Category: Scour Countermeasures

Rock Plunge Pools: A Design Approach for Limiting Scour Extent

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ABSTRACT

Most of the modern dams in the world were constructed during the 1960's and 1970's. At that point in time rock was generally considered to have the ability to withstand the erosive power of water and spills were often discharged directly onto the natural rock without enhancement of its qualities. Experience at a number of dams worldwide, including Kariba Dam, on the border between Zimbabwe and Zambia; Caborra Bassa Dam, Mozambique; Tarbela Dam, Pakistan; and Bartlett Dam, Arizona, USA revealed that rock is erodible and identified a need to limit the extent of scour in plunge pools that developed in rock. This paper presents an approach that can be used to design protection systems to limit scour of rock in plunge pools.

Optional protection systems include reducing the dynamic pressure caused by the jet below the tailwater elevation by breaking up the jet, construction of a plunge pool that is deep enough to dissipate the jet energy without causing scour of rock, providing anchors to stabilize the rock, and providing a plunge pool lining that will prevent scour. These options are discussed and methodologies that can be used to facilitate implementation are referenced.

Keywords: design, scour, rock, brittle fracture, fatigue, sub-critical failure, rock anchoring, erodibility, jet breakup, plunge pool, lining.

INTRODUCTION

Scour of rock revealed itself as an issue of concern in dam design. Examples where scour became a major issue is at Tarbela Dam, Pakistan; Kariba Dam, Zimbabwe; and Bartlett Dam, Arizona, USA. For example, Kariba Dam is 128m high and a scour pool to a depth of about 60m downstream of the dam developed soon after its construction. Similarly, the rock downstream of the spillway channel at Bartlett Dam, Arizona consisted of a mixture of coarse- and fine-grained granite when it was constructed in the 1940's. Since its construction a plunge pool to a depth of about 30m developed downstream of the spillway channel, requiring the Bureau of Reclamation to construct a concrete cyclopean wall to protect the downstream end of the spillway channel against failure. Tarbela Dam experienced significant scour of rock when water was discharged downstream of the dam.

A need to protect plunge pools against scour exists for ensuring the safety of dams. Significant plunge pool scour can adversely affect the safety of dams. This paper outlines optional design approaches for protecting plunge pools against unplanned scour. By protecting plunge pools against excessive scour the safety of the public and infrastructure is taken care of, and the environment is protected.

DESIGN APPROACH

Development of a design approach for protecting plunge pools against unplanned scour requires knowledge of the nature of the erosive capacity of water and the dominant characteristics of rock as it relates to its ability to resist scour. In essence, the erosive capacity of water causing scour of rock is characterized by pressure fluctuations and their amplification. Bollaert (2002) verified Annandale's (1995) postulate that pressure fluctuations play a dominant role in determining the erosive capacity of water as it relates to scour of rock. He found that the reduction in the pressure wave celerity of water, caused by the presence of free air introduced into plunge pools by plunging jets, can lead to resonance and amplification of the pressure fluctuations caused by jets. The amplified pressure fluctuations occurring in rock discontinuities can lead to brittle fracture, fatigue failure and direct removal of rock by dynamic impulsion (Bollaert 2002).

