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Wave characteristic and morphologic effects on the onshore hydrodynamic response of tsunamis

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ABSTRACT

While the destruction caused by a tsunami can vary significantly owing to near- and onshore controls, we have only a limited quantitative understanding of how different local parameters influence the onshore response of tsunamis. Here, a numerical model based on the non-linear shallow water equations is first shown to agree well with analytical expressions developed for periodic long waves inundating over planar slopes. More than 13,000 simulations are then conducted to examine the effects variations in the wave characteristics, bed slopes, and bottom roughness have on maximum tsunami run-up and water velocity at the still water shoreline. While deviations from periodic waves and planar slopes affect the onshore dynamics, the details of these effects depend on a combination of factors. In general, the effects differ for breaking and non-breaking waves, and are related to the relative shift of the waves along the breaking–non-breaking wave continuum. Variations that shift waves toward increased breaking, such as steeper wave fronts, tend to increase the onshore impact of non-breaking waves, but decrease the impact of already breaking waves. The onshore impact of a tsunami composed of multiple waves can be different from that of a single wave tsunami, with the largest difference occurring on long, shallow onshore topographies. These results demonstrate that the onshore response of a tsunami is complex, and that using analytical expressions derived from simplified conditions may not always be appropriate.

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1. Introduction

In the past decade alone, large tsunamis have resulted in significant destruction and loss of life in Peru (2001), the Indian Ocean (2004), the Solomon Islands (2007), the South Pacific (2009), Chile (2010), Sumatra, Indonesia (2010), and Japan (2011). These events have highlighted the need to understand better the factors, both local and far-field, that control the onshore response of tsunamis. Such an understanding is necessary to improve local tsunami preparedness and mitigate the negative impacts of future tsunamis.

Much of the early work regarding tsunamis focused on analytical solutions to simplified problems (e.g., Carrier and Greenspan, 1958; Carrier et al., 2003; Kánoğlu and Synolakis, 1998; Synolakis, 1987; Tadepalli and Synolakis, 1994, 1996) and laboratory experiments employing solitary waves (e.g., Briggs et al., 1995, 1996; Synolakis, 1987; Zelt, 1991). However, recent increases in processing power have greatly improved the utility of complex numerical models (e.g., MOST, COULWAVE, Delft3D) that can simulate tsunami propagation and inundation using more realistic wave forms and bathymetries (e.g., Apotsos et al., 2011a,b; Arcas and Titov, 2006; Grilli et al., 2007; Ioualalen et al., 2007; Lynett and Liu, 2005; Tang et al., 2009; Titov et al., 2005; Uchiike and Hosono, 1995; Vatvani et al., 2005a, 2005b; Wang and Liu, 2006; Wei et al., 2008). An extensive review of tsunami research over the past several decades is concisely summarized by Synolakis and Bernard (2006) and is therefore not detailed here.

Previous laboratory and analytical studies have been instrumental in the development of our understanding of the nearshore evolution of tsunamis, particularly in demonstrating that the characteristics of the tsunami waves and the slopes of the local morphology are important. For example, tsunami run-up has been shown to increase with increasing wave steepness for non-breaking waves (Didenkulova et al., 2007; Gedik et al., 2005; Tadepalli and Synolakis, 1994, 1996) and to be different for asymmetric and sinusoidal waves (Didenkulova et al., 2007). Similarly, several studies (Carrier et al., 2003; Tadepalli and Synolakis, 1994, 1996) have shown that leading depression (LD) waves can produce larger run-up than similar magnitude leading elevation (LE) waves owing to the reflection of the leading depression and subsequent steepening of the trailing elevation.

Previous studies (e.g., Kánoğlu and Synolakis, 1998; Kobayashi and Karajadi, 1994; Li and Raichlen, 2002; Madsen and Fuhrman, 2008) have also shown that the wave period and offshore morphology can affect the onshore response of a tsunami. These studies, along with Synolakis (1987) and Synolakis and Skjelbreia (1993), showed that different functional relationships exist for breaking and non-breaking

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waves, with the largest run-up often occurring for waves close to the initiation of breaking. In several of these studies (e.g., Kobayashi and Karajadi, 1994; Madsen and Fuhrman, 2008) wave breaking is associated with the Iribarren number (e.g., Battjes, 1974; Galvin, 1968), which is a function of the bed slope, wave height and wave period. Previous studies have also suggested that including a realistic bottom roughness can affect the onshore response of breaking and near-breaking tsunami waves (Lynett et al., 2002), but that the effect may be negligible for long, non-breaking waves (Liu et al., 1995; Lynett et al., 2002).

While these studies have been integral in the development of our understanding of the nearshore response of tsunamis, many examined single, often highly non-linear solitary waves inundating over fairly steep, planar morphologies. Such studies may not capture all the important dynamics, especially as tsunamis are often composed of several waves (e.g., Choowong et al., 2008; Hori et al., 2007; Lavigne et al., 2009), with the largest wave not always arriving first (e.g., Choowong et al., 2008; Matsutomi et al., 2001; Papadopoulos et al., 2006) and being of variable leading polarity (i.e., leading depression or leading elevation) (Arcas and Titov, 2006; Rabinovich and Thomson, 2007; Synolakis and Kong, 2006; Tadepalli and Synolakis, 1996), and inundate over non-uniform morphologies. Furthermore, several recent studies (e.g., Constantin, 2009; Constantin and Johnson, 2008; Madsen et al., 2008) have suggested that many of the solitary waves used in these previous studies are not good proxies for earthquake-generated tsunamis.

