Large-scale Failure Analysis of Reinforced Concrete Structure by Tsunami Wave Force

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SUMMARY:
In this paper, we report large-scale simulation of failure of reinforced concrete structure by tsunami wave force. Particle Discretization Scheme finite element method (PDS-FEM), which has the efficiency to use discontinuous interpolation function at the crack interface, is introduced into ADVENTURE_Solid open source framework, to simulate the crack propagation. Tsunami wave propagation is simulated by solving the three dimensional Navier-Stokes equation with free surface. The following advanced techniques have been implemented; 1) the interface capturing technique is used to model the complicated shapes of free surface caused by hydraulic jump and breaking wave; 2) the SUPG/PSPG method is used as stabilization scheme which provide numerical stability to advection and pressure term; and 3) the OpenMP and MPI hybrid parallelization is used to reduce the computational time and to distribute the memory usage.

Keywords: Failure analysis, PDS-FEM, Tsunami wave, large-scale parallel computing

1. INTRODUCTION

Tsunami has damaged critical infrastructure and many houses, buildings in Tohoku region in Japan. The protection systems for tsunami disaster like seawalls and breakwaters must have an enough performance to be proof against the tsunami impacts. And the mechanism of crack growth and failure of concrete must be clarified to estimate the damage of such a protection systems under the tsunami impacts. Numerical simulation is a powerful tool used to estimate the risk of damage by analysing the physical process of failure. In this simulation, the fluid and structure analysis methods have to be coupled to the interaction forces between their interfaces. And this structure analysis method requires finer mesh for more accurate solution, in order to estimate the propagation of small cracks which merge to a large one. High resolution mesh requires significant amount of memory and computational time. The development of multi-core/CPU parallel computer with fast networks has dramatically being realizing the large scale simulations.

In this paper, we report large-scale simulation of failure of reinforced concrete structure by tsunami wave force. Particle Discretization Scheme finite element method (PDS-FEM, Hori et al. 2005), which has the efficiency to use discontinuous interpolation function at the crack interface, is introduced into ADVENTURE_Solid open source framework, to simulate the crack propagation. Tsunami wave propagation is simulated by solving the three dimensional Navier-Stokes equation with free surface. The following advanced techniques have been implemented; 1) the interface capturing technique is used to model the complicated shapes of free surface caused by hydraulic jump and breaking wave; 2) the SUPG/PSPG method (Tezduyer et al. 1991) is used as stabilization scheme which provide numerical stability to advection and pressure term; and 3) the OpenMP and MPI hybrid parallelization is used to reduce the computational time and to distribute the memory usage. As the numerical example, a distraction of concrete structure by tsunami wave impact was carried out to show the validity of a present method.

2. NUMERICAL FORMULATIONS OF FREE SURE FLOWS

2.1. Governing Equations of Fluids

The model of free surface which Tsunami wave has, we consider two immiscible fluids, α and β, with densities ρ_α and ρ_β, and viscosities μ_α and μ_β. The interface function c serves as a marker identifying fluids α and β with the definition $c=\{1$ for fluid α and 0 for fluid $\beta\}$. In this context, the density and viscosity, ρ and μ, are defined as

$$\rho = c\rho_\alpha + (1-c)\rho_\beta, \tag{2.1}$$

$$\mu = c\mu_\alpha + (1-c)\mu_\beta. \tag{2.2}$$

The time dependent of interface color function is governed by a following advection equation

$$\frac{\partial c}{\partial t} + \mathbf{u}\cdot\nabla c = 0 \qquad \text{on } \Omega_t \quad \forall t \in [0,T] \tag{2.3}$$

The velocity $\mathbf{u}$ is obtained from the sokution of Navier-Stokes equations :

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} - \mathbf{f}\right) - \nabla\cdot\sigma(\mathbf{u},p) = 0 \qquad \text{on } \Omega_t \quad \forall t \in [0,T] \tag{2.4}$$

$$\nabla\cdot\mathbf{u} = 0 \qquad \text{on } \Omega_t \quad \forall t \in [0,T] \tag{2.5}$$

where p is the pressure and **f** is external body force.

