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The mystery of boulders moved by tsunamis and storms

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ABSTRACT

Boulders are moved differently in storm and tsunami and produce different characteristics of the boulder deposits. This contribution is motivated by two observations. One by Bourgeois and MacInnes (2010), which described that boulders were moved selectively due to different bed roughness during 15 November 2006 tsunami on the island of Matua. The second topic is motivated by the boulder lines on Ishigaki Island by Goto et al. (2010). Both topics are approached with linear wave theory and stability analysis. From both, the safety factor is derived for a spherical boulder with bed roughness and exposure as moment arms, with which we are able to quantify the influence of bed roughness on the incipient motion of boulders. For constant forces, a bed roughness of about 30% of the boulder radius will prevent boulder transport. Furthermore, the comparison between storm and tsunami waves in terms of the amplitude necessary to move boulders revealed that amplitude of storm waves is smaller than tsunami, which we ascribe to the contribution of both velocity components to lift forces. The comparison of total energy and number of waves revealed that storms have a larger total energy and a much larger number of waves, which lead us to the conclusion that tsunamis produce unorganized boulder deposits; whereas, storms are capable of organizing boulders along lines and in clusters.

1. Introduction

1.1. Motivation and background

The motivation of this paper comes from two recent observations regarding boulders moved by storms and tsunamis. The observations on the island of Matua by Bourgeois and MacInnes (2010) of the 15 November 2006 central Kuril Island tsunami revealed that boulders were moved somewhat selectively. The tsunami waves exceeded 12 m of runup with a maximum of about 20 m with inundations between 40 and 90 m. Both values demonstrate the steepness of the terrain. The main observation was that some boulders were moved, indicated by recently deceased attached intertidal fauna, and some were not moved even though the flow depth inferred from the measurement was sufficient. Bourgeois and MacInnes (2010) speculated that roughness might be the key to understanding this phenomenon. The second publication that inspired this study is from Goto et al. (2010) on the observed boulder distributions on Ishigaki Island, Japan. The key observation by Goto et al. (2010) is that boulders moved by tsunami are distributed erratically near-shore and onshore, whereas boulders moved by a storm formed a line on the reef crest, but did not travel into the moat and onto the beach.

Inversion methods have been designed to help distinguishing boulders moved by tsunamis from those moved by storms. For the boulders under consideration, wave heights of storm and tsunami waves needed for incipient motion were estimated, and then argued that, often times, storm waves have unrealistically large values and must therefore be ruled out as the causative process. In this regard, Costa (1983) derived a set of equations to infer the flow power needed to transport boulders during the flash flood peaks in the Colorado Front Range. Bryant et al. (1997) employed these equations to infer tsunami height from boulders along the Australian coast. Furthermore, Nott (2003) related the incipient motion of boulders to the causative waves and derived for different scenarios of boulder emplacement a set of equations that is widely known as Nott's equations. These equations have been extended in Nandasena et al. (2011). Alternative expressions were proposed by Benner et al. (2010) and Buckley et al. (2011). Nott's equations and its enhancements have been employed to reconstruct wave heights of the 2004 Sumatra tsunami along the coasts of Indonesia (Paris et al., 2010) and Thailand (Kelletat et al., 2007) and in the Mediterranean (Mastronuzzi and Sanso, 2004; Barbano et al., 2010). Furthermore, Nott's equations have also been used in the very controversial Australian Megatsunami Hypothesis (Bryant et al., 1997; Dominey-Howes et al., 2006).

The approaches to consider incipient boulder movement mentioned above rely on the quadratic form of the forces, in which the free stream horizontal velocity is squared. Furthermore, these approaches have a drag coefficient that needs to be approximated because for arbitrary geometries, the drag coefficient is unknown. The

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quadratic form of lift and drag force only includes the one-dimensional, horizontal free-stream velocity. The flow field under waves is two dimensional, and this was taken into account to estimate the forces exerted by the flow field. To overcome the limitations of the quadratic form of drag and lift forces, the Kelvin–Helmholtz circulation theorem was applied to compute the forces from the two-dimensional fluid motion. Furthermore, incipient motion of boulders is approached with linear theory for both the water-related forcing and stability of a boulder. It is also assumed that the boulder is circular in cross section and that is of cylindrical shape for which the lateral extent can be neglected. With this assumption, even a linear theory can provide quantitative information on the influence of bed roughness, for comparing tsunami and storm waves, and for inferences of the boulder clustering by storms and tsunamis. However, linear theory does not allow for a derivation of equations to infer wave amplitude for arbitrary boulder geometries. The derivation of Nott's equations also reveals that certain geometric characteristics need to be present. It should be noted that such an attempt in the same framework as presented herein requires the employment of non-linear wave theory with an arbitrary geometry of the integration contour used in the Kelvin–Helmholtz circulation theorem.

