The Influence of Long-term Flood Increases on Safe Design of Plunge Pools

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Abstract

Safe design of lined or unlined plunge pools is governed by the resistance to scour of the unlined rocky foundation or by the resistance to uplift of lined concrete slabs due to severe pressure fluctuations. Both phenomena have been studied following well-known cases of scour and lining failures in the past (Cahora-Bassa Dam, Malpaso Dam, etc.).

However, the increase of extreme flood intensity and frequency points out the need for significant modifications of existing spillway structures. New extreme flood predictions on the long term can be a multiple of the initial estimates. As such, future use of these modified spillways may endanger the safe functioning of the initially constructed downstream lined or unlined plunge pool.

The present paper makes use of a design method for computation of scour of rocky foundations or uplift of concrete linings. The method computes extreme water pressures inside rock joints or lining fissures and predicts break-up or uplift.

The design method is applied to a dam in the US. The influence of increased flood values on the amount of steel anchors necessary to prevent concrete slab uplift is pointed out, as well as the potential scour formation in the underlying rocky foundation during the adapted PMF flood event.

Introduction

Dynamic uplift of linings due to severe pressure fluctuations is of major concern to engineers. The phenomenon has been extensively studied because of failures in the sixties and seventies. Nevertheless, despite major advances in measurement technology and data acquisition, a safe and economic design method for any kind of concrete lined stilling basins is still missing today. Especially the transient character of pressure pulsations as a function of their two-dimensional spatial distribution above and underneath the lining is not fully assessed and implemented in existing design methods.

Concrete slabs are used as bottom protection linings of spillway stilling basins. Their design focuses on stability and resistance to severe hydrodynamic loadings during floods. The way these extreme loadings are defined, however, has been subject to significant debates since concrete slabs have at first been used. Initial design rules concentrated on resistance to impact pressures at the slab surface and on sound drainage of static pressure underneath the slabs. The shortcomings of such a design have been experienced during the 1960's by major damage of several concrete linings. Well-known examples are Malpaso Dam (Mexico) and Karnafuli Dam (Bangladesh).

The damage was found to be generated by sudden uplift or detachment of the slabs from the bottom ([1], [2]). This uplift occurred at discharges much lower than the design discharge and, as an example, at Karnafuli Dam it was found to be generated by severe pressure fluctuations that may enter the outlets of the drain system and the joints between the slabs. This has stimulated researchers to investigate the presence of dynamic pressures underneath the slabs. These underpressures travel through the joints as pressure waves with celerities that are considered much higher than the travel velocity of the surface pressures from which they originate ([3]). They may generate instantaneous net uplift pressures that are able to destabilize the slabs.

Determination of underpressures depends on the location and dimensions of both the slab joints and the pressure release pipes of the drainage system. Both types of discontinuities are present in a standard lining design and represent potential entries for underpressures. Therefore, slab joints are most often equipped with water stops that are designed to prevent pressure pulses at the slab surface from entering the joints. These water stops, however, age with time and subsequent flooding. Especially slab vibrations during floods may enhance deterioration of the water stops. Therefore, the use of water stops alone may not be considered as a sufficient countermeasure against slab uplift. Second, depending on the location of the pipe entries and the configuration of the network, drainage pipes may stimulate underpressures.

Theoretical and experimental research has been performed in the 1980's and 1990's to account for instantaneous dynamic underpressures in lining joints ([3], [4], [5]), however without accounting for transient pressure wave effects. Bellin and Fiorotto (1995) [4] directly measured uplift forces on laboratory scaled concrete slabs of different dimensions and subjected to hydraulic jump impact. The scale of the model did not allow detecting transient waves, however.

Other small-scale experiments of uplift pressures on concrete slabs and/or blocks have been performed by Yuditskii (1963) [6] for a ski-jump spillway, by Reinius (1986) [7] for water flowing parallel to the foundation, and by Liu et al. (1998) [8] for the Three-Gorges spillway. Lastly, Melo et al. (2006) [9] proposed a concrete slab design method that is solely based on time-averaged net dynamic uplift pressures.