It is, therefore, unclear how appropriate trends identified using solitary and other single pulse type waves inundating over planar slopes are to more complex tsunamis impacting actual coastlines. For example, previous studies have suggested that the number and order of the waves within a tsunami can be important to the inundation distance (Apotsos et al., 2009), and that the onshore propagation of later waves can be retarded by the backwash of a preceding wave (Lavigne et al., 2009). Furthermore, the exact effect of the wave period is difficult to identify from studies using solitary waves, as the period of these waves is neither theoretically defined nor independent of the wave height. Furthermore, although previous studies (e.g., Kánoğlu and Synolakis, 1998; Lynett, 2007) have suggested tsunami run-up can be predominately controlled by the bed slope closest to the shoreline, it is difficult to determine the length scale over which this slope should be measured as this length scale is likely dependent on both the wave period and height. Many analytical and laboratory studies have neglected the effects of realistic bottom roughness, while numerical studies often only examine the effect over a limited range of bed slopes. Finally, while many recent numerical studies have demonstrated that certain models can accurately reproduce the onshore observations from real tsunamis (e.g., Tang et al., 2009; Titov et al., 2005; Wei et al., 2008), few comprehensive studies using these models have been conducted to examine in detail the local factors that affect the onshore response of different tsunamis. Therefore, a gap in knowledge currently exists between what previous laboratory and analytical studies have taught us and the full-scale modeling of actual tsunamis. This study seeks to partially fill this gap by deriving a better quantitative understanding of how various local parameters affect the nearshore response of tsunamis.

Here, more than 15,000 one horizontal dimensional (1-HD) simulations are conducted to explore in detail the effects variations in the bed slope, wave characteristics, and bottom roughness have on the onshore response of tsunamis. Coastal features such as reefs, mangrove forests, and large dune systems can also affect the onshore impact of a tsunami (e.g., Danielsen et al., 2005; Fernando et al., 2005; Gelfenbaum et al., 2007, 2011; Kunkel et al., 2006), but are beyond the scope of this study. Similarly, two-dimensional effects, such as edge or reflected waves, may modify the results presented here, but are also beyond the scope of this study. Here, we focus on the maximum run-up elevation and water velocity at the still water shoreline, as these parameters are believed to be representative bulk measures of the onshore impact of a tsunami. Variations in the time-dependent hydrodynamic parameters, such as the temporal evolution of the onshore flow velocity, and the implications of these variations for tsunami-induced sediment transport will be analyzed in a later paper.

The numerical model and modeling approach are discussed in Section 2. Specific model setups and model results, including a comparison with analytical expressions and the effects of varying the wave and morphologic characteristics, are presented and discussed in the subsections of Section 3. Conclusions are presented in Section 4.

2. Numerical model and general model setup

Tsunami hydrodynamics are simulated using Delft3D, a coupled hydrodynamic/sediment transport/morphological change model. The focus of this paper is on the hydrodynamic component of the model, which solves the non-linear shallow water equations (NLSWEs) on a two- or three-dimensional staggered grid using a finite difference scheme (Stelling and van Kester, 1994). The numeric method used to solve the NLSWEs is based on the conservation of mass, momentum (flow expansions), and energy head (flow contractions), and was specifically developed for rapidly varying flows with a wide range of Froude numbers, and the rapid wetting and drying of grid cells (Stelling and Duijmeijer, 2003). The hydrodynamic model has been validated against analytical and laboratory data including several of the standard tsunami benchmarks (Apotsos et al., 2011a) and has been shown to model well the propagation and inundation of the 26 December 2004 Indian Ocean tsunami (Apotsos et al., 2011a,b; Gelfenbaum et al., 2007; Vatvani et al., 2005a, 2005b).

The model predicts well tsunami run-up and inundation for both breaking and non-breaking long waves (Apotsos et al., 2011a). While the non-conservative form of the NLSWEs has no unique solution at local discontinuities, the use of conservative properties, as is done here, is often sufficient to provide solutions that are acceptable in terms of the local energy losses in and the propagation speed of a bore. This is because the conservation of mass and momentum should remain valid even for discontinuities in rapidly varying flows (i.e., breaking tsunami waves) (Zijlema and Stelling, 2008), and because the dissipation of energy associated with wave-breaking-generated turbulence is inherently accounted for if momentum is conserved (Brocchini and Peregrine, 1996; Hibberd and Peregrine, 1979). However, the model may not be as appropriate for simulating short, dispersive waves (e.g., landslide- and impact-generated tsunamis) as the NLSWEs neglect dispersive terms, which play an important role in the propagation of shorter waves (Constantin and Johnson, 2006, 2008). Furthermore, the NLSWEs may not accurately represent the dynamics of near breaking waves as the omission of the dispersive terms leads to an overprediction of wave steepening during shoaling (Jensen et al., 2003) and an increase in the tendency of waves to break before physically realistic (Zelt, 1991). While higher order models based on the Boussinesq equations (e.g., Lynett et al., 2003; Madsen and Fuhrman, 2008), which include dispersive terms, may be more appropriate for simulating the propagation of dispersive waves, models based on the NLSWEs are more numerically efficient and can capture wave breaking without the addition of ad hoc parameters or breaking criteria (Brocchini and Dodd, 2008).

In this study, Delft3D is run as a 1-HD model (i.e., alongshore variations are neglected and the flow is depth-averaged) with a cross-shore grid spacing of 5 m. The conclusions drawn in this study are unchanged if a cross-shore grid spacing of 20 m, 10 m, or 1 m is used instead. Most of the morphologies examined are composed of one to three linearly sloping segments, connected to a constant depth segment that extends offshore (e.g., Fig. 1). One set of simulations (see Section 3.2.3) uses smoothly curved offshore morphologies (e.g., Fig. 1a, dashed and dashed-dotted curves). For all morphologies, the constant depth segment extends only a short distance offshore [i.e., O