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Testing the numerical models for boulder transport through high energy marine wave event: An example from southern Saurashtra, western India

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ABSTRACT

Presence of large boulders along rocky coasts can be used as archives to reconstruct past extreme wave event history, vital for the coastal hazard assessment. Dimensions of boulders lying in supratidal zone have been used to reconstruct the origin of wave responsible for their transport and processes. There are several mathematical equations available which take into account submerged, subaerial and joint bounded block scenarios for boulder transport to estimate the wave height required to transport the boulders to their final position. However, there are limited studies which validate these equations using modeling and observational analysis. Navabandar coast, situated in western India provides an excellent opportunity for such analysis as there exists three boulders derived from shore platform during the November 1982 storm. We present the analysis of these boulders and event history of region to conclude that all the mathematical equations overestimate the wave heights required to dislodge and transport these boulders by at least 5 times the actual event. We emphasize that there is a vital need to re-evaluate and improve the existing equations considering the local control variables for better visualization of 'palaeo' tsunami/storm events.

1. Introduction

Since 2004 Indian Ocean Tsunami, studies pertaining to detachment, transport and emplacement of coastal boulders have received wide attention among scientists, as they may serve as archives to past storm/tsunami history (Scheffers, 2004; Mastronuzzi and Sanso, 2004; Goto et al., 2007; Kelletat et al., 2007; Vott et al., 2008; Paris et al., 2009, 2010; Srinivasalu et al., 2009; Etienne et al., 2011; Goto et al., 2012). Most of the coastal boulder research has been focused on using the boulders as sedimentary signatures of palaeo-tsunami events and the most commonly used transport equations typically suggest that large boulder deposits are products of tsunami rather than storms, though storm waves are capable of transporting and depositing boulders of significant size at elevations well above sea level (Hansom et al., 2008; Paris et al., 2011). Recently several studies have documented the growing evidences of boulders being deposited by storms (Williams and Hall, 2004; Scheffers and Scheffers, 2006; Hansom et al., 2008; Suanez et al., 2009; Paris et al., 2011).

A detailed study of the deposited boulder features – size, shape and rock density, inland distance and their initial position prior to the transport – is extremely important and vital when reconstructing the possible transport scenarios in order to deduce the responsible events (Nott, 2003; Pignatelli et al., 2009; Nandasena and Tanaka, 2013). Nott (1997, 2003) derived equations for boulder responses to palaeo-storms and tsunamis waves. But the application of Nott's equation and its accuracy has been debated by several workers in different scenarios. Pignatelli et al. (2009) modified the Nott's equations for joint Bounded Block Scenario (JBBS), as he considered that a boulder is bounded by three sides and an underside. Similarly, Engel and May (2012) proposed revised boulder transport model and equations. Despite these attempts, there have been limited studies validating

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this mathematical equations and models with known events (Noormets et al., 2004; Goto et al., 2009).

Despite the several tsunamigenic sources in the Arabian Sea/ Indian Ocean and frequent tropical cyclones, the west coast of India has been neglected for studies pertaining to extreme wave events namely palaeotsunamis and cyclones. Limited attempts suggest this coastline being prone to extreme wave events in historical as well as geological past (Bhatt et al., 2009; Meshram et al., 2011; Sangode and Meshram, 2013; Prizomwala et al., 2015). In limited instances, observed as well as modeled data is available pertaining to effect of storms on southern Saurashtra coastline (Dube et al., 1985; Shaji et al., 2014), which enables us to examine and test the mathematical equations used for deducing wave origin. In order to test the applicability of widely used mathematical equations of wave origin, we compared the known historical events of one of the most destructive storms experienced by Saurashtra and tsunami in Arabian Sea with the numerical models. The aim of this study is to evaluate the reliability of boulders transport equations on known events along Saurashtra coast and highlight the deviations, if any.

2. Study area

2.1. Geology and geomorphology

The southern Saurashtra shows presence of rocky coast for about 150 km length (Fig. 1a). The rock formations exposed within the area consists of miliolitic limestone (Miliolite Formation) underlying the shell limestone (Chhaya Formation) of Middle to Late Pleistocene age (Fig. 1b). The coastline of Navabandar near Diu on a southern tip of Saurashtra is irregular with deeply cut rocky cliffs as high as 15 m, narrow embayment, headland and beach configuring the overall marine processes. Tidal notches are carved out in the miliolitic limestone 2–4 m above the present day sea level that has been used to interpret relative sea level changes and neotectonics in the area (Pant and Juyal, 1993; Bhatt and Bhonde, 2006). Submerged jointed platforms are exposed to the abrasive action of the sea-waves during the low tide levels. The rocky stretch of coast is punctuated by pockets of small beaches (Fig. 1c).

