Development of Simulation System for Tsunami Evacuation Using Virtual Reality Technology

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Abstract

This paper presents a simulation system for tsunami evacuation using virtual reality technology. The system can be classified into two parts: simulation part and visualization part. For the simulation part, the simulation of tsunami wave considering the collapse of building is carried by the Boussinesq equation using finite element method. Then the simulation of evacuation based on multi-agent model is performed. For the visualization part, the simulation results are visualized by the stereoscopic view using virtual reality technology. The present system is applied to the evacuation analysis by the tsunami waves at studied area is shown to be a useful tool to investigate the damage of building and human being by tsunami waves.

Keywords: Virtual Reality, Evacuation analysis, Multi-Agent, Tsunami Simulation

Introduction

A number of tsunami disasters occur annually in various part of the world. In order to estimate the extent of a disaster quantitatively, it is necessary to estimate the behavior of natural phenomena which causes the natural disaster. There have been presented a number of numerical methods to evaluate the damage by the tsunami waves, such as the methods based on the finite difference method, finite volume method and finite element method, The finite element method is one of the powerful tool to investigate the damage by tsunami wave since the finite element method can treat the arbitrary land and building shape.

Recently, the numerical evacuation analysis is becoming popular to estimate the extent of the damage of human being. In the evacuation analysis, it is very important to evaluate the evacuation behavior of the human being in the time during the disaster accurately. The evacuation behavior is strongly related to the circumstance, age and sex of the refugees. The multi-agent model is one of the techniques which can evaluate the evacuation behavior accurately (Uno and Kashiyama (2008)).

This paper presents a simulation system for Tsunami evacuation using virtual reality technology. The present system can be classified into two parts: simulation part and visualization part. For the simulation part, the simulation of tsunami wave considering the collapse of building is carried by the Boussinesq equation using finite element method (Tonegawa and Kashiyama (2009)). Then the simulation of tsunami evacuation based on multi-agent model. For the visualization part, the simulation results are visualized by the stereoscopic view using virtual reality technology. From this, users can understand the simulation results easily. Also, as the view from the refugee's eye can be created in the VR space, the user can understand the feeling of refugee easily. The present system is applied to the evacuation analysis by the tsunami waves at studied area is shown to be a useful tool to investigate the damage of building and human being by tsunami waves.

Tsunami Numerical Simulation

Governing Equation

The Boussinesq equation is employed for the governing equation in order to consider the effect of the wave and dispersion. The governing equations can be described as:

$$\frac{\partial \mathbf{U}}{\partial t} + \mathbf{A}_i \frac{\partial \mathbf{U}}{\partial x_i} - \frac{\partial}{\partial x_i}\left(\mathbf{N}_{ij}\frac{\partial \mathbf{U}}{\partial x_i}\right) = \frac{\partial^2}{\partial t \partial x_i}(\mathbf{K}) + \mathbf{R} - \mathbf{GU} \tag{1}$$

where $H(= h + \xi), u_i, c, n,$ and ν_e denote the total water depth, mean current velocity, wave velocity, Manning's coefficient and kinematic viscosity respectively, $\mathbf{U}, \mathbf{K}, \mathbf{R}, \mathbf{A}_i, \mathbf{N}_{ij}$ and $\mathbf{G}$ are unknown matrix, dispersive matrix, gradient vector, advection matrix, diffusion matrix, friction matrix respectively. The SUPG finite element method is employed for the discretization in space and the Crank-Nicolson method for the discretization in time.

