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Waves, coastal boulder deposits and the importance of the pre-transport setting

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Abstract

The pre-transport environment of a coastal boulder along with its shape, size and density determines the height of wave required for it to be transported. Different forces act on sub-aerial boulders as opposed to submerged boulders when struck by a wave. Boulders derived from joint bounded blocks on shore platforms predominantly experience lift force and require a wave of greater height to be transported than boulders in other environments. No one equation is applicable to determine the height of palaeo-waves responsible for depositing a field or ridge of imbricated coastal boulders. A range of equations and their derivation is presented here which can be applied to the respective pre-transport environment of a boulder. Such an approach is necessary when attempting to reconstruct the frequency and magnitude of past coastal wave hazards and for differentiating between tsunami and storm wave deposited boulder fields.

Keywords: coastal boulder deposits; hydrodynamic equations; tsunami; storm waves; Western Australia

1. Introduction

Coarse-grained coastal deposits such as cobble, gravel and boulder beaches are common the world over. Recent investigations have examined the size and period of waves required to transport coarse clasts from their resting position on such beaches [1]. In these situations these clasts are transported, initially and critically via pivoting, over a bed of similar clasts. And if transported inland the clasts generally move upslope. A less common, but equally important, style of coastal boulder deposit occurs in the form of boulder ridges, either as a single ridge or as multiple ridges parallel to shore, and fields of boulders deposited on shore platforms. Determining the type and size of wave responsible for deposition of these features requires a separate series of hydrodynamic equations to those moving across beaches, for these boulders have not been entrained in a flow involving pivoting over a bed of similar clasts. Rather, they have been overturned and trans-

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ported generally across flat shore surfaces such as rocky shore platforms.

Boulder fields and ridges are usually characterised by a distinct sedimentological signature – imbrication of clasts and parallel to sub-parallel alignment of the majority of boulder A-axes with the shore or perpendicular to the direction of transport [2,3]. It is rare that such a signature occurs in deposits that have resulted from rock falls and sea-cliff collapse or from deep weathering and exposure of core stones. The size of the clasts in these deposits is usually much larger (1–6 m length A-axes and weighing up to 200 tonnes) than those forming beaches, suggesting they were deposited by higher magnitude events. Identifying these mega-clast deposits, and where possible determining an age of deposition, can assist substantially in elucidating the magnitude and frequency of the waves responsible and thereby assist in deriving risk assessments of coastal hazards. Furthermore, these deposits can be used, if the clasts are large enough, to determine what type of wave was responsible – namely tsunami or storm [4].

Nott [3] developed hydrodynamic equations that relate the forces required to transport these types of coastal boulders to wave height and thereby ascertain the type of wave most likely responsible. These equations were limited in their ability to describe all likely boulder transport scenarios for they referred only to boulders that were submerged by water prior to transportation, i.e. where the boulders lay just offshore in shallow water and were then deposited onshore. Boulders can also be transported by waves from positions where they stand as sub-aerial features on shore platforms and at the base of sea-cliffs following rock falls, and where they exist as joint bounded blocks in shore platforms. In each of these situations, different forces are required to initiate transport and as a consequence the types of equations necessary to describe the height of the waves responsible differ. Identifying the likely pre-transport location or origin of a boulder is important for ascertaining which equation is most appropriate and the type of wave most likely responsible. These equations and their derivation are presented here.

2. Wave transport equations

Different forces will act on a boulder impacted by a wave depending upon that boulder's pre-transport position. For example, a boulder submerged by water will experience the forces of drag and lift when impacted by a wave and it will resist movement through the force of restraint compensated by buoyancy. On the other hand, a joint bounded block will only experience lift force when overtopped by a wave until it is incorporated into the flow, after which it will then experience drag force. Boulders located prior to transport as sub-aerial blocks will, along with drag and lift force, also experience an inertia or momentum force in addition to the force of restraint. The inertia force applies in this situation because unlike the submerged boulder and joint bounded block the sub-aerial boulder is not supported by either water or rock on the lee side of the flow. As a consequence the boulder experiences flow acceleration, albeit, as is discussed later, for a brief time (1–2 s), as the wave first impacts.