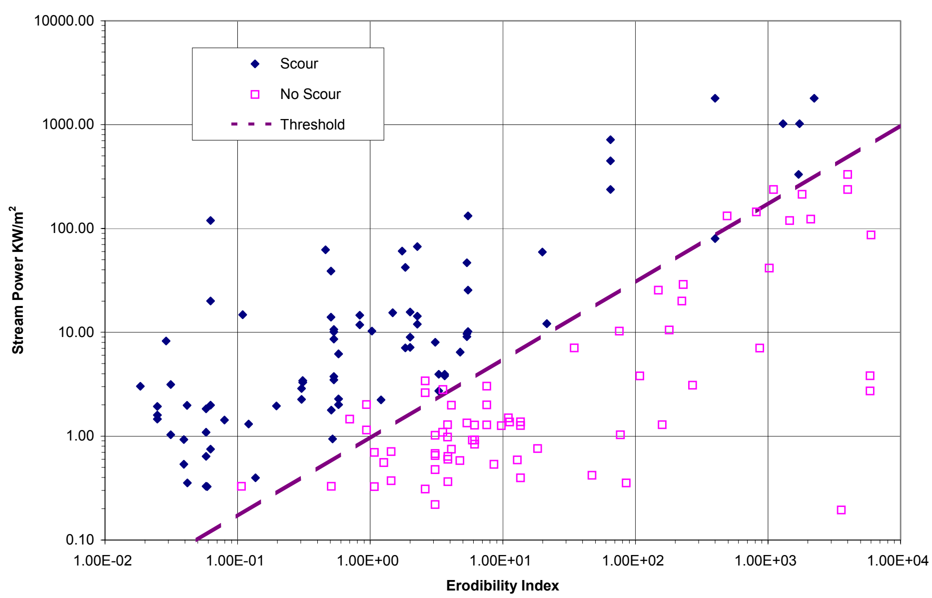
The principal characteristics of rock defining its ability to resist the erosive capacity of water are its mass strength, block size, joint shear strength and joint orientation relative to the dominant direction of flow. The mass strength of rock is related to its ability to resist failure by brittle fracture or fatigue. Amplified pressure fluctuations in close-ended rock fissures can lead to either brittle fracture or fatigue failure. If this happens the rock breaks up into smaller pieces, which are easier to remove than large blocks of rock. Even after rock has been broken up into smaller pieces, the friction between individual rock blocks help resist scour. When rock discontinuities are oriented in the dominant direction of flow it is easier for the flowing water to remove it than when it is dipped against the dominant direction of flow (Annandale 1995).

Having identified the dominant rock characteristics determining its relative ability to resist erosion, it is possible to define a geo-mechanical index expressing its erosion resistance capacity (Annandale 1995),

$$K = M_s \cdot K_b \cdot K_d \cdot J_s \tag{1.1}$$

where K = Erodibility Index; M_s = mass strength number; K_b = block size number; K_d = inter-block shear strength number; and J_s = orientation and shape number. The mass strength and block size numbers play dominant roles in determining the relative ability of rock to resist scour, and should therefore be major considerations when developing procedures to protect plunge pools against unplanned scour of rock.

Having analyzed field and laboratory observations about scour and incipient motion, Annandale (1995) developed an erosion threshold relating the Erodibility Index to the erosive power of water (Figure 1).



• Figure 1. Erosion threshold for rock and other earth materials (Annandale 1995).

Knowing the character of rock scour allows one to develop scour protection measures. The first activity obviously entails determining whether the rock will scour, and to what extent. Once it is known that the rock can potentially scour, methods to prevent excessive scour and protecting the dam and appurtenant structures against failure can be developed, assessed and implemented. The approach to developing protection systems focuses on reducing the erosive capacity of the water, increasing the erosion resistance of the rock by increasing its effective block size, covering up the rock and protecting it against direct interaction with the erosive power of the water, or combining these approaches.

SCOUR ASSESSMENT

Approaches to determine whether the rock in a plunge pool will scour have been outlined by Annandale (2002a) and Bollaert et al. (2002). A common procedure is to apply both methods to assess the scour potential of rock. Comparison of the results obtained by applying these two methods provides a means of making confident engineering decisions pertaining to the possibility that the rock will scour. The same methods are used to prepare designs for protection against scour.