2.2. Finite Element Formulations

The stabilized finite element formulation of Eqn.2.3 can be written as follows:

$$\int_\Omega c_*^h\left(\frac{\partial c^h}{\partial t} + \mathbf{u}^h\cdot\nabla c^h\right)d\Omega + \sum_{e=1}^{n_{el}}\int_{\Omega_e}\tau_{c_S}\left(\mathbf{u}^h\cdot\nabla c_*^h\right)\left(\frac{\partial c^h}{\partial t} + \mathbf{u}^h\cdot\nabla c^h\right)d\Omega$$
$$+\sum_{e=1}^{n_{el}}\int_{\Omega_e}\tau_{c_{DC}}\nabla c_*^h\cdot\nabla c^h\,d\Omega = 0 \tag{2.6}$$

where τ_{C_s} and $\tau_{c_{DC}}$ are the stabilization parameter. The stabilized finite element formulation based on SUPG/PSPG (Streamline-Upwind Petrov Galerkin/Pressure Stabilizing Petrov Galerkin) method of the governing equations of fluid Eqn.2.4, 2.5 can be written as follows:

$$\int_{\Omega_t}\mathbf{w}^h\cdot\rho\left(\frac{\partial\mathbf{u}^h}{\partial t} + \mathbf{u}^h\cdot\nabla\mathbf{u}^h - \mathbf{f}\right)d\Omega + \int_{\Omega_t}\varepsilon(\mathbf{w}^h):\sigma(\mathbf{u}^h,p^h)\,d\Omega + \int_{\Omega_t}q^h\nabla\cdot\mathbf{u}^h\,d\Omega$$
$$+\sum_{e=1}^{n_{el}}\int_{\Omega_t^e}\left\{\tau_{\rm supg}\mathbf{u}^h\cdot\nabla\mathbf{w}^h\right\}\cdot\left\{\rho\left(\frac{\partial\mathbf{u}^h}{\partial t} + \mathbf{u}^h\cdot\nabla\mathbf{u}^h - \mathbf{f}\right) - \nabla\cdot\sigma(\mathbf{u}^h,p^h)\right\}d\Omega$$
$$+\sum_{e=1}^{n_{el}}\int_{\Omega_t^e}\left\{\tau_{\rm pspg}\frac{1}{\rho}\nabla q^h\right\}\cdot\left\{\rho\left(\frac{\partial\mathbf{u}^h}{\partial t} + \mathbf{u}^h\cdot\nabla\mathbf{u}^h - \mathbf{f}\right) - \nabla\cdot\sigma(\mathbf{u}^h,p^h)\right\}d\Omega$$
$$+\sum_{e=1}^{n_{el}}\int_{\Omega_t^e}\tau_{\rm cont}\nabla\cdot\mathbf{w}^h\rho\nabla\cdot\mathbf{u}^h\,d\Omega = \int_{(\Gamma_t)_h}\mathbf{w}^h\cdot\mathbf{h}^h\,d\Gamma \tag{2.7}$$

where $\tau_{\rm supg}, \tau_{\rm pspg}$ and $\tau_{\rm cont}$ are stabilization parameter for SUPG, PSPG and Shock-capturing terms respectively.

For the discretization for time, interface color function c, velocity u and pressure p are discretized as follows by using Crank-Nicolson method,

$$c^h = \frac{1}{2}(c^h_{n+1} + c^h_n) \tag{2.8}$$

$$\mathbf{u}^h = \frac{1}{2}(\mathbf{u}^h_{n+1} + \mathbf{u}^h_n) \tag{2.9}$$

$$p^h = p^h_{n+1}. \tag{2.10}$$

From the above discretization in space and time, a linear equation system can be obtained. GP-BiCG method is used to solve the linear equation system. In order to reduce the computational time and memory usage, the MPI and OpenMP hybrid parallelization is implemented to the system.

2.2. Interface Sharpening and Mass Conservation

Only to solve the advection equation of interface function Eqn. 2.6 does not conserve the mass balance and numerical diffusion deprives the sharpness of interface. In order to satisfy the mass balance and keep sharpness of interface function, the interface function is corrected by interface sharpening and mass conservation algorithm (Aliabadi et al. 2000). The corrected value of ϕ is used to resume the computation.