Each of these forces can be described as follows:

$$F_\mathrm{d}\ (\text{drag force moment}) = [0.5\rho_\mathrm{w} C_\mathrm{d}(ac)u^2]c/2 \tag{1}$$

$$F_\mathrm{l}\ (\text{lift force moment}) = [0.5\rho_\mathrm{w} C_\mathrm{l}(bc)u^2]b/2 \tag{2}$$

$$F_\mathrm{m}\ (\text{inertia force}) = \rho_\mathrm{w} C_\mathrm{m}(abc)\ddot{u} \tag{3}$$

$$F_\mathrm{r}\ (\text{restraining force moment}) = (\rho_\mathrm{s}-\rho_\mathrm{w})(abc)gb/2 \tag{4}$$

where ρ_w = density of water at 1.02 g/ml (this could increase when sediment such as sand is incorporated in the flow), ρ_s = density of boulder at 2.4 g/cm^3, C_d = coefficient of drag = 2, C_l = coefficient of lift = 0.178, C_m = coefficient of mass = 1, g = gravitational constant, $\ddot{u}$ = instantaneous flow acceleration, u = flow velocity/wave celerity, a = A-axis of boulder, b = B-axis of boulder, c = C-axis of boulder.

Boulder transport will be initiated when, in the case of a submerged boulder:

$$F_\mathrm{d} + F_\mathrm{l} \geq F_\mathrm{r} \tag{5}$$

and for a sub-aerial boulder when:

$$F_d + F_l + F_m \geq F_r \tag{6}$$

and for a joint bounded block when:

$$F_l \geq F_r \tag{7}$$

2.1. Submerged boulder scenario

Incorporating Eqs. 1, 2 and 4 into Eq. 5 and solving for H (height of wave at shore – and in case of storm wave at breaking point) gives:

$$0.5\rho_w u^2 0.5[C_d(ac^2) + C_l(b^2c)] \geq 0.5(\rho_s - \rho_w)ab^2cg \tag{8}$$

Transposing u^2 and simplifying gives:

$$u^2 \geq \frac{0.5(\rho_s - \rho_w)ab^2cg}{0.5\rho_w 0.5[C_d(ac^2) + C_l(b^2c)]} \tag{9}$$

$$u^2 \geq \frac{2(\rho_s - \rho_w/\rho_w)ag}{(ac^2/b^2c) + C_l(b^2c/b^2c)} \tag{10}$$

$$u^2 \geq \frac{2(\rho_s - \rho_w/\rho_w)ag}{C_d(ac/b^2) + C_l} \tag{11}$$

as $u = \delta(gH)^{0.5}$

where δ is wave type parameter, which differs as a function of the difference in speed between various wave types, and H is wave height, and therefore:

$$u^2 = \delta gH$$

Substituting δgH for u^2 gives:

$$\delta gH \geq \frac{(\rho_s - \rho_w/\rho_w)2ag}{C_d(ac/b^2) + C_l} \tag{12}$$

and solving for H and simplifying gives:

$$H \geq \frac{1/\delta(\rho_s - \rho_w)/\rho_w)2a}{C_d(ac/b^2) + C_l} \tag{13}$$

Eq. 13 can be further simplified for both tsunami and storm waves as:

$$H_t \geq \frac{0.25(\rho_s - \rho_w/\rho_w)2a}{(C_d(ac/b^2) + C_l} \tag{14}$$

where H_t = height of tsunami, $u = 2\ (gH)^{0.5}$ and $\delta = 4$, and:

$$H_s \geq \frac{(\rho_s - \rho_w/\rho_w)2a}{C_d(ac/b^2) + C_l} \tag{15}$$

where H_s = height of storm wave at breaking point, $u = (gH)^{0.5}$ and $\delta = 1$.

Inherent in the drag force equation is the assumption that velocity refers to depth averaged velocity whereas the lift force equation refers to bed velocity. Baker [5] noted that because of flow turbulence bed velocity during floods in stream channels was probably close to mean velocity. Costa [6] likewise recognised that the two velocities were similar but he increased his bed velocity by 20% to equate it to mean velocity. The highly turbulent nature of a breaking wave and bore suggests that the difference between bed and mean velocity in this situation is likely to be minimal. Lift force is also a relatively minor component of the final equations for wave heights hence the two velocities (bed and mean) are assumed to be roughly equal in this analysis.