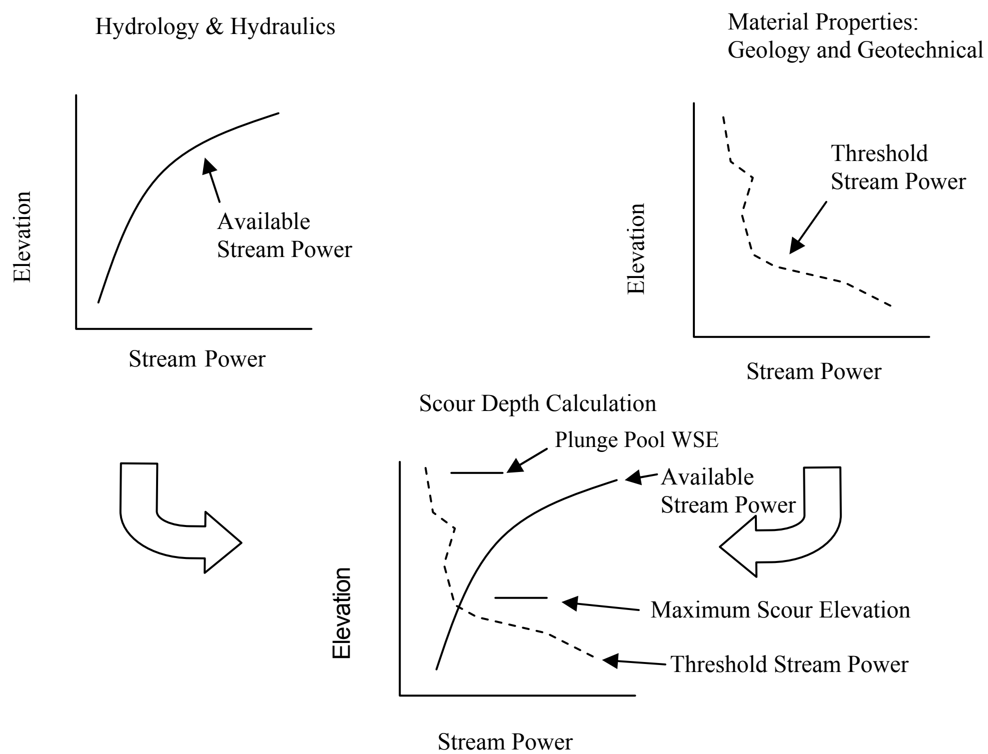
Annandale's method is based on a scour threshold that relates the erosive capacity of water to the relative ability of rock to resist scour (Figure 1). The relative ability of rock to resist scour is quantified by indexing the rock using equation (1.1) and the relative magnitude of the erosive capacity of the water is quantified by calculating the jet's rate of energy dissipation below the tailwater level. Methods have been developed to calculate the change in the erosive power of a jet as a function of depth below the tailwater elevation, which can be use to estimate scour depth (Annandale 2002a). The magnitude of the erosive power of the jet at various depths below the tailwater surface elevation is then compared with the threshold stream power of the rock. Rock scour will occur when the erosive power of the water jet in the plunge pool is greater than the threshold stream power of the rock; in cases where the threshold stream power of the rock is greater than the stream power of the jet the rock will not scour. The maximum scour depth is therefore identified as the elevation where the erosive power of the jet is equal to or less than the threshold steam power of the rock (Figure 2).

Bollaert's approach consists of quantifying the magnitude and frequency of fluctuating pressures in fissures and joints, and comparing the magnitude of these forces to the ability of the rock to resist them. In the case of intact fissured rock the stress intensity caused by the pressure fluctuations is compared to the fracture toughness of the rock. If the stress intensity is greater than the fracture toughness of the rock it fails in brittle fracture mode. If the stress intensity is lower than the rock's fracture toughness, it is possible that the rock can fail in fatigue if the pressure fluctuations are applied long enough. By comparing the time required for the rock to fail in fatigue with the duration of a flood event it is possible to determine whether the rock will scour. In the case of jointed rock the fluctuating pressures developing in the discontinuities must be large enough to remove blocks of rock from their matrix for the rock to scour. The latter process is known as dynamic impulsion. Analysis of rock scour using Bollaert's approach is required to confirm conclusions made using Annandale's method.

