Geomorphology 250 (2015) 321–333

Contents lists available at ScienceDirect

Geomorphology

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

Post-earthquake coastal evolution and recovery of an embayed beach in central-southern Chile

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ARTICLE INFO

Article history:
Received 30 December 2013
Received in revised form 14 September 2015
Accepted 20 September 2015
Available online 25 September 2015

Keywords:
Headland bay
Coast
Recovery
Coastal evolution
Subduction earthquakes
Geomorphological change

ABSTRACT

Earthquakes and tsunamis are significant factors for change along active margin shores, and influence coastal evolution. The Chilean coast was affected in 2010 by a subduction earthquake with a magnitude of Mw 8.8 and also by a trans-Pacific tsunami, which generated violent geomorphologic changes and damaged homes. Following these events, the magnitude of the changes which affect Chile's central-southern coast (37°S) and the role of subduction earthquakes in coastal evolution on a historical scale were investigated.

At Lebu bay (an embayed beach) data were generated for variations in time and space along the shoreline, topographical and bathymetric changes in the bay, and for morphodynamic littoral processes. Logarithmic and parabolic models were applied to the shoreline along with map overlays in order to determine changes. The shoreline processes were analyzed based on statistics for waves, tides and sediment transport for pre- and post-tsunami conditions.

An average accretion rate of 2.80 m/year (1984–2010) was established for the shoreline, with a strong trend towards accretion in the last 30 years. A parabolic function best represented the general form of the shoreline, although the presence of a river in the concave zone affected the fit in this sector. Two factors controlled historical changes on the beach: one of anthropic origin in addition to the earthquake and tsunami on February 27th, 2010. The post-earthquake recovery was fast, and currently the beach is in a stable condition despite the inter-seismic subsidence process previous to the event. This coastal system showed a high resilience in the face of coastal geomorphological changes induced by high-impact natural disturbances. However, the opposite occurred in relation to changes induced by anthropogenic disturbances.

1. Introduction

The models that explain the planform of headland bay beaches and changes in the position of the shoreline have been successful worldwide and have helped to interpret coastal evolution (Silvester, 1960; Sonu and Van Beek, 1971; Rea and Komar, 1975; LeBlond, 1979; Phillips, 1985; Hsu and Evans, 1989; Moreno and Kraus, 1999; Klein et al., 2010; Schiaffino et al., 2011). Depending on the form of the bay and its morphodynamic processes, a numerical function can be obtained which will reproduce the bay conditions, even in the presence of a spit (Kaergaard and Fredsoe, 2013).

The majority of these methods and others supported by remote monitoring, GIS, or statistical tools, are applied to coastal evolution in order to reconstruct paleoenvironments (Ghilardi et al., 2014) and determine trends (Maiti and Bhattacharya, 2009; Restrepo et al., 2012), which are relevant to the sustainable use of the coast (Dibajnia et al., 2011). For tectonically stable beaches, the form of the shoreline appears to be directly related to the rate of change and the hysteresis processes that come from morphodynamic states defined by Wright and Short (1984) and Short (1987, 1999).

Davidson et al. (2013) established a strong dependency between the morphodynamic processes associated with storms or seasonal cycles and the circulation of sediment between the offshore and shoreface. In pocket beaches along stable coasts, changes are explained by the inter-relation between periodic natural phenomena (storms) and man-made actions which lead to imbalances in the provision of sediment, which then causes serious erosion (Bértola et al., 2013). On Australian beaches, geomorphological characteristics condition different types of beaches along with their morphodynamic processes (Short, 2010). However, for headland bay beaches or embayed beaches affected by tectonic phenomena such as earthquakes and tsunamis, the

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http://dx.doi.org/10.1016/j.geomorph.2015.09.015
0169-555X/

kind of changes on the shoreline are not as well known (Stive et al., 2002).

For this reason, coastal evolution in Chile is a complex process given the influence of subduction earthquakes and the tsunamis associated with them, which have historically affected the country's coast (Lockridge, 1985; Lomnitz, 1970, 1971; Kausel, 1986; Díaz, 1992; Urrutia and Lanza, 1993; Monge, 1993; Lorca and Recabarren, 1994; Comte and Pardo, 1991; Lagos, 2000; Cisternas et al., 2005, 2010; Xue et al., 2010; Ruegg et al., 2011; Moreno et al., 2011; Palacios, 2012).

On a historical scale, the kind of change that affected Chile's central-southern coast is principally determined by shoreline processes associated with swell waves, a micro-tidal tide regime, and the influence of Andean rivers whose importance is strongly linked to ENSO phases (Waylen and Caviedes, 1990; Caviedes and Waylen, 1998; Escobar and Aceituno, 1998; Givovich, 2006; Martínez et al., 2012a). An important part of the coast is characterized by its open bays in the north which have pocket beaches and extensive headland bay beaches, a situation which favors the application of models to determine changes in the relative position of the shoreline (Hsu and Evans, 1989; Hsu et al., 2010; Klein et al., 2010). In these bays the shoreline exhibits historical stability (Martínez et al., 2011a, 2011b).

The last subduction earthquake Mw = 8.8 on February 27th, 2010 destroyed a large part coastal infrastructure on Chile's central-southern coast. The effects of the tsunami were also devastating in a large part of the country; in the central-southern area 500 people perished. Drastic morphological changes with co-seismic increases of up to 1.8 m occurred, which caused the extensive abraded marine platforms, generated changes in the base level of principal rivers and new beaches, massive landslides on coastal cliffs, drying of wetlands and the severe damage to the coastal benthic community (Quezada et al., 2010; Farias et al., 2010; Martínez et al., 2011a; Vargas et al., 2011, Contreras et al., 2011; Martínez et al., 2012b; Veas et al., 2013; Jaramillo et al., 2012a, 2012b; Mardones and Rojas, 2012).

