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Coastal vulnerability analysis during tsunami-induced levee overflow and breaching by a high-resolution flood model

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ABSTRACT

The coastal levee is a crucial defense element in low-lying coastal areas, but is vulnerable to overflow when water levels increase extremely. This study focuses on the failure of the concrete-armored levees caused by local scouring at the toe of their landward slope that was widely observed in the 2011 Tohoku tsunami in Japan. Using a high-resolution flood model with a shock-capturing property, we explore the actual breach processes and their impacts on the protected areas in one of the most devastated districts. The model is based on nonlinear shallow water equations and successfully reproduces detailed flow structures of the tsunami overflow at 2 m resolution. However, because we neglect the non-hydrostatic pressure over steep levee slopes, the modeled overflow discharge is slightly underestimated. During simulation, supercritical flow developed on the land side of levee sections with slowly rising tailwater water level due to hinterland topographic features, despite the large overflow discharge. Topographic data analysis revealed large-scale scour holes or trenches at the locations of the supercritical flow development, suggesting that levee vulnerability can be identified by the local flow parameters based on the high-resolution model. The levee breach was modeled as a sudden removal of the corresponding levee section, and the consequences were investigated. The levee breach changed the spatial balance of the flood intensity, but did not significantly worsen the damage in this case, because the narrow low-lying areas were fully inundated even without breach.

1. Introduction

The coastal levee is a crucial element of flood protection in low-lying coastal areas. Therefore, determining the optimum levee height is the main issue in flood risk management. The risk-based design concept, which uses probabilistic approaches, has increasingly received attention in the designs of flood defense structures against river floods, storm surges and wind waves (Voortman et al., 2002; Apel et al., 2004). However, coastal levees against tsunamis continue to be designed on the deterministic approach, partially because statistical data on the return period of the extreme event are lacking. Levees are usually designed to protect against the maximum experienced tsunami, but an incoming tsunami may exceed their crest level, causing significant overflow into hinterlands. Although the probability of such incidences is low, it is non-negligible and potentially leads to a complete breach of the levee section. Once a breach occurs, the retained water is suddenly released toward a protected area, and catastrophic damage ensues. Extreme tsunamis from uncertain seismic sources pose a potential threat to low-lying coastal communities around the globe.

In 2011, Japan was struck by the Great East Japan Earthquake and Tsunami. The disaster caused more than 18,000 fatalities and a world record-breaking economic loss. The tsunami reached over 10 m above mean sea level along a 500 km straight-distance of the Pacific Coast adjacent to the tsunami source area (Mori et al., 2012). The huge tsunami rose above the protective concrete levees and seawalls, which were 4–8 m high above mean sea level, partially or fully destroying them at numerous sites. According to post-event surveys of tsunami-induced damage on coastal structures, most of the levee failures were triggered by significant scour at the landside toe due to energetic flows accelerating down the rear slope (Kato et al., 2012). Among various modes of levee failure, overflow-induced landside damage most commonly triggers a levee breach (Hughes, 2008). The actual failure processes of an entire levee system are quite complicated and influenced by many factors such as levee geometries, local landforms, and bed materials. Furthermore, because the unsteady flows induced by the tsunami are highly complex, the overflow discharge seemed to significantly vary along the levee axis, suggesting that the local flow concentrates at specific sections.

Constructing and maintaining massive levees against low-probability extreme events such as the 2011 Tohoku tsunami is unrealistic, except in extensive low-lying areas with high population and property density. As an optimal policy, structural measures could be employed up to a certain tsunami scale; beyond this scale, flood damage could be reduced by non-structural measures such as land use

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regulations, flood warnings and evacuation systems. The appropriate balance of the two protection measures depends on the natural and socio-economic conditions of the protected coastal area. Numerous cases from the 2011 Tohoku tsunami suggested that coastal levees or seawalls had reduced the flood intensity and delayed the water rising rate in hinterlands, even when they were significantly overtopped. Therefore, the levee design also requires redundancy to cope with unexpected significant overflow.

To determine the risk posed by different tsunami scales, and thereby design a protective structural measure, we need to estimate the flood consequences of potential overflows and the levee failures by tsunamis exceeding the levee crest level. Flood vulnerability assessment has been gradually enabled by recent developments of flood simulation methods and fragility curves for different types of damage. However, the spatial resolution of these assessments is usually in order of 10^1 m, which is larger than the dimensions of coastal levees and other structures. Because tsunami-induced overflows are strongly localized, the detailed loading factors on the levee-based defense system require higher-resolution modeling. The advancement of airborne LiDAR technology has recently provided us with meter-resolution, or even submeter-resolution digital elevation models (DEMs), enabling high-resolution analysis considering structural geometries. Although slim vertical structures can not be captured by the airborne LiDAR at present, large-scale levees or embankments can be taken into account as steep topographies in numerical flood models.

In this context, we conduct a case study of severe devastation involving a levee failure under the 2011 Tohoku tsunami. This study focuses on the Unosumai district of Kamaishi—a small town located on the central Sanriku Coast—which was very severely devastated by the tsunami. Tsunami inundation on the coast and overflow into the protected areas are simulated by a high-resolution flood model with 2-m grid cells, which is sufficient to resolve the levees and other local landforms. From model results, we explore the failure process of the levee and the manner in which the breach affected flood intensity in the protected areas. Finally, we discuss the expectations and limitations of the high-resolution vulnerability analysis in the risk-based design of coastal levees against extreme tsunamis.

