Modeling the dynamic process of tsunami earthquake by liquid-solid coupling model*

CAI Yong-en[†] (蔡永恩) ZHAO Zhi-dong (赵志栋)

Department of Geophysics, Peking University, Beijing 100871, China

Abstract

Tsunami induced by earthquake is an interaction problem between liquid and solid. Shallow-water wave equation is often used to modeling the tsunami, and the boundary or initial condition of the problem is determined by the displacement or velocity field from the earthquake under sea floor, usually no interaction between them is considered in pure liquid model. In this study, the potential flow theory and the finite element method with the interaction between liquid and solid are employed to model the dynamic processes of the earthquake and tsunami. For modeling the earthquake, firstly the initial stress field to generate the earthquake is set up, and then the occurrence of the earthquake is simulated by suddenly reducing the elastic material parameters inside the earthquake fault. It is different from seismic dislocation theory in which the relative slip on the fault is specified in advance. The modeling results reveal that P, SP and the surface wave can be found at the sea surface besides the tsunami wave. The surface wave arrives at the distance of 600 km from the epicenter earlier than the tsunami 48 minutes, and its maximum amplitude is 0.55 m, which is 2 times as large as that of the sea floor. Tsunami warning information can be taken from the surface wave on the sea surface, which is much earlier than that obtained from the seismograph stations on land. The tsunami speed on the open sea with 3 km depth is 175.8 m/s, which is a little greater than that predicted by long wave theory, $(gh)^{1/2}=171.5$ m, and its wavelength and amplitude in average are 32 km and 2 m, respectively. After the tsunami propagates to the continental shelf, its speed and wavelength is reduced, but its amplitude become greater, especially, it can elevate up to 10 m and run 55 m forward in vertical and horizontal directions at sea shore, respectively. The maximum vertical accelerations at the epicenter on the sea surface and on the earthquake fault are 5.9 m/s^2 and 16.5 m/s^2 , respectively, the later is 2.8 times the former, and therefore, sea water is a good shock absorber. The acceleration at the sea shore is about 1/10 as large as at the epicenter. The maximum vertical velocity at the epicenter is 1.4 times that on the fault. The maximum vertical displacement at the fault is less than that at the epicenter. The difference between them is the amplitude of the tsunami at the epicenter. The time of the maximum displacement to occur on the fault is not at the beginning of the fault slipping but retards 23 s.

Key words: finite element; fluid-solid interaction; earthquake tsunami; numerical modeling

CLC number: P315.3[†]1

Document code: A

Introduction

The tremendous tsunami disaster induced by the 26 December 2004 Sumatra-Andaman earthquake ($M_w 9.2$) attracts lots of researchers' attention and interests again. The study of tsunami waves may be traced back to the early 19th century, the French mathematicians Cauchy and Poisson solved the simple initial value problems about the tsunami wave with small amplitude. In the

* Received 2008-06-17; accepted in revised form 2008-06-30.

Foundation item: National Natural Science Foundation of China (40521002 and 40474013).

[†] Author for correspondence: yongen@pku.edu.cn

1950s, Stoneley (1946) investigated the effect of ocean on Rayleigh wave. Pekeris (1948) studied the propagation of explosive sound in shallow water, and then Biot (1952) did the interaction between Stoneley and the Rayleigh waves. To study tsunami by pure fluid dynamics theory can be divided into 1+1 and 2+1 propagation problems. The former is a propagating direction plus time (Liu *et al*, 1991; Synolakis, 1995), Hibbert and Peregrine (1979) proposed a coastline algorithm to deal with the evolution of long-wave in the problem. The later is two propagating directions plus time, to which Shuto (2000) did a breakthrough in the non-linear shallow water (NSW) solution by numerical calculation. Titov and Synolakis presented another solution without the frictional coefficient on the sea floor, in the meanwhile, Titov and Synolakis' calculation showed that hydrodynamic problems can be solved for some initial data (Titov and Synolakis, 1998). With the improvements of bathymetric and topographic data the tsunami propagation to an extent may be simulated efficiently by the numerical calculation of hydrodynamic model (Titov and Synolakis, 1998). Masamura and Fujima (1995) proposed a model based on Euler's equation.