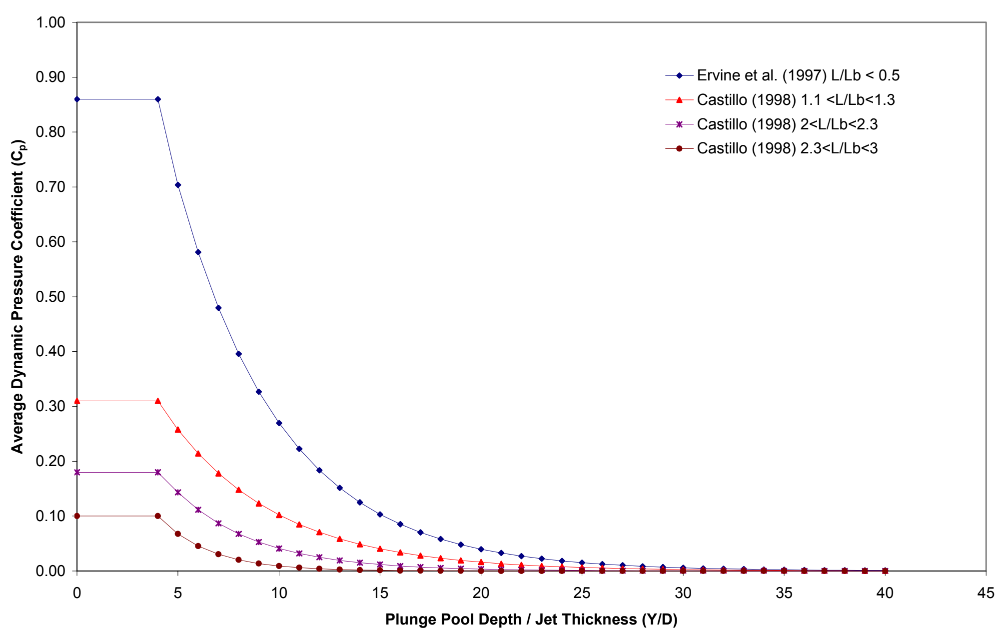
REDUCING JET EROSIVE CAPACITY

A jet plunging into a pool leads to the development of average and fluctuating dynamic pressures that can cause the breakup and removal of rock. When a jet plunges into a pool it creates dynamic pressures in the pool below the point of jet impact. These pressures consist of average and fluctuating dynamic pressures. If free air is introduced into a plunge pool by the jet, it has been found that the average dynamic pressure decreases as the amount of free air increases (Ervine et al. 1987).

Turbulence, introduced into the plunge pool by the jet, additionally causes fluctuating dynamic pressures. Introduction of free air has a different effect on the behavior of fluctuating dynamic pressures. Bollaert (2002) found that the fluctuating dynamic pressures within fissures can increase up to 20 times due to resonance if the amount of free air in the water increases.



• Figure 2. Determination of depth of plunge pool for pre-excavation.



• Figure 3 Average dynamic pressure as a function of pool depth to jet thickness and dimensionless breakup length developed from Ervine et al. (1987), Castillo (1998) and Castillo (2004).

Attempts to minimize the erosive capacity of the jet should therefore aim at reducing the average and fluctuating dynamic pressures where it interacts with the rock at the edges of the plunge pool. This can be accomplished in two ways, by breaking up the jet or by constructing a plunge pool that is deep enough to adequately dissipate the erosive capacity of the jet. The former approach is discussed here, the latter in the next section.

When breaking up a jet its character changes from a coherent mass of water plunging into a pool (i.e. when the jet is intact) to a series of blobs falling onto and penetrating the water surface. The average dynamic pressure caused by a coherent jet is greater than the average dynamic pressure caused by blobs of water falling into a pool. By combining research by Ervine et al. (1997), Castillo (1998) and Castillo (2004) it is possible to relate the average dynamic pressure coefficient (C_p) to dimensionless plunge pool depth (Y/D) for varying dimensionless jet breakup lengths (L/L_b); where Y = pool depth; D = jet diameter or thickness; L = total length of the jet; and L_b = breakup length of the jet. Figure 3 shows such relationships, indicating that if the jet breakup length is much smaller than the total length of the jet and the pool depth relative to the jet dimension is very large then the average dynamic pressure at the bottom of the plunge pool reduces to very low values. For example, if the breakup length of the jet is approximately one third (i.e. $L/L_b \approx 3$) and the dimensionless pool depth is about 15, then the average dynamic pressure coefficient is very close to zero.

Once the magnitude of the average dynamic pressure below the tailwater elevation is known, it is possible to superimpose the magnitudes of the fluctuating dynamic pressures onto the values of the average dynamic pressure following recommendations by Bollaert (2002) and Castillo (2004). This allows estimation of the maximum dynamic pressures at varying elevations below the tailwater surface. By studying the changes in total dynamic pressure below the tailwater elevation due to jet breakup for varying jet breakup length ratios it is possible to develop specifications for a spillway discharge system that will lead to conditions that are conducive to preventing rock scour.

