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Numerical modelling of flow in Little Pigeon Bay due to the 2016 Kaikoura tsunami

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ABSTRACT

The magnitude 7.8 Kaikoura earthquake on the north-eastern coast of South Island, New Zealand induced a tsunami, which affected many north-facing bays in Banks Peninsula. The V-shaped Little Pigeon Bay experienced pronounced inundation compared to adjacent bays, causing heavy damage to a cottage at the head of the bay. In order to investigate the characteristics of the tsunami flow in the bay, a numerical model based on nonlinear shallow water theory was established, using tidal levels from the neighbouring Sumner sea level gauge. Three incident wave angles were tested, ranging from due north to 30° east of north. The simulated maximum run-up heights were validated with surveyed results. For all the wave directions, a resonance with a period of 6.3 min was found from 50 to 100 min in the simulation. Based on the physical dimensions of Little Pigeon Bay, idealised models were set-up to analyse the influence of V-shaped embayment on maximum water level, maximum velocity and maximum momentum flux. Bays with sand bars of different crest heights were also investigated. A sand bar with a relatively low crest height ($d_w/d \geq 0.5$) did not significantly reduce the maximum velocity and the maximum momentum flux.

1. Introduction

Most historical tsunamis that reach New Zealand coasts are from distant origins near the Pacific coast, e.g., Japan and Chile (Eiby, 1982; Borrero et al., 2015; Borrero and Goring, 2015). However, local earthquakes, submarine landslides, volcanic eruptions or meteor-induced tsunamis can cause damage to coastal structures and buildings, posing a threat to local communities (Eiby, 1982). At 11:02:56 a.m., November 13 2016 UTC a magnitude 7.8 earthquake struck Kaikoura (42.69° S, 173.02° E) on the north-eastern coast of the South Island, New Zealand and induced a small scale tsunami in nearby coasts (Fig. 1a). The V-shaped Little Pigeon Bay in Banks Peninsula experienced pronounced inundation compared to adjacent bays.

Tsunami propagation and inundation has been studied extensively in previous research, e.g., field investigation (Matsutomi and Okamoto, 2010; Mori et al., 2011; Shimozono et al., 2012), analytical solutions (Carrier et al., 2003; Madsen and Schäffer, 2010), experimental research (Park et al., 2013) and numerical modelling (Fraser et al., 2014; Gusman et al., 2014; Nandasena et al., 2012; Synolakis et al., 2008; Wei et al., 2013). Many researchers have investigated tsunami propagation in a bay using analytical and numerical models. Didenkulova and Pelinovsky (2011) investigated tsunami wave run-up in U-shaped bays using linear shallow water theory and noted the significant wave amplification in bays with a "non-reflecting" bottom (strongly varying depth along the wave path). The geometry of a bay can amplify the tsunami flow, leading to heavy damage to buildings at the heads of bays (Didenkulova, 2013). Two models (a plane beach model and an inclined bay model) were used to estimate the tsunami run-up in Pago Pago harbour (Tutuila, American Samoa). These two models produced similar wave shapes and the inclined bay model gave higher run-up heights. Baldock et al. (2007) investigated tsunami run-up on a plane beach and in square bays, V-shaped bays and U-shaped bays, and compared the results with analytical solutions. They found the tsunami run-up was higher when shorter period tsunami waves travelled towards a small V-shaped bay. However, for longer period waves the amplification effect was much less. The run-up results are frequency-sensitive and influenced by other factors such as the size of the bay, the wave profile and the ratio of long-shore width over cross-shore length of the bay. Embayment can increase tsunami inundation, with a narrow embayment causing larger increase in inundation distance than a wide embayment. The wave amplification and the inundation distance depend on tsunami wave characteristics, tidal level and bottom roughness as well as the coastal

