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Advantages of beachrock slabs for interpreting high-energy wave transport: Evidence from Ludao Island in south-eastern Taiwan

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ABSTRACT

Powerful typhoons frequently affect eastern Taiwan. On Dabaisha beach on the SW coast of Ludao Island, a small volcanic island lying SE off mainland Taiwan, the presence of numerous beachrock slabs provides evidence of the sediment transport capabilities of high-energy waves generated by these storms. With a well-defined beachrock source from which the slabs were derived, it is easy to differentiate clasts transported in run-up or backwash flow based on their current position relative to the outcrop. In order to estimate the wave-generated flow velocities from the measured beachrock slabs, the hydrodynamic equations for boulder transport by Nandasena et al. (2011) have been rearranged so that they are appropriate for this particular geomorphic setting, where exposed in situ beachrock outcrops liberate clasts which may then be transported either by run-up onto the beach or backwash flow onto adjacent reef platforms. Such settings are common on tropical coastlines with fringing coral reefs and beaches comprising mostly biogenic sediments. In the Dabaisha beach case, the lowest flow velocities required to transport all measured beachrock slabs from their source outcrop to current positions are 2.18–3.16 m/s for run-up and 1.76–3.24 m/s for backwash. With a discussion of advantages and limitations on the use of beachrock clasts for interpreting wave behaviour, this paper presents another proxy for studying high-energy wave events that is highly suitable for certain carbonate-rich coastlines.

1. Introduction and aims

Increasing research attention has been devoted over the past 10–15 years to wave-transported large clastic sediments (i.e. coastal boulders) as a proxy tool for investigating the characteristics of past high-energy wave (HEW) events, such as those generated by intense storms and tsunamis (e.g. Scheffers, 2002; Scicchitano et al., 2007; Switzer and Burston, 2010; Etienne and Paris, 2010; Richmond et al., 2011; Engel and May, 2012; Buckley et al., 2012). Often, the presence of such coastal boulders, in particular reef-platform carbonate boulders derived from adjacent coral reefs, not only serves as direct evidence of the occurrence of HEW events in the past but also, with cautious interpretation, the characteristics of the marine inundation events responsible for boulder quarrying, transport and emplacement can be revealed through studying their size, position, geomorphic setting and geographical distribution (Noormets et al., 2002, 2004; Scheffers, 2002; Richmond et al., 2011; Goto et al., 2013).

For the purpose of HEW analysis, most previous studies have tended to focus on coastal boulders sourced either from adjacent coral reefs or local bedrock (e.g. Nott and Hayne, 2001; Noormets et al., 2002, 2004; Scheffers, 2002; Williams and Hall, 2004; Scicchitano et al., 2007; Hansom et al., 2008; Morton et al., 2008; Etienne and Paris, 2010; Switzer and Burston, 2010; Richmond et al., 2011; Terry and Etienne, 2011; Buckley et al., 2012; Goto et al., 2013; Terry et al., 2013). In contrast, the flat, slab-shaped clasts derived from the erosion of in situ exposures of beachrock, referred to henceforth as 'beachrock slabs', have rarely been examined, with the exception of recent work on the Greek Island of Lesbos in the Aegean Sea (Vacchi et al., 2012), on Huahine Island in French Polynesia (Etienne, 2012) and Taveuni Island in northern Fiji (Etienne and Terry, 2012). The paucity of beachrock slab transport research is perhaps surprising since the source of individual slabs is relatively easy to estimate from nearby in situ exposures of beachrock, which aids the determination of transport distance, direction and possibly the mode of transport. The pre-transport location of some beachrock slabs can even be identified precisely if they 'jigsaw fit' into existing cavities along the broken edge of nearby beachrock exposures, thereby allowing accurate measurements of transport distance, direction and ultimately an inference on relative wave energy.

In this study, the main aim is to explore the potential of beachrock slabs for interpreting the characteristics of HEW events, using a study site at Dabaisha beach on Ludao Island off the south east coast of mainland Taiwan. Along the coastlines of Ludao and the adjacent mainland

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coast of Taiwan, HEW events occur frequently owing to the islands' exposure to regular typhoons that traverse the north west Pacific (Chan, 1985; Terry and Feng, 2010). The specific objective for detailed geomorphological surveys carried out at Dabaisha is to demonstrate the suitability (or otherwise) of using measurements of beachrock slabs to calculate the flow velocities of HEW events that have occurred at this location in the past.

An important feature of the work is a consideration of methodology, in particular modifications that are necessary to existing hydrodynamic transport equations in order that they can be applied appropriately to the beachrock-source situation. Moreover, several advantages of investigating transported beachrock slabs compared to other types of coastal boulders are discussed.

2. Background of the study area

2.1. Vulnerability to tsunamis and typhoons

Ludao Island (also called Green Island), located at 22°39′N 121°29′E, is a small island characterised by an extinct volcano approximately 15 km^2 in area, lying 35 km south east of the main island of Taiwan in the north west Pacific. Owing to its sub-tropical latitude, the island is fringed by coral reefs. As a result of tectonic uplift in the late Quaternary, emerged fossil reefs are present on parts of the island at up to 4.5 m above mean sea level (Inoue et al., 2011). As the northernmost island along the Luzon volcanic island arc, Ludao experiences frequent seismic activity as it lies at the corner of two subduction zones: the Ryukyu and Manila trenches, although only small tsunamis have been reported on Taiwan's eastern shore throughout history (Li et al., 2006).