It has to be outlined that all of these tests have been performed at a small scale that does not allow detecting pressure wave phenomena. Recently, prototype-scaled experiments performed in the field of fracturing of rock joints due to high-velocity jet impact ([10], [11]) have shown that pressure waves in joints may travel at very low wave celerities, typically 50-200 m/s, due to the presence of air in the water. Hence, transient effects such as wave oscillations and resonance may be relevant when defining extreme pressures underneath concrete linings ([10]).

As such, the present paper outlines a new design method for concrete linings of plunge pool stilling basins and illustrates the main steps of the method.

Theory of slab uplift

General

Slab design focuses on the maximum possible net uplift pressure (force) and related impulsion. The net uplift pressure is defined by the net difference between surface pressures and underpressures at any given time instant. The net uplift impulsion is determined by the integration over time of the net uplift pressure. Pressures occurring at a lining surface can be described by dynamic pressure coefficients. These define the time-averaged pressure field and its spatial distribution over the surface of the lining. Underpressures are defined based on surface pressures that enter the joints between the slabs of the lining and the joints between the lining and its foundation. Slab uplift occurs when the time-averaged or instantaneous pressure (force) differences over and under the slabs are able to generate sufficient impulsion to displace the slab.

First, both time-averaged and instantaneous spatial pressure distributions have to be assessed at the surface of the slab. The instantaneous spatial pressure distribution can be estimated by performing large-scale laboratory measurements, which define the spatial correlation of the pressure fluctuations. Pressure correlation contours often have integral scales that differ with flow direction. The integral scale is thereby defined as the distance over which, at the average, two pressure pulses become fully uncorrelated. In other words, it defines the maximum possible area over which a pulse may reasonably act. Often, these contours are complex and difficult to obtain because requiring a lot of measurements.

Nevertheless, for slabs that are very large compared to the integral scales of the pressure pulses, the spatial distribution of the time-averaged surface pressure field constitutes a plausible alternative to pressure correlation contours ([9]). Hence, no detailed regarding the contours is needed. Figure 1 compares the time-averaged mean dynamic pressures with the instantaneous total dynamic pressures. For large slabs, the large number of pressure peaks and pressure spikes compensate each other and spatial integration of instantaneous total pressures corresponds quite well to the blue surface, i.e. the time-averaged dynamic pressure field.

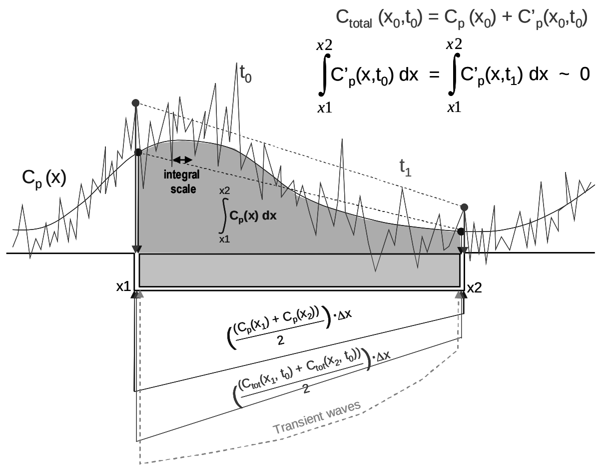

Figure 1: Instantaneous versus Time-averaged Dynamic Pressures along Upper Face of Concrete Slab

Second, slab uplift may be generated by pressures building up underneath the slab, in the confined area between the slab and its foundation. Transfer of pressures through the joints in between and underneath the slabs may then be considered in three ways:

1. Time-averaged dynamic pressure field: the pressure field underneath the slab is solely defined by the time-averaged values of dynamic pressures acting at the entrance of the joints between the slabs ([9]).
2. Instantaneous dynamic pressure field: the pressure field underneath the slab is defined by both the time-averaged and the fluctuating part of the dynamic pressures acting at the entrance of the joints between the slabs ([3]).
3. Transient dynamic pressure field: the pressure field underneath the slab is defined by the time-averaged and fluctuating part of the dynamic pressures at the entrance of the joints between the slabs and by transient waves propagating through the joints ([11]).