The tsunami affected 600 km of coast and was the result of the severe rupture of a complex mechanism of two segments (Madariaga et al., 2010; Delouis et al., 2010; Lorito et al., 2011, Vigny et al., 2011; Quezada et al., 2012; Moreno et al., 2012).

The tsunami had a run-up of up to 12 m in areas of the Arauco Gulf: 30 m in Tirúa and 20 m in Mocha Island (Sobarzo et al., 2012; Bahlburg and Spiske, 2012). The tsunami spread to the inner bay through local rivers, generating greater devastation due to the low and flat topography.

The historical recurrence of tsunamigenic earthquakes (seismic cycles) and the way the coast adjusts are elements which can be applied to the coast's management due to their prognosis potential. Until now, only historical seismic activity was known and commonly applied to the numerical modeling of tsunamis (Atwater, 1987; Atwater et al., 1992; Atwater and Hemphill-Haley, 1997; Lagos and Cisternas, 2008; Barkan et al., 2009; Cheung et al., 2011; Suppasri et al., 2012; Martínez et al., 2012a; Periáñez and Abril, 2013; Matias et al., 2013; Roger et al., 2013; González-Riancho et al., 2014), however, how a beach or coastal system re-adapts after a natural disturbance of great magnitude is a lesser known aspect in the literature (Veyl, 1960).

This would allow for better projections of coastal infrastructure and uses for the coast, as they could be used as new prediction and adaptability mechanisms when faced with changes caused by natural disturbances on different time scales. The purpose of this study is to analyze the types of change in the shoreline in an embayed beach in central-southern Chile which has been violently affected by an earthquake and tsunami across different time periods.

2. Regional setting

Lebu's embayed beach is located within Lebu bay in central-southern Chile (38°S). It possesses different local sediments, brought mainly by the Lebu River, which forms a river basin of about 750 km^2 (Fig. 1). The coastal landscape of the area is due to the tectonic evolution of the Arauco basin from the Senonion period. Tectonic processes, marine transgressions and regressions formed floodplains upon which historic shorelines, wetlands, and coal seams were developed (Bruggen, 1950; Pineda, 1983). The climate is Mediterranean with an oceanic influence and an extended dry season, with concentrated rainfall during winter (Devynck, 1970).

The coast has historically been affected by large-scale tsunamis. Records indicate that since 1562, nine destructive tsunamis provoked by local earthquakes have had magnitudes greater than Mw = 8.0. The strongest of which were the earthquakes of 1730 (Mw = 8.7) and 1960 (Mw = 9.5), both of which provoked widespread destruction in Chile's central-southern region. According to Belmonte (2012 in Martínez et al., 2012b) the central-southern region has a return period of 100 ± 15 years for events greater or equal to Mw = 8, which correlates accurately with the period of 90 ± 15 for the average inter-seismic periods between major earthquakes of magnitude for the region during ensuing years.

In particular, the Arauco and Lebu Gulf were affected by an uplift of around 1 m in the 1960 earthquake (Veyl, 1960; Servicio Hidrográfico y Oceanográfico de la Armada de Chile (SHOA), 1961; Lomnitz, 1970; Udías et al., 2012) which generated a violent trans-Pacific tsunami. These effects from recent tsunamis on the coast fit the descriptions in historical chronicles (FitzRoy, 1839; Darwin, 1876), which describe important morphological changes provoked by these earthquakes.

3. Materials and methods

In order to determine the morphological changes in the bay bathymetric and topographic data (pre- and post-earthquake) were utilized. The spatio-temporal changes in the shoreline were determined using aerial photographs and topographical surveys conducted on site for the period from 1984 to 2014.

3.1. Local geodetic network

Given that the earthquake on February 27th, 2010 destroyed the geodetic network for a large portion of the country's coast, the creation of a new network with local vertices using a GPS device with dual frequency (Trimble, model R-4) was necessary.

Vertical shifts in the coast provoked by the 2010 earthquake were measured at 1.8 m in the Arauco peninsula Arauco (Fritz et al., 2011; Vargas et al., 2011; Vigny et al., 2011). The horizontal shifts were around 3 m according to the nearest geodetic station (TIGO, Concepción). These shifts were included in the calculation of the new lowest water level (LWL). This was determined by measurements of the tide for a period greater than 30 days utilizing tide gauges located in different locations of the Arauco Gulf, which permitted the correction of errors up to 3 m for the horizontal coordinate (X) and 1.8 m for the vertical coordinate (Y).

3.2. Bathymetry

The bathymetric data were obtained on different dates (Table 1), using a Garmin echo-sounder attached to a boat and linked to a geodetic GPS. The data were collected every 10 s on a grid of 20 m. Bathymetric data from SHOA no. 6131 nautical chart (scale 1:15,000 year 1998) were used for the comparison of vertical changes pre- and post-earthquake (Fig. 3). These data were compared with bathymetric surveys conducted between 2010 and 2013.

The bathymetric data utilized (1998) were selected because until the 2010 earthquake it was official information for navigation (Hydrographic Service of the Chilean Navy, Spanish Acronym: SHOA). Furthermore between 1998 and the 2010 earthquake there was no evidence of important changes in the area's seabed associated with earthquakes or other natural or man-made phenomena.