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Empirical model for probabilistic rock stability on flat beds under waves with or without currents

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ABSTRACT

An empirical formula was developed for predicting the stability of isolated quarry rocks on relatively flat beds under waves with or without current in terms of the damage ratio. The damage ratio was examined using 100 crushed stones (median mass $M_{50} = 293$ g and mass density $\rho_s = 2.62$ g/cm^3) as scale models of quarry rocks and replicas with a lower density ($\rho_s = 1.38$ g/cm^3) by placing them on beds of different roughness in a wave flume, not only under periodic waves with periods of 2–3.5 s, but also in symmetric and asymmetric oscillatory flows (periods: 8–12 s), simulating waves without and with current in a circulating water channel. Comparison between hydrodynamic forces expressed in terms of three non-dimensional mobility indices: the maximum velocity, maximum semi-velocity amplitude (U_a), and maximum acceleration relative to the friction force (expressed in terms of the median coefficient of friction) suggested that the damage ratio was most closely related to the U_a-based mobility index (ψ_2). Nevertheless, significant differences remained between data from the wave flume and circulating water channel tests. The variation in the damage ratio, which included the effects of the oscillatory-velocity asymmetry, oscillation period, superimposed steady current, mass density of stones, and bottom friction, was reasonably well described via the product of ψ_2 and a function of a Keulegan–Carpenter number. The results of the field tests on quarry rocks (with $M_{50} = 2.04$ t) placed on a thin sand layer overlaying hard substrate show that the minimum stable mass is consistent with the prediction.

1. Introduction

Quarry rocks are commonly used as a cost-effective material for artificial reefs in civil engineering (Deysher et al., 2002; Seaman, 2007; Bohnsack and Sutherland, 1985; Grant et al., 1982). Quarry rock reefs have been often constructed at sites having a thin layer of sand overlaying a flat hard substrate, aiming to attract more fish in hard bottom habitats or to create macroalgal beds without being buried by sand (Grant et al., 1982). The proper placement of low-relief (thus small-sized) rock substrates or rocks at regular intervals on sandy bottoms can aid the development and persistence of macroalgal stands (Deysher et al., 2002; Kawamata et al., 2011; Ohno et al., 1990). The hydrodynamic stability of rocks or stones on the seabed should be treated as probabilistic in nature because of the high variabilities not only in the rock shape but also in the roughness of the substratum. The stability of rocks in coastal sites has been well studied with regard to the design of coastal structures including rubble revetments, breakwaters (Van der Meer, 1987, 1992; Kobayashi and Jacobs, 1985), near-bed rubble mounds (Van Gent and Wallast, 2001; Tørum et al., 2010; Wallast and van Gent, 2002), and the protection of rock slopes and gravel beaches (van der Meer and Pilarczyk, 1987). However, studies on the stability of isolated rocks on comparatively flat bottoms are lacking. Present common design approaches based on stability criteria, such as the stability number, Shields number, and mobility number, cannot be applied to such conditions because they assume stone layers with a particular weight, shape, and density and do not explicitly evaluate the effect of frictional resistance on stability.

In the current design criteria for artificial reefs in Japan, the critical stable mass of rocks in surf zones is given by the following formula from Akeda et al. (1992).

$$M_{cr} = CU_m^6 \tag{1}$$

where M_{cr} is the critical stable mass (in kg) of rocks, C is an experimental coefficient depending on the density of the rocks deployed, and U_m is the wave-induced maximum peak velocity (in m/s). This formula assumes that the hydraulic load and friction with respect to the rocks

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are proportional to the square of the velocity and the submerged weight, respectively, similar to the equation proposed by Isbash (1936) for steady flows. Akeda et al. (1992) found the C value to be 25 for solitary rocks by performing a scale wave flume experiment with rounded pebbles on a smooth, flat cement mortar bed. They determined the C value considering the performance in terms of the cost of constructing an artificial rock reef by defining the motion threshold as the maximum velocity at which 10% of the test stones begin to move (Akeda et al., 1992). Equation (1) is convenient for practical design but is too simplified to evaluate the effects of factors other than U_m, such as the mass density, friction, and velocity asymmetry. A critical problem is that the calculated stable mass for isolated rocks is often considerable. For example, for $U_m = 3$ m/s, Eq. (1) with $C = 25$ gives $M_{cr} \approx 18$ Mg (or t). It is unclear whether such a large stable mass is reasonable in practice.

The objective of this study was to develop an empirical formula for predicting the probability of the stability of solitary quarry rocks on relatively flat beds under the effects of waves in shallow waters, including the effects of the asymmetry of the wave oscillatory velocity, the coexisting flow, the friction coefficient between the rocks and the seabed, and the mass density of the rocks. To do so, three different laboratory experiments were conducted. The first was a common scale experiment using a wave flume, conducted to analyze the stability of the solitary crushed stones placed on different roughness beds under non-breaking and breaking wave conditions. The second was similar to the first but was conducted with lightweight replicas of the crushed stones. Finally, a circulating water channel (CWC) experiment was conducted to examine the stability of the same crushed stones as in the first case, under sinusoidal oscillatory flows with or without currents. The periods of the oscillatory flow were the same as those of sea waves, thus corresponding to conditions under which stones smaller than the actual quarry rocks are placed under the effects of full-scale waves or with Keulegan–Carpenter numbers (K_C) higher than that in the field. The laboratory experiments were conducted under the assumption that rocks are placed on flat hard substrates, such as closely packed cobble and boulder beds or flat bedrock, without overlying sand. This is the least stable condition of the rocks because the presence of a sand layer increases the stability of the rocks; however, waves frequently wash away the overlying thin layer of sand. In addition, an empirical method for predicting the friction coefficient was also developed to enable practical use of the proposed formula. Finally, a field stability test was performed on quarry rocks at shallow coastal sites to demonstrate whether the developed method provides a reasonable prediction of the minimum stable mass, compared to the previous formula based solely on U_m.

