Coastal Engineering 81 (2013) 67–81

Contents lists available at ScienceDirect

Coastal Engineering

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

Numerical assessment of bathymetric changes caused by the 2004 Indian Ocean tsunami at Kirinda Fishery Harbor, Sri Lanka

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A R T I C L E I N F O

Article history:
Received 21 August 2012
Received in revised form 8 July 2013
Accepted 11 July 2013
Available online 20 August 2013

Keywords:
Bathymetric change
Erosion
Kirinda
Sediment transport
Wind wave
2004 Indian Ocean tsunami

A B S T R A C T

Thus far various numerical models have been developed and improved to aid understanding of the sediment transport process due to tsunamis. However, the applicability of these models for the field-scale bathymetric change remains a major issue due to the scarcity of measured bathymetric data immediately before and after tsunamis. This study focuses on assessing the applicability of the sediment transport model by comparing the model results with measured bathymetry data obtained one month before and two months after the 2004 Indian Ocean tsunami at Kirinda Fishery Harbor, Sri Lanka. Obtained model results were compared with measured data along four different transects. In particular, similar to the measured data, the model reproduced the bed level change at the harbor mouth well, although it shows some discrepancy on bathymetric change along the shoreline, which is directly affected by littoral drift. Therefore, it is noted that the divergence of reproducing the local bathymetry change is due to the normal wind wave effect on measured data and the model limitations. Hence we included the wind wave effect in modeled data and the discrepancy between measured and modeled data was reduced. Furthermore, the modeled bed level change indicates a dynamic behavior in terms of the net variation during the tsunami flow, such that deposition dominates in the inflow and erosion dominates in the backflow. Both bed level variation and the suspended load concentration reveal that the large amount of eroded sediment attributable to tsunami waves was in suspended form and was deposited in the nearshore area after the water fluctuation had abated. The model results further indicate that eroded sediment at the initial depth deeper than 11 m might be brought by the incoming tsunami waves and deposited in the nearshore area where the depth is shallower than 7 m.

1. Introduction

The Indian Ocean tsunami (IOT) on December 26, 2004, caused enormous destruction to life and property in many countries bordering the Indian Ocean, with more than 35,000 deaths being recorded in southern, eastern and northern Sri Lanka (Dahanayake and Kulasena, 2008; Srinivasalu et al., 2007). Although Sri Lanka is located far from the tsunami source, the country is vulnerable to tsunamis because it faces directly towards the northern section of the Sunda subduction zone. The bathymetry configuration of an arrow continental shelf offshore with a sudden drop in water depth from approximately 150–200 m to 3000 m also increases its vulnerability (Hettiarachchi and Samarawickrama, 2005). Therefore, the wave energy that was transmitted over the shelf came directly toward the land because the shelf is not wide enough for significant energy dissipation (Hettiarachchi and Samarawickrama, 2005; Pattiaratchi, 2005).

While the destructive power of tsunamis is very well known, tsunamis can also cause significant morphological change through erosion and deposition caused by tsunami-induced currents and flows (Dahanayake and Kulasena, 2008; Gelfenbaum and Jaffe, 2003; Imamura et al., 2008). However, relative to the onshore study of tsunami deposits, the impact of the tsunami on the offshore bathymetry is poorly understood simply because of the scarcity of pre- and post-tsunami bathymetric data.

Numerical models of sediment transport can be used effectively to develop a better understanding of the offshore bathymetric changes caused by a tsunami. To explore the sedimentary process of onshore and offshore sediment transport, various models have been proposed (Apotsos et al., 2011a,b; Asai et al., 1998; Fujii et al., 1998; Jaffe and Gelfenbuam, 2007; Nishihata et al., 2005; Takahashi et al., 1993, 2000).

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http://dx.doi.org/10.1016/j.coastaleng.2013.07.004

Early models predicted sediment transport using formulas based only on the bed load transport rate, which was assumed to be proportional to the Shields number raised to a power (Takahashi et al., 1993); however, it was also recognized by these authors that the suspended load should not be neglected. Later, Kobayashi et al. (1996), using experimental data, proposed a formula estimating the bed load transport rate to be proportional to the Shields number raised to the power of 1.5. Fujii et al. (1998) and Takahashi et al. (2000) suggested that including suspended load entrainment and deposition would improve the accuracy of the prediction of bottom topography changes due to tsunamis. Furthermore, Takahashi et al. (2000) were able to validate the formulas used in the model using a water tank experiment. Takahashi et al. (1993, 2000) numerically investigated the bathymetric changes in the inner bay at Kesennuma City, Japan, caused by the 1960 Chilean tsunami using bathymetric data from four years before and one month after the tsunami. However, opportunities to test the applicability of the model to the field-scale phenomena are very rare because of the scarcity of bathymetric data just before and after the tsunami.

At Kirinda Harbor, Sri Lanka, shallow water bathymetry (<7 m depth) was measured in November 2004 and again in February 2005 (Japan International Cooperation Agency et al., 2006), thereby capturing any bathymetric changes caused by the 2004 tsunami. We note, however, that the post-tsunami bathymetry was recorded two months after the tsunami and does not capture precisely the post-tsunami conditions, as natural littoral transport processes were ongoing in that time period (LHI, 1985). Nevertheless, this data provides us with a unique opportunity to test the applicability of sediment transport models and to understand tsunami-induced bathymetric changes both onshore and offshore. A number of studies (Goto et al., 2011; Kihara and Matsuyama, 2010; Nishihata et al., 2006; Takahashi et al., 2009) have focused on the bathymetric changes near Kirinda Harbor, and these reports will be reviewed in Section 3. However, still there are some issues in results comparison with measured data that could not be solved in those previous studies. For instance, previous studies were not heavily focused on the wind wave effect on measured bathymetric data while model results were compared.