Evaluation Method of Fluid Force

The fluid force acting to building is evaluated by the weak form of the governing equation using the computational results at every time step. The weak form for the governing equation can be written as follows.

$$\int_{\Omega_0} \mathbf{U}^*\left(\frac{\partial \mathbf{U}}{\partial t} + \overline{\mathbf{A}}_i \frac{\partial \mathbf{U}}{\partial x_i} - \mathbf{R} + \mathbf{GU}\right) d\Omega + \int_{\Omega_0}\left(\frac{\partial \mathbf{U}^*}{\partial x_i}\right)\left(-\mathbf{L}_i\mathbf{U} + \mathrm{N}_{ij}\frac{\partial \mathbf{U}}{\partial x_i} + \frac{\partial}{\partial t}(\mathbf{K})\right) d\Omega = \int_{\Gamma} \mathbf{U}^* \mathbf{T} d\Gamma \tag{2}$$

where Ω, Ω_0 and Γ denotes the analytical area, area using by evaluation method of fluid force and boundary of building. The right side of Eq. (2) shows the fluid force acting on building.

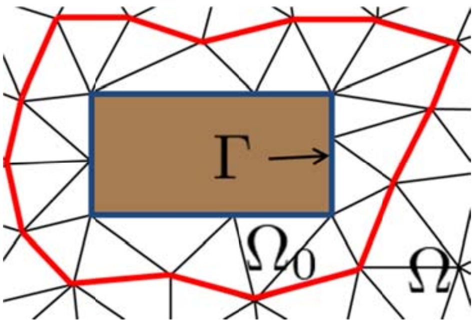

Figure 1. Evaluation Method of Fluid Force

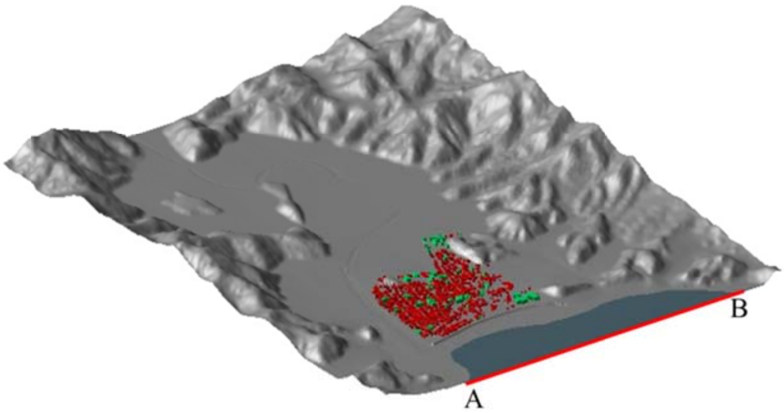

Figure 2. Initial geometry for tsunami simulation

The details of evaluation method of fluid force are described in the references (Tonegawa, Kashiyama, (2009)).

Simulation Condition

The tsunami simulation system is applied to the studied area shown in Fig. 2. In this figure, the red building denote the wooden building and the green building denote the concrete building. Fig. 3 shows the time history of the incident wave which is applied at the boundary AB (Fig. 2). Table. 1 shows the critical yield strength for the concrete and wooden buildings (Izuka and Matsutomi). The building will be collapsed when the fluid force exceed the critical strength value. The unstructured grid based on the linear triangular element is employed (total number of elements: 261,171, total number of nodes: 130,794). The time increment is assumed to be 0.05sec. The Manning's coefficient is assumed to be $0.04\, s/m^{1/3}$ on dry bed area and $0.025\, s/m^{1/3}$ in water area.

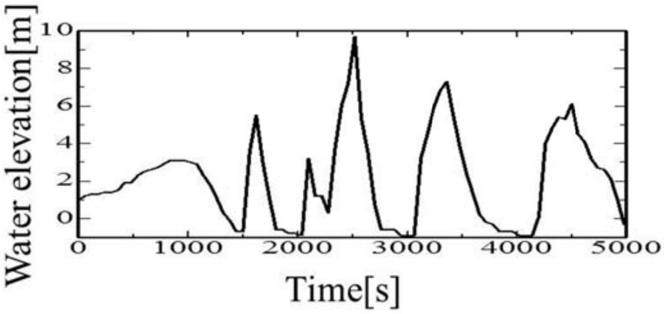

Figure 3. Condition of incident wave

Table 1. Critical strength

	Concrete building	Wooden building
Case A	332kN/m	27.4kN/m
Case B	603kN/m	49.0kN/m

Simulation Results

Fig. 4 and Fig. 5 show the largest tsunami run-up area in case A and B respectively. From the figures, it can be seen that the number of collapsed building and the wave run-up area are related to the strength of building.