In this study changes have been made to the velocity equations incorporated into the hydrodynamic transport equations used by Nott [3]. Nott, in line with Massel and Done [7], used:

$$u = 0.5(gH)^{0.5} \tag{16}$$

as the average velocity equation for a broken oscillatory wind (storm) generated wave. This equation is similar to Fredsøe and Diegaard's [8] equation for maximum near-bed wave-orbital velocity, however as noted by these authors, this equation does not hold in the surf zone. Because the movement of boulders takes place in the surf zone, or is assumed to be initiated at the point of commencement of wave breaking, and also because it is difficult to derive an average orbital-wave velocity, a conservative approach is adopted and the wave velocity/celerity for unbroken orbital-waves:

$$u = (gH)^{0.5} \tag{17}$$

is used. This is probably an overestimate of the velocity of a broken wave for these waves decrease their velocity considerably after breaking. Eq. 17 therefore really only applies when the wave commences to break and transport of the boulder is initiated. Once the boulder is entrained the velocity of the broken wave will approach that described in Eq. 16.

In the development of Eq. 13 consideration was given to Fukui et al.'s [9] analysis of tsunami bore velocity. Fukui et al.'s equation for a tsunami bore is:

$$u = \frac{\zeta[g(H+h)]^{0.5}}{2H(H-\eta\zeta)} \tag{18}$$

where H = height of bore, h = depth of 'still' water in front of bore, $\zeta = H-h$, η = friction factor.

The friction factor η was determined empirically by Fukui et al. (fig. 7, p. 75). This factor varies between $\sim$0.82 and $\sim$1.02 with increasing h/H. Using this equation η is a critical variable in determining the velocity of a tsunami bore and the relationship between η and u where $u = \delta(gH)^{0.5}$ is given by:

$$\delta = \frac{1}{[2(1-\eta)]^{0.5}} \tag{19}$$

The most appropriate value for η is suggested here to occur between these two figures of $\eta \approx 0.82$ when $h/H = 0$ and $\eta \approx 1.02$ when $h/H = 0.5$. When boulders have been transported well above sea level, and if a tsunami was responsible, the wave would have transported the boulders over dry land or where $h = 0$ and therefore $h/H > 0.5$ and $\eta > 1.02$. As shown by Eq. 19 where $\eta > 1.02$ and $\delta > 2$ the tsunami velocity would be greater than $u = 2(gH)^{0.5}$. A conservative value of $\eta = 0.875$ or where $\delta = 2$, being the same as that used by Nott [3], is therefore recommended. By incorporating Eq. 17 into Eq. 15 the difference in wave height between tsunami and storm waves required to move a given size boulder is reduced substantially compared to the equations proposed by Nott [3].

Eq. 13 is particularly sensitive to changes in the value of the drag coefficient (C_d). Noji et al. [10] observed that C_d varies substantially with time (during passage of wave) and that it decreased as the Froude number approached 1. Noji et al. [10] determined C_d for a block shaped object (cube), which is similar in shape to many boulders that have been transported by waves. In their experiment, C_d varied between approximately 5 and 1.5 and attained its lowest value when h/H was between 1.2 and 2. The coefficient of drag (C_d) has been given a value of 2 in this study because Noji et al. [10] found that $C_d = 2$ when h/H was less 1.2. This value appears therefore to be most appropriate for boulders transported from a sub-aerial position and from a shallow water setting where the wave height and water depth are close to equal.

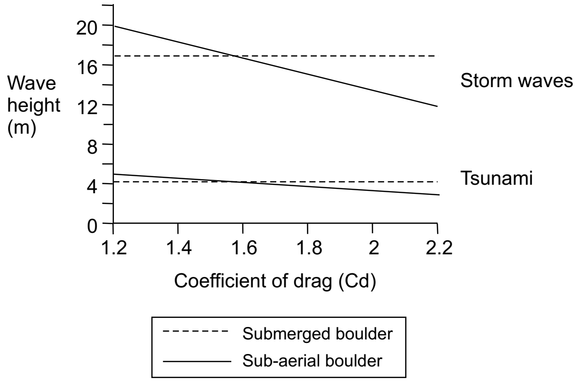

Fig. 1. Relationship between coefficient of drag, wave height and pre-transport setting of boulder.

