Creating a High-Definition Animation of Tsunami Propagation 지진해일 수치실험 결과의 고해상도 애니메이션 생성

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Abstract : Simulation of the trans-oceanic or trans-basin propagation of a tsunami is a computer-intensive task. This study demonstrates an effective and detailed visualization technique to deal with the vast amount of surface-elevation and velocity-field output. This high-definition visualization technique is used to present simulations of the 1960 and 2010 Chilean earthquake tsunamis and the 1983 Central East (Japan) Sea earthquake tsunami. This tsunami-visualization method using high-definition graphic animation is an appropriate tool to show detailed tsunami-propagation behavior over an ocean or coastal sea, as exemplified by the Pacific Ocean and East (Japan) Sea tsunami events.

Keywords : high-definition graphic animation; 1960 and 2010 Chilean earthquake tsunami; 1983 Central East (Japan) Sea earthquake tsunami

요 지 : 대양 및 분지를 횡단하는 지진해일 전파 시뮬레이션은 컴퓨터 집약적인 작업이다. 이 보고는 지진해일의 해수면 높이와 유속장에 대한 방대한 출력을 다루는 효과적이고 상세화된 과학가시화 기법을 보여준다. 이 고화질의 과학가시화 기법은 1960년과 2010년 칠레지진해일의 시뮬레이션과 1983년 동해중부지진해일의 결과를 제시하는 데 사용되었다. 고화질 그래픽 애니메이션은 해양과 연안의 지형에 따른 지진해일의 자세한 전파양상을 보여줄 수 있는 도구이다.

핵심용어 : 고해상도동화; 1960년 및 2010년 칠레지진해일; 1983년 동해중부지진해일

1. Introduction

Many researchers throughout the world have used a variety of software to develop, visualize and analyze tsunami-propagation models and simulation results. Simulation of the trans-oceanic or trans-basin propagation of a tsunami is a computer-intensive task that produces vast amount of surface-elevation and velocity-field output. Near-shore models may not be efficient when applied to large domains, and deep-water models may not contain the necessary physics or resolution to simulate near-shore run-up. Tsunami models require nesting to vary in resolution from basin to shelf to near-shore applications. Due to the rapid increase in computing power and storage, the development of models incorporating finely detailed computational grids and meshes has also increased. However, the ability to visualize the computed results remains limited. Sub-sampled data have generally been used to display computed surface elevations,

possibly obscuring fine details of the propagation pattern. Accordingly, this study describes an attempt to create visualization tools that will more adequately represent tsunami-propagation behavior. The overall design of the study is based on simulating and visualizing the 1960 and 2010 Chilean earthquake tsunamis and the 1983 Central East (Japan) Sea earthquake tsunami.

The 1960 Chilean tsunami affected almost all Pacific coasts. The main tsunami waves crossed the Pacific Ocean and struck Hawaii, killing 61 people, and 142 people were killed in Japan 22 hours after the earthquake. Another earthquake of devastating magnitude (8.8) struck Chile on Feb. 22, 2010, and global tsunami-propagation warnings were issued. However, the scale of the tsunami was smaller than expected. Based on simulation results, the Japan Meteorological Agency (JMA) warned that a run-up of more than 2-3 m might strike the eastern Japanese coasts, including the Sanriku coast. Contrary to these expectations, the tsunami

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damage on the western side of the Pacific Ocean was not serious. Considering this underestimation of tsunami damage, the PTWC (Pacific Tsunami Warning Center) has emphasized the necessity of re-evaluating the warning system. These past experiences show that a simulation system involving reasonably accurate modeling and high-definition visualization of tsunami propagation is needed to develop an accurate tsunami-warning system.

Here, we demonstrate high-definition (1080-p) graphic animations for the events of the 1960 and 2010 Chilean earthquake tsunamis and the 1983 Central East (Japan) Sea earthquake tsunami. These animations make it possible to visualize tsunami behavior in greater detail.

2. Simulation of the 1960 and 2010 Chilean Tsunamis

The initial surface profiles of the tsunami simulations were determined according to the method of Mansinha and Smylie (1971) using modified parameters for the 1960 Chilean tsunami provided by Barrientos and Ward (1990) and USGS seismology parameters for the 2010 Chilean tsunami, as shown in Fig. 1. The velocity field at the tsunami source was assumed to be zero. The bathymetric data used in this computation was ETOPO5 data generated from a digital database on a five-minute latitude/longitude grid by the National Geophysical Data Center (NGDC).