Whether or not pressure waves have an influence largely depends on the assumptions made on the wave celerity:

1. At high wave celerities, i.e. $O(10^2\text{-}10^3)$ m/s, pressures travel quasi instantaneously through the joints and a net uplift pressure is the result of the difference between an instantaneous surface pressure field and its corresponding instantaneous underpressure field. Transient effects are neglected because occurring too fast for the turbulence at the surface. This is a "dynamic" approach ([3]).
2. At low wave celerities, i.e. $O(10^1\text{-}10^2)$ m/s, and for large slab lengths of $O(10^1)$ m, a pressure wave needs time to be transferred all under the slab. Transient oscillations and resonance conditions may occur, depending on the fundamental resonance frequency of the joint (Figure 2). Hence, underpressures are not only determined by instantaneous pulses at the joint entrances but also by the transient characteristics of the joints. This is called a "transient" approach ([11]).

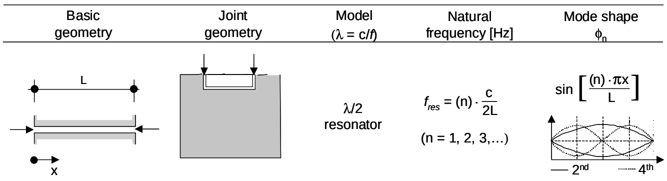

Figure 2: Resonating Frequencies of Lining Joint

Turbulent flow in stilling basins mainly occurs at rather low frequencies, i.e. a few Hz to tens of Hz ([12]). To generate transient pressures, wave celerities have to be low and joint lengths have to be significant. Recent research ([13]) has shown that waves may travel at celerities that are very low, i.e. 50-200 m/s. This is due to the presence of free air and is directly responsible for the appearance of transient effects in joints. Small-scale joints and no air are the main reason that laboratory experiments are not able to generate such effects.

The transient approach needs a quantification of pressure amplification inside the joints. This may be done: 1) by use of an appropriate pressure amplification coefficient ([11]); or 2) by direct numerical simulation of transient two-phase underpressures as a function of a time-dependent surface pressure field. The latter may be measured in the laboratory. Finally, a so generated net uplift pressure (force) may move the slab. For the most common case of anchored slabs, both the slab weight and the anchor stresses will prevent the slab from moving. This results in a dynamic equilibrium that is very similar to a spring-mass system as expressed by Newton's law ([5]). For such a system, the persistence time is of importance.

Differential equation for dynamic slab movement

Based on [5], dynamic uplift of anchored concrete slabs may be expressed by the differential equation valid for a spring-mass system with a forced vibration by means of an external forcing function. Damping effects are neglected. This is a safe-side assumption that has its merit when using dynamic pressures. For transient pressures, however, damping effects have to be accounted for because highly fluctuating as a function of the amount of air inside the joints ([13]). The basic equation expresses a balance of stabilizing and destabilizing forces as a function of time. The slab mass is defined by the concrete density ρc and the height of the slab h_s. The dynamic stiffness of the anchors is determined by the steel elastic modulus, the steel sectional area A_{st} and the length of the anchors L_{st}. The equilibrium may be written per unit of slab surface as follows (valid for positive displacements z(t)):

$$\rho_c \cdot h_s \cdot z''(t) + \frac{E_{st}\cdot A_{st}}{L_{st}} \cdot z(t) = p(t) \tag{1}$$

in which p(t) stands for the net uplift pressure on the slab. Solving this equation as a function of time expresses the uplift of the slab governed by the inertia of its mass and the stiffness of its anchors. During slab uplift, the uplift pressure pulse is assumed constant. Also, the elasticity of the water and the underlying rock are neglected. The standard solution of this 2nd order linear differential equation with constant coefficients consists of the sum of two periodic motions at a different frequency but for the same amplitude.