In this study, we apply a tsunami sediment transport model proposed by Takahashi et al. (2000), which includes the bed load rate, the suspended load rate and the exchange load rate, to test its applicability to the field-scale phenomena and to help understand the process of real-scale bathymetric change by the tsunami. In contrast to previous works, we discuss in detail the dynamic behavior of bathymetric changes during the tsunami flow and wind wave induced bathymetric change after the tsunami event.

2. Study area

The Kirinda Fishery Harbor is located on the southeast coast of Sri Lanka, as shown in Fig. 1. The harbor was constructed in 1985, and beach width changes of the order of 60 m were observed even before the construction phase due to the high littoral transport rates common along this coastline (LHI, 1985). During the southwest monsoon (April–October) the dominant wave direction is from the southwest, forcing a north-easterly directed littoral transport. In the northeast monsoon (December–March) the wave direction is reversed and waves from the northeast push sediment down the coast towards the southwest. Harbor function was suspended in June 1986 due to blockage of the harbor entrance by sediment accumulation. Several measures were proposed to address the problem (JICA, 1989), however none were successful. By 2004, several modifications were introduced, such as additional breakwaters (main breakwater (BW-A), secondary breakwater (BW-B) and northern breakwater (BW-C)) and groins (indicated in Fig. 2a) and additional dredging of the harbor entrance. The dredged material was used to create sand hills on shore with heights of 6–8 m above MSL. Despite these measures, the problem of harbor siltation persisted until the 2004 IOT, which caused considerable scour at the harbor entrance.

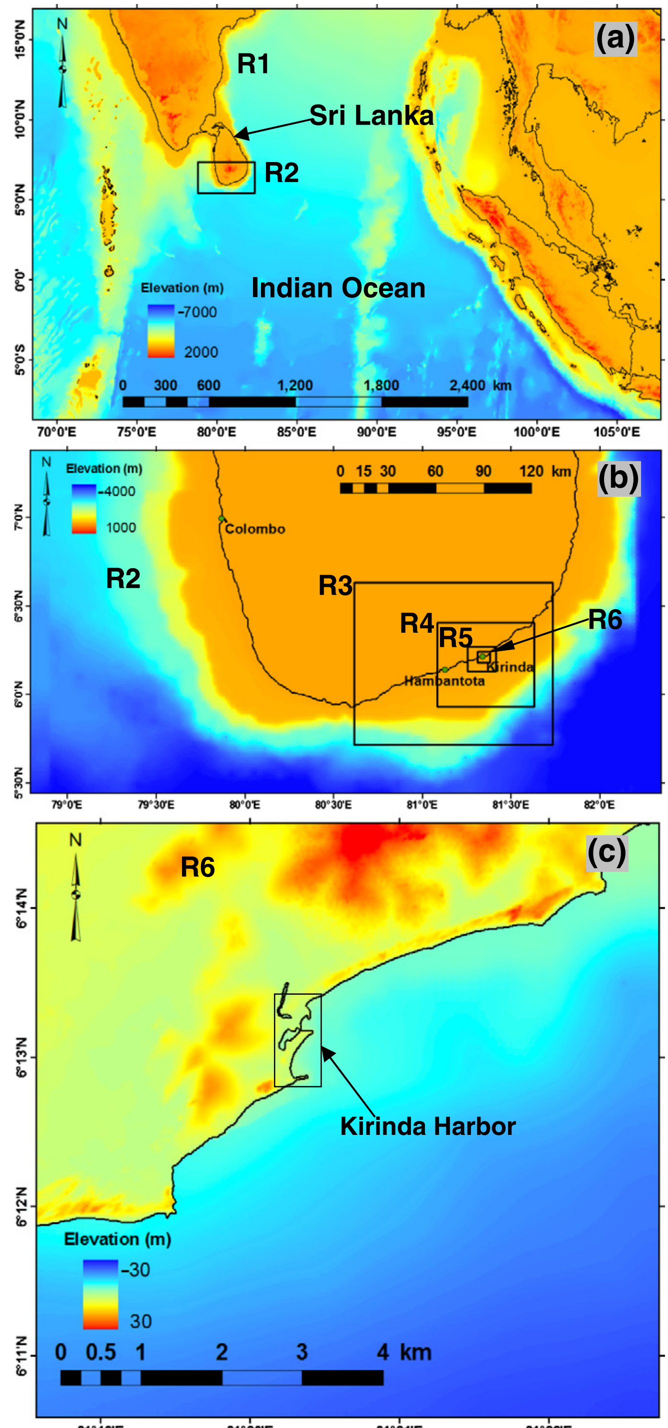

Fig. 1. Nested grids: (a) Regions 1 and 2; (b) Regions 2, 3, 4 and 5; (c) Region 6; R2, R3, R4, R5 and R6 denote Regions 2, 3, 4, 5 and 6, respectively. The green points in Fig. 1b indicate the tsunami wave heights extracted for locations in Colombo, Hambantota and Kirinda. The positive values represent the altitude, and the negative values represent the water depths.

3. Review of previous studies on sediment transport by the tsunami at Kirinda Harbor

Applying tsunami sediment transport model to the real scale phenomenon is a challenging issue. Many researches were focusing to the Kirinda Harbor to assess the tsunami impact as they could