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Mechanics and response of a surface rock block subjected to pressure fluctuations: A plucking model and its application

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ABSTRACT

Plucking (removal of rock blocks) is often the dominant mechanism for producing a scour hole on riverbeds comprised of heavily jointed rock masses being subjected to pressure fluctuations from a jet flow. This paper explores the mechanics and response of a surface block subjected to pressure fluctuations. First a particle-flow simulation was conducted to demonstrate how repeated pressure fluctuations are able to gradually remove rock bridges in discontinuities surrounding a rock block, if a pressure fluctuation's intensity is substantial. As a consequence, these weak planes may become fully persistent. The block's uplift speed then depends on the pressure differences on the opposite (horizontal) faces, and the frictional resistance of the lateral discontinuities. This paper proposes a theoretical framework to model the mechanics and response of a rock block subjected to a sinusoidal pressure fluctuation. This model can be applied to estimate the development of a scour hole, through plucking, during a specific flood event. An example demonstrates the applicability of the proposed approach in predicting the potential depth of the scour hole.

1. Introduction

Rock is generally considered to be an erosion resistant geo-material, yet during severe floods, significant incisions, or retreating banks, may be observed in riverbeds comprised of soft rock or heavily jointed rock masses. This is especially the case when the jet flow passes a man-made spillway or natural knickpoint with a large elevation drop. Then a scour hole is very likely to be created in the plunge pool or in the riverbed downstream. This is cause for concern in regard to the stability of structures or channel morphology.

The rapid evolution of the Ta-An River channel in central Taiwan is a typical example of severe erosion in a rocky riverbed. Here an incision of around twenty meters or so has developed in just a single decade (Cook et al., 2013 Huang et al., 2013;). The unusually high rate of the knickpoint's annual retreat (up to one hundred meters) was responsible for the rapid channel incision in the Ta-An River. When it is out of control, this kind of severe incision may seriously damage the structural stability of cross-river structures, or the levees along its banks.

Whipple et al. (2000) pointed out that the mechanisms for a riverbed's erosion may include: bed shear, saltation abrasion, cavitation, plucking, and others. For a rock bed without dense joints, any one of the first three types of mechanisms may dominate, depending on the characteristics of flow conditions. Usually, the erosion rate caused by these mechanisms is relatively slow. However, when the joint spacing of rock masses is sub-meter, plucking may become the major erosion mechanism on a riverbed's heavily jointed rock masses (Whipple et al., 2000). Annandale (1995) illustrated complicated processes involving plucking, including: rock weathering; wedging by sand grains, crack propagation and dislodgement by water current. Furthermore, the complex interaction between the block matrix and water flow makes it difficult to model the plucking phenomenon in detail.

Most models for predicting erosion rates are based on rational models calibrated from field data or laboratory flume tests (Shepherd and Schumm, 1974; Wohl and Ikeda, 1997; Robinson and Hanson, 2001). These types of models are not generally derived on the basis of mechanics. A few semi-analytical models for evaluating the depth of scour holes in rock riverbeds were proposed in the past (e.g., Spurr, 1985; Akhmedov, 1988; Liu, 2005), but were not intended for modeling the plucking behavior in fractured rock masses. Most laboratory tests are aimed at determining the erosion rate of soils tested under controlled flow conditions. Laboratory tests on intact rock or rock masses are more challenging than those on soils, for the following reasons: (1) low erosion rate, (2) difficulty of obtaining reproducible data and (3) the scale effect. As a result, there are not much available data resulting from these tests on rock erosion, especially on the plucking behavior of rock masses.

A jet flow passing a spillway, or an overflow dam, often generates a scour hole in the plunge pool. Estimation of the scour-hole's potential depth is often an important concern for dam designs. Many empirical approaches have been proposed for estimating the ultimate depth of a scour hole in a granular riverbed. These approaches usually contain

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parameters (including the elevation drop, tail-water depth, maximum discharge and mean grain size) calibrated through a set of observed data (e.g., Martins, 1973; Mason and Arumugam, 1985).

Apart from these empirical approaches, some semi-empirical approaches were based on simplified principles of energy and/or momentum conservation and riverbed characteristics, with certain empirical correlations (e.g., Spurr, 1985; Akhmedov, 1988; Fahlbusch, 1994; Liu, 2005). Other approaches compare the stream power of water flow with the erodibility of the riverbed's geo-material to determine the maximum scouring depth (Annandale, 2005).

Noting that plucking is often responsible for the development of a scour hole on jointed rock masses, Bollaert (2002) proposed using the intensity of pressure fluctuations to evaluate the uplift displacement of the rock block, based on a dynamic impulsion concept. If the maximum uplift displacement reaches a critical ratio to the rock block's height, the block can escape, resulting in plucking. When the tail water becomes deeper, the intensity of the pressure fluctuations gradually declines. Eventually, there is a depth limit where plucking is no longer possible; ultimately, this limit is the scour-hole's depth.

Initially, if the discontinuities surrounding a rock block are not fully extended, the pressure fluctuations must first break all of the rock bridges before the block can be lifted. Bollaert (2002) employed a fatigue concept and attempted to model the crack propagation of a joint using basic fracture mechanics. He suggested comparing the stress intensity factor that corresponds to the maximum water pressure acting on the joint's end, with the fracture's toughness. If pressure fluctuations cannot cause fracture propagation in a single loading cycle, he proposed estimating the number of loading cycles required to extend the joint through an empirical relationship.

Robinson and Hanson (2001) studied the erosion of fractured rocks with physical tests, using a matrix of concrete blocks downstream of a controlled waterfall. Their results showed that the potential for block matrix failure depended on the maximum discharge, the waterfall's height, as well as the block's size and joint orientation. The pressure below the block matrix was measured; they pointed out that pressure variations on a block matrix were essential for the dislodgement of rock blocks and for plucking to cause erosion.

