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Boulder transport by storms – Extreme-waves in the coastal zone of the Irish west coast

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ABSTRACT

This study is concerned with large boulders located along exposed shorelines in higher latitudes, which have become dislocated onshore by winter storms and have moved against gravity. To identify the transportation processes that these boulders have undergone in detail, their direct investigation during storm wave conditions is necessary, or at least near time inspections after extraordinary wave events. As both methods are rare, a wide range of questions and contradictions with regards to the processes that have acted on these boulders, remains. Despite a lack of applicable methods as for fine sediments, the depositional environment and processes of boulder movement can be determined from geomorphologic evidence in the landscape itself. Examples are presented in this paper. To progress understanding of boulders in rocky coastal environments, qualitative and quantitative data are acquired during a near time inspection following extreme storms in winter 2013/14 with special focus on an extraordinary boulder site near Doolin at the entrance to Galway Bay (central west coast of Ireland). The comparison of these data to previously published research on coastal boulder movement results in agreements and discrepancies (e.g. on boulder forms and mode of transport, difference in wave and bore transport) which are discussed.

1. Introduction

Land based boulder deposits dislocated by marine forces exist on all continents and in all latitudes, and are most frequently found along exposed rocky shorelines. Previous research have predominantly attributed storm waves as the only important mechanism in these boulders deposition (e.g. Cox et al., 2012; Etienne and Paris, 2010; Fichaut and Suanez, 2008, 2011; Hall, 2010; Hall et al., 2006, 2010; Hansom et al., 2008; Lau et al., 2014; Noormets et al., 2004; Paris et al., 2011; Suanez et al., 2009; Terry and Etienne, 2010; Terry et al., 2013; Williams, 2004, 2011; Williams and Hall, 2004). Relatively few papers have focused on near time inspections of strong impacts on coastlines, and the majority of them with storm waves (e.g. Bartel and Kelletat, 2003; Engel et al., 2014; Erdmann et al., 2015; Goto et al., 2009, 2010; Kennedy et al., 2017; Khan et al., 2010; May et al., 2015; Saintillan and Rogers, 2005; Scheffers and Scheffers, 2006). A number of papers have focused on natural settings where boulders are moved on a planar surface and not against gravity, in particular on reef platforms. These settings offer comparable simple conditions, but irregular boulder forms (as from coral reefs) and roughness of the platforms are complicating factors.

Evaluating published documents for physical calculations, modelling or wave tank experiments, significant discrepancies are found in the mode of movement between waves and bores, in particular regarding the energy for a specific transport process (sliding, overturning/rotation, saltation), and the importance of transport parameters involved (e.g. wave height, flow velocity, boulder forms, bed roughness). Some examples are given at the end of this introduction.

Size, form and origin of boulders, organization of boulder deposits (single, in clusters, imbricated, in ridges etc.), bathymetry, and wave regimes are among the parameters that inhibit the transfer of the environments into models or physical tests on a smaller scale. In particular, theories and models work with simplified conditions, which focus on specific processes. The development of such models are further complicated if the deposits represent a longer history in which changes of climate, wave regimes, bathymetry, sea level or processes in the coastal landscape, with positive or negative impacts on preservation, influence the picture that is trying to be analyzed. The local relief points at which a wave breaks and friction affects wave velocity and transport competence. Wave impact may set a boulder in motion, but bore flow is

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necessary to keep it in motion and dislocate it significantly (Benner et al., 2010).

For boulder dislodgement to occur strong forces have to act on the rock from which it originates. Although the direct observation of the dislocation process during a storm is difficult, in some areas with carbonate rocks boulder movements scrape the bedrock or neighboring fragments, and these signatures can be observed for some time (up to years in some cases) after an event. These marks enable the collection of quantitative data on mass, distance, direction and the kind of movement the boulders have undergone, and may enable clarification of physical processes of boulder transport (e.g. continuous lines by sliding/shifting, interrupted lines by jumping or – if shown as series of similar marks, points or short lines – by rolling of an angular fragment). Despite such data, there are still more questions to be answered than a general agreement with regards to dislocation processes of boulders and the most important parameters at work in these processes.

Nott (2003) distinguished boulders of different forms (cubic or platy), and identified three pre-transport settings (submerged, subaerial and joint bounded). He concluded, that the form of a boulder is much more important than its mass, and a cube is transported more easily than a plate form. Conversely, Nakamura et al. (2014) found that the flatter the boulder the lower the velocity needed to move it. Imamura et al. (2008), Goto et al. (2009), Nandesana and Tanaka (2013), and Nakamura et al. (2014) found that boulders need relatively low wave and bore velocities (3–3.5 m/s) for sliding, whilst higher velocities are needed for rotation, and even higher velocities for saltation. However, centrifugal forces and interaction/collision of fragments may lead to a greater range of transport from rotation and saltation compared to sliding.

Sliding is the process of boulder movement that exhibits the greatest friction. Weiss (2012) and Weiss and Diplas (2015) exclude the sliding process if bed roughness is 30% or more of a (spherical) boulder's radius. During rotation or saltation, however, bed roughness/friction are nearly insignificant. A longer transport distance needs bore flow, which, according to Ryu et al. (2007), may reach a maximum horizontal velocity 1.5 times the phase speed of a wave. Hansom et al. (2008) modelled green water bore flows which, however, accelerate with the factor of 2.4 at each (structural) step on a cliff-top.