The corresponding maximum possible steel stress is written:

$$\sigma_{st,\max} = \frac{z_{\max}}{L_{st}} \cdot E_{st} = 2 \cdot \frac{p(t)}{A_{st}} = 2 \cdot \sigma_{st,static} \tag{2}$$

As pointed out by [5], dynamic equilibrium results in steel stresses $\sigma_{st,max}$ that are twice as high as the static steel stress $\sigma_{st,static}$. However, this dynamic stress can only be reached provided that the persistence time of the net uplift pressure equals or exceeds the time period T needed to build up the cosinusoidal motion of the slab. Hence, the persistence time of the net uplift pressure is essential. Short-duration pulses are not able to develop the full cosinusoidal motion and, thus, static steel stresses are valid. Pulses of longer duration allow cyclic motion and stresses to fully develop.

New slab design method

Types of flow impact

A new design method for uplift of concrete linings has been developed for two types of flow impact: 1) hydraulic jump turbulent flow, and 2) falling jet turbulent flow.

For falling jets, the flow conditions are determined by the conditions at issuance of the jet and modified during the fall of the jet. Dam issuance conditions are defined by the outlet structure, the upstream head and energy losses. The principal forces that act on a jet during its fall are gravitational contraction, spread due to turbulence and air drag ([14]). These allow determination of the exact point of impact of the jet, as well as the characteristics of the jet at this location.

For hydraulic jumps, the flow conditions are defined at the start of the jump, i.e. near the toe of the dam. The main parameters of interest are the average flow velocity, the flow height and the Froude number at start of the jump.

Dynamic pressures over the lining surface

Instantaneous pressures acting over the slab upper face can be approximated by their time-averaged values provided the slabs are large compared to the integral scales of the pressure fluctuations. Integral scales can be derived from available near-prototype scaled laboratory tests of high-velocity jet impact on slab joints ([10]). When a physical model is available, however, they may also be defined based on pressure fluctuation measurements. Integral scales can then be estimated by a correlation function based on data from the physical model, but approached by an exponential law $\rho(n) = e^{(\alpha \cdot n)}$, in which n stands for the characteristic length and α is a calibration coefficient ([3]). For hydraulic jumps, the characteristic length is equal to the incoming flow height. For jets, the characteristic length is the jet diameter.
The parameters of interest are the mean dynamic pressures and the root-mean-square (RMS) and extreme values of the fluctuating dynamic pressures, as well as their 2D spatial extension. These values can be assessed by means of pressure coefficients. These coefficients are obtained by dividing the absolute pressure values (in [m]) by the incoming kinetic energy of the flow ($V^2/2g$, in [m]).
For falling jets, pressure coefficients can be estimated based on available laboratory experiments and corresponding theoretical developments ([9], [13]). Similarly, for hydraulic jumps, dynamic pressures can be assessed based on literature ([3], [12]). Moreover, for hydraulic jumps, the pressure field is generally considered homogeneous in the lateral direction. For jets, however, the pressure field is considered two-dimensional. Figure 3 presents the theoretically defined RMS dynamic pressure field for 3,200 m^3/s jet impact flow conditions at a dam in the US (see case study).

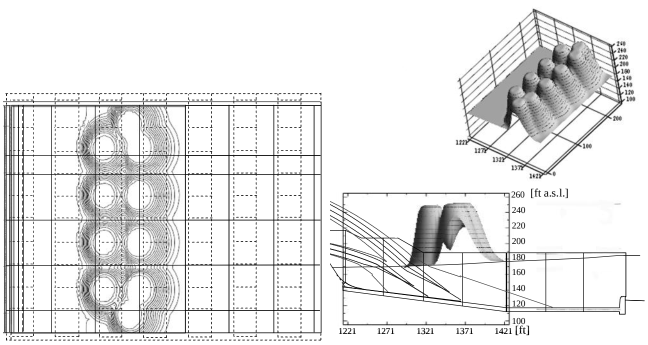

Figure 3. RMS Pressure Fluctuation Coefficients Generated by Multiple Jets Impacting the Stilling Basin Lining.