Figure 4. Tsunami run-up area in case A

Figure 5. Tsunami run-up area in case B

Tsunami Evacuation Simulation

The evacuation simulation system based on multi-agent model is developed using the multi-agent simulator “Net Logo”. Users can set the simulation condition and parameter (walking speed of refugees, traffic speed of car leading refuge and the time to start the refuge action) using the panel on the screen as shown in Fig. 6.

Input data

The initial positions of refugees are set to the center of gravity of the building as shown in Fig. 7. In order to prepare the data, the data of the road centerlines and the connecting points, which is referred as intersection nodes are prepared by the GIS data. For the evacuation analysis, the data for land elevation, distance from refuge is prepared at every intersection node. The distance from refuge is obtained by the computation of the distance between intersection nodes and refuge points along the road. The shortest route is obtained by the Dijkstra algorithm (Dijkstra (1959)). The new nodes are generated on the land at constant interval as shown in Fig. 8. The unsteady water depth and velocity are evaluated and stored at every new node using the tsunami simulation data. As the tsunami simulation is performed by the triangular mesh (Fig.9), the water depth and velocity are evaluated at new nodes by the linear interpolation using the triangular mesh as shown in Fig. 8.

Figure 6. Screen of evacuation simulation

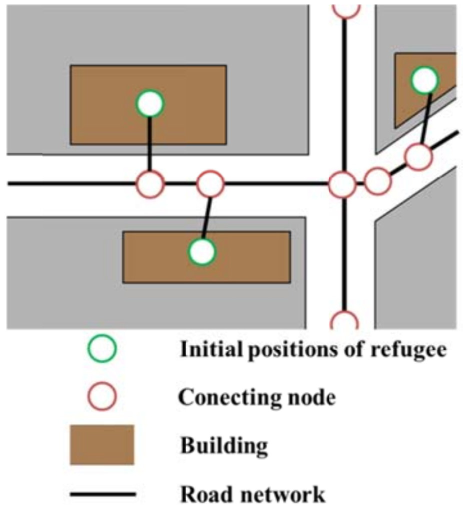

Figure 7. Evacuation route

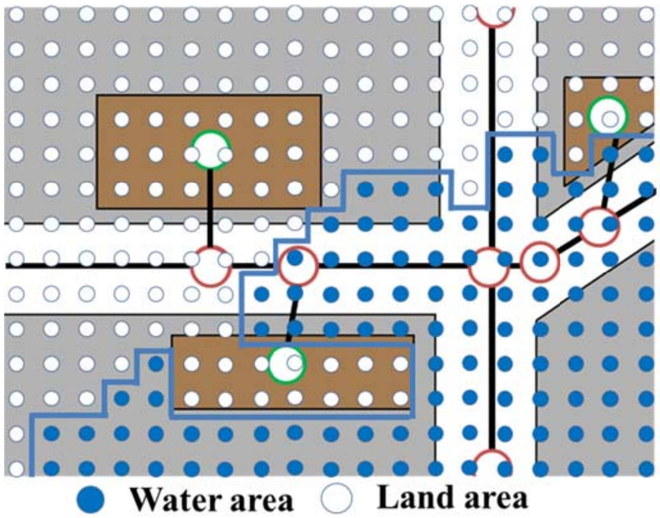

Figure 8. Generation of new nodes

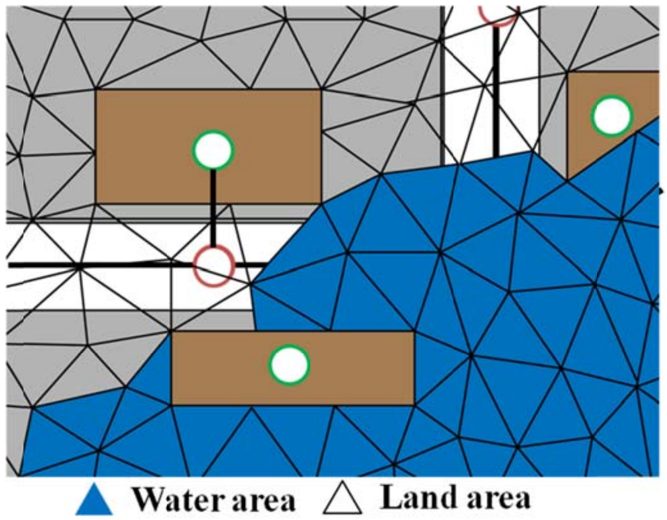

Figure 9. Triangular mesh

Judgment of refugee's route