1.2. Boulder and sand transport

In geology and sedimentology, boulders are defined to represent grain sizes larger than 256 mm in diameter ($\phi < -8$). Sand has ϕ values between -1 and 4. In terms of size, there are three to five orders of magnitude between sand and boulders, which leads to the intuitive conclusion that sand is transported differently by a storm or tsunami waves than boulders. Furthermore, the magnitude of storm and tsunami waves can vary over several orders of magnitude. Hence, sediment transport by tsunami and storm waves is a multi-scale problem in terms of grain sizes involved as well as causative power, which may be the reason for the challenge that respective deposits pose for inferences of the causative process and respective magnitudes.

Boulder and sand deposits are expected to be different, which can be ascribed to the very different fashion of sand and boulder transport. The obvious difference between sand and boulder transport is that sand grains are easily lifted and will spend significant amount of time in the water column before they touch the ground again. Boulders on the other hand, probably will rotate or be pushed very close to the bed with very short or even neglectable lift periods compared to the time it takes to travel one diameter.

A fluid body that exhibits circulation exerts drag and lift forces, which can be quantified with the help of the vorticity. Circulation and vorticity are an expression of the turbulence. From the stochastic nature of turbulence, it follows that the eddies created by circulation have a size distribution. For a boulder under consideration, we can assume that the mode of the eddy distribution $M(l_e)$ is $M(l_e) \leq l_b$, in which l_b is a boulder length scale. A boulder length scale is the radius of a boulder or a length of its horizontal extent. From this condition for the mode of the eddy distribution, it follows that drag and lift forces exhibit large gradients along the boulder, and it is possible that drag and lift forces do not exceed the threshold of motion on one side of the boulder. However, the lift force on the front side causes a reduction in resistance. If the drag force is smaller than the lift force, the boulder will rotate; if the drag force is similar, the boulder will be pushed.

For sand grains, we define that the mode of the eddy distribution is $M(l_e) >> l_s$, in which l_s is a sand-grain length scale, such as the grain diameter. Therefore, the force gradient along the sand grain can be neglected, resulting in a lift of the entire grain. Once lifted, these particles experience the delicate and complex balance between turbulent fluctuations of the flow and gravity. If the influence of turbulence is larger than the influence of gravity, the particle pathways become completely random due to the stochastic nature of turbulence and the relatively weak influence of gravity. This transport mode is commonly known as suspended load. If gravity has a larger influence on the particle under consideration than turbulence, the pathway of the particle in the fluid will obey a ballistic pathway (with stabilizing Magnus effect). This transport mode is commonly known as bed load. The duration of the lift phase of these grains in case of bed load depends on the magnitude of the turbulence and respective stresses compared to gravity. However if the duration is much longer than it takes for a grain to travel the distance of its size, then different grain sizes are sorted and are able to form sedimentary structures that are larger than the grain size.

1.3. Setting

In order to be able to compare transport of a boulder by storms and tsunamis, it is assumed that boulder transport takes place in some water depth and not directly at the wave front of the tsunami. However, transport of boulders by the wave front may also be possible for tsunamis. The effects of a storm consist of a surge and the storm waves. The surge may flood low-lying land with storm waves bringing destructive energy to the inundated areas.

Boulder characteristics are described by the height of the boulder, d, and its length, l_b. For theoretical analysis, a cylindrical boulder shape is employed for which only the circular cross section of radius is considered. Then the boulder is defined by the radius $r_b = l_b/2 = d/2$.

For wave theory, it is assumed that A is the wave amplitude, L is the wavelength, and d is the water depth. The two-dimensional velocity ($\mathbf{u} = (u, w)$) field is determined with the help of linear wave theory, in which ω is the angular frequency ($\omega = (2\pi)/T$; T-wave period) and k is the wave number ($k = (2\pi)/L$). Linear wave theory defines the framework for storm waves because the storm surge causes an increase in water depth. Furthermore, depth-limited waves are employed, which means that the height of the waves is limited to 0.8 of the water depth. Even though it is assumed that boulder transport in a tsunami takes place well behind the moving wave front, from the length-scale to water-depth ratio of a tsunami it can be concluded that the horizontal velocity u computed with linear theory represents a gross underestimation of the actual velocity. The computation of the vertical velocity w with linear theory is thought to be robust even for tsunamis. In this setting, it can be assumed that the velocity is related to the depth of the flow. The scaling constant in the relationship between the flow velocity and depth of flow is the Froude number Fr. Spiske et al. (2008), Jaffe and Gelfenbaum (2007), and Matsutomi et al. (2001) reported maximum Froude numbers of 2. However, Lynett (2007) found Froude numbers as high as 5 for the largest waves employed in the study, but using a reference height. Employing the entire water column, $Fr = 5$ decreases to about $Fr = 3$. Hence, we assume that the Froude number can vary from 0.5 to 3.

2. Boulder transport model

2.1. Drag and lift forces

Usually, drag and lift forces are expressed in a quadratic form of the velocity, which works well for one-dimensional flows. For example this approximation is used in Nott (2003). However, a wave can only be described by a two-dimensional flow field $\mathbf{u} = (u, w)$. Hence, drag and lift forces are exerted by the two-dimensional wave motion. As an assumption, the circulation of the flow under a wave can be calculated with the Kelvin–Helmholtz circulation theorem to the first order.

$$\Gamma = \oint_C \mathbf{u} \cdot dl \tag{1}$$