A Block Theory approach for rock erodibility assessment incorporating 3D high-resolution site characterization data

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ABSTRACT: Scour of rock in dam foundations and spillways during flood events is an important issue for dam safety. A new approach using Block Theory to evaluate erodibility of 3D rock blocks has been developed using physical hydraulic model and prototype testing. The use of high-resolution remote sensing technology for 3D site characterization of the rock mass (e.g., photogrammetry and LiDAR) in combination with the Block Theory Rock Erodibility (BTRE) method has permitted a more detailed, site-specific, examination of rock erodibility than previously attainable. This includes delineation/analysis of site-specific 3D rock blocks, monitoring/change detection of scour over time, and rapid collection of thousands of discontinuity measurements for probabilistic scour analysis.

Keywords: Rock scour, Block Theory, remote sensing, erodibility, dams, spillways.

1 INTRODUCTION

Scour of rock foundations for dams and spillways during normal and extreme flood events is an important issue for dam safety. This was highlighted during the 2017 events at Oroville Dam in California where concerns arising from scour in the spillways lead to the evacuation of nearly 200,000 downstream residents. Removal of rock blocks is a dominant mechanism by which scour occurs, however, tools for assessment of rock scour have historically been hydraulically focused with limited or no parameters to represent the rock mass (e.g., Mason & Arumugam 1985) or based on empirical relationships to characterize rock potential to resist scour (e.g., Annandale 1995, 2006, Pells 2016). More recently, physics-based approaches have attempted to simulate the mechanics of the scouring process (e.g., Bollaert 2002, George 2015). Prior to George (2015), however, all block studies focused on cubic or rectangular block geometries. Extension of these simplified block shapes to actual sites can be challenging when rock mass discontinuities yield non-cubic block geometries.

A new approach using Block Theory is presented to evaluate erodibility of 3D rock blocks has been developed. The Block Theory Rock Erodibility (BTRE) method provides a systematic approach to assess block removability, kinematics, and stability for rock masses subject to hydraulic loading associated with dam overtopping and spillway flows.

2 BLOCK THEORY ROCK ERODIBILITY

The role of rock mass discontinuities, their 3D orientations, and their impact on stability of rock blocks and wedges in rock engineering is broadly known within the rock mechanics community. The Block Theory approach was originally developed by Goodman & Shi (1985) as a means systematically identify and analyze 3D rock blocks within blocky rock masses. Block Theory has three main components (removability, kinematics, and stability). For rock erodibility analysis using Block Theory, the same three components are incorporated with some minor deviations.

Removability relates to the identification of specific block types within a rock mass that can physically be removed (or 'eroded' in the case of scour analysis) based on 3D geologic structure. Goodman & Shi (1985) provide a hierarchy of different block types that can exist within a rock mass (Figure 1). These include infinite blocks (Type V) (i.e., blocks that extend infinitely into the rock mass and cannot be removed), non-removable finite blocks (Type IV) (i.e., blocks that have a finite geometry but cannot be physically removed from the rock mass), and removable finite blocks (Types I, II, III) (i.e., blocks that have a finite geometry and can be physically removed from the rock mass). Removable finite blocks can further be refined based on their in-situ condition: blocks stable without friction (Type III), blocks stability with sufficient friction (Type II), and unstable blocks (Type I).

Type I blocks are referred to as 'key blocks' and are the focus of typical Block Theory analysis as loading is predominantly driven by gravity. For erodibility analysis, however, all removable block types (Types I, II, and III) are of interest given the nature of the hydrodynamic loading to act in varying orientations.

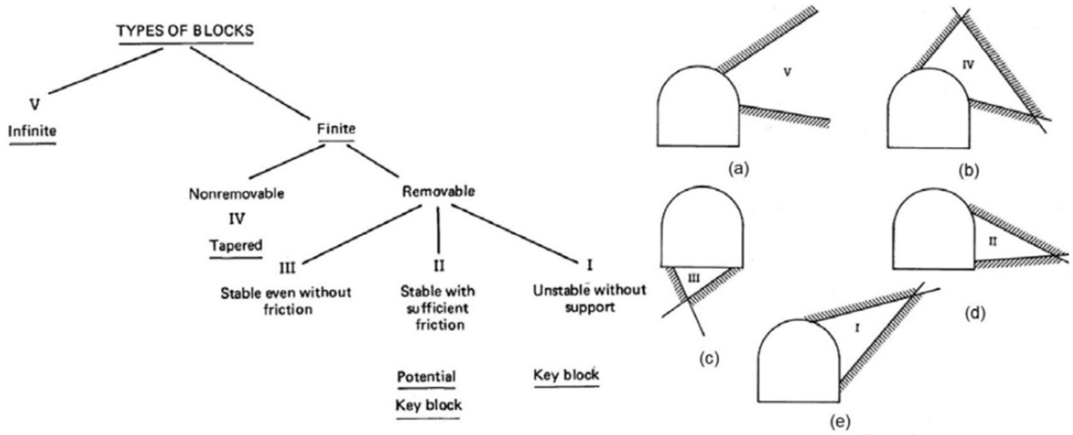


Figure 1. Hierarchy of block types within a rock mass, from Goodman & Shi (1985).

