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Three-Dimensional Visualization of Tsunami Propagation and Inundation
地震海溢의 전파 및 처오름에 관한 3차원 映像化

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Abstract □ A three-dimensional visualization of the tsunami transoceanic propagation and associated run-up process is described. The visualization is done by using high performance graphic computer and video system. As a case study, a three-dimensional animation of the 1960 Chilean tsunami propagation across the Pacific Ocean and inundation at Hilo Bay, Hawaii is made and presented.

要　旨 : 고화질의 그래픽 컴퓨터와 映像장치를 이용한 地震海溢의 전파 및 이에 부수되는 처오름 과정의 3차원 映像化에 관하여 기술하였다. 실제로, 1960년 칠레지진에 의해 발생한 지진해일이 태평양에서 진행하는 과정 및 하와이 힐로灣에서의 氾濫하는 과정에 관한 수치해석의 결과를 3차원으로 映像化하였다.

1. INTRODUCTION

Tsunami is a combined Japanese word: "tsu" means habor and "nami" means wave. Therefore, tsunami literally means "harbor wave." The word might be created to describe large amplitude oscillations in a harbor under the resonance condition. Most of tsunami-spawning earthquakes occur in subduction zones around the Pacific Ocean rim, where the dense crust of the ocean seafloor dives beneath the edge of the lighter continental crust and sinks down into Earth's mantle (Folger, 1994). These subduction zones include the west coast of North and South America, coasts of Japan, East Asia and many Pacific island chain.

The impulsive seafloor movement in the fault region causes the deformation of water surface instantaneously. The suddenly gained potential energy is converted to kinetic energy by the gravitational force, which serves as the restoring force of the system. The wave height of a tsunami may be in the order of several meters, while the wavelength can be up to 1,000 km in the ocean, where the average water depth is about 4 km. Therefore, the leading wave can be considered as a long wave propagating with a speed of a linear long wave, i.e. $\sqrt{gh}$, where g is the acceleration due to the gravity and h is the water depth. For example, the leading wave of a tsunami travels approximately at a speed of 700 km/hr in the ocean. However, as a tsunami propagates over a continental shelf and approaches a coastal area, the wavelength decreases and the amplitude increases. A tsunami could cause a severe coastal flooding and property damage.

Recently, three undersea earthquakes, triggering huge tsunamis, occurred in the Pacific Ocean area. The epicenter of the first earthquake was about 100 km off the Nicaraguan coast and it happened on September 2, 1992. The second one was near Flores Island in Indonesia, which occurred on December 12, 1992. The third one was near Hokkaido Island in Japan, which striked Okushiri and Hokkaido Islands on July 12, 1993. These earthquakes occurred near residential areas. Therefore, the damage caused

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Table 1. Recent earthquakes occurred in the Pacific Ocean area

location	scale (Richter)	loss of lives	observed run-up (m)
Nicaragua	7.0	168	10
Indonesia	7.5	2,080	26
Japan	7.8	237	30

by subsequent tsunamis was unusually large. Table 1 shows magnitudes of these earthquakes, loss of lives and observed maximum run-up heights. It is noted that the loss of lives in Table 1 is the combined effects of both earthquake and tsunami.

Several numerical and experimetal studies have been carried out to investigate physical phenomena and engineering problems involved in tsunamis generated by these earthquakes listed in Table 1 (e.g. Choi *et al.*, 1993, Choi and Woo, 1994, Liu, *et al.*, 1994a, 1994b). In general, the numerical simulation of tsunami transoceanic propagation and inundation requires a huge amount of computer memory size and computing time. However, these requirements have rapidly become a less problem because of the advancement of computer technology. In the on-going research program, we have made several video tapes documenting the real tsunami events such as 1960 Chilean tsunami, 1992 Flores tsunami and 1993 Hokkaido tsunami.

It is not our purpose in this paper to present a detailed description and discussion of the numerical simulation of the tsunami propagation and inundation. We will only focus on the three-dimensional visualization which may provide insight into the mechanisms of tsunami propagation and inundation. As an example, we present the transoceanic propagation and inundation at Hilo Bay, Hawaii of the 1960 Chilean tsunami. Because of space limitation, we only present several visualized color plates showing tsunami propagation across the Pacific Ocean and run-up process at Hilo Bay. In the next section, we briefly describe the numerical model. Numerical results and discussions are then presented in Section 3. Finally, concluding remarks are given in Section 4.

