PHYSICAL MODELLING OF SOLITARY WAVE OVERTOPPING IN THE PRESENCE OF A COASTAL DUNE

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ABSTRACT
Oceanic underwater disturbances are associated with submarine landslides, volcano eruptions, or seismic activity occurring below or near the ocean basin, which can produce tsunami, which have a small amplitude in deep water with a very long wavelength, so they generally pass unnoticed offshore (Robke and Vott, 2017). These types of tsunami waves can cause massive damage or failures to coastal structures (Kato et al., 2007). From the field surveys after the 2004 Indian Ocean and 2011 Japanese tsunami, it was revealed that natural coastal features such as dunes, dense vegetation, and a combination of dunes with vegetation, acted as natural buffers and provided protection to infrastructure and communities further landward (Fritz and Borrero, 2006; Wijetunge, 2006; Murthy et al., 2012; Wijetunge, 2012). The role of coastal forests, such as mangrove vegetation, on tsunami run-up and inundation reduction, have been extensively studied by many researchers with physical and numerical modeling (Husrin et al., 2012; Yao et al., 2015; Esteban et al., 2017), but not the influence of coastal dunes in offering direct protection. Hence, the present research aims to investigate the mitigation of tsunami run-up and overtopping by coastal dunes.

Since the mid of 20th century, both breaking and non-breaking solitary waves have been used to model tsunamis in experimental research. Many experimental studies were conducted to understand the solitary wave run-up process on plane beach slopes (Hall Jr and Watts, 1953; Synolakis, 1987; Vinodh and Tanaka, 2020). After the 2004 and 2011 tsunami, laboratory experiments with tsunami-like waves, such as solitary waves overtopping on embankments and seawalls, have received considerable attention because coastal inundation due to the tsunami wave overtopping of natural or artificial sea defense is of social-economical importance (Hsiao and Lin, 2010; Hunt-Raby et al., 2011; Esteban et al., 2017). In addition, some experimental and numerical studies are available in the literature, which were focused on regular and irregular wave reflection, overwash, erosion, and sediment transport on the dunes (Hancock and Kobayashi, 1995; Kobayashi et al., 1996).

Numerous studies from tsunami field surveys state that coastal dunes shielded their respective neighbourhoods from the disastrous impact of the tsunami (Jayakumar et al., 2005, Murthy et al., 2012). Data from field studies have identified that removing coastal natural protection for public practice, such as mangrove vegetation and dunes, increases the impact of tsunami (Chang et al., 2006; Wijetunge, 2006). The National Park of Yala is the perfect example of how the combination of dense vegetation with dunes can protect the land from tsunami. The public resort on Yala beach was destroyed due to the removal of dunes for the improvement of the ocean view for tourism purposes. Villages in the same area, covered with dunes of 7 to 10 m in height, were protected from the tsunami with no property destruction or death (Wijetunge, 2006, Tanaka et al., 2007). The available laboratory experimental and numerical model data of dam break waves, regular and irregular waves overtopping over a dune are very limited, and most of the research has focussed on dune erosion during the tsunami. Hence, in the present study, physical experiments were carried out to understand the physical processes and the phenomenon of solitary waves overtopping a dune on different beach slopes.

In order to study the protective behavior of the coastal dunes against tsunami, laboratory experiments were conducted with a scale model of a dune (with a rigid surface) on different plane beach slopes (1/5, 1/10, 1/15, 1/20). The experiments were conducted for conditions with and without the dune to understand the different overtopping behaviour, using a 20m long, 0.8m wide, and 1m deep wave flume with a smooth rigid bed, glass sidewalls, and a piston wavemaker with 1.5m stroke. The model dune profile geometry is similar to a fore-dune with a relatively steep front slope (1/1.4) and a milder back slope (1/3.26) on the landward side. Scaling to typical dune sizes on the Indian east coast, the dune dimensions were chosen as 0.8 m alongshore, 0.35 m in width in the flow direction, and 0.075 m in height. This is a large dune width compared to the solitary wavelength in the lab, whereas in the field the dunes are narrow compared to the tsunami wavelength. Hence, there is also a need for numerical modelling over real bathymetry. Solitary waves have been used in experiments to model tsunami waves since the 1970's due to the easy representation of the waveform with only two parameters, still water depth and wave height (Goring, 1978; Synolakis, 1987). Run-up and overtopping were measured with a run-up wire, and video, and an overtopping tank, with the dune toe elevation also varied relative to the still water line. Fig. 1 provides an illustration of the overtopping tank and flows over the dune.

