ARTICLE IN PRESS

Quaternary Science Reviews xxx (2014) 1–12

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

Beach ridge patterns in West Aceh, Indonesia, and their response to large earthquakes along the northern Sunda trench

Katrin Monecke [a,*], Caroline K. Templeton [a], Willi Finger [b], Brian Houston [c], Stefan Luthi [d], Brian G. McAdoo [e], Ella Meilianda [f], Joep E.A. Storms [d], Dirk-Jan Walstra [d,g], Razali Amna [f], Neil Hood [c], Francis J. Karmanocky III [h], Nurjanah [f], Ibnu Rusydy [f], Sam Unggul Sudrajat [i]

[a] Wellesley College, Wellesley, MA, USA
[b] Swiss Agency for Development and Cooperation, Zurich, Switzerland
[c] University of Pittsburgh, Johnstown, PA, USA
[d] Delft University of Technology, Delft, The Netherlands
[e] Yale-NUS College, Singapore
[f] Tsunami and Disaster Mitigation Research Center, Banda Aceh, Indonesia
[g] Deltares, Delft, The Netherlands
[h] West Virginia University, Morgantown, WV, USA
[i] United Nations Development Program, Jakarta, Indonesia

ARTICLE INFO

Article history:
Received 2 June 2014
Received in revised form
8 October 2014
Accepted 16 October 2014
Available online xxx

Keywords:
Paleoseismology
Coastal morphology
Beach ridge plain
December 2004 Sumatra-Andaman earthquake
2004 Indian Ocean tsunami
Aceh (Indonesia)

ABSTRACT

The morphology of beach ridge plains along active margins can be used to reconstruct coastal subsidence during large megathrust earthquakes. Here we use satellite imagery and automatic level surveys to reconstruct the build-up of a new beach ridge along a 10 km long stretch of the western Acehnese coast after the complete destruction of the beach during the great Sumatra -Andaman earthquake and successive tsunami in December 2004. The western Acehnese coast is characterized by ridge and swale topography reflecting the long-term progradation of the coastline. Radiocarbon dates obtained from marshy deposits in between ridges indicate an average progradation rate of 1.3–1.8 m per year over the last 1000 years. As a result of coseismic subsidence of 0.5–1 m and tsunami inundation in 2004, the most seaward beach ridge was destroyed and the coastline receded on average 110 m landward representing 65–85 years of average progradation. However, by 2006 a new 22 m wide ridge had formed. In the following years the coast prograded by an additional 30 m, but has not yet recovered to its pre-December 2004 position. In addition to the spatial data, topographic surveys conducted in 2009, 2012 and 2013 indicate that the crest of the newly formed beach ridge is 0.8–1.3 m higher than the crests of older beach ridges further inland. The source material for the new ridge is most likely sand transported seaward by the back flow of the 2004 tsunami and stored on the upper shoreface. In the months and years after the tsunami, this sediment is reworked by regular coastal processes and transported back to shore, leading to the reconstruction of a higher beach ridge in equilibrium with the vertical displacement of the coast and the resulting higher relative sea level. The preservation potential of the newly formed ridge depends on sediment availability within the coastal system to balance coastal profile adjustments due to rapid postseismic uplift. In Aceh, the preservation of seismically modified beach ridge morphology seems likely and another prominent ridge can be found in 640 m distance to the shoreline. It most likely formed in the aftermath of a previous megathrust earthquake and tsunami about 600 years ago matching sediment and coral records for this region.

1. Introduction

Growing coastal communities around the world are increasingly threatened by extreme events as recently witnessed when Typhoon Hayian hit the Philippines and portions of Southeast Asia in November 2013 or, when the March 2011 Tohoku-oki tsunami

* Corresponding author.
E-mail address: kmonecke@wellesley.edu (K. Monecke).

http://dx.doi.org/10.1016/j.quascirev.2014.10.014
0277-3791/

struck Eastern Japan and coastal areas throughout the Pacific basin. Using satellite imagery, detailed ground surveying and sediment analysis, the immediate impacts on the coastal zone have been well documented for recent extreme events allowing the quantification of hydrodynamic parameters and geomorphic change with possible implications for storm surge forecasting (e.g. Fritz et al., 2007; Spencer et al., 2014) and tsunami hazard assessment, warning and preparedness (e.g. Jaffe et al., 2006; Vargas et al., 2011; Tappin et al., 2012). Only very few studies have focused on the longer term coastal recovery after extreme events, which is equally important since coastal planners have to allocate resources and design appropriate structures for future hazard mitigation. The partial or complete rebuilding of sandy beaches after large storm events is site specific and has been observed to take in the order of a few months depending on inherited hydrologic and sedimentary parameters (e.g. Wang et al., 2006; Yu et al., 2013). The recovery of sandy shorelines and establishment of equilibrium after devastating tsunamis might take from a few months up to a few years (e.g. Choowong et al., 2009; Liew et al., 2010) and can be expected to be more complex in tectonically active regions experiencing co- and postseismic land level changes (Meilianda et al., 2010). In order to prepare coastal communities for future hazards it is critical to understand the frequency and magnitude of past events. Numerous studies of deposits in coastal areas have revealed millennia spanning records of coseismic land level changes (e.g. Atwater, 1987; Shennan et al., 2014) and tsunami inundation (e.g. Nanayama et al., 2003; Cisternas et al., 2005). Latter studies have often been successful in marshy beach ridge plains where tsunami sand sheets have been preserved in low-lying depressions (e.g. Pinegina and Bourgeois, 2001; Jankaew et al., 2008; Atwater et al., 2013). In this paper we combine spatial imagery analysis and topographic surveys to quantify the recovery of a beach ridge plain in West Aceh, Sumatra, Indonesia over a time span of 9 years after the 2004 Indian Ocean tsunami, and determine the effects of large-scale events on beach ridge morphologies and growth patterns. We will compare the obtained morphological data to previous paleoseismic studies of the coastal sediments in this area (Monecke et al., 2008) and discuss if beach ridge morphologies are suitable to reconstruct past earthquake histories.

