INTEGRATED SIMULATION OF TSUNAMI HAZARDS

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ABSTRACT

It is impractical to give warning and evacuate people from the direct effects of an earthquake, since the fault rupture and ground motion occur almost concurrently. In contrast, the lead time between detection of a seismic signal and the resulting tsunami make warning and evacuation at least possible. We developed an integrated simulator as a tool to improve both warning systems and evacuation methods. The simulator combines three distinct numerical models simulating the hydrodynamics of wave propagation and runup, the dissemination of warning information, and human response to the warnings. The simulations are integrated and presented in a GIS (geospatial information system) framework using realistic computer graphics. Its results can be utilized for planning warning systems and evacuation strategies, the primary mitigation measures for rare events like tsunamis. The visual GIS presentation also makes the simulator effective for educating the general public on the consequences of how they respond to warnings. As a test case, we applied the simulator to the city of Owase, Japan, which will be vulnerable if an anticipated large submarine earthquake triggers a tsunami event.

Introduction

Tsunamis are rare events whose behavior and characteristics are extremely difficult to measure or understand. The effects of tsunamis on a particular region of coast cannot be predicted from similar events in other regions, nor by extrapolating previous local phenomena such as storm waves or hurricane surges. This is particularly unfortunate because the timing of tsunamis makes effective response feasible. Unlike direct seismic effects, where ground shaking is practically concurrent with fault rupture, there is usually a (short) lead time for predicting tsunami attack after receiving the seismic signal. This lead time can range from a few minutes for a local source to ten or more hours for a distant source. Even though tsunami warning times are much shorter than those of many other natural hazards (e.g., volcanic eruptions, hurricanes, and floods), effective warning and evacuation could minimize the loss of life from these rare natural hazards.

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The Sumatra Tsunami that struck the countries of the Indian Ocean on December 26, 2004, provided a grim reminder of the power of surge hazards. Then on August 29, 2005, category-4 Hurricane Katrina struck the Central Gulf Coast. For those at risk from tsunamis and hurricane surges, the best protective action is evacuation. Specialized detection networks have been developed to provide forewarning, but even well established systems such as the Pacific Tsunami Warning Center (PTWC) and West Coast and Alaska Tsunami Warning Center (WC&ATC) cannot provide complete protection, especially for locally-generated tsunamis. The forecasting of tsunami impact involves significant uncertainties that affect local emergency managers' decisions about whether to recommend protective actions, and when to initiate them. Remotely generated (e.g., the 1960 Chilean) tsunamis may provide 15 hours of forewarning for Hawaii and California (Wiegel, 1964). Tsunamigenic earthquakes in the Cascadia Subduction Zone, however, occur only a few hundred miles off the Pacific Northwest coast and the resulting surge could strike the shore within 20 minutes. Such locally-generated tsunamis strike with little warning – just the ground shaking associated with the earthquake itself.

Comprehensive hazard/vulnerability analyses are needed to identify which geographic areas and population segments are at risk, and evacuation models are required if emergency managers are to make decisions about which groups to evacuate from the risk area, which should seek shelter in safe havens, and when the actions should be initiated. It is to enable such analyses that effective computational tools are needed. Because safety ultimately depends on human behavior during a hazard situation, the tools must integrate the behavior of the physical event, dissemination of warning information, and human response to that information.

Simulation of Tsunami Scenarios

A comprehensive scenario simulator was developed to support rational tsunami hazard and vulnerability analyses. The simulator integrates three modules: 1) hydrodynamic numerical simulation of tsunami propagation and runup; 2) warning transmission simulation; and 3) evacuation simulation. Although the hydrodynamic simulation is deterministic, the other two components are probabilistic.