It is difficult to find an analytical solution for the tsunami propagations due to the complexities of the sea floor topography, coastal morphology and earthquake focus. Experimental and numerical simulations are main directions for the tsunami studies. The tsunami caused by submarine landslide can be modeled by hydrodynamic sink experiment (Grilli *et al*, 2002; Langford *et al*, 2006; Liu *et al*, 2005). This method may be suitable to study the violently fluctuation and split of the tsunami at sea shore, however, it could not reveal the effects of the complex topography of the sea shore on the tsunami wave in quantity and details as the limitations of the experimental conditions.

The super computer and parallel cluster made the numerical simulation of the tsunami come true. Hydrodynamic model is mainly employed to model the process of the tsunami. Due to that the wavelength of the tsunami is much greater than the average depth of the sea the shallow-water wave equations to control the tsunami wave can be derived from the Navier-Stokes equations (Lamb, 1945; Batchelor, 1967). The finite difference method (LeVeque, 2007), finite element method (Leclerc *et al*, 1990; Myers and Baptista, 1995) and finite volume method (LeVeque, 2002) for solving the tsunami wave propagation are almost based on the equations. Among these methods the finite difference method is widely used as its higher efficiency and fast speed in calculation and easier programming than others, however, it is difficult to use the method for the problems with complex geometric boundaries, especially for the tsunami propagating on land. The displacements or velocity obtained from seismic dislocation model (Okada, 1985) are taken as the tsunami source (initial or boundary condition on the sea floor). This model may be fine for plane sea floor. However, it is difficult to provide the displacement field of the sea floor with complex topography, the model especially cannot deal with the effect of the interaction between the sea water and sea floor on the displacement field.

In this paper the commercial finite element program ADINA based on potential flow theory and fluid-solid coupling is employed to simulate the dynamic process of the tsunami induced by the earthquake.

1 Liquid-solid coupling model of tsunami earthquake

Owing to the sea floor, deformation induced by the earthquake is affected by the sea water and the boundary shape of the sea water in contact with the sea floor is changed by the deformation, however, the shape is unknown in advance. Therefore it is difficult to calculate the deformation by seismic dislocation theory, especially when the sea floor topography is complex. To study

the process of the interaction between the earthquake and tsunami in details it is necessary to build a liquid-solid coupling model of the tsunami earthquake. If liquid is incompressible or slightly compressible, inviscid and the flow velocity of the sea water is less than a sonic one, and the displacements on the sea surface and the sea water boundary are much small in comparison with the tsunami wave length, then the Navier-Stokes problem for the velocity and pressure fields can be changed to a fluid potential problem. The velocity and pressure fields can be calculated by the potential. The fluid potential theory is widely used to solve the fluid-solid coupling problems in the aero industry, nuclear reactor and oil or waste storage tanks (Hirsch, 1988; Anderson *et al*, 2003; Stuart *et al*, 1995; Sussman and Sundqvist, 2003).

In this study, the fluid potential theory is employed to study the total process of the tsunami generated by the earthquake instead of using the theory of shallow water wave as usually. The two-dimensional geometry model to simulate the tsunami earthquake is divided into the liquid region and solid region, which are denoted by "I" and "II", respectively (Figure 1). The earthquake occurs in the solid one and the tsunami induced by the earthquake is in the liquid one.

Figure 1 Two dimensional geometrical model of the tsunami earthquake in basis of fluid-solid coupling theory

I: Sea water; II-1: Fault zone; II-2: Absorbing layer of reflected wave; II-3: Sea floor and continent

The tsunami earthquake can be attributed to the following boundary-value problems. In the liquid region:

$$-\rho_0 \ddot{\phi} + k \nabla^2 \phi = -\rho_0 \ddot{\Omega} \quad (1)$$

$$\mathbf{v} = \nabla \phi \quad (2)$$

$$p = \rho_0 [\Omega(x) - \dot{\phi}] \quad (3)$$

where, equation (1) is the continuity equation expressed by velocity potential ϕ , $\mathbf{v}$ is velocity vector, $\Omega(\mathbf{x})$, body potential, k , volume compressible modulus, p , fluid pressure, ρ_0 , initial density. Both ϕ and $\mathbf{v}$ are the functions of space and time. If $\Omega(\mathbf{x})$ is gravity potential, then $\nabla \Omega(\mathbf{x}) = \mathbf{g}$, where $\mathbf{g}$ is gravity acceleration,