Kinematics relates to the different failure modes that exist for a given removable block (i.e., lifting, sliding, rotation) based on the geometric constraints provided by the 3D orientations of the discontinuities that bound the block volume. Equations for evaluation of the different kinematic failure modes are not provided here but can be found in Goodman & Shi (1985) or George (2015).

Kinematic constraints defining these failure modes can have a profound influence on the displacement response and erodibility threshold of 3D rock blocks when subject to hydraulic loads. Research by George (2015) through physical hydraulic model and protype tests showed that differences in block orientation relative to flow direction resulted in different controlling block kinematic failure modes and, in turn, different block erodibility thresholds (i.e., hydraulic conditions that result in removal of block from the rock mass). Furthermore, block orientations that had a relatively low kinematic resistance (e.g., blocks that could easily slide on a low-level discontinuity plane/intersection to be removed) showed a different displacement response than block orientations that had a relatively high kinematic resistance (e.g., blocks that had to move up a steep discontinuity face to be removed) (Figure 2).

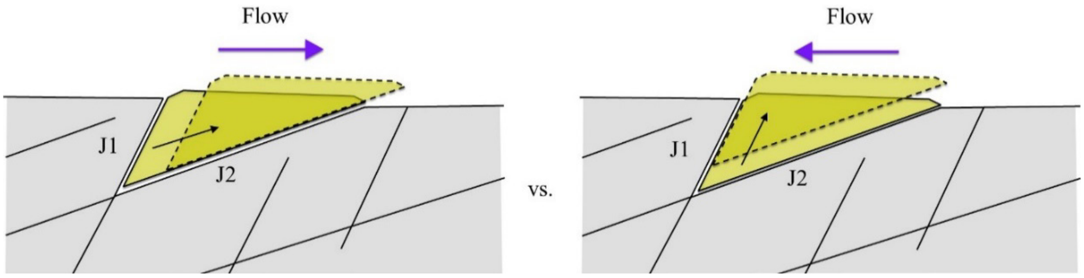


Figure 2. Schematic showing low (left) and high (right) kinematic resistance concept for a rock block in a near-horizontal spillway channel.

Incorporation of 3D kinematic analysis into rock erodibility assessment was a key driver of the BTRE methodology given the profound impact of 3D geologic structure on block stability/erodibility. Other erodibility methods, like empirical relationships developed by Annandale (1995, 2006) and Pells (2016) that represent the rock mass erodibility resistance through an empirical index or physics-based methods like Bollaert (2002) that represent the rock mass with cubic/rectangular block geometries, do not account for the role of 3D kinematics in the evaluation of rock erodibility.

The kinematic conditions can be particularly relevant for erodibility in locations such as steep abutment slopes where the influence of gravity plays a greater destabilizing role in the block erodibility. As shown in Figure 3, the same block is considered for a spillway channel bottom and a steep dam abutment slope. For the spillway block, hydraulic loading must overcome a significant portion of the block weight to pluck the block from the channel (as noted by the rotation angle, θ_R, required for the active resultant force vector, **R**). For the abutment block, the absence of the rock mass to the right of block allows the block to slide out more readily on the low-angle joint plane. Here, gravity is driving removal of the block and only a small rotation of **R** is needed to overcome joint friction. As such, the erodibility threshold of the abutment block would considerably less than that of the spillway block with the same size and shape. This difference in erodibility threshold is captured with the BTRE method, but not with other current scour prediction methods.

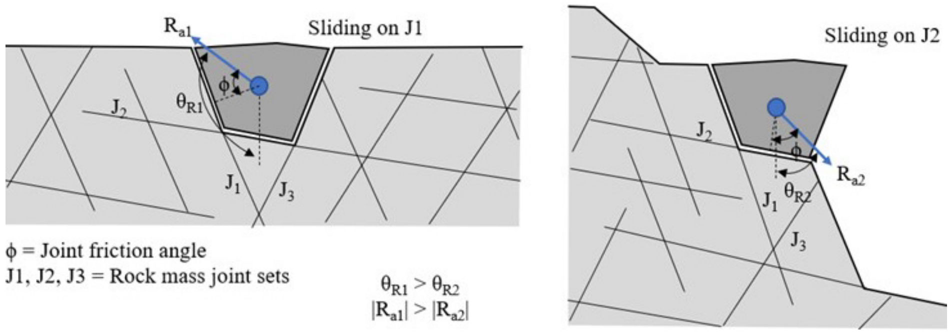


Figure 3. Schematic showing spillway block (left) and abutment block (right) highlighting the influence of kinematic constraints on block erodibility.