Hydrodynamic simulation models for tsunami generation, propagation, and runup have been used often in practice (e.g., Titov & Synolakis, 1998; Lin, et al., 1999; Imamura, 1996). Most models used in practice employ finite-difference methods based on fully nonlinear shallow-water-wave theory. While the numerical algorithm itself is considered adequately accurate (e.g. Yeh, et al. 1995), it remains difficult to determine practical tsunami-source conditions; prediction of sea-floor displacement is still a formidable task. (Note that in the last two years or so, the seismology community has made significant advances in the ability to model the rupture process in detail; Ammon et al. (2005) presented detailed temporal and spatial movements of the sea-floor displacement from the December 26, 2004, Sumatra Earthquake.) Even when the initial tsunami condition is known, it is difficult to acquire accurate and high-resolution bathymetry and coastal-topography data. Tsunamis typically have wavelengths of 10s to 100s of kilometers and particle motion occurs over the whole water column, so the deep ocean bathymetry is important. Tsunami simulations therefore require integrated shallow and deepwater bathymetry including detailed information from the continental slope and shelf. (As a rule of thumb (after Shuto et al., 1986), a minimum of 30 grid points per wavelength are required for the models. Thus, in deep (4000m) water, a wavelength of 60-600 km will require a minimum grid or 2-20 km; on the continental shelf (250m), a wavelength of 15-150 km means a minimum grid of 0.5-5 km; in shallow (100m) water, a wavelength of 10-100 km requires a minimum grid of 0.3-3km; and in very shallow (10m) water, a wavelength of 3-30 km means a minimum grid of 0.1-1km. For the runup region, a grid size less than 10 m is needed to resolve complex on-shore features.) For our simulator, we used the leap-frog type finite difference model, similar to Lin, et al, (1999) and Imamura (1996).

The warning transmission module models both official ("broadcast") and informal ("contagion") processes. The informal network (person-to-person oral communications) is the primary method of warning transmission, since official warnings (processed by government authorities and transmitted by loudspeakers, route alert vehicles, radio, and TV) are relatively slow in responding to a locally-generated tsunami (and, indeed, might be totally destroyed by the earthquake that caused it). In the model, informal communications are controlled by four parameters: 1) the number of households, 2) the distances among households, 3) the delay in initiating contact, and 4) preference parameters. Rather than being based on a purely random-choice diffusion process, it includes preferential contacts based on a probabilistic biased network model (e.g. Rapoport, 1979; Fararo,1981; Skvoretz, 1985). In addition, there are control parameters distinguishing "normal" days from those with stressed conditions during disasters. For example, the number of contacts (receivers) is larger during disasters, the communication distances between contacts are shorter, and the preference parameter is weaker. The values assigned to control parameters have been computed from data collected in surveys conducted by Katada, et al. (1996, 1997, and 1999). Additional parameters control the loudspeaker warning system (loudspeaker locations, audible distances, audience share, announcement frequency, and timing), route alert vehicles such as police cars and fire engines (routes and speeds, dispatch timing, audible distance, and audience share), and radio/television (audience share, announcement frequency, and timing).

Evacuation simulation is modeled in two steps: 1) individuals' decision-making and preparation processes for evacuation, and 2) the actual evacuation process. The first step reflects:

- the number of repeated warnings received (and from which channels)
- evacuation actions taken by neighbors and friends
- location of the household
- prior knowledge and/or experience of tsunamis
- time to evacuate after the decision is made

Those parameters are assigned based on data collected by questionnaire surveys (Katada, et al., 1996, 1997, and 1999). The current model only simulates the evacuation of individuals moving on foot toward the closest shelters or high ground, but evacuation methods (e.g., motor vehicles) and potential setbacks (road blockage, bridge failure, etc.) will be introduced in future versions.

The integrated simulator uses a GIS framework to produce an animation of the tsunami runup (typically occurring in multiple waves), warning transmission patterns, and individuals' protective responses. Figure 1 shows how the components interact. To evaluate the overall outcome, the program determines 1) the number and spatial distribution of households receiving a warning, 2) the temporal distribution of those warnings, and 3) the cumulative effects of informal communication (oral and telephone) patterns. The third item is important, since informal person-to-person communication is apt to degrade the accuracy of information transmission (for example, if the probability of incorrect warnings is 30% at each step, only 34% of warning messages are correct after 3 steps). Once an area is inundated by a tsunami, all people within it are assumed dead; the current model does not include a formal casualty model.

The animated display is useful in identifying the effects of hazard mitigation measures (such as seawalls), emergency response resources (e.g., number and capacity of evacuation routes, locations of tsunami shelters) and emergency response procedures (e.g., amount of forewarning and routing of route alert vehicles). The simulator is still under development, but provides a good framework for incorporating empirical warning and evacuation data.

