Tsunami Run-Up Simulation Using Particle Method and its Visualization with Unity

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Abstract

This paper presents a mobile-processed virtual reality (VR) tsunami simulator, which could help people evacuate in the event of a powerful tsunami in the future. The explicit moving particle simulation (E-MPS) method is developed for a tsunami simulation, and the results are demonstrated on the proposed VR with the help of Unity, an open-source software product for VR visualization using a head-mounted display. The experience of the developed VR system might be also helpful for training related to tsunami disaster preparation.

Keywords: **Tsunami simulation, Virtual reality, Unity, Particle method**

Introduction

The Great East Japan Earthquake, which occurred on March 11, 2011, inflicted serious damage on civil structures in northeastern Japan. In particular, the tsunami generated by the earthquake caused heavy damage not only to civil structures but also to the Japanese economy. Since this heavy disaster, several measures have been taken to prevent tsunami disasters, such as the one that followed the Nankai Trough Earthquake, which may occur in the future. Evacuation training and drawing-up hazard maps for tsunamis are important measures. However, residents are likely to forget what they have learned about tsunami disaster prevention. Therefore, it is necessary to take additional measures to raise citizens' awareness of tsunami disaster prevention.

Recently, virtual reality (VR) technology has been developed and is attracting attention in many engineering fields. Virtual reality is a computer-generated scenario that simulates an experience in a VR space. The advantage of VR is its ability to take us to places we have never been before and experience things that we could not otherwise experience with any sense of realism. In general, we cannot experience a tsunami many times in our life. Consequently, we sometimes fail to remember past catastrophic natural disasters, such as earthquakes and tsunamis. Therefore, the application of VR to tsunami disaster preparation may help residents create memories of catastrophic tsunami disasters, such as the incident that occurred on March 11, 2011. The key to increasing the effect of a VR system for tsunami disaster preparation is to reproduce realistic tsunami behaviors in a VR space. Innovative numerical simulation tools are helpful in reproducing such realistic tsunami disasters in a VR space. Motohashi et al. [1] used an open-source software program to estimate the hydraulic force exerted on a bridge by a tsunami. Flouri et al. [2] implemented a simulation of earthquake-generated tsunamis using a finite difference computational model. Wei et al. [3] calculated the hydraulic force of a tsunami using smoothed particle hydrodynamics (SPH), which is one of the particle methods. That particle method is known as a powerful numerical technique and does not require computational meshes, such as the ones used in the finite element method (FEM) [4] and boundary element method (BEM) [5][6][7]. Moreover, a particle method can easily handle the large deformation of continuum bodies. As mentioned here, the particle method [8] has many advantages for fluid analysis.

Therefore, in this research, the explicit-moving particle simulation (E-MPS) [9][10], which is one of the particle methods, is developed and integrated into a VR system to create a tsunami disaster experience. A smartphone is used for high portability and usability of the developed VR system. Unity, which is an open-source software product for VR experience development, is utilized to visualize the numerical results obtained by the E-MPS and construct the VR space of the developed system. The following text explains the E-MPS formulation. Then, the VR visualization obtained with Unity is discussed. Finally, the developed VR system for tsunami disaster preparation is demonstrated, and some comments on our future research works are provided.

E-MPS formulation

In this research, the continuity and Navier Stokes equations at time t are solved using the E-MPS. The continuity and Navier Stokes equations are defined as

$$\frac{D\rho}{Dt} + \rho\nabla \cdot \boldsymbol{u} = 0 \tag{1}$$

$$\frac{D\boldsymbol{u}}{Dt} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\boldsymbol{u} + \boldsymbol{g} \tag{2}$$

where ρ is the density, $\boldsymbol{u}$ is the fluid velocity, and P is the fluid pressure. Moreover, ν is the kinematic viscosity and $\boldsymbol{g}$ is the acceleration of gravity. The continuity and Navier Stokes equations defined in Eqs. (1) and (2), respectively, are calculated as