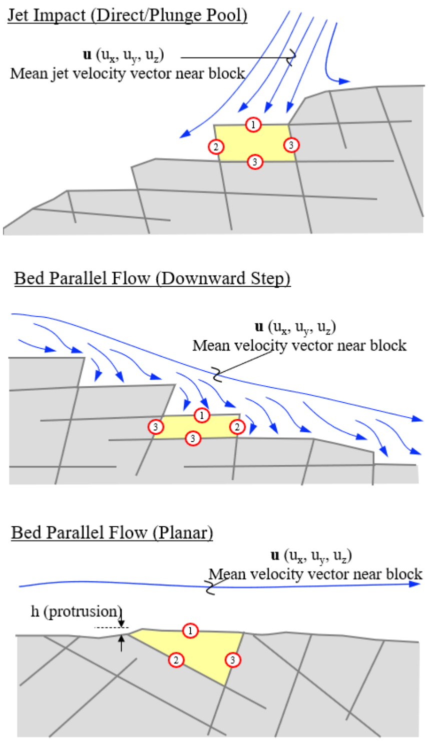
Stability is final component of Block Theory analyses and relates to the ability of a removable block to be destabilized from the rock mass for a given loading condition and kinematic failure mode. Stability equations are not provided here but can be found in Goodman & Shi (1985) or George (2015). Application of Block Theory in the BTRE method occurs predominantly through modification of the active resultant force vector (**R**) to include hydraulic loads applied to the block:

$$\mathbf{R} = \sum_{i}^{n} P_i \cdot A_i \cdot \mathbf{v}_i + \mathbf{W'}_b = \sum_{i}^{n} \frac{1}{2} \cdot \rho \cdot u^2 \cdot C_{ti} \cdot A_i \cdot \mathbf{v}_i + \mathbf{W'}_b \quad (1)$$

Where, P_i = hydrodynamic pressure applied to the i^{th} block face (Pa), A_i = area of the i^{th} block face (m^2), $\mathbf{v}_i$ = block side normal unit vector for the i^{th} block face (dimensionless), $\mathbf{W'}_b$ = vector for the submerged block weight (N), u = flow velocity in the block vicinity (m/s) C_{ti} = total dynamic pressure coefficient on the i^{th} block face (dimensionless) = C_p (average dynamic pressure coefficient) + C'_p (fluctuating dynamic pressure coefficient).

Data on pressure coefficients within rock discontinuities to evaluate **R** is dependent on flow conditions surrounded the block. Guidance on selection/determination of an appropriate pressure coefficient for individual block faces is shown in Figure 4. Flow velocity and turbulence conditions can be estimated using hydraulic models and/or analytical calculations. Once **R** is evaluated, the applicable kinematic failure mode can be determined, and the block stability can be assessed.

Validation of the BTRE method has been shown by George (2015) using physical hydraulic model studies for tetrahedral block shapes within a flume channel, as well as for instrumented prototype blocks in an unlined spillway channel (George & Sitar 2018). In both cases, the block erodibility threshold predicted using Block Theory was able to closely represent the observed block erodibility threshold.



Face Location	*Avg. & Fluc. Dynamic Pressure Coef.*	*Total Pressure Coef.*	*Notes*
① Free Face (impact):	$C_p = C_{p\_surf/pool}$ $C'_p = C'_{p\_surf/pool}$	$C_t = C_p - C'_p$	- $C_{p\_surf/pool}$ & $C'_{p\_surf/pool}$ estimated at rock air/pool surface interface based jet break-up and plunge pool jet theory.
② Free Face (no impact):	$C_p = 0$ $C'_p = 0$	$C_t = 0$	- 0.35 & 0.75 reduction factors for joint pressures based on testing from Federspeil (2011) for jet impact on a rock block
③ Joint Face:	$C_p = 0.35 \cdot C_{p\_surf/pool}$ $C'_p = 0.75 \cdot C'_{p\_surf/pool}$	$C_t = C_p + C'_p$	

Face Location	*Avg. & Fluc. Dynamic Pressure Coef.*	*Total Pressure Coef.*	*Notes*
① Free Face (top):	$C_p = 0.08$ $C'_p = T_u^2$	$C_t = C_p - C'_p$	- C_p on top free face and joint face estimated based on research by Reinius (1986) as summarized by Bollaret (2012)
② Free Face (side):	$C_p = 0$ $C'_p = 0$	$C_t = 0$	- C'_p estimated based on flow turbulence intensity (T_u). Reinius (1986) provides average uplift pressures.
③ Joint Face:	$C_p = -0.11$ $C'_p = T_u^2$	$C_t = C_p + C'_p$	- Additional geometries summarized in Reinius (1986) and Bollaert (2012).