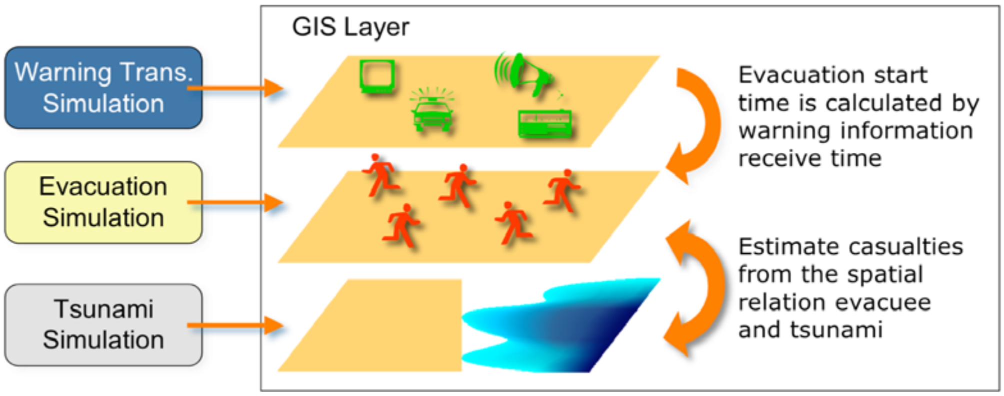

Figure 1. Schematic representation of the integrated tsunami scenario simulator

Applying the Simulator to Owase, Japan

Owase City is a mid-sized coastal community (population 23000; area 193 km^2) along Japan's Pacific coastline (see Figure 2). About 90% of its area is steep, mountainous terrain, and 80% of the population resides in the vicinity of Owase's port. The coastline is so rugged that any tsunami is amplified locally and the community has suffered from many tsunami events in the past. The 1944 Tou-Nankaido and the 1946 Nankaido tsunamis, for example, were generated along the Nankai Trough Seismogenic Zone, approximately 150 km offshore from Owase, and if a similar event occurs in the future, an approximately 7m-high tsunami would hit the city within 20 minutes of the earthquake. Figure 3 shows the present state of preparedness, including the locations of warning loudspeakers and tsunami shelters, the routes of alert vehicles, and areas of high ground (30+ m above sea level). Note that this community not only has a port facility, but also an oil terminal berth, an electric power plant, two rivers, and several major bridges.

The wave (hydrodynamic) simulation was performed with a grid size of 50m throughout the domain. Because this is adequate for the simulation of tsunami propagation, but too coarse for the runup, a resolution of 16.7m was used to present the runup results. Accurate hydrodynamic simulation is a challenge, due to the complex structure of the area and its infrastructure, so the hydrodynamic simulation must be considered preliminary at this point.

For simplicity, the following parameters were used to simulate warning transmission to the 6,651 are households:

- walking speed to accomplish oral communications = 80m/min
- degradation rate of information = 30%
- effective audible radius for loudspeakers and route alert vehicles = 250m
- audience share for loudspeakers, route alert vehicles, and mass media = 30%
- speed of alert vehicles = 20 km/hr.

Figure 2. Map of Owase City (Kii Peninsula, Japan)

Figure 3. Owase's current warning transmission and evacuation facilities (35 emergency warning loudspeakers, 4 route alert vehicles, and 25 shelters, serving 6,651 households)

A Monte-Carlo simulation of 100 trials was conducted and the average values were compiled. Figure 4 shows the distribution map of warning reception timing, assuming the official warnings were issued 3 minutes after the earthquake. This type of map can provide emergency response managers with information to improve their strategies, such as determining additional locations for loudspeakers and more effective routes for alert vehicles. Figure 5 shows the distribution map of the timings for individuals to reach safety; this could help, for example, to identify locations for additional tsunami shelters.