2. Definition of damage and its governing variables

It is difficult to accurately define the motion threshold of stones resting on bed roughness elements under the effects of waves with or without currents. In this study, considering the process of movement and the design and construction practices of artificial reefs, 'significant movement' or 'damage' was defined as the shifting of a stone entirely out of its initially occupied area after placing it on the bed at a random position, but with the largest flat surface oriented downward to make the stone more stable. Such an orientation can readily occur via toppling due to flows, even if the stones are initially placed in unstable postures. As the oscillatory velocity increases, stones placed on the irregular surfaces of the bed shake at first, occasionally with a slight slide, and then distinctly move in a sudden manner by either sliding, rolling, or both. Most of the initial movements cease at once, indicating that they are primarily attributed to the initially unstable positions after placement. Additionally, natural flat beds have irregular surfaces. Therefore, an unexpectedly low flow velocity may lead to a small shift even in large rocks. Thus, the above definition of the movement relative to the size of the stones is preferred to an absolute definition. Considering the probabilistic nature of rock stability, the damage ratio r_d was defined as the relative number of quarry rocks 'damaged' under given physical conditions.

The mobility of stones on a relatively flat bed can be expressed simply by the ratio of the maximum drag force (proportional to $\rho {U_m}^2 {D_{n50}}^2$) to the frictional force ($\mu_{50}(\rho_s - \rho) g {D_{n50}}^3$), i.e.,

$$\psi_1 = \frac{U_m^2}{\mu_{50} \Delta g D_{n50}} \tag{2}$$

where $D_{n50} = (M_{50}/\rho_s)^{1/3}$ with ρ and ρ_s being the mass densities of water and stones, respectively, and where M_{50} is the median mass of the stones; μ_{50} is the median friction coefficient between the stones and the bed; $\Delta = (\rho_s/\rho - 1)$, defining the submerged specific density of the stones; and g is the acceleration due to gravity. Note that if the friction coefficient in Eq. (2) is omitted under an implicit assumption of the constant friction coefficient, then the ψ_1 is equivalent to the well-known "mobility number" for sediment particles (Brebner, 1980; Nielsen, 1992) or the frequently used "mobility parameter" for rubble-mound materials (Van Gent and Wallast, 2001; Tørum et al., 2010; Wallast and van Gent, 2002). However, the hydrodynamic force is due to not only the drag, which is proportional to the square of the velocity u, but also the inertia force, which is proportional to the acceleration of the fluid a. Therefore, the hydrodynamic force is at its maximum before the velocity reaches its maximum. Thus, there might be a better alternative to ψ_1. In the study, the maximum semi-velocity amplitude U_a and the maximum acceleration $a_{\max}$ (Fig. 1) were compared to U_m in terms of its explanatory power in determining the damage ratio of stones on a given substratum. Two additional mobility indices can be defined using U_a and $a_{\max}$ as the ratios of $\rho {U_a}^2 {D_{n50}}^2$ and $\rho a_{\max} {D_{n50}}^3$, respectively, to $\mu_{50}(\rho_s - \rho) g {D_{n50}}^3$:

$$\psi_2 = \frac{U_a^2}{\mu_{50} \Delta g D_{n50}} \tag{3}$$

$$\psi_3 = \frac{a_{\max}}{\mu_{50} \Delta g} \tag{4}$$

The successive trough and crest velocities in the wave cycle with maximum peak-to-peak velocity amplitude are denoted as $u_{\min}$ and $u_{\max}$, respectively (thus $U_a = (u_{\max} - u_{\min})/2$). In case of a sinusoidal velocity variation, $a_{\max} = 2\pi u_{\max}/T$, and therefore, if $U_m = u_{\max}$ (as in most test cases), the ratio of ψ_1 to ψ_3 is proportional to K_C, which is defined as $u_{\max} T / D_{n50}$, where T is the period of an individual oscillation cycle. However, when the velocity asymmetry increases, the above equation with respect to $a_{\max}$ may be invalid. Instead, $u_{\max}/T_{zp}$ can be used as a better index for $a_{\max}$, where T_{zp} is the zero-to-peak period. Accordingly, the ratio of ψ_1 to ψ_3 can be assessed as follows.

$$K_C = 4 u_{\max} T_{zp} / D_{n50} \tag{5}$$

The mobility index among ψ_1, ψ_2, and ψ_3 that is most closely related to the damage ratio will be used to predict the stone stability. However, if there are considerable systematic deviations in the relationship between the best explanatory index and the damage ratio, the residual components may be a function of K_C. An attempt will be then made to establish a better predictor to determine the damage ratio by multiplying the candidate by possible functions of K_C.

3. Laboratory model experiments

3.1. Experimental setups and procedures

Stone stability was examined under various physical conditions (Table 1) using a wave flume and a CWC at the National Research Institute of Fisheries Engineering. First, scale model experiments were conducted to determine the stability of the stones under the effects of waves in a 70 m long, 0.7 m wide, and 2.2 m deep wave flume with a smooth sloping bottom made of cement mortar (Fig. 2). A 210 cm long