Face Location	*Avg. & Fluc. Dynamic Pressure Coef.*	*Total Pressure Coef.*	*Notes*
① Free Face (top):	$C_p = 0.005$ C'_p = NA	$C_t = C_p$	- C_p estimated based on emperical relationships developed by George (2015) as a function of block orieintation (Ψ) with respect to flow direction (**u**) and block protrusion height (h).
② Joint Face (u/s):	$C_p = f(\Psi, \mathbf{u}, h)$ C'_p = NA	$C_t = C_p$	- C'_p not estimated as C_p values are based on 'High' turbulence condition from George (2015).
③ Joint Face (d/s):	$C_p = f(\Psi, \mathbf{u}, h)$ C'_p = NA	$C_t = C_p$	

Figure 4. Pressure coefficient estimation for rock block faces for jet impact and bed parallel flow conditions.

3 INCORPORATION OF 3D HIGH RESOLUTION REMOTE SENSING DATA

A key challenge to site specific, physics-based scour analysis is representation of the rock mass and hydraulic conditions to a level of detail sufficient for evaluation of discrete rock blocks. Another challenge is quantifying scour potential given the inherent variability within the scouring process, both in terms of the geology and hydraulic parameters.

The rapidly expanding field of remote sensing technology (such as LiDAR, photogrammetry/structure from motion (SfM), and even video) has permitted capture of high resolution spatial and temporal rock mass and flow data to levels that have previously been unattainable. Combined with quick, cost-effective, acquisition through the use of unmanned aerial vehicles (UAVs), these technologies have the ability to capture vast amounts of site-specific data before, during, and after scour events at actual dam and spillway sites. The detailed monitoring of these sites over time (i.e., through detection of geometric changes) is instrumental to advance understanding of scour processes in actual field conditions (versus laboratory settings) and ultimately facilitate better, more detailed scour prediction methods.

From a scour perspective, this data provides many benefits. It is commonly used for rock mass characterization such as for structural mapping, measurement of discontinuity plane orientations, spacing and persistence, identification of specific rock blocks and their sizes, as well as assessment of surface roughness to estimate discontinuity friction/dilation angles or block protrusion heights. Detailed information on blocks within a dam foundation or spillway channel can be combined with 3D computational fluid dynamics (CFD) software output to provide a level of resolution in assessment of scour not previously attenable (Figure 5). The author has found drone-based photogrammetry appears to yield point cloud data most conducive to delineation of rock blocks. Ground-based LiDAR, while often obtaining higher point density, is more susceptible to gaps in the point cloud due to limited station set-ups and reduced line of site.

With detailed geometric data also comes the ability to make numerous (e.g., 1000's) of measurements on the rock mass. This is helpful to develop PDFs of individual variables (such as discontinuity orientation) to support probabilistic assessment of rock erodibility (George 2015). Probabilistic characterization of scour potential provides a more meaningful way to incorporate and quantify variability in the scouring process versus simply examining a range of material parameters.

Repeat LiDAR/photogrammetric scanning of a spillway or foundation geometry over time allows detection of detailed changes in geometry associated with different spill events and can provide key insight into rates of scour in rock, which are not well documented in literature. (Figure 6).

The use of digital video can also be used to extract flow characteristics during spill events by making use of Large-Scale Particle Image Velocimetry (LSPIV) techniques (Patalano et al. 2017). With LSPIV, features in the flow field (such as turbulent eddies) can be tracked from frame to frame in the video such that the instantaneous velocity field at the fluid surface can be evaluated spatially and temporally (Figure 6). Instantaneous velocity measurements obtained from LSPIV may be used to estimate local flow magnitude, direction as well as turbulence intensity at specific locations within the flow field. These parameters comprise the hydraulic input needed for detailed erodibility assessment (George 2015). This provides a powerful tool to perform back-analyses of specific eroded blocks from spill events that have been identified through change detection analysis from repeat LiDAR/photogrammetric scans of the spillway/foundation geometry. Furthermore, LSPIV analysis data may be used to calibrate numerical computational fluid dynamics (CFD) models of spillways that could inform prediction of scour for larger flood events.