With regards to boulder settings before movement, Nott (2003) argued that a submerged boulder requires the smallest waves for transportation, in contrast to subaerial or joint bound scenarios. However, a submerged boulder needs the highest lift against gravity to reach a new position on land, and may be exposed to a subaerial position just before a large wave hits, as water recedes strongly in front of breaking waves.

As all theories and models are based on simplifications of natural conditions, field data on the size of boulders and distance moved against gravity are valuable for validation of such models.

Richmond et al. (2011) support the idea that storm boulders of medium size cannot be found further than an average of 50 m to 100 inland. Terry et al. (2013) found a significant difference between the large mass (> 40 m^3) of existing boulders, mostly unaffected by a TC (Tropical Cyclone) of cat. 4–5, and those moved by a storm of this energy with a maximum boulder size < 5 tons. May et al. (2015) quantified the dislocation of the largest boulder observed during a storm on Samar Island, eastern Philippines, from TC Haiyan in 2013 (the strongest ever on record, with sustained winds of 315 km/h and gusts up to 375 km/h). The authors used multi-temporal satellite imagery, direct observation of the event, and eyewitness accounts including videos. The location is a boulder of coral rock with a mass of 180 tons, which has been moved around 40 m along the coastline, not against gravity. The authors argue that a rare combination of storm waves, surge and infra-gravity waves resulted in this extreme block movement. Kennedy et al. (2017) used field data from Typhoon Haiyan to discriminate the suitability of boulder forms (rectangular and non-rectangular cross sections), mass (up to > 100 tons) and elevation (max. 15 m MSL) for different kinds of movement.

It can be found that at many exposed sites around the world's coastline coastal boulders exist in individual dimensions and distances (vertical and horizontal) to the actual shorelines which needed significantly more energy as is offered from modern extraordinary winter storm waves or waves from strong tropical cyclones. In particular because of different sources of information (fieldwork, wave tank experiments, theories on wave motion, calculations on wave transport energies, bore flow physics, models of boulder transport etc.), a balanced review of all coastal boulder transport processes is not possible in a paper with limited length.

The discussion on boulder movement onshore remains difficult if information on important facts are missing, e.g.

- methods of identifying boulder forms, volumes and boulder mass, or source area,
- distance of boulder movement (from its source, from the shoreline, at which elevation, how far against gravitation),
- friction/bed roughness,
- mode of movement (single or with other fragments, in one or many steps, by one or many events),
- kind of movement (sliding, rotation, saltation, no surface contact between start and place of final deposition),
- process of movement (waves, bores, tsunamis, infra-gravity waves, freak waves),
- age since deposition (with relative or numerical methods).

2. Study area and methods

Conclusions from local and regional studies are most valid for these specific sites and regions. The same is true for theories, tests and models, due to their focus on specific parameters. To undertake an overall validation more investigations into the phenomenon of coastal boulder dislocation is needed. Consequently, we will concentrate on an area of an exceptional variety of boulder settings (single blocks, boulder clusters, imbrication trains, kilometres long ridges on high cliff tops) from the Aran Islands and the SE-coast of Galway Bay, on the central west coast of Ireland (Fig. 1).

The 60 km W-E axis of Galway Bay separates a granite landscape in the north from a Carboniferous limestone terrain in the southeast (Fehman, 1999; McNamara and Hennessy, 2010). In a landscape with very variable topographies, exposure and water depth, bedding and jointing deliver all sizes of boulders and blocks in elevations from sea level to > 50 m asl. The results is, that marine transport forces can act upon a diverse range of material available for dislocation and for each storm or other extreme process, an "envelope" for dislocated material can be identified. The same is true for the younger Holocene and for different sea levels, so far as a matrix of numerical ages are established. This all positions the Aran Islands and parts of Galway Bay as a perfect natural test area for the topic of coastal boulder movements.

The storm history with emphasis on exceptional events is discussed in Brayne (2003), Burt (2006), Erdmann et al. (2015), Hickey (2001), Lamb and Frydendal (1991), MacClenahan et al. (2001), and O'Brian et al. (2013), Shields and Fitzgerald (1989), as well as in Erdmann et al. (2015) and Masselink et al. (2016) for the winter season of 2013/14.

Several indicators for the relative age of boulder dislocation such as small morphologies from intertidal/subtidal organisms like sea urchins, limpets, boring bivalves, and *Cliona* borings, and rock pools formed by bio-erosion have been studied (compare also Kelletat, 1986, 1988; Spencer, 1988; Trudgill, 1987; Trudgill and Crabtree, 1987; Trudgill et al., 1987). Their intensity is compared with terrestrial limestone dissolution on boulders (e.g. using the height of pedestals under glacial erratics in the study area, and data from Pfeffer (2010)).

Text documents and photographs on the boulder deposits of the exposed sides of the Aran Islands are found (chronologically) in Williams and Hall (2004), Hall et al. (2006, 2010), Hansom et al.