3. NUMERICAL FORMULATIONS OF STRUCTURE FAILURE ANALYSIS

3.1. Formulation of PDS-FEM

The governing equation of elastic body is written as follows:

$$\nabla \cdot \sigma(\mathbf{v}) = \mathbf{0} \qquad \text{on } \boldsymbol{\Omega} \tag{3.1}$$

here, **v** is displacement. In the Particle Discretization Scheme (PDS) formulation, the displacement field is discretized by using discontinuous shape function as follows:

$$\mathbf{v}^h(\mathbf{x}) = \sum_{\alpha} \mathbf{v}^h_\alpha \phi_\alpha(\mathbf{x}) \tag{3.2}$$

where ϕ_α is shape function based on Voronoi diagram on block Ω_α. ϕ_α satisfies $\phi_\alpha = 1$ for $\mathbf{x} \in \Omega_\alpha$ and $\phi_\alpha = 0$ for $\mathbf{x} \notin \Omega_\alpha$. And strain fields are discretized by using continuous shape function in element as:

$$\nabla \mathbf{v}^h(\mathbf{x}) = \sum_{\beta} \mathbf{v}^h_\beta \psi_\beta(\mathbf{x}) \tag{3.3}$$

So, the distribution of displacement and strain fields are as shown in **Figure 3.1.** From this discontinuous shape function for displacement, the PDS-FEM has the efficiency at the interface of crack. More details were discussed in Hori et al. (2005) and Wijerathne et al.(2009).

The PDS-FEM formulation is implemented into ADVENTURE_Solid, which is developed in ADVENTURE open source framework. The parallelization method based on Hierarchical Domain Decomposition method (HDDM, Miyamura et al. 2002) by using MPI/OpenMP hybrid scheme.