Dynamic pressures under the lining surface

The underpressure field may be computed by determining the dynamic surface pressures that act on the joints between the slabs or on fissures created in the concrete of the slabs and by supposing that these pressure travel through the joints/fissures (by failure of the water stops). A safe side assumption is to consider the maximum possible pressures that may act along the surface along the joints. A more realistic assumption is probably to consider the mean dynamic surface pressures.
The methodology proposed to define net uplift pressures and impulsions on a slab is of pseudo-2D character because performed separately along the X and Y directions in a 1D manner (corresponding to the orthogonal joint directions in a Cartesian coordinate system). Potentially positive (pressure releasing) influences of the drainage system between the slabs and the foundation are safely neglected.
The maximum dynamic pressure coefficients at the slab surface (C_{max}) are first spatially averaged along each of the two opposite slab joints in both the X and the Y-direction (Figure 4). These “$C_{max,average}$“ coefficients account for lateral diffusion of local pressure peaks through the slab joints. Then, the underpressure field is formed by taking the mean value of the two $C_{max,average}$ values and by applying an amplification factor Γ that accounts for transient effects. Next, this corrected value is applied to a percentage of the total area underneath the slab (Figure 4). Due to 2D diffusion effects of pressure waves, application to the total area would be far too conservative. The considered area has a length that is equal to the joint length L_j in the perpendicular direction and a width W_j as defined by a 2D calibration that is explained in detail hereafter. The process is performed in both the X and Y directions separately; the most critical result is retained.
Determination of the width W_j of the 1D strip that results in the exact total force under the slab can be done if measurements of net uplift forces on similar slabs are available. For spillway flow, such direct force measurements on 2D slabs are available from physical model tests ([4]). When subtracting the time-averaged spatially distributed dynamic surface pressure field from these the strip width can be defined. The 1D approach is thus calibrated based on 2D model tests for hydraulic jumps. It is assumed that this relationship holds for all possible flow conditions in the basin. The net uplift force on a slab is then described as follows:

$$F_{\max}(t) = \Omega\left(\frac{I_x}{y_1}, \frac{l_x}{\lambda_x}, \frac{l_y}{\lambda_y}\right) \cdot \left(C_p^+ + C_p^-\right) \cdot \gamma \cdot \frac{V^2}{2g} \cdot l_x \cdot l_y \quad (3)$$

in which Ω is function of the instantaneous spatial pressure distribution over the total slab surface, C+p and C-p are the positive and negative dynamic pressure coefficients, γ is the specific weight of the water, and finally lx and ly are the slab dimensions in the X-and Y-directions respectively. Ω depends on the shape of the slabs and on the ratios of the slab length to the integral scales λx, λy in both X and Y directions. Bellin and Fiorotto (1995) [4] provided direct experimental evaluation of the uplift coefficient Ω for a wide range of slab shapes and Froude numbers of the incoming flow field. This was performed by simultaneous measurements of pressures underneath slabs and net uplift forces on slabs. For jet impact, however, no such measurements are available. It is proposed to use values obtained for hydraulic jumps with similar Froude numbers and ratios of slab length to integral scales.

The Ω values highly depend on the ratios l_y/λ_y and l_x/λ_x. For very small and very high ratios, Ω theoretically tends towards zero. In between, a maximum value is obtained for ratios between 2 and 4, assuming that maximum pulses occur at both slab joints and a minimum pressure occurs in between. The ratios tested by [4] equal 0 to 2 for l_y/λ_y and 0 to 10 for l_x/λ_x.