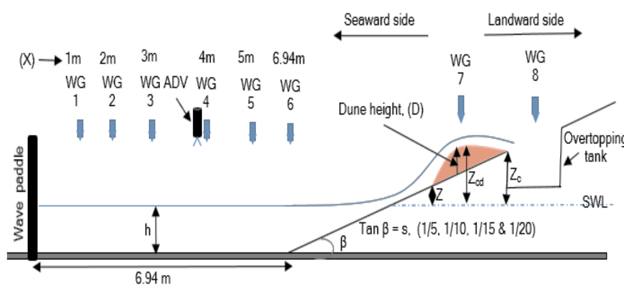

Figure 1. Schematic diagram of the experimental layout. Elevation of the dune toe position, Z; water depth, h; dune height, D (exaggerated); dune crest elevation, Z_{cd}; truncation elevation of overtopping tank, Z_c; wave gauge distance from wave maker, X.

Solitary wave breaker types based on Grilli et al. (1997) slope parameters will be provided in the full-length paper.

The variation of the normalised solitary wave overtopping without the dune versus normalised wave heights on all beach slopes is summarised in Fig. 2. The solitary wave volume V_0 can be calculated by $V_0 = \sqrt{16Hh^3/3}$ (Baldock et al., 2012). Fig. 2 indicates that the non-dimensional breaking and non-breaking solitary wave overtopping volume (V/V_0) is approximately a linear function of non-dimensional wave height (H/h), but different for different beach slopes. The experimental results have been used to identify the important non-dimensional parameters that affect the overtopping volume. The ratio of overtopping volume with the dune and without dune versus non-dimensional dune height (D/H) is presented in Fig.3. Fig.3 illustrates that D/H is an important parameter in describing the reduction in the overtopping volume. Nonetheless, the disadvantage of using this scaling is that the non-dimensional overtopping volume results do not converge for different beach slopes.

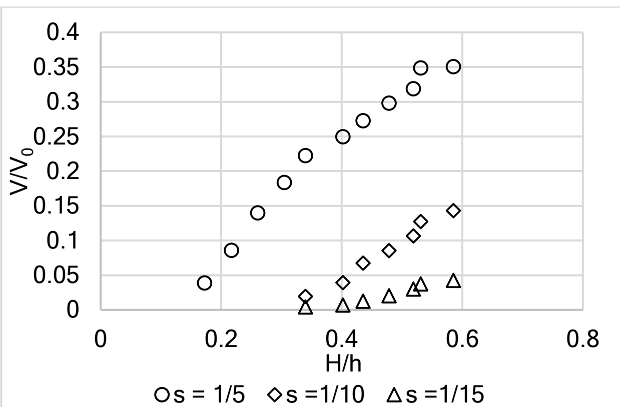

Figure 2. Normalised overtopping volume versus normalised solitary wave height (for a plane beach without a dune).

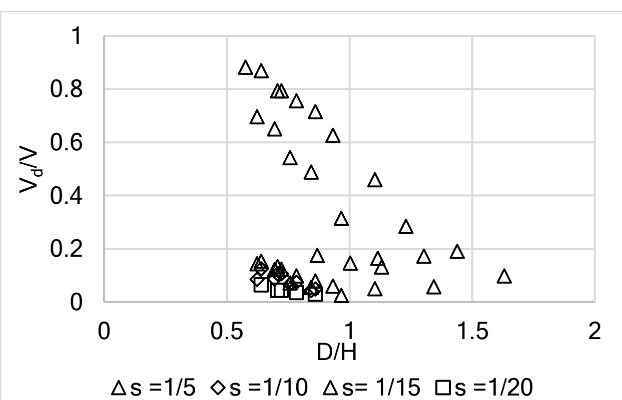

Figure 3. The ratio of overtopping volume with the dune and without dune against non-dimensional dune height (D/H).

Fig. 4 illustrates the ratio of overtopping volume with the dune and without dune with respect to the non-dimensional dune crest elevation (Z_{cd}/H). This scaling is more effective than the dune height in reducing the scatter in overtopping volume for different beach slopes. In the present experimental conditions, it was observed that when Z_{cd}/H is 1.8, the dune provides 80%, 91%, 93%, and 97% overtopping volume protection for s = 1/5, 1/10, 1/15, and 1/20 beach slopes, respectively. It is noted that this degree of protection is likely larger than in the field due to the greater relative dune width, or greater wave steepness in the laboratory.

