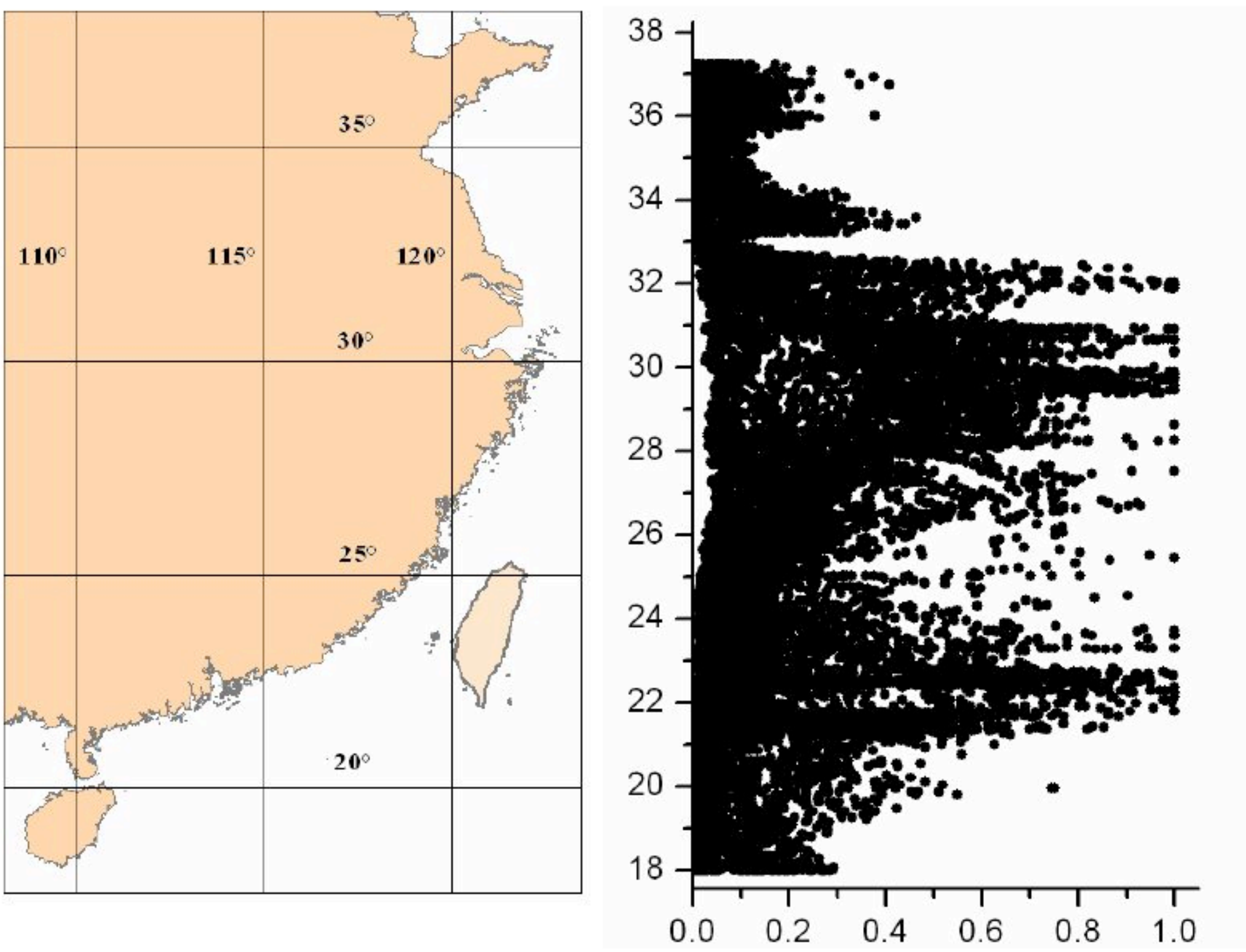

Figure 9. Values resulting from normalizing all tsunami run-up height.

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REFERENCES

Annaka, T., Satake, K., Sakakiyama, T. et al. (2007). Logic-tree Approach for Probabilistic Tsunami Hazard Analysis and its Applications to the Japanese Coasts. *Pure Appl. Geophys*., 164, 577-592.