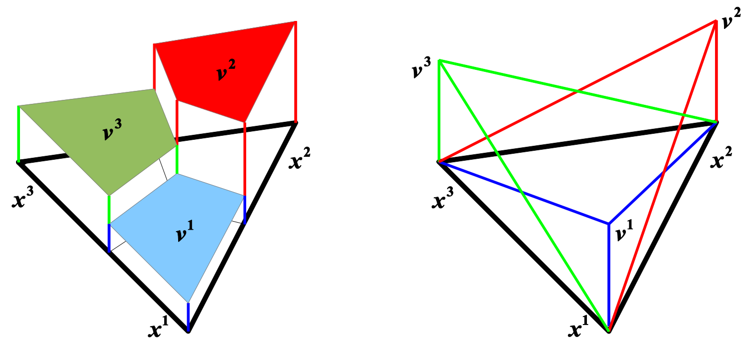

Figure 3.1. Distribution of displacement (left) and strain (right) in an element

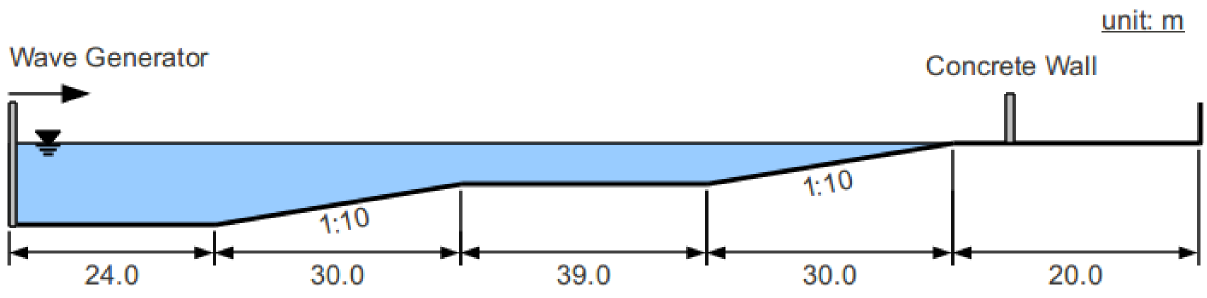

Figure 4.1. Model of water way

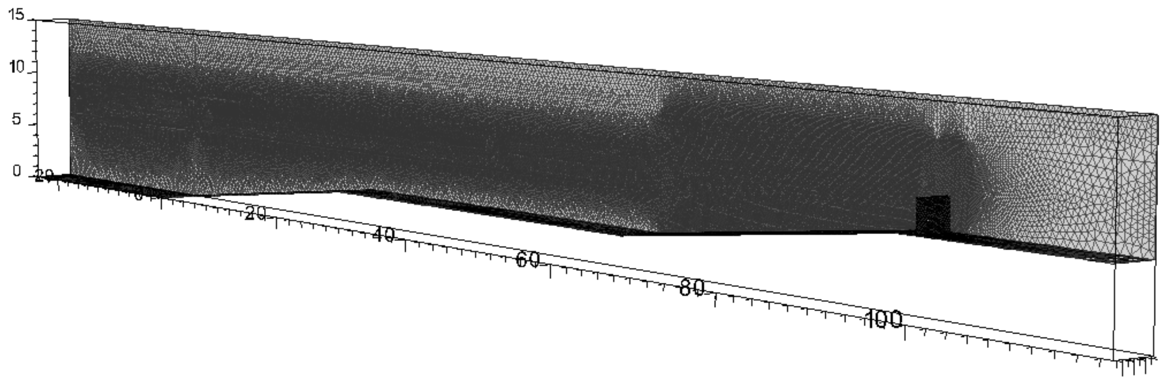

Figure 4.2. Finite element mesh of fluid domain

4. NUMERICAL EXAMPLES

4.1. Distraction of Concrete Structure Due to Tsunami Wave

As numerical example to show the validity of the developed free surface flow analysis program, the distraction of concrete structure due to tsunami wave was carried out. The experiment have been done by Arikawa et al. (2007) at the Port and Airport Research Institute (PARI) of Japan. The model of large scale water way of PARI used in this experience is as shown in **Figure 4.1.** And three dimensional finite element mesh of fluid domain is shown in Figure 4.2., which has about 2 million nodes and 10 million tetrahedral elements and minimum element size is 0.1 m. The tsunami wave height is 2.5, which is generated by the wave generator located at the left side in **Figure 4.1.**