2. Study area

2.1. Incoming tsunami properties

Sanriku Coast is a typical ria coast with numerous semi-enclosed bays in which tsunamis generated from active seismic sources around the Japan Trench tend to be amplified. Fig. 1a shows a map of the central to northern part of the Sanriku Coast and the distribution of watermark heights above the mean sea level along the latitude. These watermark heights that are measured soon after the 2011 Tohoku tsunami (Tohoku Tsunami Joint Survey Group, 2012) range from 5 to 40 m along the intricate coastline, reflecting topographic effects. Fig. 1b shows the offshore tsunami profiles captured by two GPS buoys at about 200 m depth. The buoy locations are labeled as 802 and 804 in Fig. 1a (Kawai et al., 2013). Using buoy data, we numerically investigated the propagation and inundation characteristics along this section of coast in our previous study (Shimozono et al., 2012, 2014).

The study area (Unosumai district) is located at the head of Otsuchi Bay—a narrow rectangular bay opening to the northeast. The topography and bathymetry around Otsuchi Bay are depicted in Fig. 1c. Water depth at the bay mouth is approximately 80 m, and the bay is about 8 km long along its axis. Land topography around the bay is mountainous, with high cliffs except for narrow coastal plains at the bay head. The huge tsunami propagated into the bay and evolved into a larger wave with a steep front that cascaded over the mild seabed slope and hit the coastal plains, leaving watermarks at 8–14 m elevation. Unosumai was one of the most devastated areas throughout the disaster. Its coastal towns were severely damaged with many casualties and destroyed houses.

2.2. Damage in low-lying areas

Fig. 2a shows a high-resolution topographic map of the Unosumai district before the 2011 Tohoku tsunami. The map is created from LiDAR DEM (spatial resolution = 2 m) acquired in September 2008 with buildings and trees removed. Data were provided by MLIT, Japan. The district lies on an alluvial plain at the mouth of Unosumai River.

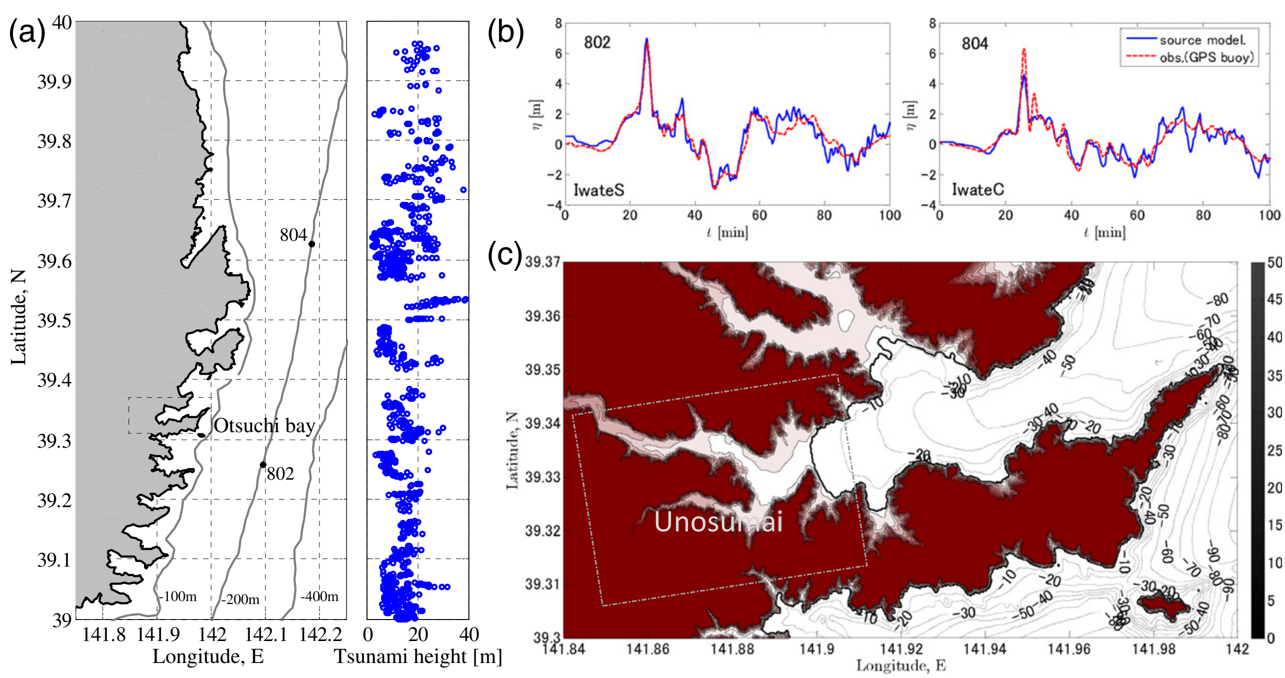

Fig. 1. Overview of the study area and incident tsunami profiles. (a) Central to northern Sanriku coast and the distribution of measured tsunami heights along the latitude. (b) Tsunami profiles measured by GPS buoys 802 and 804 (see panel a for locations) and computed with the source model of Satake et al. (2013). (c) Topographic/Bathymetric map of the Otsuchi Bay and Unosumai district.