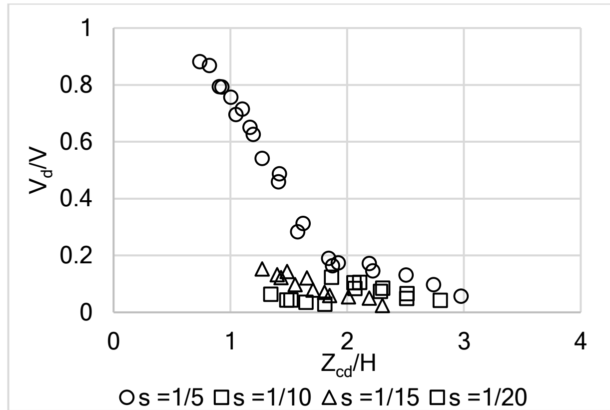

Figure 4. The ratio of overtopping volume with the dune and without dune against non-dimensional crest elevation.

Fig. 5 illustrates an alternate scaling, where the horizontal axis is the dune crest elevation, Z_{cd}, normalized with the run-up elevation without the dune (R). The results in Fig. 5 indicate that the reduction in overtopping is significant and increases rapidly with the increase of non-dimensional dune crest elevation (Z_{cd}/R). The data for different beach slopes collapse well by scaling with Z_{cd}/R, and gives less scattered results compared to scaling with D/H and Z_{cd}/H. However, since scaling with Z_{cd}/H or Z_{cd}/R does not converge the results for different positions of the dune toe, a new parameter $(Z_{cd} - Z_c)/R_d$ was adopted, which is the normalised dune freeboard above the plane beach elevation at the truncation point (in the absence of the dune). Fig. 6 illustrates this scaling has reduced scatter compared to the previous scaling (D/H, Z_{cd}/H, and Z_{cd}/R), and the data asymptote to well-defined physical limits.

The experiments indicate that the overtopping volume decreased by 12% to 98% in the presence of the dune, with a greater reduction on the mild beach slopes (1/15, 1/20) compared to the steep beach slopes (1/5, 1/10). Moreover, a similar result was observed for the influence of the dune on the run-up (Patel et al., 2022). Furthermore, the experimental results from the current study has been used to validate numerical models for large-scale investigations. The full presentation will provide an in-depth analysis of the influence of the dune on both run-up and overtopping and provide a summary of numerical model results at field-scale that are consistent with the experimental data. Thus, coastal dunes can act as a barrier or protection against tsunami waves, with the present data indicating the influence of different scaling paramters. The ratio of the overtopping with and without a dune scales well with ($(Z_{cd} - Z_c)/R_d$), independent of beach slope. However, because undistorted models with long tsunami waves and a measureable elevation are difficult to measure in laboratories, further studies with different dune parameters are needed to fully understand the influence of dune shape and width on reducing tsunami overtopping.

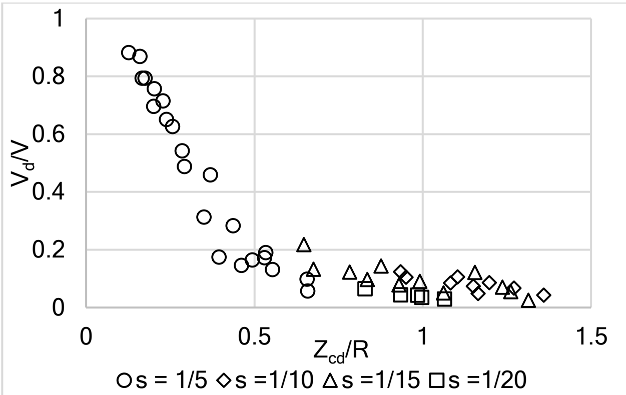

Figure 5. The ratio of overtopping volume with the dune and without dune against non-dimensional crest elevation.

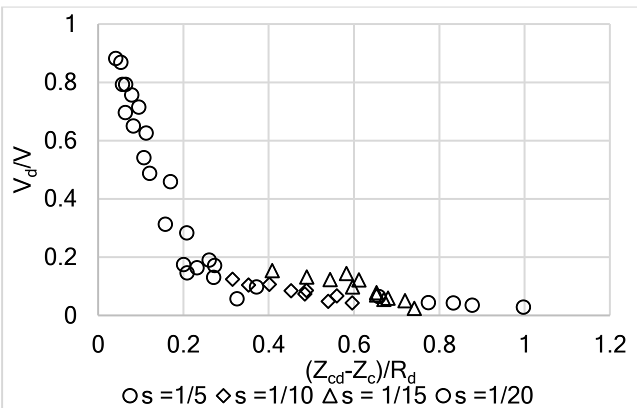

Figure 6. The ratio of overtopping volume with the dune and without dune against the non-dimensional dune freeboard.

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