The selection of refugee's route performs when the refugee arrives at the intersection node as shown in Fig. 10, and refugee compares the potential value of the neighbor intersection nodes on the evacuation route. The potential values are evaluated by the gravity model as:

$$S = \frac{a}{s^{\alpha}} - \frac{b}{z^{\beta}} \quad (3)$$

where s [m] is the distance from refuge, z [m] is the elevation of intersection node, α and β are the weighting coefficients for *s* and *z*, respectively. The evacuation route is decided to the direction of intersection node which has the highest value of S by Eq. (3).

Evacuation speed

The evacuation speed is related to sex and age. However the speed is changed by the refugee's status which is related to the flood status and the density of refugee.

The flood status can be classified into three patterns as shown in Tab. 2 according to the water depth and flow velocity. Fig. 11 shows the relationship between flood status and refugee's status. In this figure, the region A denotes the status that the refugee can evacuate safely (class 2 in Table. 2) but the evacuation speed is reduced by half, and region B denotes the status that the refugee can not evacuate safely (class 3 in Table .2) and evacuation speed is assumed to be zero.

The evacuation speed of refugee is also related to the density of refugee. The evacuation speed is changed by number of refugee in this area.

$$V = v - 0.17\rho \quad (4)$$

where V [m/s] is evacuation speed considered density, v [m/s] is evacuation speed decided and ρ [number of refugee $/ m^2$].

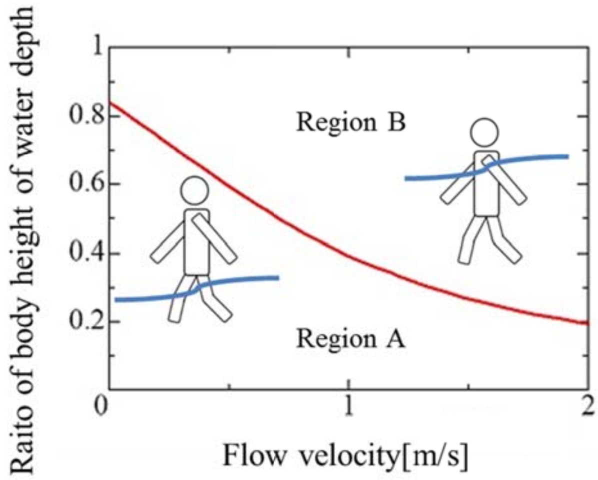

Figure 11. Relationship between flood and refugee's status

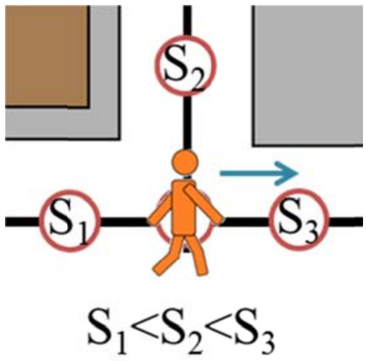

Figure 10. Judgment of refugee's route

Table 2. Categories of refugee's status according to flood status

Class	Flood status	Refugee's status
1	Water depth is 0[m]	No influence
2	Region A in Fig. 8	Speed reduced by half
3	Region B in Fig. 8	Victim