2.2. Event history: storms and tsunami

The region experiences cyclonic storms frequently from May to November months during the period of the Indian Summer Monsoon (ISM). The highest category cyclone to hit the Saurashtra coastline was the 18th of May, 2001 cyclone (category-IV) with maximum wind speed of 215 kmph and wave height of 4 m. However, it hit the Saurashtra coastline with a reduced wind speed of 55 kmph. Similarly, 1975 Porbandar cyclone was category IV cyclone with maximum wind speed of 212 kmph and wave height of 4.1 m at Madhavpur (120 km from present study site) along Saurashtra coastline (Dube et al., 1985). In 1982 a cyclone hit the Saurashtra coastline with wind speed of 93 kmph. Veraval town, west of present site was flooded by a sea surge of at least 5 feet high. The event led to tremendous destruction. Based on local reports three boulders were thrown from the sea on the land of Navibandar Coast, which was considered by locals as an act of the God. Table 1 shows List of historical storm events which affected the Saurashtra Coast during the period between 1975 and 2014.

Table 1
List of historical storm events from 1975 to 2014 which affected the Saurashtra Coast.

Name of cyclone	Date and year	Observed/Estimated max. wind
Severe cyclonic storm over the Arabian Sea	October 19–24, 1975	180 Knots/74 kmph
Severe cyclonic storm over the Arabian Sea	May 31 – June 5, 1976	90 Knots/167 kmph
Severe cyclonic storm over the Arabian Sea	October 28 – November 3, 1981	65 Knots/120 kmph
Severe cyclonic storm over the Arabian Sea	November 4–9, 1982	50 Knots/93 kmph
Severe cyclonic storm over the Arabian Sea	June 17–20, 1996	60 Knots/111 kmph
Very severe cyclonic storm over the Arabian Sea	June 4–10, 1998	90 Knots/167 kmph
Very severe cyclonic storm over the Arabian Sea	May 16–22, 1999	55 Knots/102 kmph
Super cyclone “GONU”	June 01–07, 2007	127 Knots
Cyclonic storm WARD (Arabian Sea)	Dec 10–15, 2009	45 Knots (83 kmph)
Cyclonic storm Bandu	May 19–23 2010	40 Knots
Cyclonic storm Phet	May 31–07 June, 2010	85 Knots

Although the Arabian Sea hosts several potential tsunamigenic sources, one of the most active tsunamigenic sources is the Makran Subduction Zone (MSZ). The present study area is located in the southeastern part of Southern Saurashtra region (Fig. 1), which falls under shadow zone for tsunami waves originating from the MSZ (Prizomwala et al., 2015). Similarly, Owen Fracture Zone (OFZ) lies southwest of the present study area which is strike slip in nature, hence can only lead to weak tsunamis (Jaiswal et al., 2008). Prizomwala et al. (2015) reported similar boulder deposits from Diu Island (west of present site) and using Pignatelli et al. (2009) equations concluded them being tsunamigenic. Those boulders showed imbrications towards southwestern direction, hinting at a submarine landslide along Southern Owen Ridge, which triggered the tsunami. The present study site is east of Diu Island, along the southeastern coast of Saurashtra. Table 2 shows a list of historical tsunami events recorded in the northern Arabian Sea.

Table 2
List of historical tsunami events recorded in the northern Arabian Sea which could possibly affect Gujarat coastline.

Year	Location	Reference
326 BC	Indus delta	Murty et al. (1999)
1008 AD	Strait of Hormoz	Ambraseys and Melville (1982)
1524 AD	Off the coast of Dabhol, Maharashtra, India	Bendick and Bilham (1999)
1618 AD	Offshore of Mumbai	Rastogi and Jaiswal (2006)
1819 AD	Rann of Kutch	Rastogi and Jaiswal (2006)
1845 AD	Kori creek	Rastogi and Jaiswal (2006)
1945 AD	Pasni, Offshore Pakistani coast	Ambraseys and Melville (1982)

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