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A deterministic analysis of tsunami hazard and risk for the southwest coast of Sri Lanka

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ABSTRACT

This paper describes a multi-scenario, deterministic analysis carried out as a pilot study to evaluate the tsunami hazard and risk distribution in the southwest coast of Sri Lanka. The hazard and risk assessment procedure adopted was also assessed against available field records of the impact of the Indian Ocean tsunami in 2004. An evaluation of numerically simulated nearshore tsunami amplitudes corresponding to 'maximum-credible' scenarios from different subduction segments in the Indian Ocean surrounding Sri Lanka suggests that a seismic event similar to that generated the tsunami in 2004 can still be considered as the 'worst-case' scenario for the southwest coast. Furthermore, it appears that formation of edge waves trapped by the primary waves diffracting around the southwest significantly influences the nearshore tsunami wave field and is largely responsible for relatively higher tsunami amplitudes in certain stretches of the coastline under study. The extent of inundation from numerical simulations corresponding to the worst-case scenario shows good overall agreement with the points of maximum penetration of inundation from field measurements in the aftermath of the 2004 tsunami. It can also be seen that the inundation distribution is strongly influenced by onshore topography. The present study indicates that the mean depth of inundation could be utilised as a primary parameter to quantify the spatial distribution of the tsunami hazard. The spatial distribution of the risk of the tsunami hazard to the population and residential buildings computed by employing the standard risk formula shows satisfactory correlation with published statistics of the affected population and the damage to residential property during the tsunami in 2004.

1. Introduction

The massive tsunami unleashed by the mega-thrust earthquake of magnitude M_w=9.3 (Stein and Okal, 2007) in the Sumatra–Andaman subduction zone on 26 December 2004 caused unprecedented loss of life and damage to property in several Indian Ocean countries including Indonesia, Sri Lanka, India and Thailand. For example, in the island nation of Sri Lanka located off the southern tip of India, the death toll exceeded 35,000 with 20,000 injured and about 100,000 dwellings completely or partially damaged leaving half a million people homeless and causing massive disruption to livelihoods, according to statistics published by the Department of Census and Statistics (DCS), Sri Lanka (DCS, 2005).

Nevertheless, the impact of the Indian Ocean tsunami in 2004 ('2004 tsunami') along the coastline of Sri Lanka was not uniform: there was considerable destruction in some localities whilst little or no destruction in certain other areas in proximity (Wijetunge, 2006). For instance, the tsunami impact on the city of Addalachchenai in the east coast of Sri Lanka was minimal although there was considerable destruction in the neighbouring cities to the north and the south: statistics on the number of people affected and the number of dwellings damaged along this stretch clearly confirm this (Fig. 1).

Such observations reveal that the level of risk of tsunami hazard to coastal communities exhibits considerable variation even along a short stretch of the shoreline. Also, the high cost and the scarcity of coastal lands in many areas demand an accurate assessment of the tsunami risk rather than arbitrary conservative zonation (Pararas-Carayannis, 1988). Moreover, information relating to the spatial distribution of the severity of the tsunami hazard and risk is essential in formulating post-tsunami coastal land use plans, development and management strategies, mitigation measures as well as in planning of evacuation of people during tsunami warnings (Wijetunge, 2012).

Clearly, sustainable development of the coastal environment requires an understanding of the degree of potential impacts of hazards and incorporation of measures to mitigate the risk to life and property. It must also be added that, any overestimation of the tsunami risk significantly increases the cost of development, whereas underestimation of probable peak tsunami heights may lead to catastrophic consequences (Kulikov et al., 2005). For

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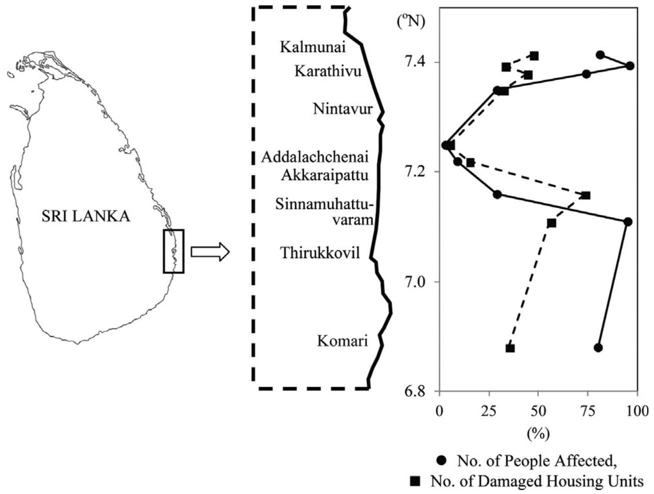

Fig. 1. Spatial variation of statistics on the number of people affected and the number of houses completely or partially damaged by the 2004 tsunami in the coastal stretch between Kalmunai and Komari in the Eastern Province of Sri Lanka (Data from DCS (2005)).

instance, considerable underestimation of probable tsunami heights led to the Fukushima Daiichi nuclear disaster in Japan following the Tohoku earthquake of magnitude $M_w=9.0$ (Fritz et al., 2012; Liu et al., 2013) in March 2011.

Guidelines for assessing the tsunami hazard and risk as well as utilisation of such information include the publications of Cabinet Office of the Government of Japan (COGJ, 2008), UNESCO-IOC (2009a, 2009b), and International Centre for Water Hazard and Risk Management (ICWHRM, 2010). Further, Nadim and Glade (2006) discuss the challenges in risk evaluation and suggest that a scenario-based approach is particularly well-suited for evaluation of the risk posed by tsunami.