In the solid region:

$$-\rho_0 \ddot{\mathbf{u}} - \eta \dot{\mathbf{u}} + L \boldsymbol{\sigma} = -\mathbf{f} \quad (4)$$

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \lambda + 2\mu & \lambda & \lambda \\ \lambda & \lambda + 2\mu & \lambda \\ \lambda & \lambda & \mu \end{bmatrix} \begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{bmatrix} = D \boldsymbol{\epsilon} \quad (5)$$

$$\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \frac{\partial u_x}{\partial x} \\ \frac{\partial u_y}{\partial y} \\ \frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x} \end{bmatrix} = \mathbf{L}^T \mathbf{u}, \quad \mathbf{u} = \begin{bmatrix} u_x \\ u_y \end{bmatrix}, \quad \mathbf{L} = \begin{bmatrix} \frac{\partial}{\partial x} & 0 & \frac{\partial}{\partial y} \\ 0 & \frac{\partial}{\partial y} & \frac{\partial}{\partial x} \end{bmatrix} \quad (6)$$

where $\mathbf{u}$ is displacement vector, f , body force, η , viscosity constant, λ, μ , Lamé constants, respectively. The boundary conditions of this problem are

$$p|_{B_1} = 0, \quad \text{on the sea surface } B_1 \quad (7)$$

$$\sigma_n|_{B_2} = \tau_n|_{B_2} = 0, \quad \text{on } B_2 \text{ the ground surface} \quad (8)$$

$$\begin{cases} n \cdot \mathbf{v}|_f = n \cdot \dot{\mathbf{u}}|_s \\ p|_f = p_n|_s \end{cases}, \quad \text{on } B_3 \text{ the interface of the liquid and solid} \quad (9)$$

$$n \cdot \mathbf{u}|_{B_4} = 0, \quad \text{on } B_4 \text{ the lateral boundaries} \quad (10)$$

The subscripts f and s on the interface B_3 denote fluid and solid, respectively. P is pressure, σ_n and τ_n are normal and shear stresses on the ground surface. From the equations (1) and (4) as well as the contact boundary condition (9), the fundamental equations to derive finite element method (FEM) with the liquid-solid coupling at $t+\Delta t$ can be obtained by the Galerkin weighted residual technique (CAI and YIN, 1997)

$$\int_{V_f} \rho_0 \ddot{\phi} \delta \phi dV + \int_{V_f} (k \nabla \phi \cdot \nabla \delta \phi) dV + \int_S k \mathbf{n} \cdot \dot{\mathbf{u}} \delta \phi dS = \int_{V_f} \rho_0 \dot{\Omega} \delta \phi dV \quad (11)$$

$$\int_{V_s} \rho_0 \ddot{\mathbf{u}} \delta \mathbf{u} dV + \int_{V_s} \eta \dot{\mathbf{u}} \cdot \delta \mathbf{u} dS + \int_{V_s} (\nabla \mathbf{u} \cdot \mathbf{D} \cdot \nabla \delta \mathbf{u}) dV = \int_{V_s} \mathbf{f} \cdot \delta \mathbf{u} dV - \int_S p \mathbf{n} \cdot \delta \mathbf{u} dS \quad (12)$$

where V_s is the volume of the solid region, $\delta \phi$ and $\delta \mathbf{u}$ are the weighted residual functions, $\mathbf{n}$ is the normal unit vector to S . Take

$$p(t + \Delta t) = \rho_0 \Omega + \rho_0 \frac{\partial \Omega}{\partial x} \cdot \mathbf{u} - \rho_0 \dot{\phi}$$

into equation (12), then the finite element formulae to solve the liquid-solid coupling problem can be derived from equations (11) and (12)

$$\begin{bmatrix} M_{ss} & 0 \\ 0 & M_{FF} \end{bmatrix} \begin{bmatrix} \Delta \ddot{\mathbf{U}} \\ \Delta \ddot{\boldsymbol{\Phi}} \end{bmatrix} + \begin{bmatrix} C_{ss} & -C_{FU}^B \\ -C_{FU}^B & 0 \end{bmatrix} \begin{bmatrix} \dot{\mathbf{U}} \\ \dot{\boldsymbol{\Phi}} \end{bmatrix} + \begin{bmatrix} K_{UU}^S + K_{ss} & 0 \\ 0 & K_{FF} \end{bmatrix} \begin{bmatrix} \mathbf{U} \\ \boldsymbol{\Phi} \end{bmatrix} = \begin{bmatrix} \mathbf{R}_U^B + \mathbf{R}_s \\ \dot{\mathbf{R}}_F \end{bmatrix} \quad (13)$$