The shallow-water equations for the global tsunami-

Fig. 1. Computed initial sea-surface elevations for the source areas of the 1960 and 2010 Chilean tsunamis.

propagation simulation were solved using a staggered-leapfrog finite-difference scheme. To achieve a stable computation of the convection term, the leapfrog method was applied in an upwind difference scheme (Imamura, 1995).

$$\frac{\partial \xi}{\partial t} + \frac{1}{R \cos \theta} \left[\frac{\partial P}{\partial \lambda} + \frac{\partial}{\partial \theta} (Q \cos \theta) \right] = 0,$$

$$\frac{\partial P}{\partial t} + \frac{gh}{R \cos \theta} \frac{\partial \xi}{\partial \lambda} - fQ = 0,$$

$$\frac{\partial Q}{\partial t} + \frac{gh}{R} \frac{\partial \xi}{\partial \theta} + fP = 0,$$

In the equations above, ξ is the elevation of the sea surface above the undisturbed level; θ is latitude and λ is longitude; P and Q are discharge per unit width in the θ and λ directions, respectively; h is the undisturbed level; R is radius of the earth; g is the acceleration due to gravity; and f is the Coriolis parameter. The results of this model have been reported extensively (Imamura et al., 1988), and we do not restate them here.

Figs. 2 and 3 show snapshots of the trans-Pacific tsunami propagation of the 1960 and 2010 Chilean tsunamis, respectively. These photorealistic images were constructed using the high-definition rendering technique described in section 3 (below). The initial states of the 1960 and 2010 events are shown in Figs. 2(a) and 3(a), respectively, and the states of propagation at 16 hours after the initiation of the events are shown in Figs. 2(c) and 3(c). At that time, the leading waves were already passing the Hawaiian Islands. Figs. 4 and 5 show zoomed images of the area around the Hawaiian Islands between 13 and 15 hours after the propagation began. The propagation patterns of the 1960 and 2010 Chilean tsunamis were similar in time but different in magnitude, as shown in Fig. 4 (the same vertical exaggeration was applied to both images). The earlier event brought heavy damage at Hilo, while the latter did not.

3. Simulation of the 1983 Central East (Japan) Sea Tsunami

At noon on May 26, 1983, a huge earthquake occurred in the eastern East (Japan) Sea. The highest run-up of the subsequent tsunami was measured at more than 15 m above mean sea level (MSL) along Japanese coasts. The tsunami crossed the East (Japan) Sea and damaged the central portion of the eastern coast of Korea, inundating the ports

Fig. 2. Trans-Pacific propagation of the 1960 Chilean tsunami.

Fig. 3. Trans-Pacific propagation of the 2010 Chilean tsunami.

Fig. 4. Tsunami wave passing the Hawaiian Islands (1960 Chilean tsunami).

Fig. 5. Tsunami wave passing the Hawaiian Islands (2010 Chilean tsunami).

of Mukho and Imwon.

Several studies have performed numerical modeling of the tsunami propagation that occurred on the eastern coast of Korea in 1983 (Tsuji, 1986; Choi et al., 2003, 2006; Yoon,

2002; Cho et al., 2004). Lee and Kim (2000) and Choi et al. (2008) have specifically modeled the propagation of the wave toward the Imwon area.

In the tsunami source area, which is several tens of kilometers in width and length and is located in a sea that is several kilometers in depth, the ratio of depth to wavelength is generally 2:10 and the wave steepness is generally 3:10. For our simulation, we chose to apply Aida's Model 10 (Aida, 1984). Based on several parameters associated with the 1983 Central East (Japan) Sea earthquake (magnitude 7.2), this model is considered to be the most effective yet proposed to explain the total amount and distribution of tsunami energy and has been used in previous studies of tsunami propagation in the East (Japan) Sea (Abe and Ishii, 1987; Lee and Kim, 2000; Choi et al., 2003, 2006, 2008).