1.1. The morphology of beach ridge plains

Many parts of the Sumatran coast consist of beach ridge plains, where shore-parallel sand ridges alternate with marshy swales, typical for a prograding coastline. Although their geometries look quite regular, large magnitude earthquakes along the Sunda trench cause vertical ground displacement and tsunamis of devastating force which can modify coastlines significantly, as evidenced by the December 26, 2004 Sumatra-Andaman earthquake and ensuing Indian Ocean tsunami (Liew et al., 2010). In Aceh, the northernmost province of Sumatra, Indonesia, a retreat of the coastline of several tens of meters was observed and can be attributed to coseismic subsidence, tsunami scouring and sediment redistribution (Jaffe et al., 2006; Meltzner et al., 2006; Meilianda et al., 2010). More recent satellite images, however, show that in many places the shoreline has built rapidly seaward forming a new prominent beach ridge since the 2004 event (Liew et al., 2010).

The formation of beach ridge coastlines and possible modifications by large-scale events is still a matter of debate (see Tamura, 2012; for a review). A beach ridge plain is characterized by sets of sandy ridges separated by low-lying swales that run parallel or subparallel to the coast for several kilometres. Individual ridges mark former positions of the shoreline with older ridges located further inland while new ones build progressively seaward. Prograding coastlines experiencing significant wind transport may show extensive dune development on top of ridges; such strandplains are sometimes identified as dune or foredune ridges (e.g. Wells and Goff, 2007; Masselink et al., 2011) or might be included under the term beach ridge plain (e.g. Otvos, 2000; Bristow and Pucillo, 2006). If aeolian processes are secondary, beach ridge evolution is primarily a result of swash processes under varying wave energy conditions (Taylor and Stone, 1996). A low shoreface gradient as well as an abundance of sediment are favourable for progradation of beach ridges (Taylor and Stone, 1996; Bristow and Pucillo, 2006) with sediment supply being the most important factor controlling the spatial and temporal variation in beach ridge development (Anthony, 1995). Sediment supply to the littoral environment can increase significantly during extreme climate events (Goy et al., 2003; Shafer Rogers et al., 2004) or the mobilization of sediment as a result of earthquake shaking (Wells and Goff, 2007). Geometries of beach ridge systems have successfully been used to reconstruct sea and lake level histories on millennial to decadal scales (Tanner, 1995; Thompson and Baedke, 1995; Engels and Roberts, 2005; Storms and Kroonenberg, 2007). Rates of beach ridge progradation are commonly determined by optical luminescence dating of sandy ridge deposits (e.g. Ballarini et al., 2003; Bristow and Pucillo, 2006) but radiocarbon dating of organic material from within beach ridges (e.g. Goy et al., 2003) or from inter-ridge swales (e.g. Thompson, 1992) has been used as well.

In a few cases beach ridge patterns have been shown to reveal earthquake cycles. Bookhagen et al. (2006) interpret a sequence of uplifted beach berms in South-Central Chile as paleoshorelines that were progressively exposed during earthquakes along the Nazca-South America plate interface. Briggs et al. (2008) document a set of seaward climbing beach berm crests on Nias Island in West Sumatra, which might respond to slow interseismic subsidence along this part of the Sunda trench subduction zone. Mobilization of large amounts of sediments produced during earthquake shaking is suggested as the driving force for the formation of dune ridges in New Zealand (Wells and Goff, 2007). A link of beach ridge formation and earthquake activity is tentatively suggested for a strandplain in eastern Japan, yet, the complex interplay of seismic, volcanogenic and climatically-driven processes needs more thorough investigation (Goff and Sugawara, 2014).

1.2. Land level changes during subduction earthquakes

It can be assumed that, in seismically active areas, growth rates of beach ridge plains are severely affected by coseismic land level changes, which affect the local sea level and shoreface gradient. Large subduction earthquakes cause a characteristic pattern of vertical ground displacement: Uplift up to a few meters occurs closer to the trench often visible by emergence of offshore islands, while subsidence dominates in the forearc region causing the drowning of coastlines (e.g. Plafker, 1972). Significant land level changes continue after the event and comprise afterslip in the months following the earthquake, mantle relaxation over decades after the event and relocking of the fault thereafter (Wang et al., 2012). The latter two processes are generally opposite in direction to coseismic slip; areas experiencing coseismic uplift are subsiding whereas coseismically subsiding areas are uplifted (e.g. Savage and Plafker, 1991; Natawidjaja et al., 2007; Suito and Freymueller, 2009). Continuous GPS measurements along many active margins (but not in Aceh), over the past 20 years have allowed the quantification of co-, post- and interseismic deformation and the development of sophisticated earthquake dislocation models that predict the land level changes in subduction zones over one earthquake cycle (for a review see Wang et al., 2012). Since the 2004 Sumatra-Andaman earthquake and ensuing tsunami caused relative sea level rise along the coastline of West Aceh, in addition

Please cite this article in press as: Monecke, K., et al., Beach ridge patterns in West Aceh, Indonesia, and their response to large earthquakes along the northern Sunda trench, Quaternary Science Reviews (2014), http://dx.doi.org/10.1016/j.quascirev.2014.10.014