Fig. 1 shows the relationship between C_d and wave heights required to move both submerged and sub-aerial boulders. The equation for submerged boulders (Eq. 13) is considerably more sensitive to changes in C_d than the equation for sub-aerial boulders. This suggests that there is a difference in wave height necessary to transport boulders that are submerged compared to those standing initially in a sub-aerial position (Fig. 1). In reality there is likely to be a range of wave heights that could transport a given size and shape of boulder depending upon the depth of water above a submerged boulder and the nature (Froude number) of the wave/bore.

2.2. Sub-aerial boulder scenario

Inertia force must be incorporated into an equation to describe the impact of a wave upon a boulder that is not submerged or buttressed. Eq. 6 which incorporates the inertia force can be rearranged and expressed as:

$$F_d + F_l \geq F_r - F_m \tag{20}$$

Incorporating Eqs. 1–4 into Eq. 20 gives:

$$0.5\rho_w u^2 0.5[C_d(ac^2) + C_l(b^2c)] \geq 0.5(\rho_s - \rho_w)ab^2cg - C_m\rho_w abc\ddot{u} \quad (21)$$

Transposing u^2 and simplifying gives:

$$u^2 \geq \frac{0.5(\rho_s - \rho_w)ab^2cg - 2C_m\rho_w abc\ddot{u}}{0.5\rho_w 0.5[C_d(ac^2) + C_l(b^2c)]} \quad (22)$$

$$u^2 \geq \frac{2[(\rho_s - \rho_w/\rho_w)ab^2cg - 2C_m(abc/b^2c)\ddot{u}]}{C_d(ac/b^2) + C_l} \quad (23)$$

$$u^2 \geq \frac{2[(\rho_s - \rho_w/\rho_w)ag - 2C_m a/b\ddot{u}]}{C_d(ac/b^2) + C_l} \quad (24)$$

as $u = \delta(gH)^{0.5}$, $u^2 = \delta gH$, substituting u^2 for δgH gives:

$$\delta gH \geq \frac{(\rho_s - \rho_w/\rho_w)2ag - 4C_m a/b\ddot{u}}{C_d(ac/b^2) + C_l} \quad (25)$$

and solving for H (height of wave at shore – and in case of storm wave at breaking point) gives:

$$H \geq \frac{1/\delta[(\rho_s - \rho_w/\rho_w)2a - 4C_m(a/b)(\ddot{u}/g)]}{C_d(ac/b^2) + C_l} \quad (26)$$

Eq. 26 can be further simplified for both tsunami and storm waves as:

$$H_t \geq \frac{0.25(\rho_s - \rho_w/\rho_w)[(2a - C_m(a/b)(\ddot{u}/g)]}{C_d(ac/b^2) + C_l} \quad (27)$$

where H_t = height of tsunami, $u = 2\ (gH)^{0.5}$ and $\delta = 4$, and:

$$H_s \geq \frac{(\rho_s - \rho_w/\rho_w)[(2a - 4C_m(a/b)(\ddot{u}/g)]}{C_d(ac/b^2) + C_l} \quad (28)$$

where H_s = height of storm wave at breaking point, $u = (gH)^{0.5}$ and $\delta = 1$.

By incorporating the inertia force, Eqs. 27 and 28 acknowledge that flow acceleration occurs when a boulder is standing as a sub-aerial feature prior to impact by a wave. Flow acceleration occurs when the wave initially strikes the boulder after which the acceleration diminishes rapidly to be negligible once the wave front passes and boulder motion commences. As discussed by Noji et al. [10], the value for acceleration is difficult to ascertain. Acceleration ($\ddot{u}$) is relatively insignificant in Eq. 26 because variations in this value have little effect on the total force applied to the boulder and hence the wave height at the shore. Noji et al. [10] noted that, despite the insignificant change in total force resulting from variations in acceleration, it is nonetheless important to include the acceleration term in the inertia force equation otherwise the computation becomes unstable.