The bathymetric data used in this computation was compiled from digitized hydrographic charts of the East (Japan) Sea and existing offshore depth data (Choi et al., 2002). To compute the tsunami run-up and inundation, bathymetric data with an extremely fine-mesh grid (less than 5-10 m) is generally needed to achieve results that can be applied in a practical manner. However, it is impossible to use such a fine-mesh grid for the whole region of the East (Japan) Sea. Therefore, we used a dynamic-interfacing method to overcome this problem. In this method, larger grids in the deep sea are dynamically linked with grids in the shallower region that are

one-third of the size of the larger grids. In the computation, water levels and discharges are exchanged with each other at every linked boundary, and their relationships must satisfy a dynamic balance. To compute the tsunami run-up in the area of interest, the process is continued until the required grid resolution is achieved. This procedure makes it possible to reproduce the local variation in topography and shoreline on discrete grid meshes. In this case, a discrete 1.1-km grid mesh was used to divide the total area of the East (Japan) Sea. Based on the dynamic-linkage concept, bathymetric data for seven regions along the eastern Korean coast were compiled for the computation that connected each region (Choi et al., 2003).

A total of six sub-regions were used, each of which had a different grid size. A larger-mesh grid in the outer region was connected to a smaller-mesh grid in the inner region. The terminal region was the Imwon Port. Fig. 6 shows a computational domain covering the entire region of the East (Japan) Sea. In Fig. 6, the boxed area represents the dynamic linkage between the larger and smaller grid meshes. This linkage was accomplished through a refinement of three times the 1:3 grid (specifically, 1.1 km to 370 m, 370 m to 123.3 m and 123.3 m to 41.1 m) near the Imwon Port, as shown in Table 1. To compute the tsunami inundation at the Imwon Port, the grid mesh was again divided consecutively into a 13.7-m mesh, a 4.56-m mesh and finally a 1.52-m mesh size, all of which were dynamically linked. The computational region for the Imwon Port is shown in Fig. 6. Snapshots of the tsunami propagation in the East (Japan) Sea, computed in the framework of this model, are shown in Fig. 7. Approximately

Table 1. Computational parameters

	O	A	B	C	D	E	F
Dx ^a	1110	37	123.3	41.1	13.7	4.56	1.522
Dt	3.6	1.2	0.6	0.6	0.3	0.1	0.5
Nx ^b	1170	916	580	562.0	169.0	217.0	586.0
Ny ^c	1170	970	955	490.0	235.0	268.0	748.0
GE ^d	LLW ^e	LLW	SWT ^f	SWT	SWT	SWT	SWT
LB ^g	VW ^h	VW	VW	VW	MB ⁱ	MB	MB
OB ^j	RC ^k	DLI	DL	DL	DL	DL	DL

^aGrid size in the x-direction (same size in the x- and y-directions).

^bTotal number of grid cells in the x-direction.

^cTotal number of grid cells in the y-direction.

^dGoverning equation.

^eLinear long-wave equation.

^fShallow-water theory.

^gLand-boundary parameter at the shoreline.

^hVertical-wall parameter.

ⁱMoving-boundary parameter.

^jOffshore-boundary parameter.

^kRadiating parameter.

^lDynamic linkage.

100 minutes after the tsunami began, the tsunami waves approached the eastern Korean coast.

The layout of the Imwon Port has recently been altered by the extension of the breakwater. Identical simulations using the new topography and breakwater layout in the finest-scale domain are shown in Fig. 8. The new port (breakwater) layout reduces the tsunami-induced vortex within the port, thus protecting the inner-port area from tsunami damage. The high-definition animation showing tsunami-induced current-vector fields shows remarkable changes in vortex patterns depending on the breakwater layout, providing useful engineering information. Three-dimensional modeling and visualization of the tsunami run-up and inundation at the port of Imwon has been reported previously (Choi et al., 2008).

4. Procedure to Create the High-Definition Animation

The procedure followed to create the high-definition animation and to produce a Blu-ray video of the results is described below. High-resolution printable graphics can be created using a variety of visualization software. However, animations showing the simulation results are necessary to demonstrate predicted effects and to make intuitional decisions without sub-sampling.

We chose to employ the HD (high definition) format to display animations of our simulation results. Just as HD is more engaging for the viewer than SD (standard definition), 4K projection is far more immersive than HD (Fig. 9). The

Fig. 6. Nested-grid system used in the tsunami model for the East (Japan) Sea, showing the bathymetry of the basin.

Fig. 7. Snapshot images of computed sea elevations for the tsunami that occurred on May 26, 1983, in the East (Japan) Sea.

Fig. 8. Computed vortex field in the port of Imwon after 150 minutes for two different breakwater layouts.

Fig. 9. Standard Definition (SD) and High Definition (HD) versus 4K.