CONSTRUCTION OF A PLUNGE POOL

The intent with constructing a plunge pool is to provide a pool with adequate water depth to prevent unwanted scour of rock. If the pool is deep enough the energy of the jet will dissipate and prevent scour of rock from occurring. This can be accomplished in a number of ways:

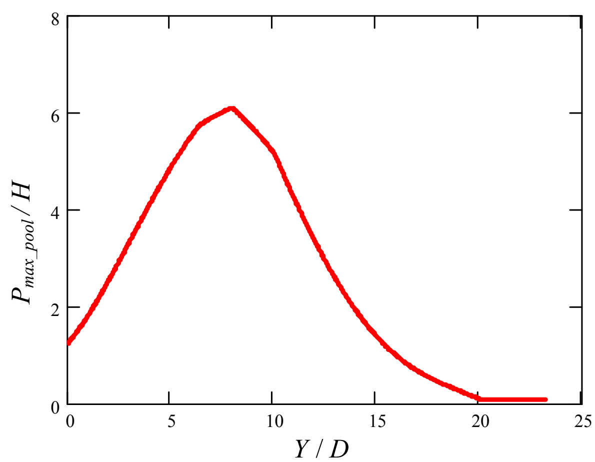
- constructing an above ground retaining structure that will store water that is deep enough to dissipate the jet energy and prevent scour,
- pre-forming a pool in the rock (by means of excavation) that will resemble the ultimate scour hole depth and shape, or
- combining the construction of a retaining structure and pre-forming approach.

The bottom of the pool is optimally located at the elevation where the water depth is such that the erosive capacity of the jet is just less than the scour threshold strength of the rock. At this pool depth the jet energy will dissipate without causing additional rock scour. Determination of this depth can be accomplished in two ways. From a stream power point of view (Annandale 1995), the optimal depth is determined using the same approach implemented to calculate the maximum scour depth in a plunge pool. This is accomplished by comparing the available stream power from the jet with the threshold stream power of the rock. The excavation depth of the plunge pool is set at the elevation associated with the maximum scour depth (Figure 2)

When using average and fluctuating dynamic pressure distributions in a plunge pool to determine the required plunge pool depth it is necessary to combine equations developed by Ervine et al. (1997), Bollaert (2002) and Castillo (2004). When considering brittle fracture or fatigue failure the combined equation for the maximum rock fissure pressure ($P_{\max\_pool}$) is found to be,

$$P_{\max\_pool} = \gamma \cdot \phi \cdot \frac{V_j^2}{2 \cdot g} \cdot \left(C_{pa} + \Gamma_{\max} \cdot C_{pa}^{'} \right) \tag{1.2}$$

where γ = unit weight of water; ϕ = 1 = kinetic energy coefficient; V_j = jet velocity at the point of impingement into the plunge pool; g = acceleration due to gravity; C_{pa} = mean dynamic pressure coefficient; $\Gamma_{\max}$ = fluctuating dynamic pressure amplification coefficient; $C_{pa}^{'}$ = fluctuating dynamic pressure coefficient.



• Figure 4. Dimensionless maximum fissure pressure as a function of dimensionless plunge pool depth.

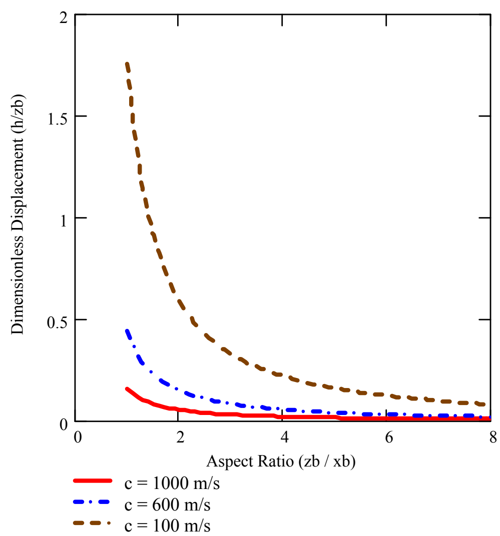
When plotting the dimensionless maximum fissure pressure ($P_{\max\_pool} / H$ where H = kinetic energy head of the jet) as a function of dimensionless plunge pool depth (Y / D) it is found that the maximum pressure occurs at a depth of approximately eight times the jet dimension. This does not mean that the maximum plunge pool is at approximately eight times the jet dimension, but this relationship can be used to assess the maximum scour depth by considering the brittle fracture and fatigue characteristics of the rock (Bollaert 2002). This is done by calculating the stress intensity in a fissure and comparing it with its fracture toughness. The complete procedure for doing this is quite involved and, due to space limitations, is not repeated here. It is useful to note that the maximum pressure decreases to minimal values at dimensionless depths of 15 or more. Obviously, the absolute value of the maximum pressure will be a function of whether the jet is intact or broken and can be determined using approaches referred to in the previous section.