$$\langle\nabla P\rangle_i = \frac{d}{n_{grad}^0}\sum_{j\neq i}\left[\frac{(P_j + P_i)(\boldsymbol{r}_j - \boldsymbol{r}_i)}{|\boldsymbol{r}_j - \boldsymbol{r}_i|^2}\omega_{grad}(|\boldsymbol{r}_j - \boldsymbol{r}_i|)\right] \tag{3}$$

$$\langle\nabla^2\boldsymbol{u}\rangle_i = \frac{2d}{\lambda^0 n^0}\sum_{j\neq i}[(\boldsymbol{u}_j - \boldsymbol{u}_i)\omega(|\boldsymbol{r}_j - \boldsymbol{r}_i|)] \tag{4}$$

where d and λ^0 represent the number of space dimensions and correction parameters used in the particle method, respectively. In addition, $\boldsymbol{r}$ is the position vector of the particle. Note that the subscript i (or j) indicates the parameter of the i (or j)-th particle. Meanwhile, $\omega(|\boldsymbol{r}|)$ and n_0 indicate the weight function and initial value of the particle number density, respectively. The subscript "$grad$" represents the calculation term for gradient. The weight functions $\omega_{grad}(r)$ and $\omega(r)$ are defined as follows:

$$\omega_{grad}(r) = \begin{cases} \frac{r_e}{r} - \frac{r}{r_e} & (r < r_e) \\ 0 & (r \geq r_e) \end{cases}, \tag{5}$$

$$\omega(r) = \begin{cases} \frac{r_e}{r} + \frac{r}{r_e} - 2 & (r < r_e) \\ 0 & (r \geq r_e) \end{cases} \tag{6}$$

In Eqs. (5) and (6), r is the distance between particles and r_e is the influence radius of a particle. The parameters n^0_{grad} and n^0 are defined as follows:

$$n^0_{grad} = \sum_{j \neq i} \omega_{grad}(|\boldsymbol{r}_j - \boldsymbol{r}_i|) \tag{7}$$

$$n^0 = \sum_{j \neq i} \omega\left(|\boldsymbol{r}_j - \boldsymbol{r}_i|\right). \tag{8}$$

The Navier Stokes equation (2) can be calculated using Eqs. (3) and (4) [8]. However, in this study, the left-hand side of Eq. (2) can be calculated by the explicit Euler method in the E-MPS algorithm using the intermediate velocity $\boldsymbol{u}_i^*$ as

$$\frac{D\boldsymbol{u}}{Dt} = \frac{\boldsymbol{u}_i^{k+1} - \boldsymbol{u}_i^k}{\Delta t} = \frac{\boldsymbol{u}_i^* - \boldsymbol{u}_i^k}{\Delta t} + \frac{\boldsymbol{u}_i^{k+1} - \boldsymbol{u}_i^*}{\Delta t} \tag{9}$$

where $\boldsymbol{u}_i^k$ denotes the particle velocity of particle i at the *k*-th time step. In addition, Δt represents the time increment. The superscript * denotes the physical quantity at the intermediate time step. The intermediate particle velocity u_i^* can be calculated as follows:

$$\boldsymbol{u}_i^* = \boldsymbol{u}_i^k + \left(\nu\langle\nabla^2\boldsymbol{u}\rangle_i^k + \boldsymbol{g}\right)\Delta t. \tag{10}$$

Moreover, the particle position $\boldsymbol{r}_i^*$ at the intermediate step can be obtained as follows:

$$\boldsymbol{r}_i^* = \boldsymbol{r}_i^k + \boldsymbol{u}_i^*\Delta t. \tag{11}$$

The particle velocity $\boldsymbol{u}_i^{k+1}$ and position $\boldsymbol{r}_i^{k+1}$ can be calculated using Eq. (9) as

$$\boldsymbol{u}_i^{k+1} = \boldsymbol{u}_i^* - \frac{\Delta t}{\rho_i^0}\langle\nabla P\rangle_i^{k+1} \tag{12}$$

$$\boldsymbol{r}_i^{k+1} = \boldsymbol{r}_i^* + \left(\boldsymbol{u}_i^{k+1} - \boldsymbol{u}_i^*\right)\Delta t \tag{13}$$

where ρ^0 is the initial density of the fluid. In the conventional MPS, Poisson's equation for the pressure obtained by Eq. (12) can be solved implicitly to obtain the pressure P^{k+1}. However, in the E-MPS, the pressure P^{k+1} can be evaluated as a function of density, as follows:

$$P^{k+1} = \begin{cases} c^2(\rho^* - \rho^0) & (\rho^* > \rho^0) \\ 0 & (\rho^* \leq \rho^0) \end{cases} \tag{14}$$