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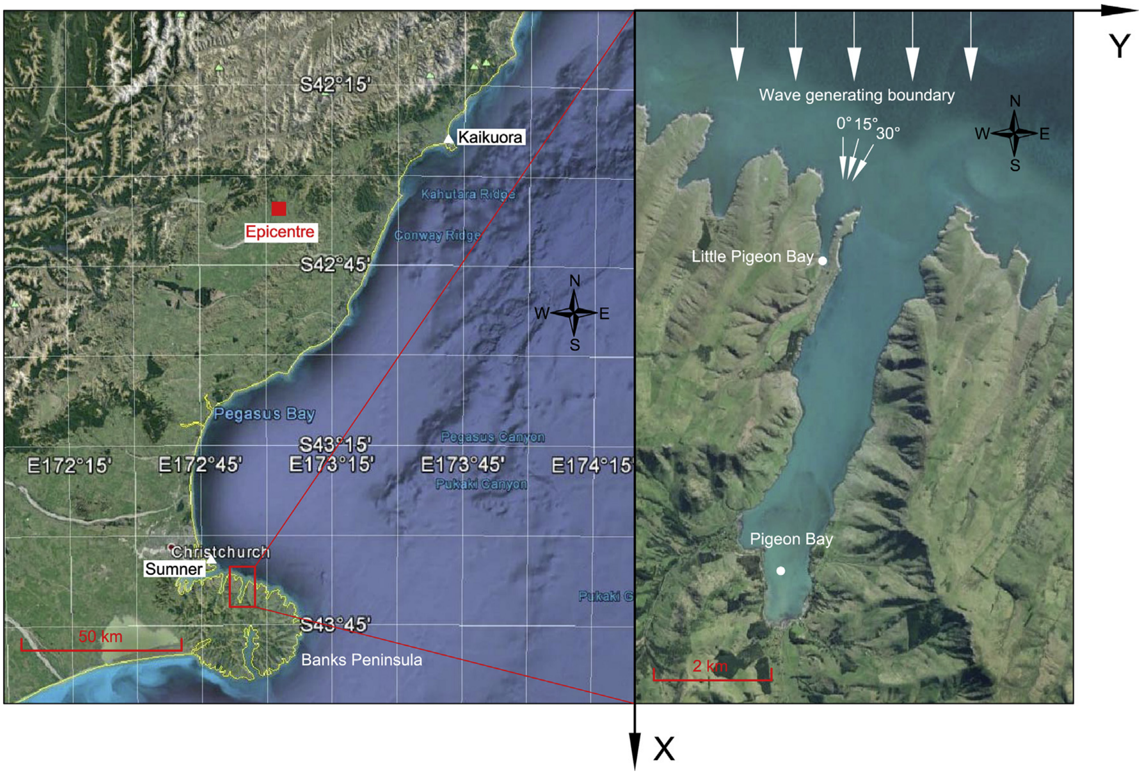

Fig. 1. (a) Map showing earthquake epicentre (red square), the location of Sumner sea level gauge (white triangle near Christchurch); (b) map of the model domain with wave generating boundary (waves from the north) and three incident wave angles (satellite images are from Google Earth). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

bathymetry (Gelfenbaum et al., 2011). Apotsos et al. (2011) investigated sediment deposition in Fagafue Bay on America Samoa as well as in idealised bays of similar dimensions. It was suggested that the limited sediment supply and steep onshore topography could reduce the deposition onshore.

Few studies have been conducted to investigate the influence of tsunami waves on the flow in a bay with complex bathymetries. The balance between wave shoaling and dissipation in such bays is related to coastal morphology, characteristics of the shoals and the tsunami (Gelfenbaum et al., 2011; Kunkel et al., 2006). Fritz et al. (2011) simulated tsunami behaviour in Pago Pago Harbour using different source models. A single normal fault source mechanism was able to reproduce the water level in the bay satisfactorily. Løvholt et al. (2015) used measured surface elevation as input to Boussinesq models and long-wave solvers to investigate tsunami propagation in a fjord system. They found that leading waves are influenced by nonlinearity and dispersion while dispersion and dissipation are more important for trailing waves. Iglesias et al. (2014) explored the influence of the morphology and orientation of submarine canyons on tsunami propagation and impact. The tsunami-related wave resonance was also studied by some researchers. Two categories of natural modes, i.e., local resonance generated by coastline features and a large scale resonance of the continental shelf can contribute to tsunami amplification (Bellotti et al., 2012). The combined oscillations of shelf and embayment concentrate the tsunami energy and exacerbated the tsunami wave impact (Roeber et al., 2010).

In order to understand the tsunami propagation and flow characteristics in Little Pigeon Bay, the authors carried out numerical simulations using three incident wave angles. The effect of the wave angles on tsunami run-up was investigated. Further, the authors set up idealised numerical models with and without a sand bar in a V-shaped bay to investigate the effect of embayment and the effect of the crest height of the sand bar in the bay on maximum water level, maximum velocity and maximum momentum flux per unit mass per unit width.

2. Numerical model of Little Pigeon Bay

2.1. Governing equations

To simulate the tsunami flow in shallow water and overland, two-dimensional depth-integrated nonlinear shallow water wave equations were applied. The continuity and the momentum equations are respectively:

$$\frac{\partial \zeta}{\partial t}+\frac{\partial Q_x}{\partial x}+\frac{\partial Q_y}{\partial y}=0 \tag{1}$$

$$\frac{\partial Q_x}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Q_x^2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{Q_xQ_y}{h}\right)+gh\frac{\partial \zeta}{\partial x}+\frac{\tau_x}{\rho}=0 \tag{2}$$

$$\frac{\partial Q_y}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Q_xQ_y}{h}\right)+\frac{\partial}{\partial y}\left(\frac{Q_y^2}{h}\right)+gh\frac{\partial \zeta}{\partial y}+\frac{\tau_y}{\rho}=0 \tag{3}$$

where h is the flow depth, ζ the water surface elevation, Q_x, Q_y the discharge fluxes in x and y direction respectively, g the gravitational force, ρ the water density, τ_x, τ_y the bed shear stress in X and Y directions defined in Eq. (4) and Eq. (5) respectively.

$$\tau_x=\rho g n^2 Q_x\sqrt{Q_x^2+Q_y^2}\Big/h^{7/3} \tag{4}$$

$$\tau_y=\rho g n^2 Q_y\sqrt{Q_x^2+Q_y^2}\Big/h^{7/3} \tag{5}$$

where n is the Manning's roughness coefficient. The tsunami flow was assumed to be quasi-steady at any instant in the simulation.