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Estimating tsunami runup with fault plane parameters

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ABSTRACT

Forecasting the maximum runup height and inundation area caused by a tsunami event has often been done by solving a numerical model describing the physical process. This approach requires data of fault plane parameters and bathymetry. The time required to prepare and execute the numerical model could be substantial. Therefore, it might not be suitable for the purpose of warning tsunami coastal flooding. In this paper we offer an alternative method that provides analytical relationship between the runup height and the fault plane parameters and the characteristic slope of coastal bathymetry. The method uses Okada's linear elastic dislocation model (Okada, 1985) to estimate the coseismic seafloor deformation and the corresponding (initial) sea surface displacement for a given set of fault plane parameters. Once the tsunami waves are generated, Carrier & Greenspan's solution (1958) is adopted to yield analytical expressions for the time histories of shoreline elevation and velocity. Two types of problems are investigated. In the first scenario, the bathymetry is modeled as a constant slope that is connected to a constant depth region, where a seismic event occurs. In the second scenario, the bathymetry is further simplified as a constant slope, on which a seismic event occurs. As far as the Carrier–Greenspan's solution for shoreline movement is concerned, the former is treated as a boundary-value-problem (BVP) and the latter as an initial-value-problem (IVP). For both problems the relationships between dimensionless runup height and dimensionless fault plane parameters are developed and discussed. In addition, since Carrier–Greenspan's approach is valid only for non-breaking waves, expressions limiting the applicability of the present solutions are obtained. Application of the present solutions is demonstrated with two examples: the 2004 Sumatra and 2010 Chile earthquakes. Acceptable agreements are obtained with the field measurements of these events. The present solutions offer a fast way to estimate the runup heights with the simplified beach geometry.

1. Introduction

Many numerical models have been developed to calculate the overland flows and runup heights caused by a tsunami (e.g. Wang, 2009; Yamazaki et al., 2012). These models require the incident tsunami information and coastal bathymetry data. The incident tsunami wave characteristics can be obtained directly or indirectly from the rupture plane parameters associated with a co-seismic event. The preparation and execution of these numerical models demand time and resources. Therefore, numerical modeling approach is excellent in preparing tsunami hazard map for coastal planning and management purpose. It is not effective, however, for tsunami warning, which requires very fast response once a tsunmai is generated. The alternative method is to develop analytical expressions linking the incident tsunami waves and coastal bathymetry to the tsunami runup. If the incident tsunami waves could be further expressed in terms of the fault plane parameters and coastal bathymetry, these expressions would be very useful to provide first estimate of tsunami runup height.

In the seminal paper by Carrier and Greenspan (1958) analytical solutions for nonlinear shallow water equations are obtained for non-breaking waves on a constant slope (it is referred to as C-G theory herein). Synolakis (1987) extended C-G's theory to the bathymetry where the constant slope is connected to a constant depth region as shown in Fig. 1. Synolakis showed that the incident wave must be sufficiently small such that the hodograph transformation introduced in C-G's theory can be linearized in the vicinity of the toe of the slope. He found the analytical expression for the runup of solitary wave in the integral form. A closed form solution for solitary wave runup height was further developed by adopting the asymptotic expressions for Bessel functions inside the integral. Madsen and Schaeffer (2010) derived closed form solutions for the

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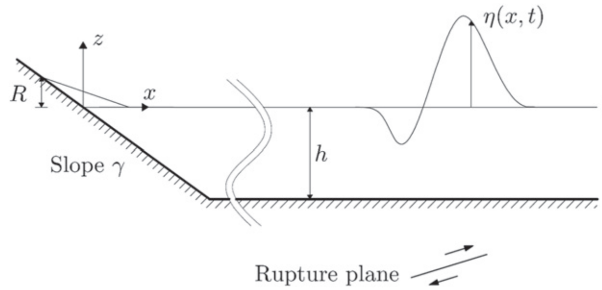

Fig. 1. Incident wave propagating in the negative *x* direction over a constant depth followed by a uniform slope. SWL denotes the Still Water Level.

runup height of periodic progressive waves and transient waves whose surface elevations are described by $\text{sech}^2()$-profiles. To obtain these solutions the toe of the slope must be sufficiently far from the shoreline and no water velocity at the initial time is allowed.

Rybkin et al. (2014) further extended C–G's theory to investigate wave run-up in inclined channels of arbitrary cross-section. The hodograph transformation was applied to the cross-sectionally averaged nonlinear shallow water wave equations. Analytical solutions of runup of periodic waves in U-shaped bays were presented. The common characteristic of this group of work is that the runup on the slope is generated by the prescribed incident waves at the toe of the slope. Thus, these problems are classified as boundary value problems (BVP).