Several researchers conducted laboratory tests on models to investigate the induced pressure oscillation on a surface block due to jet flow (e.g., Castillo, 1989; Ervine et al., 1997). The pressures on the top (and sometimes the bottom) of the model block were measured and analyzed. Pressure fluctuations are often characterized by the non-dimensional mean dynamic pressure coefficient C_p and the non-dimensional root-mean-square (RMS) dynamic pressure coefficient C_p'. Coefficient C_p is the mean dynamic pressure head ratio to $\frac{V_j^2}{2g}$. The coefficient C_p' describes the intensity of the fluctuating dynamic pressure, and is defined by the following equation:

$$C_p' = \frac{(RMS/\gamma_w)}{\frac{V_j^2}{2g}} \tag{1}$$

where RMS is the root mean square of fluctuating dynamic pressure, and γ_w is the unit weight of water. The term $\frac{V_j^2}{2g}$ stands for the jet flow's kinetic energy with velocity V_j, and the symbol g represents the gravitational acceleration.

In general, coefficient C_p remains approximately unchanged for low tail-water depths (the limit is approximately 5) and decreases with an increase in the $\frac{Y}{D_j}$ when $\frac{Y}{D_j}$ is beyond the limit. Symbol Y represents the tail-water depth, and D_j denotes the jet flow's density. The coefficient C_p', increases with the increase in $\frac{Y}{D_j}$ and reaches its peak value at a critical $\frac{Y}{D_j}$ ratio (usually 5 to 7). For depth ratio $\frac{Y}{D_j}$ to be larger than the critical ratio, the C_p' declines when the $\frac{Y}{D_j}$ increases. The time history for pressure fluctuations from the jet flow is always irregular in nature, and its extreme amplitude can be a few times higher than the RMS (Bollaert, 2002). However, the time that is influenced by the extreme amplitude is extremely short.

Bollaert and Schleiss (2003) also conducted laboratory tests using a collection of metal plates fixed to the base of a water tank to imitate an artificial joint under a powerful jet flow. The purpose of this setup was to examine the pressure variations on the top and bottom of a riverbed's surface rock block due to the jet flow. Pore pressures on the top and bottom of the artificial joint were measured continuously throughout the test. Bollaert and Schleiss (2005) observed that the dominant frequency of pressure fluctuations at the joint's bottom is close to the fluid-joint system's fundamental resonance period, which depends on both the air-trapped water wave's velocity and the fracture's geometry. Because of the resonance, it is possible that the pressure is greater at the base of the block than at the top.

If the unbalanced instantaneous pressures acting on the top and bottom are able to overcome the buoyant weight and the joint resistances, the rock block can be lifted and displaced under pressure fluctuations. A power spectrum analysis of the measured pressure fluctuations shows that their frequency range is within 2 Hz and 500 Hz, and that the energy magnitude declines quickly with the increase in the frequency of pressure fluctuations (Bollaert and Schleiss, 2003). For example, the amplitude of a power spectrum corresponding to 100 Hz is two orders less than one that corresponds to 2 Hz.

Bollaert and Schleiss (2005) further evaluated the net force acting on a rock block with a width of x_b and height of z_b. The acting forces included the uplift, due to the jet pressure, the effective weight $(\gamma_s - \gamma_w) \cdot x_b^2 \cdot z_b$ and joint resistance F_{sh}. The terms γ_s and γ_w are the saturated unit weights for the rock and water, respectively. Uplift height h_{up}, from the resultant force, is derived from the following concept for dynamic impulsion:

$$h_{up} = \left[2\frac{(x_b + 2z_b)}{c}\right]^2 \cdot \frac{1}{2g \cdot x_b^4 \cdot z_b^2 \cdot \gamma_s^2} \times \left[C_I \cdot \gamma_w \cdot \frac{V_j^2}{2g} \cdot x_b^2 - (\gamma_s - \gamma_w) \cdot x_b^2 \cdot z_b - F_{sh}\right]^2 \tag{2}$$

where the term, $C_I \cdot \gamma_w \cdot \frac{V_j^2}{2g} \cdot x_b^2$, in the square bracket, stands for the magnitude of the uplift force acting on the rock block due to jet pressure. The uplift force is dependent on the jet flow's velocity V_j, jet flow thickness D_j and tail water depth Y. In Eq. (1), c is the water wave's velocity depending on the trapped air content.

Coefficient C_I in Eq. (2) denotes the dynamic impulsion coefficient. By compiling experimental data, Bollaert and Schleiss (2005) looked into the relationship between C_I and $\frac{Y}{D_j}$; by regression, they proposed an empirical parabolic function to express the relationship between C_I and $\frac{Y}{D_j}$. The coefficient C_I monotonically decreases with the increasing $\frac{Y}{D_j}$.

Bollaert and Schleiss (2005) suggested that the rock block's plucking potential could be evaluated by examining the $\frac{h_{up}}{z_b}$, and ascertained that the block could escape when the $\frac{h_{up}}{z_b}$ was greater than a critical ratio of 0.5. The jet-flow's velocity, when passing a spillway or an overflow dam differs with various floods, especially in the case of an overflow dam. The above approach uses the dynamic impulsion concept, and accounts for the largest flood that corresponded with a long returning period. The scour hole's maximum depth was determined by checking whether or not the $\frac{h_{up}}{z_b}$ was greater than 0.5 for the maximum discharge during the designated flood.

In principle, Bollaert–Schleiss's approach ignores the possible accumulation of smaller irreversible uplift displacements subjected to a lower intensity of pressure fluctuations corresponding to a shorter returning period. The question may be raised: Is it possible for the