Climatically, the East Asian Monsoon influences Taiwan and the islands experience seasonal reversals in dominant wind direction, SW in summer and NE in winter (Yen and Chen, 2000). Facing the Philippine Sea, eastern Taiwan and Ludao Island are particularly exposed to north-east and easterly winds. Mainland Taiwan monitoring stations at Taitung (22°43.3′N, 121°8.4′E) and Chenggong (23°8.0′N, 121°25.2′E) provide the nearest data for wave conditions on the coast of Ludao. At Chenggong the monthly average significant wave height (Hs, calculated as the average wave height of the highest one-third of all waves) is 0.71–1.81 m and monthly mean wave period is 7.6–8.6 s (Central Weather Bureau (CWB), 2013a). In general, the east coast of Taiwan experiences annual average wave heights of approximately 1 m.

Both Ludao Island and the neighbouring eastern coasts of mainland Taiwan are also susceptible to waves generated by intense storms of much higher energy than typical monsoonal conditions. This is due to the high frequency of typhoons and tropical cyclones in the western North Pacific basin, averaging some 27 events per year over the period 1959–2011 (Angove and Falvey, 2011). A typhoon is an upper category of tropical cyclone, with sustained wind speeds exceeding 118 km/h. The typhoon season in Taiwan generally lasts from May to October, with the highest frequency of occurrence over July to September (CWB, 2013b). According to historical records archived by CWB, Taiwan has been affected by 347 typhoons in the 100-year time span 1911–2010 (CWB, 2013c). However, because these records are probably incomplete for earlier years, Doong et al. (2009) noted that on average 6.7 typhoons affected Taiwan per year over the more recent period between 1997 and 2008. Between 1911 and 2010, 174 typhoons (~50%) made landfall on Taiwan, and approximately 74% of these were on the eastern coast of the island (CWB, 2013d). Consequently, Ludao is often affected by HEW events, as illustrated by Typhoon Tembin in August 2012, which had a maximum sustained wind speed of 148 km/h (80 knots) when it tracked only 20 km to the south of Ludao. Under the influence of this typhoon system, a maximum Hs of 8.69 m and wave period reaching 10–11 s were recorded at Taitung (personal communication with WRA on 15 April 2013).

2.2. Dabaisha study site

Da-Bai-Sha beach, meaning “Great-White-Sand” in Chinese, is located on the south western coast of Ludao (22°38.3′N 121°29.6′E; Fig. 1a). It faces west towards the main island of Taiwan and is approximately 400 m long and 20–30 m wide. The beach is oriented in a NNW–SSE direction, and is slightly wider at its northern end, narrowing to the south east. In contrast to Ludao's eastern coast, which is exposed to the open Philippine Sea, Dabaisha is moderately sheltered under normal wave conditions, being on the western side of the island. The overall beach profile exhibits some seasonal change, although the general beach slope angle varies between 9.5° and 11°. Scrubby vegetation and grasses mark the beginning of the coastal vegetation, where the top of the beach slope gives way to an area of low coastal dunes.

Adjacent to Dabaisha beach is a fringing reef platform with living corals that extends 80–100 m offshore. In contrast to the beach itself, the reef flat tends to be wider at its southern end, becoming slightly narrower towards the north. The beach sediments comprise predominantly coarse coralline sands sourced from the fringing reef. Lag deposits of pebble-sized shell and coral fragments are dispersed widely on the beach surface, whilst rounded basaltic and coral cobbles are often observed along the beach–reef interface.

Dabaisha is surrounded by a landscape of low basaltic hills. Basaltic bedrock is exposed at the northern end of the beach. The southern boundary is a rocky shoreline characterised by weathered remnants of a Quaternary emerged reef (Chen and Liu, 1992; Inoue et al., 2011). This exists as a seaward-dipping limestone platform that extends inland a short distance to merge into a line of low limestone cliffs.

A distinctive feature of the coastal geomorphology is a linear band of in situ beachrock up to 8 m wide exposed along almost the entire length of Dabaisha beach (Fig. 1b). Beachrock is a calcareous sedimentary rock (i.e. calcarenite) formed by the lithification of beach materials that comprise coralline sands and gravels. Cementation is aided by the outflow of fresh groundwater slightly above the level of low tide (Russell, 1963; Stoddart and Cann, 1965; Bricker, 1971; Vousdoukas et al., 2007). The beachrock at Dabaisha is a cream-coloured, moderately to poorly sorted sandstone made up of sub-angular to rounded grains. It is fossiliferous with numerous visible coral fragments. In addition to biogenic grains, the beachrock also contains sand to cobble-sized basalt of terrigenous origin. The exposed outcrop surface dips seaward at a similar angle to the beach itself, i.e. 9.5° to 11°. The rock is bedded and exhibits a rectangular jointing pattern.

Hundreds of beachrock slabs have been detached from the beachrock exposure on Dabaisha. It is clear that the majority of these slabs have undergone phases of post-detachment wave transport as they are now present either under water on the reef flat itself, becoming exposed at low tide, or are scattered over the modern beach surface. Several beachrock slabs were also observed just beyond the vegetation line within the zone of vegetated dunes that starts at the top of the beach. Overall, the variety of depositional sites for the beachrock slabs, their abundance, their simple geomorphological settings, their identifiable geological origin, and their ease of access for measurement, are all factors indicating that beachrock slabs at Dabaisha offer great potential for the interpretation of past HEW events.

3. Methodology

3.1. Field methods

Initial field investigations at Dabaisha were conducted at the end of November 2012, three months after Typhoon Tembin. Considering the great abundance of beachrock slabs at the study site, their examination and measurement was organised along 11 separate transects, in a chain-survey format, spaced out along a 220 m section of the beach. The transects were not marked out equidistantly, but were spaced between 10 and 20 m apart, at locations chosen where beachrock slabs