where the superscript B denotes the interface B_4 of the liquid and solid. The matrices of the solid mass M_{ss} , damping C_{ss} , stiffness K_{ss} and the load vector $\mathbf{R}_s$ are from the first, second, third terms of the left side and the first term of the right side of equation (12), respectively. The matrices of K_{uu}^s , $C_{FU}^s = C_{uF}^s$ and $\mathbf{R}_u^B$ are from the second term of equation (2). The matrices of M_{FF} , K_{FF} , C_{FU}^B and $\dot{\mathbf{R}}_F$ are from the first, second, third terms of the left side, and the first term of the right side of equation (11), respectively.

2 Numerical modeling of the tsunami-earthquake coupling

Figure 1 shows the 2-D geometry model. Its horizontal and vertical dimensions are taken as 2 000 km and 23 km, respectively. The region I is the sea water, its maximum depth is 3 km, its density and volume compressible modulus are $1\,000\text{ kg/m}^3$ and 2.1 GPa, respectively. The length and thickness of the fault to generate earthquake are 10 km and 1 km, respectively, its dip is 30° . The density, volume compressible modulus and Poisson's ration in the solid region II are $2\,700\text{ kg/m}^3$, 83.0 GPa and 0.25, respectively. The damping parameter in the absorbing layer is taken as 0.25. Figure 2 shows the finite element model and its local regions with meshes marked by dashed rectangular line. Figures 2a, 2b and 2c show the finite element model, the local meshes of the left sea shore and the meshes near the earthquake fault. The geometry of the east sea shore is symmetric to the west one. There are 1 636 elements and 1 900 nodal points in the liquid region and 5 618 elements and 4 262 nodal points in the solid region, respectively. The boundary conditions of the finite element model are given by equations (7)~(10), *i. e.*, the surfaces of the sea and ground are free, the vertical displacement and stress are continuous across the interface of the liquid and solid, the normal displacements and tangential tractions on the lateral and the bottom of the model are zero, respectively. Both the initial displacement and velocity of the model are zero. The initial fields of the pressure in the liquid region and stresses in the solid region are from the weight of the sea water and rock, respectively. The gravity acceleration is taken as 9.8 m/s^2 in calculation.

As the earthquake is considered as that the fault softens suddenly in mechanics, therefore the earthquake to generate the tsunami is simulated by reducing Young's modulus. The amount to be reduced may be constrained by the fault dislocations from geological survey or inverse results from seismic waves. In this paper the Young's modulus is reduced from 83.0 GPa to 4.2 GPa under the restriction of the fault dislocation of 4 m.

Figure 2 Finite element model and its local meshes of tsunami earthquake
(a) Global region of liquid-solid coupling finite element model (enlarged 2 times in the vertical direction); (b) Meshes near the west seashore; (c) Meshes near the fault

3 Results and discussions

To view the propagations of the tsunami and seismic waves, 6 observation points are set (see Figure 1). There are 3 points, W_1 , W_2 and W_3 , marked by circle on the sea surface. W_1 and W_2 are on the deep sea surface, the former is at the epicenter and the later is 600 km away from the epicenter, W_3 is on the sea shore away from the epicenter of 816 km. The remaining points, S_1 , S_2 and S_3 , marked by rectangular on the sea floor, their distances from the epicenter are the same as those of W_1 , W_2 and W_3 .

