Marine Geology 264 (2009) 41–52

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margeo

Hydrodynamic modeling of tsunamis from the Currituck landslide

Eric L. Geist [a,*], Patrick J. Lynett [b], Jason D. Chaytor [c]

[a] U.S. Geological Survey, 345 Middlefield Rd., MS 999, Menlo Park, CA 94025, USA
[b] Department of Civil Engineering, Texas A&M University, College Station, Texas, USA
[c] Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA

ARTICLE INFO

Article history:
Accepted 24 September 2008

Keywords:
tsunami
landslide
hydrodynamic
runup
numerical model
sensitivity analysis

ABSTRACT

Tsunami generation from the Currituck landslide offshore North Carolina and propagation of waves toward the U.S. coastline are modeled based on recent geotechnical analysis of slide movement. A long and intermediate wave modeling package (COULWAVE) based on the non-linear Boussinesq equations are used to simulate the tsunami. This model includes procedures to incorporate bottom friction, wave breaking, and overland flow during runup. Potential tsunamis generated from the Currituck landslide are analyzed using four approaches: (1) tsunami wave history is calculated from several different scenarios indicated by geotechnical stability and mobility analyses; (2) a sensitivity analysis is conducted to determine the effects of both landslide failure duration during generation and bottom friction along the continental shelf during propagation; (3) wave history is calculated over a regional area to determine the propagation of energy oblique to the slide axis; and (4) a high-resolution 1D model is developed to accurately model wave breaking and the combined influence of nonlinearity and dispersion during nearshore propagation and runup. The primary source parameter that affects tsunami severity for this case study is landslide volume, with failure duration having a secondary influence. Bottom friction during propagation across the continental shelf has a strong influence on the attenuation of the tsunami during propagation. The high-resolution 1D model also indicates that the tsunami undergoes nonlinear fission prior to wave breaking, generating independent, short-period waves. Wave breaking occurs approximately 40–50 km offshore where a tsunami bore is formed that persists during runup. These analyses illustrate the complex nature of landslide tsunamis, necessitating the use of detailed landslide stability/mobility models and higher-order hydrodynamic models to determine their hazard.

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1. Introduction

Potential sources for tsunamis affecting the east coast of the U.S. include submarine landslides that have been identified along the North American continental slope (Chaytor et al., 2009-this issue; Twichell et al., 2009-this issue). The occurrence of potentially tsunamigenic landslides off North America is infrequent, with return times measured in thousands of years and possibly waning with time since the last glacial/deglaciation period (Lee, 2009-this volume). Landslide tsunami hazards are still a present-day threat, however, as evidenced by the 1929 Grand Banks landslide tsunami (Fine et al., 2005). To assess the severity of this hazard along the U.S. Atlantic coast, we model the generation, propagation, and runup from tsunamis triggered by the Currituck landslide, one of the largest landslides along the North American Atlantic offshore margin. The headwall of the landslide is located approximately 100 km offshore North Carolina and Virginia, just down slope from the continental shelf edge. The morphology, stability, and dynamics of the slide have been studied by Prior et al. (1986) and by studies presented in this volume (Locat et al., 2009-this issue; Twichell et al., 2009-this issue). The Currituck landslide complex is thought to be composed of at least two separate events, although the mobility analysis presented by Locat et al. (2009-this issue) suggest that these events occurred contemporaneously. Locat et al. (2009-this issue) also suggests that the landslide was triggered by a sudden increase in pore pressure, most likely from an earthquake. The geologic age of the landslide complex is 25–50 ka, occurring at a sea-level low stand (Lee, 2009-this issue). Although the Currituck landslide occurred thousands of years ago under different sea-level conditions, we can use the detailed analysis of this landslide to assess the range of potential, present-day tsunamis emanating from this type of source.

Previous studies of landslide-generated tsunamis uncovered distinct differences compared to earthquake-generated tsunamis (Lynett and Liu, 2002; Trifunac and Todorovska, 2002; Okal and Synolakis, 2004). Because of their smaller source dimensions, tsunamis from landslide sources are more affected by frequency dispersion (cf., Carrier, 1971). During open-ocean propagation, this will result in a long-wavelength leading wave with a higher-frequency wave train trailing behind. In addition, because of the large vertical displacements at the source in comparison to earthquake sources, hydrodynamic

* Corresponding author. Tel.: +1 650 329 5457; fax: +1 650 329 5411.
E-mail address: egeist@usgs.gov (E.L. Geist).

0025-3227/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.margeo.2008.09.005

nonlinearity also becomes a significant factor in understanding the wave evolution for landslide tsunamis in the near field. Both of these factors, as well as the potential for wave breaking, become increasingly important as tsunami waves approach and runup onshore.