2. NUMERICAL MODEL

An effective and economic way for the tsunami hazard mitigation planning is to construct inundation maps along those coastlines vulnerable to tsunami flooding. These maps should be developed based on the historical tsunami events and projected scenarios. The generated inundation map could be used by the civil defense organizations to make evacuation plans in the event of a real tsunami assault. To produce realistic and realiable inundation estimates, it is essential to use a numerical model that calculates accurately tsunami propagation from a source region to the coastal areas of concern and the subsequent tsunami run-up process.

In this study, we use two numerical models describing the transoceanic propagation and the associated run-up process of tsunamis, respectively. For a distant tsunami, tsunami could travel across the ocean. Both the frequency dispersion and Coriolis force could play important roles. On the other hand, the wave slope of a typical tsunami is very small. Therefore, the nonlinear convective inertia force is not significant and can be ignored. The linear Boussinesq equations including Coriolis force are adequate to describe the transoceanic propagation of tsunamis (Imamura *et al.*, 1988; Liu *et al.*, 1993).

As tsunamis propagate into the shallow-water region, the wave amplitude increases and the wavelength decreases due to shoaling. The nonlinear convective inertia force becomes increasingly important. In the very shallow water, the bottom frictional effects become significant, while the significance of the frequency dispersion diminishes. Therefore, the nonlinear shallow-water equations including bottom frictional terms should be used in the description of the tsunami inundation. To obtain the information on the inundation area, a special treatment is required along the shoreline to track the location of a moving shoreline as waves rise and recede.

An explicit leap-frog finite difference scheme has been developed to solve both linear and nonlinear shallow-water equations. By manipulating the time step size and spatial grid size, numerical solutions of the finite difference approximations for the linear shallow-water equations satisfy the linear Boussinesq equations. A moving boundary technique has also been developed, in conjunction of the leap-frog

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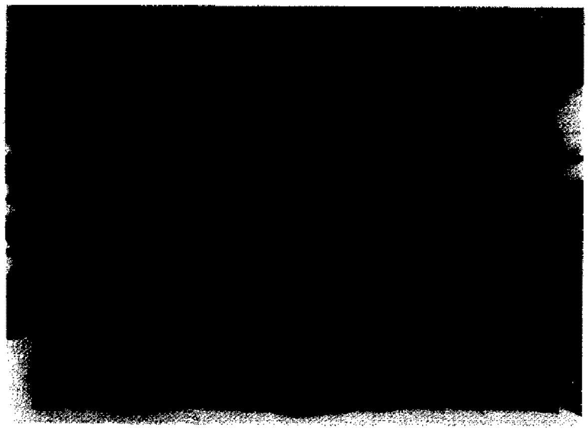
scheme, to trace the shoreline movements. More detailed description of numerical models including the moving boundary treatment can be found in Liu *et al.* (1993) and Liu *et al.* (1994b).

Both numerical models are applied to the 1960 Chilean tsunami, which was recorded as one of the most devastating tsunamis in the Pacific Ocean area. The linear model is used to simulate the propagation of tsunami from the source region near the Chilean coast to the Hawaiian Islands chain. The linear model is extended to include the varying depth by using a multiple-grid system (Liu *et al.*, 1993). The nonlinear model is then used to simulate the flooding inside Hilo Bay, Hawaii.

3. NUMERICAL RESULTS AND DISCUSSIONS

Several frames showing vibration of the entire Pacific Ocean are displayed in Plates 1-5. These plates are taken from the numerical simulation of tsunamis generated by an earthquake off the west coast of Chile in 1960 that devastated not only along the Chilean coast but also at Hilo Bay and along the Japanese coast, which are away about 10,000 and 16,000 km from the source region, respectively. Leading waves reached at the Hawaiian Islands chain and the Japanese coast after roughly 14 and 22 hours traveling, respectively. In Plates



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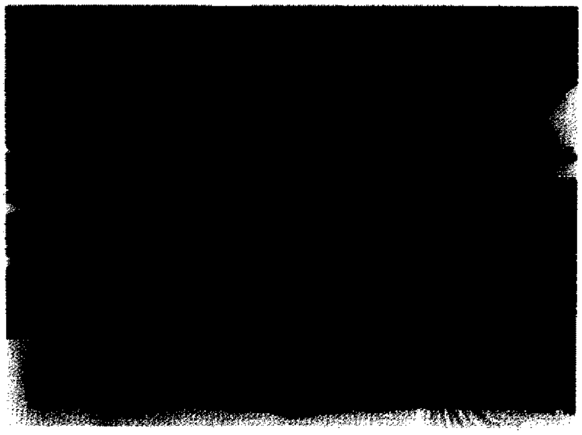