When considering scour of jointed rock, another approach is to estimate the potential for rock removal by dynamic impulsion (Bollaert 2002). This can be accomplished by solving an equation representing dynamic impulsion of the rock, which can be expressed as follows:

$$h_{up} = \left[2 \cdot \frac{\left(x_b + 2 \cdot z_b \right)}{c} \right]^2 \cdot \frac{1}{2 \cdot g \cdot x_b^4 \cdot z_b^2 \cdot \rho_s^2} \cdot \left[C_I \cdot \phi \cdot \gamma \cdot \frac{V_j^2}{2 \cdot g} \cdot x_b^2 - \left(\gamma_s - \gamma \right) \cdot x_b^2 \cdot z_b - F_{sh} \right]^2 \tag{1.3}$$

where x_b = bottom dimension of a rock block, assumed square in plan (m); z_b = height of the rock block (m); ρ_s = rock density; c = pressure wave celerity of the water; C_I = dynamic impulsion coefficient; and F_{sh} = shear force on the edges of the rock (often assumed = 0). Using equation (1.3) it is possible to express the dimensionless displacement height as a function of aspect ratios (z_b / x_b) and water pressure wave celerity (Figure 5). When the amount of free air in water increases, its pressure wave celerity decreases.

Figure 5 indicates that removal of rock blocks is more likely when both the aspect ratio and the pressure wave celerity of the water are small. The optimal plunge pool depth using this approach can be determined by varying the impulsion coefficient, which can be expressed as a function of Y / D , according to Bollaert (2002). The plunge pool depth where the rock will just stop scouring can thus be determined by using the criteria presented in Table 1. Once the stable configuration for the plunge pool has been determined the excavation depth can be set at or below this elevation.



• Figure 5. Dimensionless vertical displacement of a rock block for varying pressure wave celerity.

The equation for calculating C_I is expressed as,

$$C_I = 0.0035 \cdot \left(\frac{Y}{D_j} \right)^2 - 0.119 \cdot \left(\frac{Y}{D_j} \right) + 1.2 \tag{1.4}$$

• Table 1. Proposed criteria to assess rock scour potential by dynamic impulsion (Bollaert 2002).

$\frac{h_{up}}{z_b} \le 0.1$	Rock block remains in place.
$0.1 \prec \frac{h_{up}}{z_b} \prec 0.5$	Rock block vibrates and most likely remains in place.
$0.5 \le \frac{h_{up}}{z_b} \prec 1.0$	Rock block vibrates and is likely to be removed, depending of ambient flow conditions.
$\frac{h_{up}}{z_b} \ge 1.0$	Rock block is definitely removed from its matrix.

ROCK ANCHORS

When using rock anchors to prevent scour of rock the objective is to increase the effective size of the rock blocks so that the erosive capacity of the water will not be able to remove the rock. For example, if the rock under consideration has an RQD of 50 its erosion resistance can be increased by anchoring the rock in a manner that will result in its effective RQD increasing to, say, 100. This can most probably only be accomplished if the rock anchors are stressed over long enough distances, forcing the individual rock block elements to act as a single unit. This approach will also only be effective if the mass strength of the rock is high enough to prevent if from failing in brittle fracture or fatigue.

The effectiveness of using rock anchors can be assessed using two optional and complimentary approaches. The one approach is to use Annandale's (1995) Erodibility Index Method, and the other is to use Bollaert's (2002) Comprehensive Scour Method. When using the Erodibility Index Method the two most important factors are the mass strength number (M_s) and the block size number (K_b) (see equation (1.1)). The mass strength number represent the relative ability of the rock to resist brittle fracture and failure by fatigue, while the block size number represent the relative ability of the rock to resist scour due to the increase in effective weight of the rock blocks created by anchoring.

When using Bollaert's (2002) approach to assess the effectiveness of using rock anchors the potential for the rock to fail by brittle fracture or fatigue can be determined directly by comparing the fracture toughness of the rock to the stress intensity caused by the fluctuating pressures in close-ended fissures. If it is determined that the rock will not fail in either brittle fracture or fatigue, the length of the stressed rock anchors can be determined by conducting a dynamic impulsion analysis. This analysis will provide an indication of the required size of rock blocks that should be created by stressing individual rock blocks together by anchoring. Once this is known, methods to bind the rock together with stressed anchors can be determined by considering the stratigraphy of the rock.