Florence, L.W., Eric, L.G. and Angie, J.V. (2005). Probabilistic Tsunami Hazard Maps and GIS. 2005 ESRI International User Conference, San Diego, California, proceedings, 11pp.

Gao, H. and Min, Q. (1994). Analysis on the possibility of tsunami generation in Bo Hai. *Marine Forecasts*, 11:1, 63-66 (in Chinese).

Geist, E.L. and Parsons, T. (2006). Probabilistic Analysis of Tsunami Hazards. *Natural Hazards*, 37:3, 277-314.

Ho, C. and Sung, J.H. (2001). Simulation of prognostic on the Korean coast. *Geophys. Res. Lett.*, 28:10, 2013-2016.

Hu, Y. (1988). Earthquake Engineering, Seismological Publishing House, China.

Kurkin, A.A., Pelinovskii, E.N., Choi, B.H. and Lee, J.S. (2004). A Comparative Estimation of the Tsunami Hazard for the Russian Coast of the Sea of Japan Based on Numerical Simulation. *Oceanology*, 44:2, 163-172.

Liu, Y., Santos, A., Wang, S.M., Shi, Y., Liu, H., Yuen, D.A. (2007). Tsunami hazards along Chinese coast from potential earthquakes in South China Sea. *Phys. Earth Planet. Int*., 163, 233-244.

Priest, G.R. (1995). Explanation of mapping methods and use of the tsunami hazard maps of the Oregon coast. Oregon Department of Geology and Mineral Industries Open-file Report O-95-67.

Priest, G.R., Myers III, E.P., Baptista, A.M., Fleuck, P., Wang, K., Kamphaus, R.A. and Peterson C.D. (1997). Cascadia Subduction Zone, Tsunamis-Hazard mapping at Yaquina Bay, Oregon. Oregon Department of Geology and Mineral Industries Open-File Report O-97-34, 144pp.

Ren, Y. (2007). Study on China Earthquake Tsunami Hazard Analysis Based on Numerical Simulation: [Master's Degree Thesis]. Harbin: Institute of Engineering Mechanics, China Earthquake Administration, 135pp (in Chinese).

Rikitake, T. and Aida, I. (1988). Tsunami hazard probability in Japan. *Bull. Seismol. Soc. Am.*, 78:3, 1268-1278.

Salamon, A., Rockwell, T., Ward, S.N., Guidoboni, E. and Comastri, A. (2007). Tsunami Hazard Evaluation of the Eastern Mediterranean - Historical Analysis and Selected Modeling. *Bull. Seismol. Soc. Am.*, 97:3, 705-724.

Wai, O.W.H., Chau, K.T. et al. (2005). A preliminary numerical study of tsunami generated wave patterns in Hong Kong waters. 2005 Annual Meeting, Asian-Pacific Network of Centers for Earthquake Engineering Research, Jeju, South Korea, November 10-13.

Watts, P. (2004). Probabilistic predictions of landslide tsunamis off Southern California. *Marine Geology*, 203, 281-301.

Wei, B. and Chen, Y. (2005). Earthquake and tsunami. *South China Journal of Seismology*, 25:1, 43-49 (in Chinese).

Wen, R. and Ren, Y. (2007). Preliminary study on tsunami hazard analysis in China. *World Earthquake Engineering*, 23:1, 6-11 (in Chinese).

Wen, R., Ren, Y., Zhou, Z. (2007). Preliminary study on numerical simulation of near-field tsunami. *Journal of Disaster Prevent and Mitigation Engineering*, Supplement, 447-450 (in Chinese).

Yang, M. (2005). The Risk Analysis of Seismic Tsunami and the Conception of the Warning System in Guangdong Province. *South China Journal of Seismology*, 25:4, 25-33 (in Chinese).

Yang, M. and Wei, B. (2005). The Potential Seismic Tsunami Risk in South China Sea and its Surrounding Region. *Journal of Catastrophology*, 20:3, 41-47 (in Chinese).

Zhou, Q. and Adams, W.M. (1988). Tsunami Risk Analysis for China. *Natural Hazards*, 1:2, 181-195.