Transient excitation frequencies and related steel stresses: The fundamental resonance frequency of a joint f_{res} is a function of the wave celerity c and the joint length L_j (Figure 2). The inverse T_{res} expresses the the average persistence time T_{res} of a pressure pulse. For example, for celerities of 100-500 m/s and joint lengths of 10-20 m, T_{res} is written:

$$T_{res} = \frac{1}{f_{res}} = \frac{2 \cdot L_j}{c} = 0.04 - 0.4[s] \quad (4)$$

For steel anchors that are 2 m long and slabs that are 1.5 m high and 15 m long, and for a steel area density of 4 cm^2/m^2, the time periods necessary for pressure pulses to reach the static and dynamic steel stresses are 0.015 sec respectively 0.03 sec. In this case, pressure waves through the joints have a persistence time that easily allows reaching the dynamic steel stresses in the anchors. If this is not the case, static stresses might be more realistic.

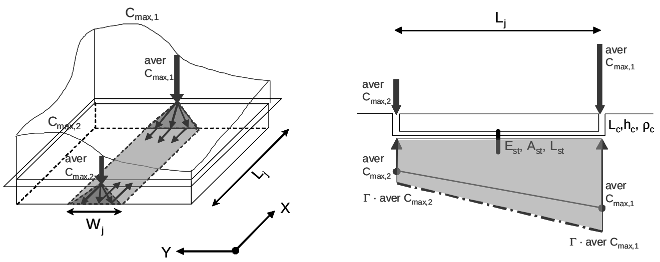

Figure 4. Determination of Pressures Acting Underneath the Slab Based on the Average Values of Maximum Pressures Along Opposite Surface Joints

A 1D transient two-phase numerical model has been developed to compute underpressures between the slabs and the underlying foundation. Detailed characteristics of the numerical model and the used equations can be found in [10]. The model needs pressures measured at the joint entrances as input data. The model defines the force as:

$$F_u = \sum_i p_{ui} \cdot A_{ui} \quad (5)$$

in which A_{ui} stands for the area of application of p_{ui}. For sake of simplicity, each area of the five points p_{ui} has been taken equal to 1/5th of the total slab area. The uplift force is then computed as the average of underpressures times total slab area. The influence of transient waves on net uplift forces can be expressed by means of a transient amplification factor Γ defined as the ratio of the average underpressure to the average of the maximum surface pressures p_{sj}.

The amplification factor defines the amplification that the underpressures may exhibit due to transient wave effects in the joint. Hence, for a transient slab uplift computation, the dynamic underpressures are simply multiplied by this amplification factor to obtain fully transient values. The amplification factor Γ has been computed for two different celerity-pressure relationships, corresponding to low (0-2 %) and high (5-10 %) air concentrations in the slab joints and directly defining the damping of the transients ([13]). For practice, Γ amplification values of 1.35 for jet impact and 1.20 for hydraulic jumps seem plausible.

Computational Methodology

1. Determine integral scale of pressure fluctuations (based on theory and/or physical model experiments) and check plausibility of time-averaged surface pressures.
2. Determine pressure coefficients along upper face of lining
3. Choose initial slab dimensions and joint/fissure locations
4. Determine pressure coefficients along joints between the slabs of the lining or along fissures through the lining
5. Determine "joint/fissure length"-averaged values of the maximum dynamic surface pressures for the X (longitudinal) and the Y (transversal) direction.
6. Determine width of the 1D strip based on [4].
7. Multiply the underpressures/forces by a transient amplification factor to account for transient wave effects.
8. Determine fundamental resonance frequency and average persistence time of pressure pulses. Compare with time duration necessary for dynamic steel stresses to develop.
9. Choose final slab dimensions and determine necessary steel area based on the spring-mass equation and allowable elastic steel stresses.

Case study

The new slab design method has been applied to a concrete gravity dam in the US, equipped with a 74 m by 107 m concrete lined stilling basin. Due to a substantial increase of the PMF event (23'000 m^3/s instead of 15'500 m^3/s, i.e. + 50%) since the time of dam construction, the outlet works of the dam have to be enlarged. This results in an increase of the dynamic pressures impacting the lining of the stilling basin, and 14 to 18 of the concrete slabs would be uplifted under current design. Hence, the new steel area necessary to prevent future slab uplift has been computed with the new design method and is illustrated in Figure 5. The necessary area was found to be up to twice the steel area currently in place. Second, Figure 6 shows the scour potential in the rock following eventual failure of the concrete lining.