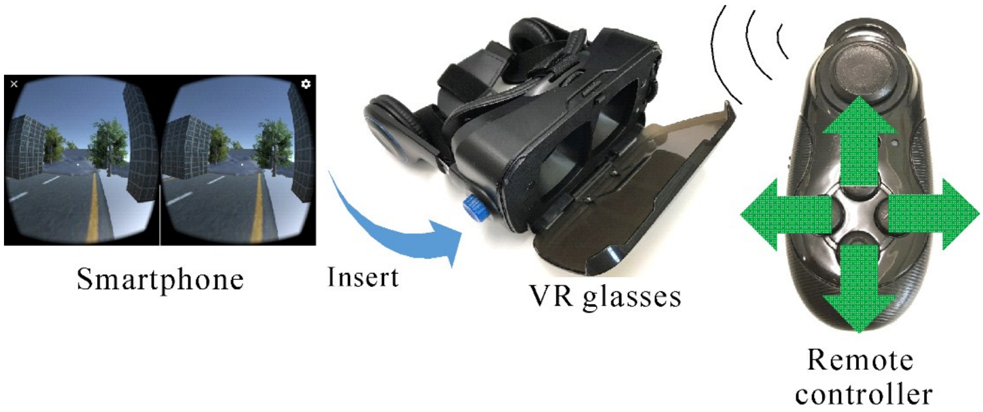


Figure 1. VR system using smartphone and remote controller.

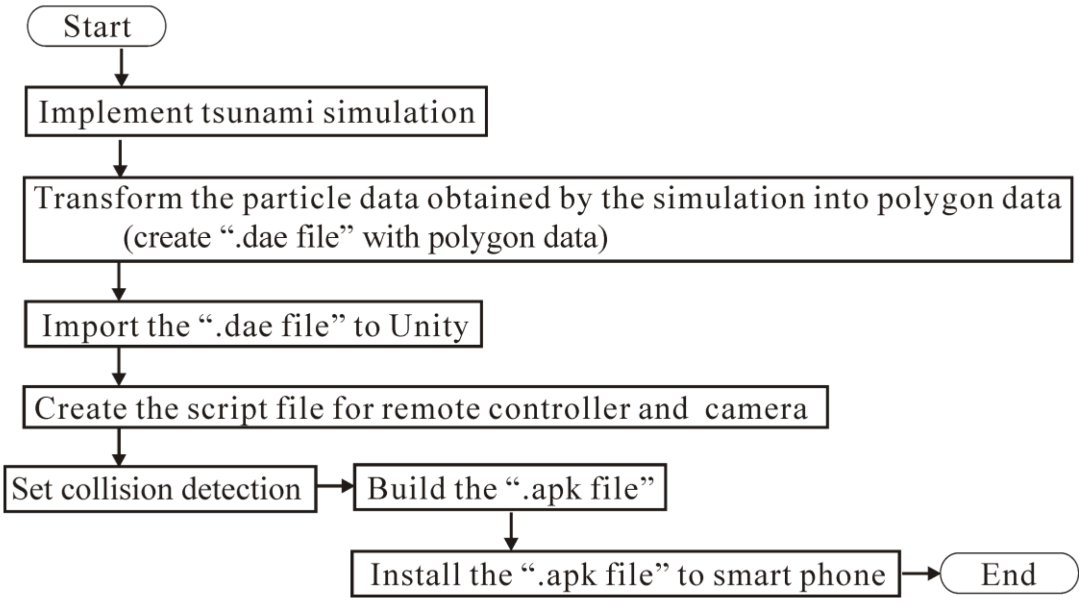


Figure 2. Flowchart of creating the ".apk file" required for the proposed VR system.