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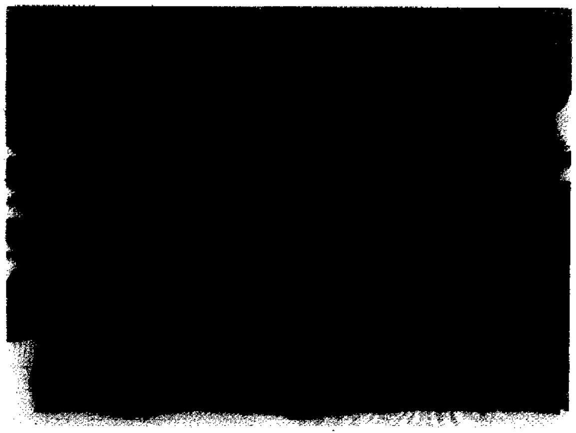

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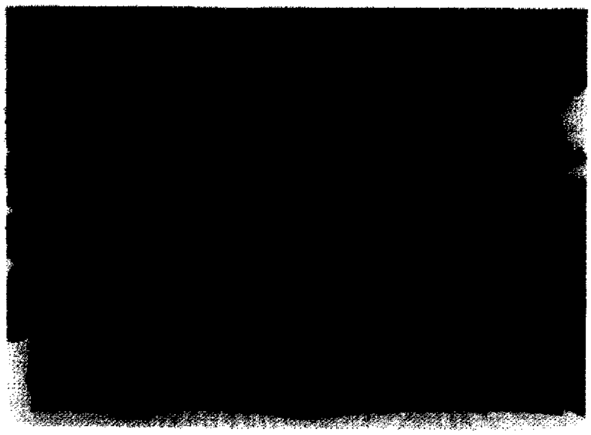

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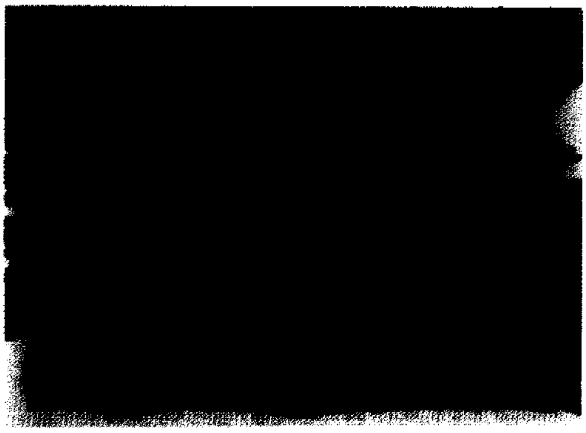

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1-5, images are approximately zero, four, eight, twelve and sixteen hours after the earthquake.

In Plate 1, the coastlines around the Pacific Ocean are shown. A positive hump appears near the Chilean coast in the very early stage. As tsunamis propagate into the Pacific Ocean, the wave front spreads over a large area, reducing the leading wave amplitude in Plates 2-5. The high frequency oscillations are also amplified during the ocean journey. Most of countries adjacent to the Pacific Ocean are affected by tsunamis in Plate 5.

In Plates 6-10, the run-up process inside Hilo Bay is closed up. In the numerical simulation, both the bathymetry of the bay and the land topography are digitized and stored for each mesh. As shown in Plate 6, no initial motion is assumed inside Hilo Bay. The white contour denotes initial shoreline. The continuous run-up and run-down of incoming tsunamis along the shoreline are clearly shown. The diffraction around the breakwater is also shown. The contour lines in Plates 6-10 are simply used to increase visibility. The red contour represents the highest wave, whereas the blue one does the lowest wave.

The developed video tape not only documents the numerical results, but also provides educational materials for the public domain. Snapshots presented in this paper are frames of computer animation generated using IBM Data Explorer software on the IBM POWER Visualization System of the Engineering and Theory Center at Cornell University.

4. CONCLUDING REMARKS

It has been shown that the visualization is a powerful tool to deliver numerically simulated results efficiently and clearly. An animation for the 1960 Chilean tsunami propagation and inundation was made by using the high performance graphic computer and video system. This visulaization can replace the laboratory experiment to some extent and can also be used to verify numerical models. Another three-dimensional visualization for interactions between incoming solitary waves and a circular island will be reported soon. The visualization for other tsunami events was also tried and reported in Choi *et al.* (1993).

It is remarked that although the initial tsunami shape is not mentioned here, this topic is important in determining the maximum run-up height on a beach. This should be studied carefully and extensively.

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