In summary, rock anchors (without a pool lining) can be used to resist plunge pool scour if the mass strength of the rock is adequate to prevent breakup of the rock into smaller pieces by either brittle fracture or fatigue. Once it has been determined that the mass strength of the rock is adequate to resist breakup, the next part of the design entails development of an anchoring system that will increase the effective rock block size. The required anchoring length and pattern will stress individual rock blocks together to form effective rock blocks that are large and heavy enough to prevent removal by the erosive capacity of the jet.

PLUNGE POOL LINING

If the rock anchor analysis indicates that the rock could potentially fail in either brittle fracture or fatigue modes, it is unlikely that such an approach (i.e. using rock anchors only) will result in adequate plunge pool protection. In such a case the use of a liner, such as concrete, could be considered. Such a lining can be provided with or without anchors.

Lining a plunge pool without anchoring can be successful if the material used to line the pool, say, concrete, is strong enough to resist brittle fracture and fatigue failure, while concurrently being heavy enough to resist uplift. If it is not possible, or economical, to construct a concrete lining that is by itself heavy enough to resist uplift, it is advisable to use post-tensioned anchors to secure the concrete to the underlying rock. Concrete lining without anchoring is often not economical for solving most plunge pool problems, and the use of anchors is usually preferred.

Using a concrete lining accomplishes two things; it can protect the plunge pool against the effects of rock failure that can occur due to brittle fracture or fatigue, and it increases the effective rock block size. If the concrete lining is strong enough to resist failure, it will protect the underlying rock. Even if water stops in the concrete joints fail and water pressure fluctuations penetrate underneath the lining and enter the rock discontinuities, failure can be prevented if the lining is correctly designed and anchored. Should the fluctuating pressures underneath the lining result in failure of the underlying rock, removal of the rock fragments will be prevented by the lining when appropriately anchored. Therefore, by covering the rock joints with the concrete lining and using long enough anchors, the effective rock block size is increased and the surface of the rock is effectively strengthened.

The design of an effective liner requires consideration of the following:

- The lining should be thick and strong enough to prevent failure by brittle fracture or fatigue, which could result from pressure fluctuations that could occur in cracks within the concrete that might develop in the lining over time.

- The water stops sealing the concrete joints should be robust to prevent fluctuating water pressures from penetrating underneath the lining. Such pressures can lead to uplift of the lining.

- Fluctuating water pressures penetrating below the lining can potentially lead to failure of the rock underneath the lining should it penetrate the rock discontinuities. The anchoring of the lining should be such that it will prevent removal of rock fragments from underneath the lining.

- The tensile strength of the lining material should be high enough to resist failure by brittle fracture or fatigue. This can be accomplished by using steel reinforcement or other means of increasing the tensile strength of the concrete. The design should aim at reducing the possibility of crack formation, either due to age or vibration during spill events.

- A drainage system underneath the lining that will relieve pressures is of critical importance. The design of such a system should be executed in a manner that will prevent resonance of the fluctuating pressures. Careful attention to the geometric design of the drainage system is important.

- The anchors should be designed to resist the maximum pressures that could occur underneath the lining.

- The anchors should be designed to resist failure by fatigue.

- The anchor lengths selection should take account of the rock characteristics, particularly the number of joint sets and discontinuity spacing. One of the objectives of using anchors is to increase the effective rock block size, and thus the total weight of the lining / rock system.

- The rock anchors should be designed in a manner that will prevent punch failure, i.e. the detail where the anchors terminate on the surface of the concrete should be designed in a manner that will prevent failure by punch-out.

SUMMARY

An approach for designing rock plunge pools to limit the extent of unplanned scour is presented in this paper. The elements of the design approach entails reducing the erosive capacity of the plunging jet, constructing a plunge pool, using rock anchors, lining the plunge pool, and using a combination of lining and rock anchors. These design elements can be used independently or can be combined in any manner to derive at the most optimal design solution. Calculation techniques that can be used to implement the design approach are referenced. In principal, two complimentary analysis approaches can be used; the Erodibility Index Method (Annandale 1995) and the Comprehensive Scour Method (Bollaert 2002). It is prudent to use both approaches when analyzing plunge pool scour and designing plunge pool protection systems.

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