Simulation Condition

The present method is applied to the evacuation simulation by tsunami disaster in studied area. The number of refugees is assumed to be 697 which involve 210 refugees over 65 years old. Table 3 show the height and evacuation speed for refugee. The traffic speed of public information car is assumed to be 2.78m/s, the effective area of the public information car is assumed to be a circle with a radius of 150 m. It is assumed that refugees do not know the refuge place, the time to start the car moving T [time] is changed from 20 min to 40 min with 1 min interval (42 cases simulated in all). The time means that the evacuation action starts after the occurrence of tsunami. The present method is applied to the following two cases, case 1: comparison of the consideration of refugee's year or not, case 2: comparison between case A and case B (Table 1) with the consideration of age.

Table 3. Refugee's data

	number	Height	Evacuation speed
Over 65	210	1.6m	1.33m/s
Under 65	487	1.7m	1.54m/s

Simulation Results

Fig.12 shows the results of tsunami evacuation simulation when the wave run-up area is the largest. The simulation results of case 1 and case 2 are shown in Fig. 13 and fig. 14. From this figure, it can be seen that the number of victims are increased in accordance with the time delay to start the evacuation action. Fig.13 shows that number of victim considering refugee over 65 years old is larger than that without the consideration, because the evacuation speed of refugee over 65 years old is slow. The victim appears at 25 minutes, because the first tsunami waves flow over the breakwater at that time. On the other hand, Fig.14 shows the number of victim in the case A is larger than the number of victim in the case B, because the flood area is larger than the case B. Fig.12 shows that result of tsunami evacuation simulation in case A (left) and case B (right) when the time to start the refuge action is 36 minutes and the wave run-up area is the largest.

Figure 12. Tsunami evacuation simulation (left case A, right case B)

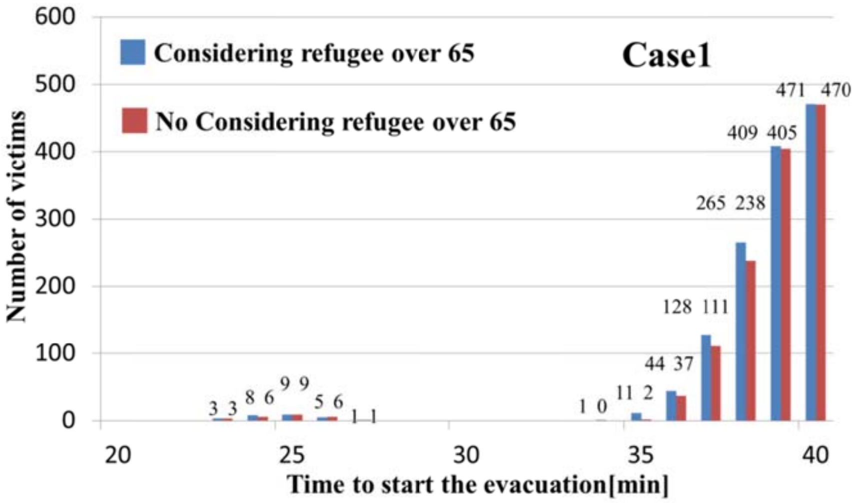

Figure 13. Simulation result (case 1)