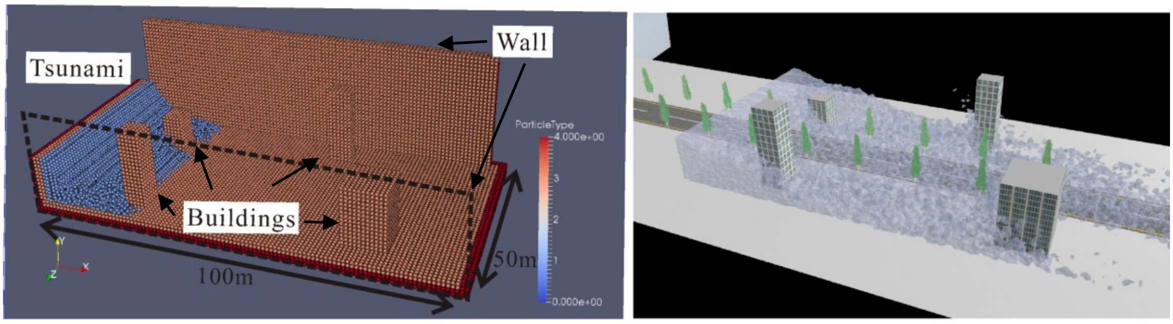
where c is the speed of sound. The density ρ^* in the intermediate step can be calculated by assuming that ρ^* is proportional to the sum of the weight function ω, as follows:

$$\rho^* = \frac{\rho^0}{n^0} \sum_{j \neq i} w\left(\left|\boldsymbol{r}_j^* - \boldsymbol{r}_i^*\right|\right). \tag{15}$$

In Eq. (14), the speed of sound c is given by $c = u_{max}/0.2$, where u_{max} is a predicted value of the maximum fluid velocity.

VR visualization using Unity

The tsunami run-up behavior can be calculated using the E-MPS, as explained in the previous section. Therefore, in this section, we briefly describe how to integrate the numerical results obtained by the E-MPS into a VR space. Although there are several kinds of VR systems, a mobile VR head-mounted display (HMD), which uses a smartphone for the display, is considered in this research, as shown in Fig.1. A VR system with a large-scale screen for



(a) (b)

Figure 3. Visualization results for tsunami simulation. An example of (a) particle data used in this analysis and (b) visualization of the numerical result with the aid of Maya.

tsunami simulation was developed by Kawabe et al. [11]. In addition, Tanaka et al. [12] proposed a tsunami virtual reality system using a head-mounted display connected to a high-performance notebook PC with a graphics-processing unit (GPU). However, their proposed system requires expensive high-performance equipment. Such systems are not suitable for allowing many people to experience a VR system in different places at the same time. For that reason, a VR system using a smartphone, which can easily and inexpensively provide a virtual tsunami experience, was constructed in this research.

Hereafter, a brief description of the VR system construction procedure is provided. The procedure used Maya [13] and Unity [14], which are the 3D computer software product with powerful modeling and widespread use as free VR development platform, respectively. In this research, first, a tsunami simulation using the E-MPS was implemented as the scenario that the VR user experiences. In general, the numerical results are output as a binary or text file. However, these file extensions are not suitable for Unity. Therefore, the output files are transformed by Maya into files with the extension ".dae", which are compatible with Unity. In this process, the particle data, which show the tsunami behavior, are obtained by the E-MPS and are transformed into polygon data. At that time, some models used in the E-MPS analysis, such as buildings, grounds, and timbers are rendered for a more realistic visualization. The setting of the camera, movement operation using the remote controller, and collision detection for walls, buildings, and trees, are also performed using Unity. This setting is implemented through the C#-like script programming in Unity. Finally, a file with the Android application extension, ".apk" is built and copied to a smartphone that is inserted into the VR glasses, as shown in Fig.1. The flowchart of these operation procedures can be seen in Fig.2. Obviously, this developed VR system is economical and does not need a high-performance PC and large screen, except for the workstation used in the particle simulation. Therefore, this system is suitable for disaster preparation training, such as in a situation in which the instructor has a large number of trainees for tsunami evacuation drills.