Following C–G's theory, Kanoglu (2004) presented runup solutions, in the integral form, for waves generated by an initial free surface displacement from the still water level on a constant slope. Kanoglu's solutions require zero initial velocity everywhere and zero initial surface elevation at the shoreline. Tinti and Tonini (2005) adopted a similar approach and solved a similar problem as Kanoglu's with the exception that the initial free surface profiles were expressed in terms of a special parametric function, allowing closed form solutions for runup. They also showed that the special parametric function can be used to mimic the seafloor displacement (hence the initial free surface displacement) of a seismic event calculated from Okada's linear elastic dislocation theory (Okada, 1985). The parameters in the parametric function were determined by curve fitting to Okada's solutions, in a case-by-case base. This type of problems is classified as initial-value-problem (IVP).

In both BVP and IVP described above, the incident waves for BVP and the initial free surface profiles for IVP are not directly expressed in terms of the fault plane mechanism associated with a tsunamigenic seismic event. However, it is important to make this connection since it is desirable to quickly estimate the tsunami runup at a specific coast once the fault plane parameters are known.

The objective of this study is to derive runup solutions in terms of the fault plane parameters, such as rupture plane geometry, slip, focal depth and dip angle of a seismic event. The earthquake could occur on a constant slope or in the constant depth region that is connected to a constant slope. In this paper Okada's linear elastic dislocation model (Okada, 1985) is used to estimate the coseismic seafloor deformation and the corresponding (initial) sea surface displacement for a given set of fault plane parameters. Once the tsunami waves are generated, Carrier & Greenspan's solution (1958) is adopted to find analytical expressions for the time histories of shoreline elevation and velocity. The relationships between dimensionless runup height and dimensionless fault plane parameters are developed and presented graphically. Since these solutions are valid only for non-breaking waves, the wave breaking conditions should also be expressed in terms of the fault plane parameters and the slope.

The paper is organized as follows. In Section 2 runup solutions for BVP are first presented. The wave breaking condition which limits the applicability of the solutions, is also derived. In Section 3 runup solutions and wave breaking condition are derived for IVP. Applications of both types of problems are demonstrated in Section 4. Finally, conclusions are presented in Section 5.

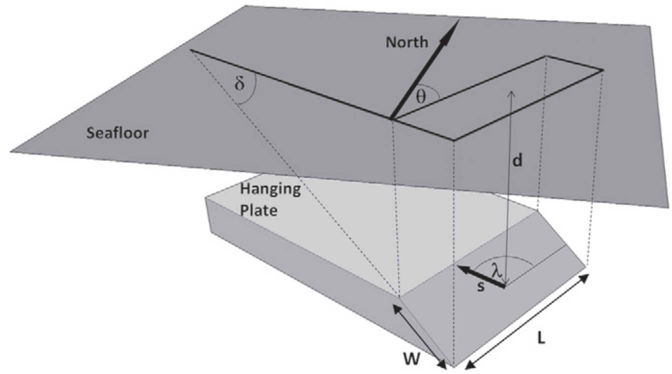

Fig. 2. Fault parameters for Okada's model to compute seafloor displacements. *W*: Fault plane width, *L*: Fault plane length, *d*: Fault depth, *s*: Fault slip, θ: Strike angle, δ: Dip angle, λ: Rake angle.

2. Runup for tsunami waves generated in a constant depth region

In this section solutions for the runup of tsunami waves generated by a submarine earthquake in the constant depth region away from the toe of a slope (see Fig. 1) are presented. The definition sketch of the fault plane is depicted in Fig. 2.

2.1. Tsunami waves generated by a seismic event

The rupture mechanism during a seismic event in subduction zones is complex. The corresponding tsunami wave generation mechanism is equally challenging. The simplest conceptual model for tsunami generation can be described as follows. Tsunami waves are generated mainly by vertical seafloor displacements, which can be estimated by using a linear elastic dislocation model, such as the model of Okada (1985). Okada's model provides analytical solutions for the seafloor deformation in terms of a set of fault plane parameters, including the length (L), and width (W) of the rupture plane, slip (s), depth (d), dip angle (δ), strike angle (θ) and rake angle (λ) of the fault plane, which are defined in Fig. 2. Okada's solution adopts many simplifications, including that the earth can be modeled as a semi-infinite half-space, bounded by a horizontal seafloor surface, and that earth's properties are homogeneous and isotropic. Once the seafloor deformation is determined, it is further assumed that the sea water surface responds instantaneously and its shape mimics the seafloor deformation. The latter simplification is reasonable since the rupture speed of fault plane is one or two orders of magnitude larger than the propagation speed of tsunami waves, and the duration of rupture for a main seismic event is usually much smaller than the typical tsunami wave period. Finally, since the compressibility of water is weak, the entire water column is being pushed up or pulled down by the vertical seafloor displacement during the earthquake.

In the present study we examine only the situation in which (1) the length of the rupture plane "L" is much longer than the width, (2) the fault is parallel to the toe of the sloping beach, and (3) the rake angle λ is 90°. Assumption (2) is reasonable because the orientation of coast is frequently sculpted by the same tectonic mechanism generating seismic events. Assumption (3) is a conservative one, since the maximum vertical displacement is generated when the dip direction $\lambda = 90^\circ$. With the additional assumption (1), the runup problem becomes 2D (in the vertical and on-offshore plane). The