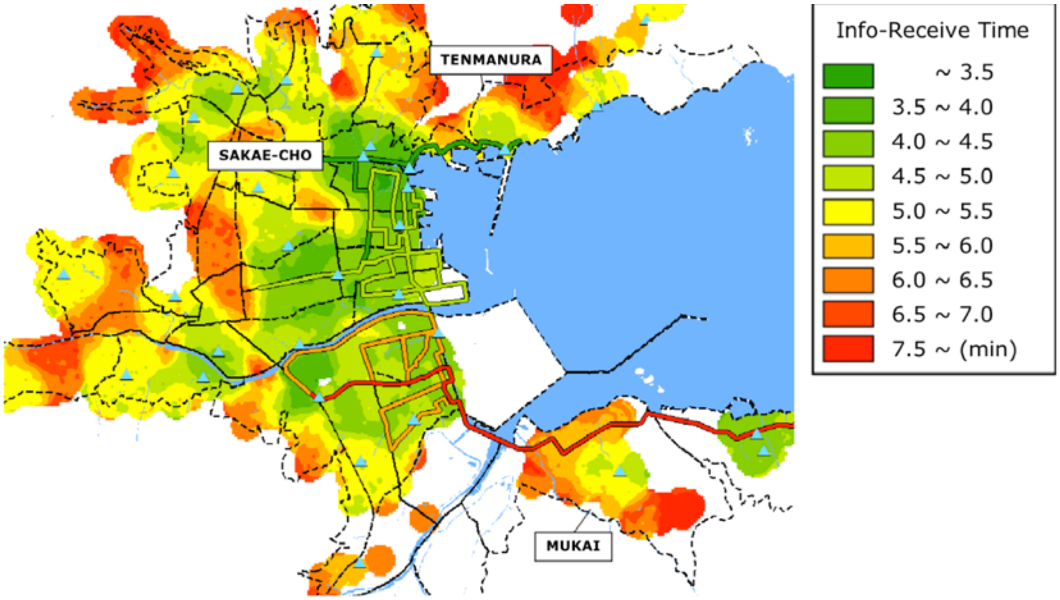

Figure 4. Warning reception times, assuming official warnings are issued 3 mins after the earthquake; 98.5% of households received the warning, with an average reception time of 4 min. 58 sec.

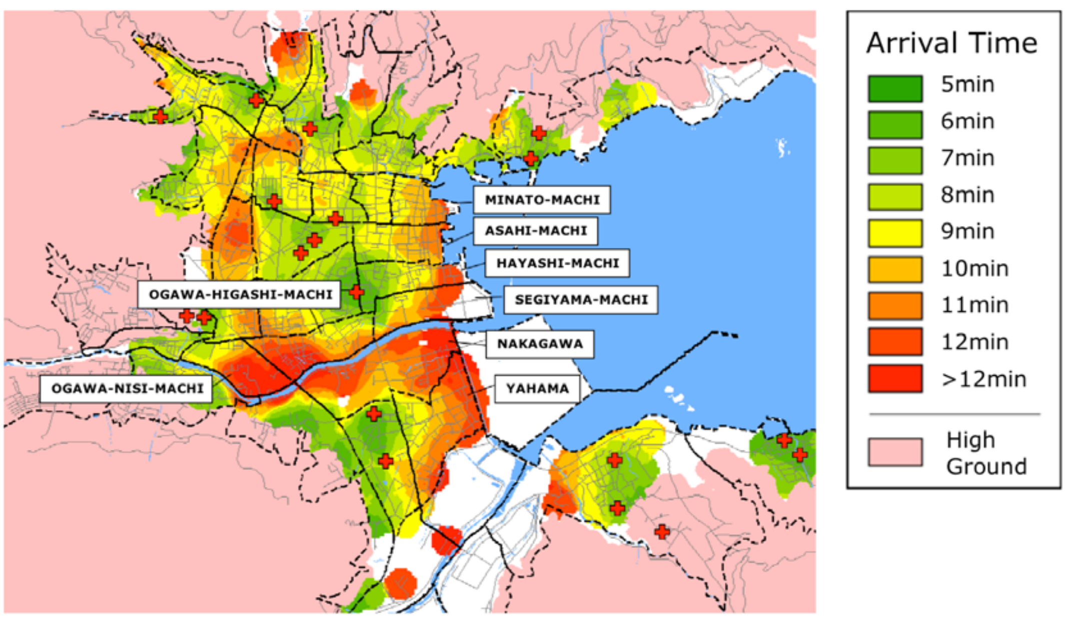

Figure 5. Evacuees' arrival times at shelters and high ground, assuming they start to evacuate immediately after receiving the first warning; average time to safety is 8 min. 27 sec.

Table 1 shows the simulated results of human casualties for scenarios where the timing of official warning announcements and individuals' holding times (for decision-making/preparation) are varied. The results show no casualties when the official warning was issued within 3 minutes of the earthquake and individuals began evacuation within 5 minutes of receiving the warning. If they waited more than 10 minutes, on the other hand, 14 people were killed. Similarly, if the official warning occurred 10 minutes after the earthquake, people must begin evacuating within 2 minutes; waiting for 10 minutes would result in 165 deaths. These are just a few examples of many potential results that can be extracted from the simulations and utilized for mitigation planning.