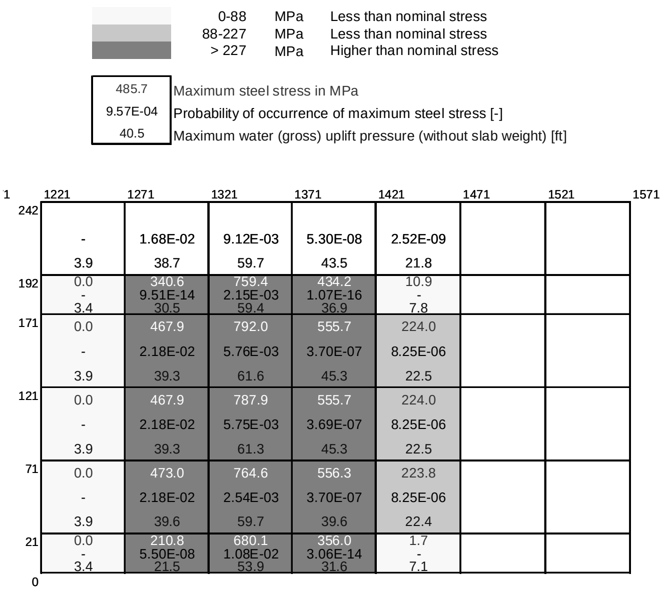

Figure 5. Maximum steel anchor stresses in the stilling basin for all outlet works functioning during the increased PMF.

Conclusions

This paper presents a new method for designing concrete linings of stilling basins against sudden uplift due to impact of turbulent flows. The method is valid for any type of turbulent flow provided that the turbulent pressures of that flow can be statistically described by means of pressure coefficients.

The method uses time-averaged dynamic pressures along the upper face of the lining and supposes a transfer of peak pressure pulses through the joints to determine the pressures acting along the lower face of the lining. Based on detailed laboratory measurements of net uplift forces on slabs for different flow conditions ([4]), the total underpressure can be derived by adding the time-averaged surface pressure field to the laboratory measurements of the net uplift pressure. As such, the peak pressure values that are supposed to act under the slabs are applied over a restricted area of the slab to comply with the total underpressure measured in the laboratory. Because the small-scale laboratory tests did not account for transient waves, these peak pressure pulses have then to be multiplied by an amplification factor accounting for transient wave effects through the joints. Finally, subtracting the computed surface pressure field from the corrected underpressures results in transient net uplift pressures and forces on the slabs. Use of a differential equation valid for a spring-mass system then allows dimensioning the necessary steel area of the slab anchors. The method has already been applied on real-life studies of stilling basin design.

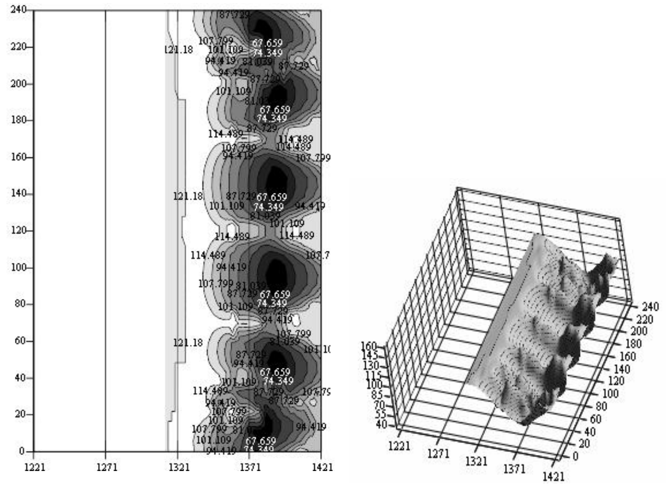

Figure 6. Potential scour formation in rock mass.

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