Figure 3 shows the vertical displacements, velocities and accelerations at S_1 and W_1 . It is seen that the maximum dynamic displacements downward at S_1 and W_1 are 3.9 m and 6.0 m at the time of 23 s and 25 s, respectively. The difference of 2.1 m is the amplitude of the tsunami source at the epicenter on the sea surface. The time reached to the maximum displacement at S_1 retarded 23 s from the beginning of the earthquake. The average amplitude of the vertical displacement is larger than 0.5 m which appeared about 100 s after the earthquake initiated, it reduced to 0.2 m after 250 s. This result implies that the tsunami amplitude may be under estimation if static seismic dislocation (Okada, 1985) is used as an initial or boundary conditions. The time reached to the maximum displacement at W_1 retarded 2 s in comparison with that at S_1 . It is the time that compression wave P travels from S_1 to W_1 . The water particle at W_1 vibrates below and above the sea surface at balance (negative amplitude) before and after 90 s, respectively. Thus the period of the tsunami source is about 180 s. It can be seen that its frequency is higher than that of the tsunami. The vibration is controlled by the movement of the earthquake fault. The maximum displacement at W_1 is 6 m (the average amplitude of 3.0 m) and 2.2 m (the average amplitude of 1.1 m) before and after 90s, respectively. After 500 s the displacement is about 0.5 m in average, it means that the time of the vibration of the tsunami source is very short and so small displacement is difficult to be identified from standard sea wave. The maximum vertical velocities of the sea water at S_1 and W_1 are 2.3 m/s and 3.2 m/s reached at 19 s and 35 s, respectively. The velocity at W_1 is greater than that at S_1 . It can be attributed to that the point W_1 at the sea surface is without vertical restriction. The maximum accelerations are 16.3 m/s^2 ($=1.65 \text{ g}$) and 5.9 m/s^2 reached at 13 s and 12 s at S_1 and W_1 , respectively, the former is 2.8 times the later. Therefore the sea water is a good shock absorber.

Figure 3 The displacements, velocities and accelerations at S_1 and W_1

(a) Displacement, velocity and acceleration on the sea floor; (b) Displacement, velocity and acceleration on the sea surface

The seismograms calculated at W_2 , S_2 , W_3 and S_3 are shown in Figure 4. At point W_2 , two remarkable wave groups can be seen from the first seismogram in Figure 4a. The first one with the largest amplitude is the tsunami wave towards the sea shore, and the second one is the reflected tsunami wave, its amplitude is less than that of the first as a part of the energy of the tsunami wave is refracted into land at the sea shore. A small wave train before the tsunami wave can be found from the second seismogram in Figure 4a if the displacement is only focus to the time interval of 800 s in the first seismogram. It can be verified by the seismic wave theory that there exist three phases in the train. The first one is P wave refracted from the sea floor, the second one is SP wave which is converted from S wave traveling along the sea floor to P wave in the sea, and the third one is the surface wave. The amplitude of the surface wave is the largest one among the three waves, its maximum is 0.55 m, which is far larger than those of P and SP, and much small than that of the tsunami wave. The fast group velocity is 1 800 m/s, which is smaller than that of P wave in the sea water. This result reveals that P, SP and the surface waves on the sea surface can be found besides the tsunami wave. The travel time of the surface wave to arrive at W_2 is 48 minutes earlier than that of the tsunami, it implies that the surface wave may be used as the tsunami warning information which is much earlier than that obtained from the seismograph stations on land.

The third seismogram in Figure 4a is recorded at point S_2 located at the sea floor. It can be seen that the vertical displacement amplitudes are much smaller than that of tsunami wave in the first seismogram. The arrival times of P and S waves in the forth seismogram are almost the same as those of P and SP in the second seismogram, this is due to that the travel time of P wave from S_2 to W_2 only takes 0.97 s. So it is difficult to tell the difference of the arriving time between them. It also can be seen that the features of the surface waves at S_2 and W_2 are very similar, however the amplitude on the sea surface is greater than that on the sea floor.

The seismograms of the horizontal and vertical displacements with time at the sea shore W_3 are shown in Figure 4b, this point is 816 km away from the epicenter. The time intervals of the seismograms in the left and right columns are 7 000 s and 800 s, respectively. More attention should be paid to the fact that part of the sea shore is without water and thus is a moving boundary to the sea water, on which the frictional resistance is zero, so the water goes up and down freely, the position and amplitude of the water particle are controlled by the liquid-solid coupling boundary condition. In the first period the “ebb” with a vertical drop of 1.3 m appears after the time of 41.5 s from the tsunami wave arriving at W_3 . It is not easy to be identified when tide is in and out. The first flood tide with a vertical crest of 3.1 m and toward shore displacement of 17 m appears 124.5 s later. In the second period the “ebb” with a vertical drop 6.8 m and an offshore displacement of 33.0 m appears. The second flood tide (the largest tsunami wave) with a vertical crest of 10.0 m and a toward shore displacement of 55.0 m appears 320.5 s later. The wave is so high that tends to bring a disaster. SP wave in the 800 s seismograms is still recognized easily, and its arrival time is the same as S wave at S_3 . The vertical amplitude of the surface wave attenuates at W_3 attenuates significantly faster than that at W_2 .