The simulator can also be useful for educating the general public about the importance of rapid response to tsunami warnings. A web portal, shown in Figure 6, is used to demonstrate the simulation. Users can select parameters and observe results in animated form. This can be considered as a dynamic tsunami hazard map, providing users with compelling examples of the disastrous effects of delay during natural disasters.

Table 1. Examples of casualties resulting from simulation runs

		Timing (min) of Official Tsunami Warning												
		1	2	3	4	5	6	7	8	9	10	20	30	60
Evacuation Start Timing (min)	0	0	0	0	0	0	0	0	0	0	0	1	1	7
	1	0	0	0	0	0	0	0	0	0	0	1	1	10
	2	0	0	0	0	0	0	0	0	0	0	2	2	17
	3	0	0	0	0	0	0	0	1	1	1	4	6	32
	4	0	0	0	0	0	1	2	2	4	3	7	14	50
	5	0	0	0	1	2	4	6	7	8	7	12	20	75
	6	0	1	2	5	8	9	9	9	11	10	17	44	120
	7	1	2	7	9	9	13	14	13	12	12	36	94	190
	8	1	8	10	10	12	15	17	19	16	19	81	148	302
	9	9	11	13	12	12	24	26	51	53	56	189	273	440
	10	11	14	14	17	41	72	91	124	148	165	373	463	566

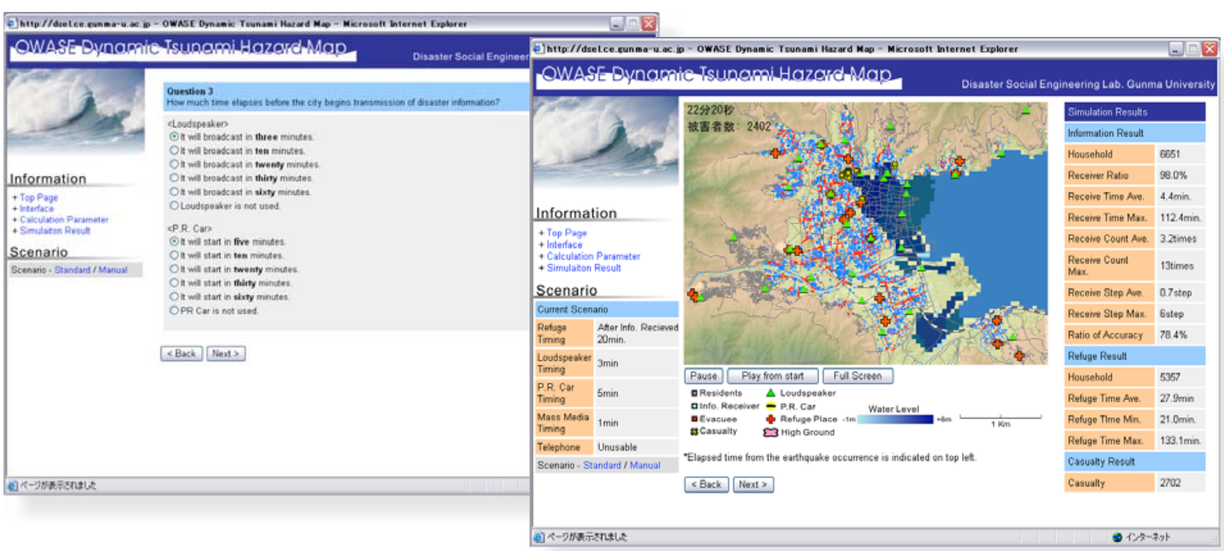

Figure 6. Screenshots from the tsunami scenario simulation portal: parameter selection page (left) and results animation page (right).

Conclusions

An integrated simulator was developed to portray the effects of human behavior during tsunami events. It includes three distinct modules, reflecting the hydrodynamics of wave propagation and runup, the transmission of warning information, and evacuation behaviors. Although the simulator is still under development, useful applications have already been demonstrated. This type of simulator – which integrates quantitative models from engineering mechanics, social sciences, and communications – will be critical if emergency response managers are to make appropriate planning decisions. Furthermore, the simulator's animated portrayals offer an effective tool for educating the general public, as well as schoolchildren, about the consequences of their behavior during an emergency situation. Lastly, the simulator offers a framework that can be extended to many other types of hazard situations, both natural and human-induced.

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