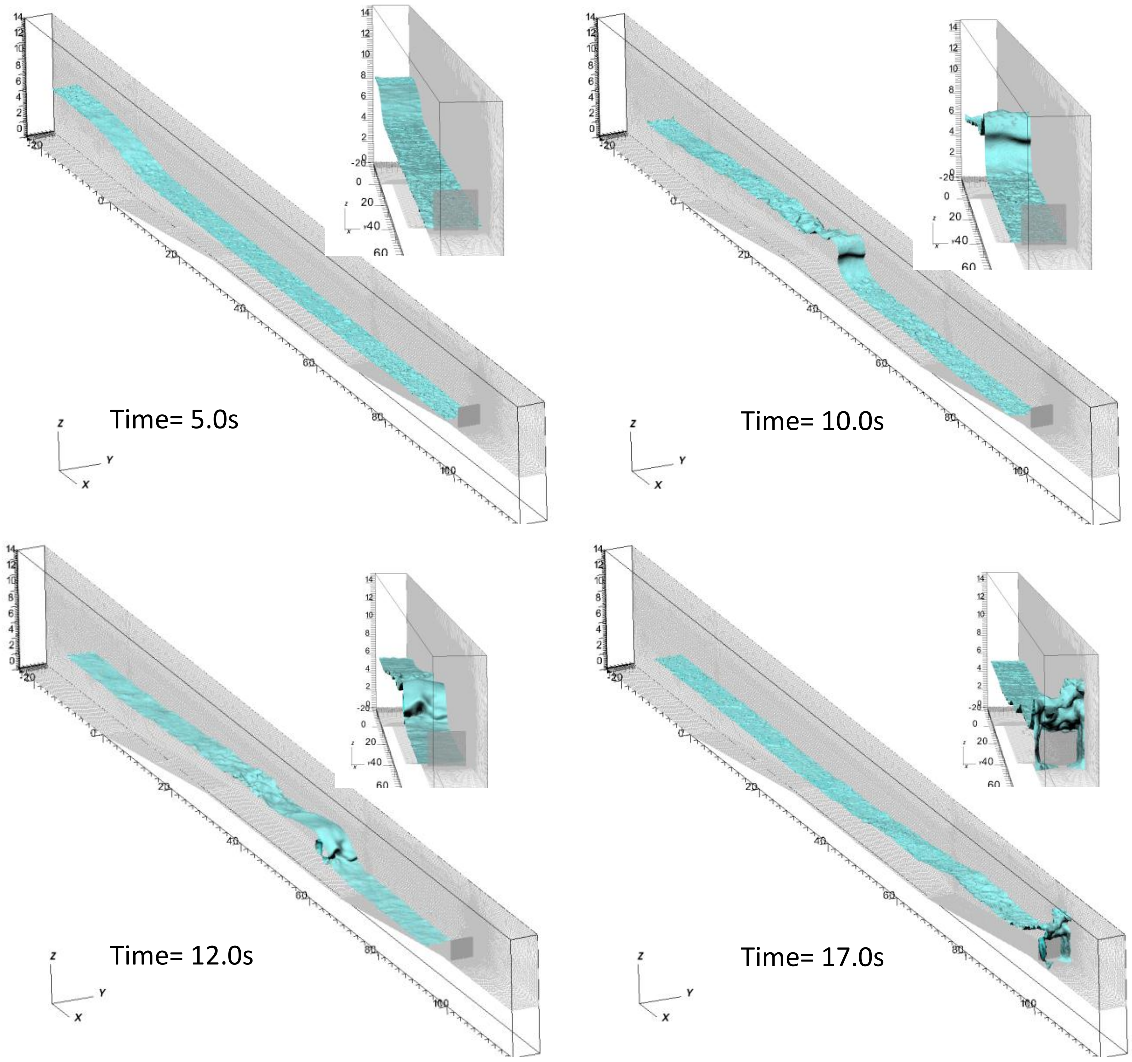

Figure 4.3. Time snaps of free surface shape

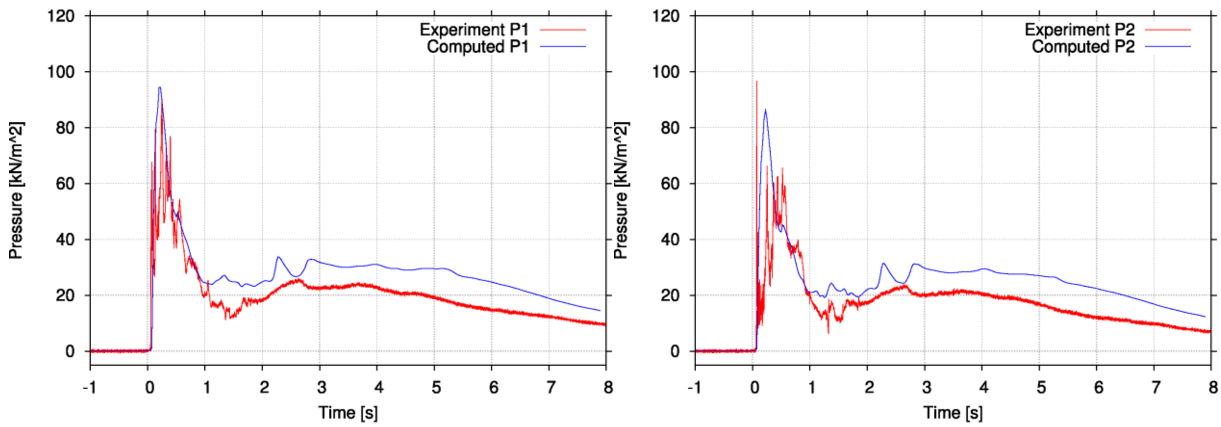

Figure 4.4. Time history of pressure on the wall

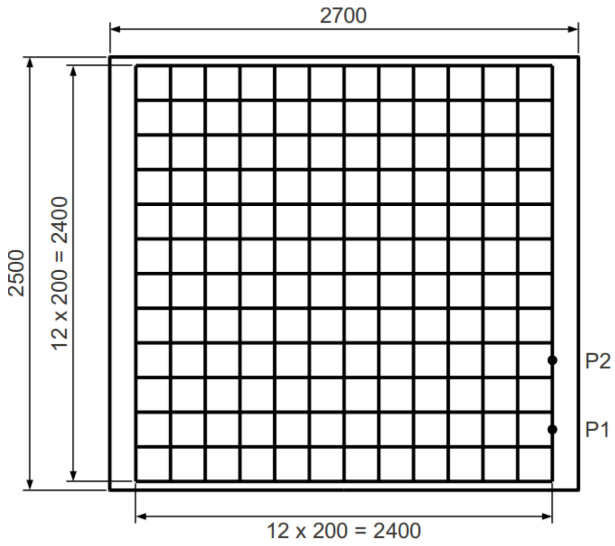

Figure 4.5. Model of concrete wall

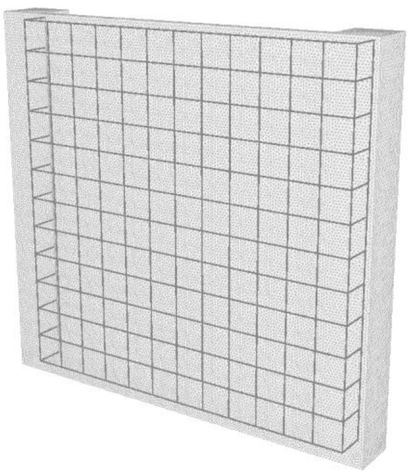

Figure 4.6. Finite element mesh of wall

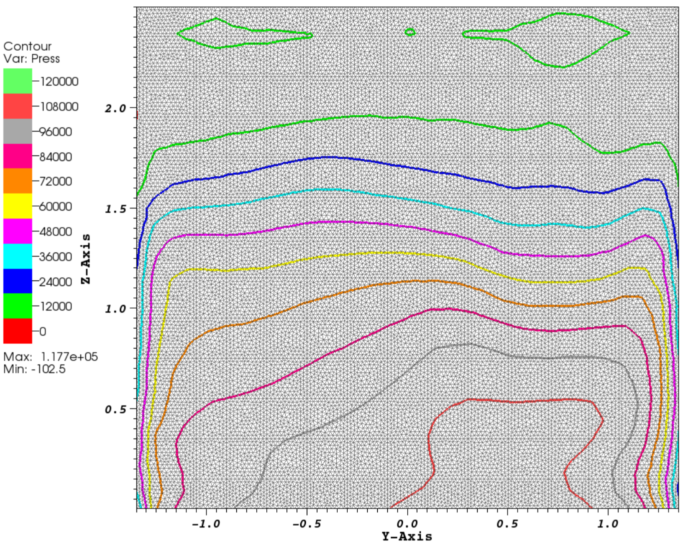

Figure 4.7. Pressure distribution on wall surface

As the numerical results, the time snaps of water surface location are shown in **Figure 4.3.** From these snaps, you can see the propagation of generated wave to inshore with wave breaking and tsunami wave attack a concrete wall. Also **Figure 4.4** shows the time history of pressure at the surface of concrete wall (observed location is shown in **Figure 4.5.**). In this figures, time starts when the wave reaches to the wall. The computed results are in good agreement with the experimental results. There is a difference between experimental and computed result after the impact. One reason why the difference appears is the computation does not consider the wave suppresser which we should consider on the next stage.

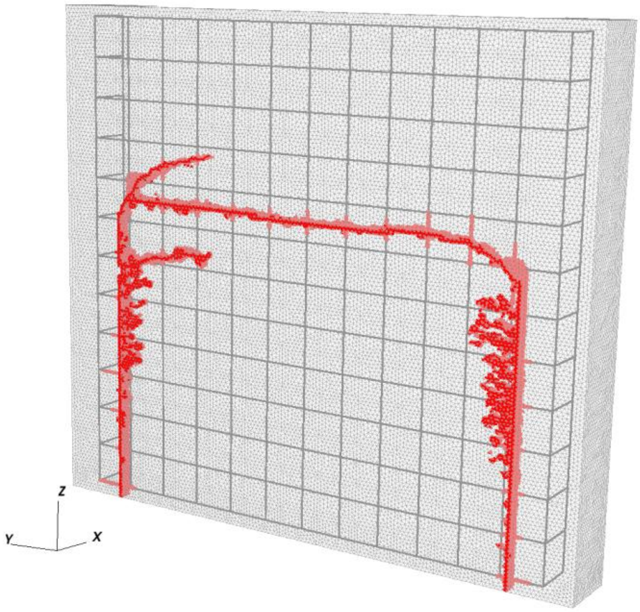

Figure 4.8. Crack pattern obtained by PDS-FEM

The pressure distribution at the surface of concrete wall, which obtained by this wave propagation simulation, will be passed to the structure analysis based on PDS-FEM as the input loading data. Model of concrete wall is as shown in **Figure 4.5.** and the thickness of concrete wall is 6 cm and diameter of steel bar is 6 mm. The design strength of concrete is 18 MN/m^2. **Figure 4.6.** shows a finite element mesh for this model. The minimum element size is 2mm, which is appeared around steel bar. Total number of nodes of this model is 1.7 million, and it has 10 million tetrahedral elements. The pressure distribution on concrete surface obtained by wave simulation is shown in **Figure 4.7.** This pressure was converted to load condition as the static force of structure analysis. As a result, **Figure 4.8.** shows the crack pattern, the crack interface is expressed by red line. From this figure, the crack is caused by the Tsunami wave force. We plan to couple a tsunami wave analysis program and structure analysis program.

5. CONCLUTIONS

We have developed large-scale parallel computing method for failure analysis of reinforced concrete structure by tsunami wave impact force. We showed the result of tsunami propagation simulation in large water way. The computed result obtained by the presented scheme based on stabilized finite element method is in good agreement with the experimental result. And failure analysis of concrete wall by tsunami impact can be simulated successfully. At the next stage of our research, we will plan to develop a fluid-structure interaction scheme to couple the tsunami wave force and failure analysis, and will carry out it on the large-sale supercomputer with detailed model.

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