Figure 4c shows the seismograms of the horizontal and vertical displacements at S_3 with time. It can be seen that the largest amplitudes in the vertical and horizontal directions are much smaller than those at W_3 . The seismic wave phases in the seismograms with the time of 800 s are similar to those at W_3 . The amplitudes of the surface waves at the sea surface are also larger than those of the surface waves at the sea floor.

Figure 5 presents the snapshots of the vertical displacements on the sea surface at 1 000 s, 2 000 s, 3 000 s, 4 000 s, 4 450 s and 4 560 s. It can be seen that the tsunami wave reaches to the

Figure 4 The displacements at sea and sea b from different epicentral distances
 (a) Vertical displacements of the sea floor and sea surface at 600 km; (b) Vertical and horizontal displacements of the fluid particle at 815 km; (c) Vertical and horizontal displacements of the solid particle at 815 km

place of 183.8 km from the epicenter at 1 000 s, its largest peak is 1.3 m which is less than its trough of 3.3 m. The maximum amplitude in average is 2.3 m. The velocity, period and wavelength of the tsunami wave with the maximum amplitude in the deep sea can be determined by the snap-

shots from 1 000 s to 4 000 s. They are 175.8 m/s, 182 s and 32 km, respectively. The period is almost the same as that of the tsunami source; it means that the dispersion of the tsunami wave is very small. The velocity is greater than $\sqrt{gh}=171.5$ m/s calculated by long wave theory. The average maximum amplitude of the tsunami wave decrease with time from 3.3 m at 1 000 s to 1.8 m at 4 000 s, respectively. When tsunami wave arrives at the continental shelf, its velocity and the wavelength decrease with that the depth of the water diminishes, *e.g.*, the velocity, period and wavelength reduce to 112.9 m/s, 56 s, and 6.3 km at the depth of 400 m.

Figure 5 The snapshots of tsunami wave at different time

4 Concluding remarks

1) In the open sea, the dispersion of the tsunami wave is very small and its maximum velocity is almost the same as that predicted by long wave theory. The velocity and the wavelength of the tsunami wave decrease with the water diminishing and its amplitude increases, especially when tsunami wave arrives at the sea shore its amplitude becomes much larger than that on the open sea. These results are consistent with general understandings to tsunami waves.

2) The results reveal that P, SP and surface waves can be found on the sea surface besides the tsunami wave. The P wave phase is difficult to identify as its amplitude is very small, their arrival times at a place on the sea surface are almost the same as those at its corresponding solid point.

The maximum amplitude of the surface wave is 0.55 m, and its group velocity with the maximum displacement amplitude is 10 times greater than that of the tsunami wave, it implies that the surface wave may be used as the tsunami warning information which is much earlier than that obtained from the seismograph stations on land.

3) The maximum acceleration on the earthquake fault is 1.65 g which is 2.8 times that of the water on the sea surface. The sea water is a good shock absorber. The acceleration of the tsunami wave decreases 10 times on the sea shore in comparison with that at the epicenter on the sea surface. Different from the acceleration, the velocity of the sea water at the epicenter is 1.4 times that of the earthquake fault. The maximum vertical displacement of earthquake fault is smaller than that of the water on the epicenter, and the difference is the amplitude of the tsunami wave source.

4) The maximum displacement reached on the earthquake fault is not at the beginning of the fault slipping. The dynamic fault displacement obtained by calculation is significantly greater than that from the quasi-static seismic model, therefore the tsunami amplitude may be under estimation if the static seismic dislocation (Okada, 1985) is used as initial or boundary conditions.

Acknowledgment We thank Dr. GE Xiao-yue for his help in finite element mesh generation.