The coefficient of mass (C_m) was determined empirically by Noji et al. [10] and expressed by the equation:

$$C_m = 1.15 + 1.15\tanh[(-2.0 + 2.5h/H)\pi] \quad \text{for } h/H < 1.0 \quad (29)$$

Noji et al. [10] observed that C_m is a function of relative water depth (h/H) and it increases dramatically when an object is initially impacted by a wave (bore), i.e. during the first second. After this C_m diminishes rapidly to approach zero. Once the object is completely submerged in the flow the value of C_m does not make any difference to the total force because acceleration becomes negligible [10]. Noji et al. used a value of $C_m = 2$ representing the time when the boulder is completely submerged, but they noted that the adopted value should not make any difference to the total force because by this time the acceleration is negligible.

Like acceleration ($\ddot{u}$), C_d and C_m appear to increase dramatically during the first second of impact by the wave front and diminish rapidly after this time. Such high values, when incorporated into Eqs. 27 and 28, show that considerably less force is required to move boulders during the first second of wave impact due to the rapid change in momentum, which is related to water depth. This change in momentum initiates boulder movement, but considerably more force is then required to transport the boulder some distance inland. Because it is highly unlikely for a wave of given height to increase its force or height following the first second of impact with a boulder at the shore, more conservative values of $C_d = 1.5$, $C_m = 2$ and $\ddot{u} = 1$ m/s^2 are recommended.

Eqs. 27 and 28 suggest that a wave of greater height is required to transport a boulder some distance inland than that required to initiate movement of a boulder during the first second of wave impact. After the boulder is submerged by the wave, and providing that the water or flow

Table 1
Wave heights (m) calculated using submerged boulder, sub-aerial boulder and joint bounded block hydrodynamic transport equations

ρ_s	ρ_w	C_d	C_l	a	b	c	Vol.	C_m	Acc.	T (sm)	S (sm)	T (sa)	S (sa)	T (lift)	S (lift)
2.1	1.02	2	0.178	3	2.1	0.7	4.4	2	1	1.4	6	1.3	5.3	4.6	18.5
2.1	1.02	2	0.178	2.4	1.8	0.7	3.0	2	1	1.0	4	1.1	4.2	3.7	14.8
2.1	1.02	2	0.178	2.8	1.8	0.6	3.0	2	1	1.2	5	1.2	4.9	4.3	17.3
2.1	1.02	2	0.178	2.2	1.5	0.5	1.7	2	1	1.0	4	0.9	3.6	3.4	13.6
2.1	1.02	2	0.178	2	1.2	0.7	1.7	2	1	0.5	2	0.9	3.6	3.1	12.4
2.4	1.02	2	0.178	3.15	1.22	0.23	0.9	2	1			2.2	8.6		

Examples given are for Exmouth beach rock platform and last row for 1998 PNG (Sissano) tsunami.
ρ_s = density of boulder (beach rock) at 2.1 g/cm^3 (note that ρ_s is only 2.1 g/cm^3 as the 'beach rock' is less dense than typical sandstone), ρ_w = density of water at 1.02 g/ml, C_d = coefficient of drag = 2, C_l = coefficient of lift = 0.178, a = A-axis of boulder (m), b = B-axis of boulder (m), c = C-axis of boulder (m), Vol. = volume of boulder (m^3), C_m = coefficient of mass = 2, Acc. = instantaneous flow acceleration, T = tsunami, S = storm wave, (sm) = submerged boulder, (sa) = sub-aerial boulder, (lift) = boulder lifted from joint bounded block position through lift force only.

depth is at least 0.35 grain diameters above the boulder, lift force will also act upon the boulder [11].

2.3. Joint bounded block scenario

To initiate motion of a joint bounded block, the lift force must overcome the force of restraint less buoyancy providing the block has weathered completely free from its substrate. Eq. 7 can be expressed as follows:

$$[0.5\rho_w C_l(bc)u^2]b/2 \geq (\rho_s-\rho_w)(abc)gb/2 \tag{30}$$

Solving for H gives:

$$u^2 \geq \frac{0.5(\rho_s-\rho_w)ab^2cg}{0.5\rho_w C_l(b^2c)} \tag{31}$$

$$u^2 \geq \frac{(\rho_s-\rho_w/\rho_w)ag}{C_l} \tag{32}$$

$$\delta gH \geq \frac{(\rho_s-\rho_w/\rho_w)ag}{C_l} \tag{33}$$

$$H \geq \frac{1/\delta[(\rho_s-\rho_w/\rho_w)a]}{C_l} \tag{34}$$

Eq. 14 can be further simplified for both tsunami and storm waves as:

$$H_t \geq \frac{0.25(\rho_s-\rho_w/\rho_w)a}{C_l} \tag{35}$$

where H_t = height of tsunami, $u = 2\ (gH)^{0.5}$ and $\delta = 4$, and:

$$H_s = \frac{(\rho_s-\rho_w/\rho_w)a}{C_l} \tag{36}$$

where H_s = height of storm wave at breaking point, $u = (gH)^{0.5}$ and $\delta = 1$.

As shown in Table 1 the height of a wave required solely to lift a lithic block from its joint bounded position on a shore platform is much greater than that required to move boulders that are either submerged or sub-aerial. This is because the latter two experience drag force. In some settings, it is obvious that the boulders that comprise the deposit must have come from joint bounded

Fig. 2. Shore platform showing 'excavations'. Here joint bounded blocks have been lifted and deposited as a ridge of imbricated boulders that extend for over 1 km adjacent to the platform near Exmouth, northwest Western Australia. Ridge can be seen in top left corner of photo.

blocks on platforms. Such an example occurs near Exmouth in northwest Western Australia where a ridge of imbricated boulders, shaped as slabs or rectangular prisms, rises up to 2.5 m above the mean high tide level and extends along more than a kilometre of shoreline at the rear of the beach (Fig. 2). The boulders have been derived from the carbonate-cemented platform of 'beach rock' at the toe of the beach and the ridge only occurs adjacent to the outcrop of this stratum. In many instances it is obvious that the boulders were derived from the landward side of the outcrop for 'cavities' of the same shape and size as the boulders in the ridge occur here. It is likely that there is a component of drag force involved in initiating movement of the boulders from this position because of turbulence in the flow which could act against the C-axis if there has been sufficient weathering and separation of the block from the surrounding strata. Hence, Eq. 34 may slightly overestimate the height of wave required to transport boulders from such a setting.

It is worth noting that the sub-aerial tsunami equation was tested against the 1998 Sissano tsunami in Papua New Guinea. Here a concrete slab measuring $3.15 \times 1.22 \times 0.23$ m was overturned and transported inland by the tsunami. At this location, being 400 m inland from the shore, the tsunami height or flow depth was 5 m as determined from debris left in trees [12]. The sub-aerial tsunami equation states that only a 2.2 m tsunami was required to overturn this slab (Table 1). Hence the 5 m tsunami was easily able to transport the slab and could have transported a much larger slab if one was available.

The equations presented here refer only to those situations where boulders are entrained within the flow. In some situations, it is possible that a block of rock may be 'blasted' by a wave impacting on the vertical seaward face of a shore platform at low tide. Here wave turbulence and cavitation may play a role in initiating transport of that boulder and it may be 'tossed' landward. This mode of transport, however, is unlikely to result in a field or series of imbricated boulders but rather would leave the boulder standing as an isolated feature. If that boulder is entrained in the flow after being 'tossed', or during some subsequent event, the same forces described here in the equations will apply.

3. Conclusion

Along with shape, size and density, the pre-transport environment of a coastal boulder determines the height of wave required for it to be transported. Boulders resting on a bed of similar clasts experience pivoting during entrainment and require a separate set of hydrodynamic equations to describe their transport mechanism than that described here. Boulders resting in a sub-aerial position on a bare rock shore platform experience the force of inertia as well as drag and lift force, whereas submerged boulders only experience the latter two forces. Boulders derived from joint bounded blocks on shore platforms are largely influenced by lift force alone and require much higher waves to initiate transport. The depth of water above a submerged boulder is also an important determinant of the size of the transporting wave as is the Froude number of the wave or onshore flow. Because of the difficulty in determining these two factors for submerged boulders, only a range of possible transporting wave heights can be estimated. Recognising these conditions is important when attempting to reconstruct both the magnitude and frequency of coastal wave hazards and for differentiating between boulders transported by tsunami and storm waves.***[RV]***

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