4K projection format enables the viewer to sit close to the screen and still perceive a seamless, continuous picture. 4K content can be created from scans of 35-mm or 65-mm

motion-picture film, from computer animation and from emerging 4K digital-acquisition systems. For digital cinema, this content is typically played through a growing selection of third-party servers that are compatible with the 4K signal. Furthermore, 4K is a dramatic departure in image resolution, with four times the pixels of HD presentation. The details of the technique of creating the HD animation are described below.

4.1 Data preparation

The file size of the simulation output for HD animation becomes larger as the model grid domain and time-step length increase. A binary file with a header consisting of model information, such as netCDF, is good solution to save storage space. In this approach, we used the netCDF

format to save the output of the model and the input of the visualization tools.

4.2 Snapshot production using OpenDX

The simulation usually produces a huge amount of information at each step. To appropriately interpret this information, it is necessary to use state-of-the-art visualization techniques and data processing. IBM's Visualization Data Explorer is a modular visualization environment that makes it possible to construct complex graphical systems using simple elementary tasks. In 1999, this system became an open-source software package (OpenDX, <http://opendx.org>), and it is now available to all scientists without cost. OpenDX is a simple and cost-free way to create professional visualizations (Fig. 10).

Basically, OpenDX consists of three fundamental parts: (1) a graphical user interface (GUI), which enables the user to control all visualization parameters, (2) an execution environment, which executes the so-called visualization program and (3) a data model, which constructs a well-defined representation of the data. Fig. 10 shows an example of the “data-flow” execution model. Data provided to OpenDX flow through a network of modules, and finally an image is

generated. The network of modules is a simple graphical representation of the process to be executed on the data. This method provides a simple and intuitive way to produce sophisticated graphical applications without any technical programming work.

OpenDX supports variable formats for data input, including the ASCII native format (*.dx) with a specific structure, netCDF (*.nc) and heading files (*.general) containing information for other ASCII or binary data files. The netCDF format is suitable for regular-grid data to save disk space and reduce the number of files. However, unstructured data (e.g., the FEM mesh system) must use the OpenDX native format. For output, the program natively supports JPG, RGB and TIFF image formats. External commercial modules make it possible to produce DXF CAD and Postscript files.

4.3 Creating a movie file (AVI) of the high-definition animation

The sequential image output in TIFF format was converted to BMP using the “convert” function of ImageMagick software. Next, the sequential BMP files were encoded into a clip (AVI) using VirtualDub with time control of 1 fps (frame per

Fig. 10. Examples of the data-flow execution model using OpenDX and its results.

second). VirtualDub is an open-source freeware program and is easy to use. To maintain image quality, the video was set to “Compression to Uncompressed RGB/YCbCr”.

Title and text pages appended to the animation were made using Adobe Photoshop and imported using Adobe Premier. Adobe Premier is essential software to compose clips, sound, title and text pages. After rendering using Adobe Premier, one very large non-compressed AVI file was built. For HD animation, the frame size and rate were set to 1920×1080 and 24 fps (1080/24 p). The size of this non-compressed AVI file was about 200 GB for 10 minutes of playing time. The file can be compressed to be playable on a PC using a codec that supports 1080-p resolution, such as MPEG2, H.264 or divx. Encoding with H.264 produces the best quality and smallest size. Microsoft supports H.264 encoding using the Windows Media Encoder program.

4.4 Formatting for Blu-ray movie players using Blu-ray or DVD disk media

Blu-ray is the only format capable of playing the high-definition animations, except for playback on a PC. We used Adobe Encore to create a Blu-ray movie on a Blu-ray disk using H.264 and MPEG 2 formats. This movie can be played on a Blu-ray movie player or a Sony Playstation 3. Nero Vision 5 is a DVD authoring tool using the AVCHD format. AVCHD is the general format used to create HD movies on DVD disks (Fig. 11). However, Nero Vision 5 supports only 1080i mode. All of the resources necessary to create high-definition

tsunami-propagation animations are stored at <http://sites.google.com/site/hdtsunami> and on separate DVD-ROMs.

5. Conclusions

This study demonstrates an effective method for the high-definition visualization of tsunami models. Using high-definition graphic animation, the propagation of a tsunami can be closely reproduced and subjected to detailed analysis. The use of high-definition animation makes it possible to better understand the behavior of tsunami propagation and to effectively prepare for tsunami damage, such as by creating tsunami-inundation maps for coastal areas based on the detailed results.

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Fig. 11. AVCHD video of the high-definition tsunami animation produced as a joint project of the IUGG/TC and ICG/ITSU (<http://sites.google.com/site/hdtsunami>).

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