VR demonstration results

The VR demonstration results can be seen in this section. The E-MPS was applied to the tsunami simulation, whose model is illustrated in Fig.3(a). The scenario in this simulation is that of a virtual urban area with some buildings, which is hit by a tsunami. In general, the numerical models for particle methods are represented as an assembly of particles. Therefore, the fluid, riverbed, and buildings are represented by particles, as shown in the figure. The virtual walls are set with reflected boundary conditions for front and back, as shown in the same figure,

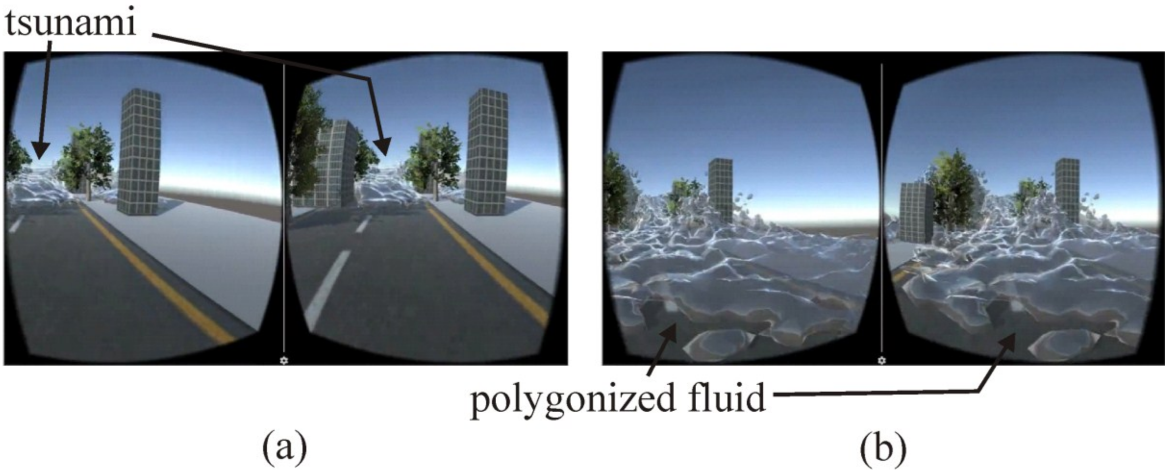


Figure 4. VR demonstration results at selected time steps:(a) a VR user can see the tsunami behind the building; (b) a VR user is swallowed by the tsunami.

to prevent the fluid from spreading widely in the VR space. The walls and buildings are treated as wall particles. In this analysis, the density of the fluid ρ (or ρ^0), speed of sound c, gravity $\boldsymbol{g}$, and time step size Δt are set as $\rho\ (\text{or}\ \rho^0) = 1000\text{kg/m}^3$, $c = 100.0\text{m/s}$, $\boldsymbol{g} = (0.0, -9.8\text{m/s}^2, 0.0)$, and $\Delta t = 1.0 \times 10^{-2}\text{s}$, respectively. In addition, the kinematic viscosity ν and number of the space dimension d are given by $\nu = 1.301 \times 10^{-2}\text{m}^2/\text{s}$ and $d = 3$, respectively. The particle data obtained by the E-MPS are transformed into polygon data and visualized by Maya, as explained in the previous section. Figure 3(b) shows an example of the visualized E-MPS numerical result obtained using Maya. Note that the trees in that figure are not considered in this numerical analysis model. In fact, the trees are simply located in the VR space to enhance the realism of the simulation in the steps of the Maya-visualization. The realistic visualization of this simulation was achieved with the aid of Maya. All of the static images for each time step, as shown in Fig.3(b), are prepared for the VR demonstration with a smartphone. These static images are gathered in Unity. Then, the Android application with the extension ".apk" is built and the resulting file is copied to the smartphone, which is inserted into the VR glasses.