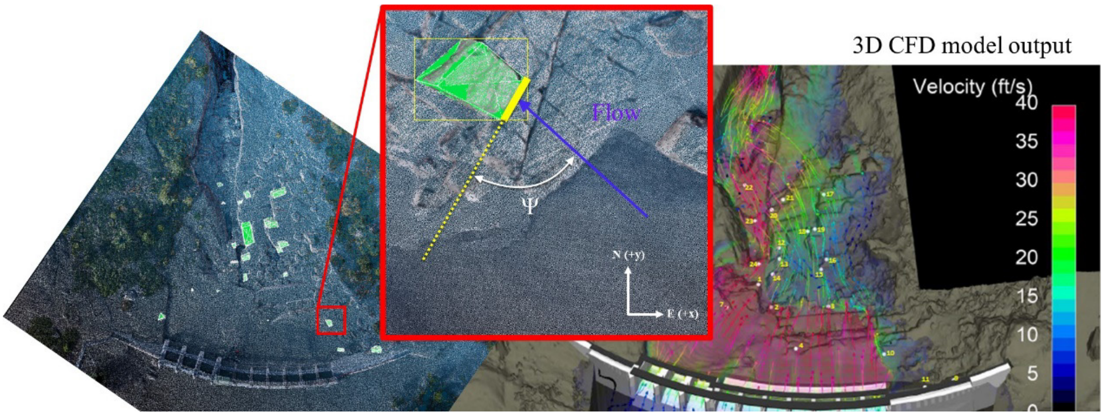


Figure 5. Delineation of blocks in a spillway using point cloud data combined with 3D CFD modeling.

4 CONCLUSIONS

A new rock scour prediction tool is presented based on Block Theory. The BTRE method allows for incorporation of 3D site-specific geologic structure and kinematic constraints on discrete rock blocks subject to dam overtopping or spillway flows, which is not accounted for in other current scour prediction methods. Scour analysis using BTRE is greatly enhanced incorporating high-resolution

3D remote sensing data from LiDAR, photogrammetry, and video which present an opportunity for greater resolution in the analysis of site-specific 3D rock blocks.

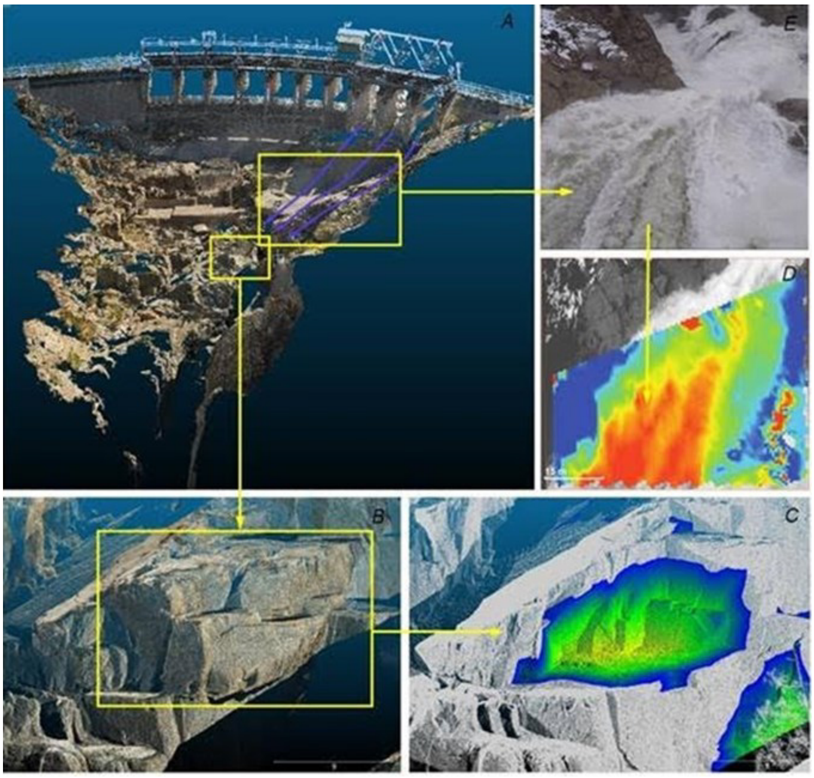


Figure 6. High resolution spillway monitoring – (A) Point cloud of unlined rock spillway, (B) Removable rock block group, (C) Mold of eroded block identified using change detection between subsequent LiDAR scans after a flow event, (D) Instantaneous spillway flow velocity magnitudes obtained from video in "E" using LSPIV, (E) Video from spill event taken from spillway crest.

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