With regard to landslide dynamics, it is well known that speed of the failed mass is linked to the amplitude of the out-going wave (i.e., the wave propagating in the direction of slide movement) (e.g., Ward, 2001; Trifunac et al., 2002) as well as the initial acceleration, slide length and thickness, and whether the slide fails retrogressively (Haugen et al., 2005; Løvholt et al., 2005). The closer the landslide speed is to the phase speed of tsunamis (c), given in the long-wavelength limit by $c = \sqrt{gh}$ where g is the gravitational acceleration and h is the water depth, the higher the out-going tsunami amplitude. Even though a strong directivity is associated with the outgoing tsunami, the back-going tsunami propagating toward the near shore is the part of the wavefield that is potentially more dangerous, because of the shorter propagation distances (for a typical continental margin setting; fjords are a notable exception), and this is the part of the wavefield we focus on in this paper. Because the back-going tsunami quickly leaves the source region and is not "tuned" by seafloor movement in the slide direction, it is more complexly related to initial displacement of the slide mass immediately after failure. In the past, a poor understanding of submarine landslide dynamics, in combination with the higher-order hydrodynamic theory needed to model dispersion and nonlinearity, have been major obstacles in understanding landslide tsunamis. Recent research, however, has resulted in new modeling methods to address both of these problems (e.g., Imran et al., 2001; Lynett and Liu, 2002; Elverhøi et al., 2005; Lastras et al., 2005) that will undoubtedly lead to accelerated progress in estimating the severity of this natural hazard.

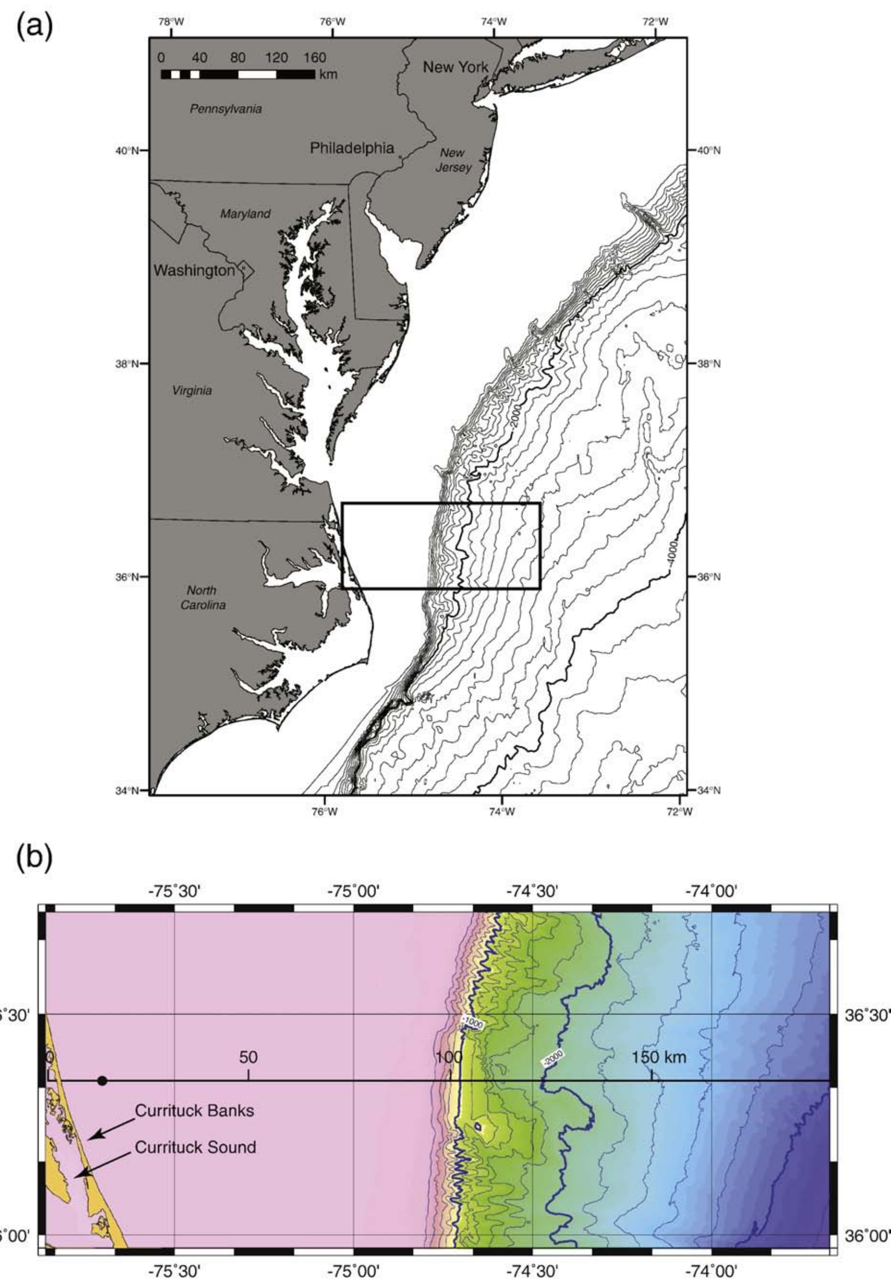

Fig. 1. (a) Regional bathymetric setting offshore central U.S. Rectangle represents region encompassing the Currituck landslide shown in (b). (b) High resolution DEM of the Currituck landslide and nearshore region representing the model domain for local propagation models. Primary bathymetric contour interval 1000 m; secondary contour interval 200 m. Black line shows location of transect and distance scale where maximum tsunami amplitude is displayed in Figs. 5–7; black dot, nearshore location where tsunami time series (marigram) is displayed.

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