Choi et al. (2005) evaluated the tsunami hazard to Korean and Russian coasts in East Japan Sea using a combination of historic and prognostic tsunami events. Okal et al. (2006) analysed historical records and numerical model results to quantify tsunami hazard along a portion of South American coastline. Tsunami inundation maps and vulnerability functions for buildings have been developed by Koshimura (2007) for the city of Banda Ache in Indonesia. Wijetunge et al. (2008) carried out high-resolution inundation modelling to develop tsunami hazard maps for three cities in the southern province of Sri Lanka. Garcin et al. (2008) discuss use of Geographical Information Systems (GIS) for an integrated approach to coastal hazards and risks in Sri Lanka. Hettiarachchi et al. (2010) outline investigative studies conducted for the assessment of tsunami risk and development of mitigation measures for the city of Galle in Sri Lanka, whilst Poisson et al. (2009) examine the effect of ground roughness on the extent of inundation in the same city. A tsunami hazard assessment for the port city of Trincomalee in the east coast of Sri Lanka is described in Wijetunge (2010).

Probabilistic tsunami hazard assessments for Western Australia and for the Indian Ocean region in general have been carried out by Burbidge et al. (2008) and Burbidge et al. (2009), respectively. Taubenbock et al. (2009) assessed risk and vulnerability parameters for the tsunami threatened city of Padang, Indonesia whilst Greenslade and Warne (2012) assessed the effectiveness of the existing sea-level observing network for tsunami warnings in the Australian region. More recently, a detailed multi-scenario tsunami hazard and risk assessment has been carried out by Strunz et al. (2011) as a pilot study for three localities in Indonesia. They assessed the risk of tsunami hazard to the exposed population by convoluting numerically simulated tsunami inundation depths with the time required for evacuation as an indicator of vulnerability. Among many others, tsunami hazard assessments have also been discussed in Qinghai and Adams (1988), Tinti (1991), Zahibo and Pelinovsky (2001), Clague et al. (2003), Gonzalez et al. (2005), Løvholt et al. (2006), Tsunami Pilot Study Working Group (2006), Theilen-Willige (2008), and ten Brink (2009). Further, tsunami vulnerability assessments are described in, for example, Papathoma et al. (2003), Dominey-Howes and Papathoma (2007), and Dall'Osso et al. (2009).

However, only a few of the above studies have proceeded beyond the first stage of assessing the hazard, to the next steps of assessing the vulnerability and risk. Moreover, comprehensive multi-scenario tsunami hazard and risk assessments involving high-resolution inundation modelling beyond city levels have not yet been carried out for the vulnerable coastline of Sri Lanka. Therefore, it is necessary, first of all, to comprehensively assess the level of threat to Sri Lanka from tsunamigenic seismic zones in the Indian Ocean region, and then, to extend such hazard assessments to risk evaluations despite constraints on vulnerability data. We also need to examine which metrics or indicators are more appropriate to quantify the hazard and vulnerability, and to develop and streamline the hazard and risk assessment procedure specifically for the typical situation in a developing country like Sri Lanka. Accordingly, this paper describes a tsunami hazard and risk analysis carried out, as a pilot study, for the densely populated southwest coast of Sri Lanka which was devastated by the 2004 tsunami.

2. Study area

The 90 km-long shoreline of the study area stretches from Bentota (79.991°E, 6.441°N) to Ahangama (80.382°E, 5.965°N) across six administrative divisions, namely, Bentota, Balapitiya, Ambalangoda, Hikkaduwa, Galle Four Gravets, and Habaraduwa (Fig. 2).

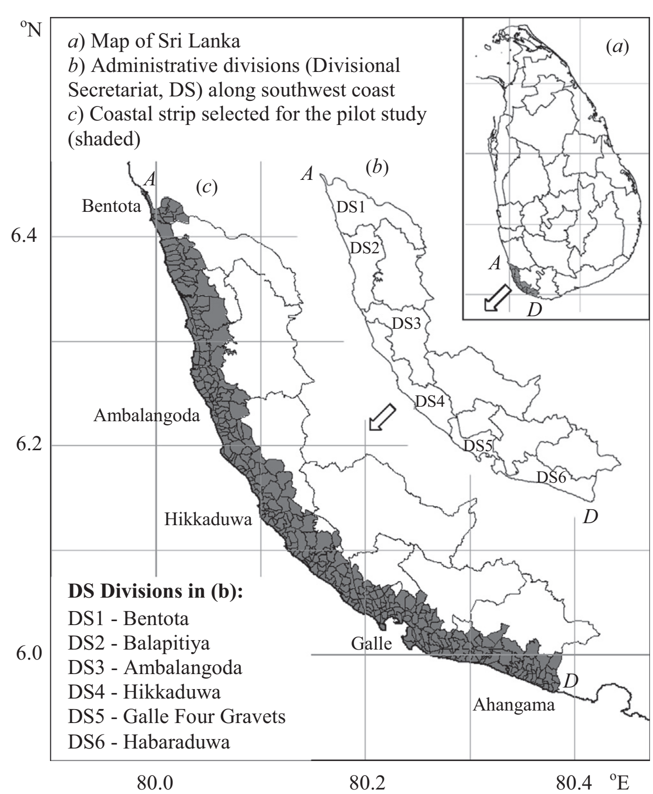

Fig. 2. Location map showing the study area along the southwest coast: (a) Map of Sri Lanka (See Fig. 3 for location of Sri Lanka with respect to Indian Ocean region), (b) Southwest coast stretching across six coastal divisions, and (c) 3 km-wide coastal strip selected for the pilot study.