Figure 4 shows an example of the VR demonstration results, which were obtained using Unity, according to the flowchart in Fig.2. Figure 4(a) and (b) show the stereo rendering images for the left and right eyes, respectively, through the VR glasses. In Fig.4(a), a VR user sees the tsunami approaching from behind the building. In Fig.4(b), the VR user is swallowed by the tsunami. From Fig.4, someone using the developed VR system using a smartphone can feel the velocity and height of the tsunami approaching, something that cannot be readily experienced in the real world. For example, a big tsunami such as the one observed after the Great East Japan Earthquake of March 11, 2011 occurs only once every several hundred years. Therefore, it was concluded that the developed VR system for experiencing a tsunami may be helpful as a method for tsunami disaster preparation drills.

Conclusion

In this study, a tsunami simulation was implemented using the E-MPS, which is one of the particle methods. The particle data obtained from the E-MPS were transformed into polygon data using Maya, and realistic static images were created. These static images were gathered, and the VR application was built using Unity. The VR demonstration results with a smartphone device installed (containing the developed VR application) were shown to prove that it worked properly. In the future, this developed VR system will be used for tsunami disaster preparation drills.

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References

[1] Motohashi, H., Sugatsuke, K., Nonaka, T., Kawasaki, K. and Harada, T. (2013) Tsunami damage simulation of KOIZUMI bridge, *Journal of JSCE*, B2 **69**, 831-835 (in Japanese).

[2] Flouri, E. T., Kalligeris, N., Alexandrakis, G., Kampanis, N. A., and Synolakis, C. E. (2013) Application of a finite difference computational model to the simulation of earthquake generated tsunamis, *Applied Numerical Mathematics* **67**, 111-125.

[3] Wei, Z. and Dalrymple, R. A. (2016) Numerical study on mitigating tsunami force on bridges by an SPH model, *Journal of ocean engineering and marine energy* **2**(3), 365-380.

[4] Zienkiewicz, O. C., Taylor, R. L., and Nithiarasu, P. (2013) The finite element method for fluid dynamics, Seventh Edition, Butterworth-Heinemann.

[5] Saitoh, T., Hirose, S., Fukui, T. and Ishida, T. (2007) Development of a time-domain fast multipole BEM based on the operational quadrature method in a wave propagation problem, *Advances in Boundary element technique*,Ⅷ, 355-360.

[6] Saitoh, T. and Hirose, S. (2010) Parallelized fast multipole BEM based on the convolution quadrature method for 3-D wave propagation problems in time-domain, IOP Conf. Series: *Materials Science and Engineering* **10**(1), 012242.

[7] Brebbia, C. A., Telles, J. C. F. and Wrobel, L. C. (2012) Boundary element techniques: Theory and applications in engineering, Springer.

[8] Koshizuka, S. and Oka, Y. (1996) Moving-particle semi-implicit method for fragmentation of incompressible fluid, *Nucl. Sci. Wng* **123**, 421-434.

[9] Shakibaeinia, A. and Jin, Y. C. (2010) A weakly compressible MPS method for modeling of open-boundary free-surface flow, *Int. J. Numer. Methods Fluids* **63** (10), 1208-1232.

[10] Oochi, M., Koshizuka, S. and Sakai, M. (2010) Explicit MPS algorithm for free surface flow analysis, *Proc. conf. Comput. Eng. Sci*. **15**(2), 589-590.

[11] Kawabe, T., Kashiyama, K., Miyachi, H., Iwatsuka, Y., Furumaki, D. and Nishihata, T. (2014) Development of a simulation based experience system for tsunami using sonification technology, *Journal of JSCE*, F3 **70**(2), 235-242.

[12] Tanaka, N., Saito, F. and Kitajima, M. (2015) Development of tsunami virtual reality system using head-mounted display, *CFD Symposium of Japan society of Fluid Mechanics*, A05-3.

[13] Riddell, D. and Britt, A. (2001) Maya: visual quickstart guide, Pearson Education.

[14] Linowes, J. (2015) Unity virtual reality projects: explore the world of virtual reality by building immersive and fun VR projects using Unity 3D, Packt Publishing.