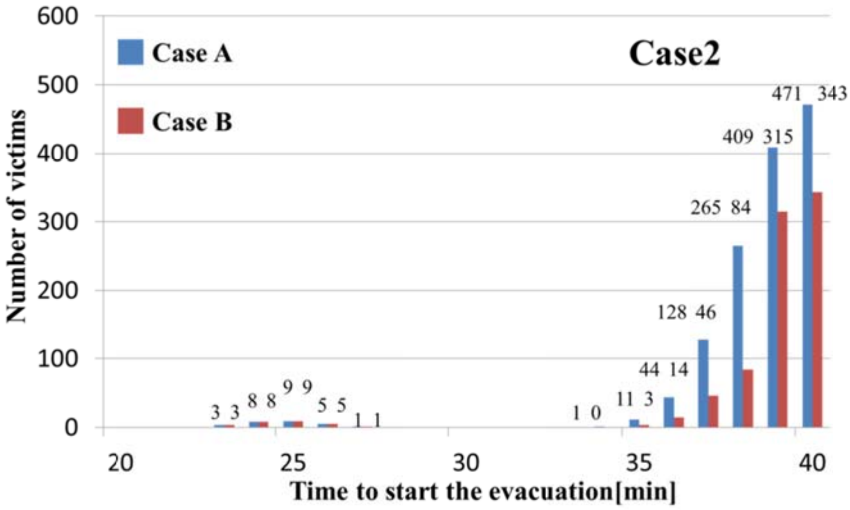

Figure 14. Simulation result (case 2)

Visualization Using VR technology

The simulation results are visualized by the stereoscopic view using virtual reality technology. Fig. 15 and Fig. 16 show the VR system "Holostage" and the shutter glasses and controller for users The results of tsunami and evacuation simulation are visualized by different visualization software. In this paper, the attempt to combine the different CG images created by different visualization

Figure 15. VR system

Figure 16. Device for VR system

software is performed. Fig.17 shows the visualization process of the software, Fusion VR (Miyachi et al. 2005). Fig.18 shows the scene the user check the visualization result in VR space. The users can understand the simulation results easily. Also, as the view from the refugee's eye can be created in the VR space, the user can understand the feeling of refugee easily.

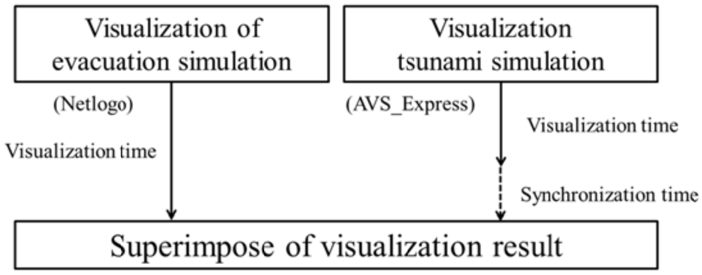

Figure 17. Controlling display time

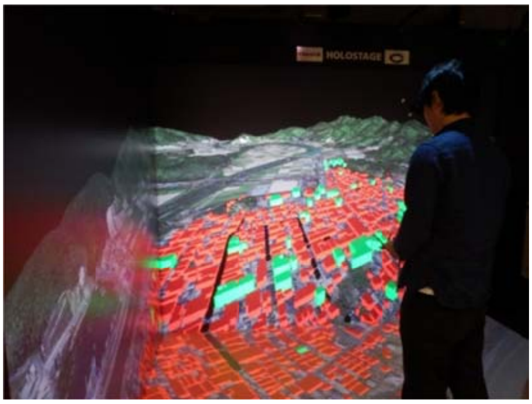

Figure 18. Visualization Using VR technology

Conclusions

The simulation method for the tsunami evacuation using virtual reality technology has been presented. The present system can be classified into two parts: simulation part and visualization part. For the simulation part, the simulation of tsunami wave considering the collapse of building is carried by the Boussinesq equation using finite element method. Then the simulation of tsunami evacuation based on multi-agent model. For the visualization part, the simulation results are visualized by the stereoscopic view using virtual reality technology. The present system is applied to the studied area and is shown to be a useful tool to investigate the damage of building and human being by tsunami waves.

The verification and modification of evacuation model is left for the future work.

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