References

- Andersson L, Andersson P, Lundwall J, *et al*. 2003. On the validation and application of fluid-structure interaction analysis of reactor vessel internals at loss of coolants accidents [J]. *Comprcrers & Srrucrures*, **81**(8/11): 469-476.
- Batchelor G K. 1967. *An Introduction to Fluid Dynamics* [M]. Cambridge: Cambridge University Press: 223-245.
- Biot M A. 1952. The interaction of Rayleigh and Stoneley waves in the ocean bottom [J]. *Bull Seism Soc Amer*, **42**(1): 81-93.
- CAI Yong-en and YIN You-quan. 1997. *Thermo-elastic Finite Element Method and Its Programming* [M]. Beijing: Peking University Press: 38-69 (in Chinese).
- Grilli S T, Vogelmann S, Watts P. 2002. Development of a 3D numerical wave tank for modeling tsunami generation by underwater landslides [J]. *Engineering Analysis with Boundary Elements*, **26**(4): 301-313.
- Hibbert S and Peregrine D H. 1979. Surf and runup on a beach: A uniform bore [J]. *J Fluid Mech*, **95**(2): 323-345.
- Hirsch C. 1988. *Numerical Computation of Internal and External Flows* [J]. Chichester: John Wiley: 426-507.
- Lamb H. 1945. *Hydrodynamics*: The 6th edition [M]. New York: Dover Publications: 7-43.
- Langford P S, Roger I N, Roy A W. 2006. Experimental modeling of tsunami generated by underwater landslides [J]. *Science of Tsunami Hazards*, **24**(4): 267-287.
- Leclerc M, Bellemare J F, Dumas G, *et al*. 1990. A finite element model of estuarine and river flows with moving boundaries [J]. *Adv Water Resources*, **13**(4): 158-168.
- LeVeque R J. 2002. *Finite Volume Methods for Hyperbolic Problems* [M]. Cambridge University Press: 132-156.
- LeVeque R J. 2007. *Finite Difference Methods for Ordinary and Partial Differential Equations: Steady-State and Time-Dependent Problems* [M]. Philadelphia: SIAM: 25-38.
- Liu P L F, Synolakis C E, Yeh H H. 1991. Report on international workshop on long-wave run-up [J]. *Journal of Fluid Mechanics*, **229**: 675-688, doi:10.1017/S0022112091003221.
- Liu P L F, Wu T R, Raichlen F, *et al*. 2005. Runup and rundown generated by three-dimensional sliding masses [J]. *Journal of Fluid Mechanics*, **536**: 107-144, doi:10.1017/S002211200500479.
- Masamura K and Fujima K. 1995. Three-dimensional analysis of long wave runup on a conical island by using the MAC method [G]/Harry Y, Liu P, Synolakis C. *Long Wave Runup Models*. Hackensack: World Scientific Publishing Company, Incorporated: 321-331.
- Myers E P and Baptista A M. 1995. Finite element modeling of the July 12, 1993 Hokkaido Nansei-Okai tsunami [J]. *Pure and Applied Geophysics*, **144**(3): 769-801.
- Okada Y. 1985. Surface deformation due to shear and tensile faults in a half-space [J]. *Bull Seism Soc Amer*, **75**(4): 1 135-1 154.
- Pekeris C L. 1948. *Theory of propagation of explosive sound in shallow water* [M]. New York: Geol Soc Amer Mem, **27**: 1-117.
- Shuto N. 2000. Numerical simulation for tsunami disaster prevention [J]. *Journal of the Japan Society for Simulation Technology*, **19**(1): 46-49.
- Stoneley R. 1946. The effect of the ocean on Rayleigh waves [J]. *Mon Not Roy Astron Soc Geophys*, **1**(Suppl): 349-356.
- Stuart R, Shipley L, Ghose A, *et al*. 1995. Dynamic analysis of high-level waste storage tanks [J]. *Comprcrers & Srrucrures*, **56**(2/3): 415-424.
- Sussman T and Sundqvist J. 2003. Fluid-structure interaction analysis with a subsonic potential-based fluid formulation [J]. *Computers and Structures*, **81**(8/11): 949-962.
- Synolakis C E. 1995. Tsunami prediction [J]. *Science*, **270**(5233): 15-16.
- Titov V V and Synolakis C E. 1998. Numerical modeling of tidal wave runup [J]. *J Waterw Port Coast Ocean Eng*, **124**(4): 157-171.