# EFFECT OF GEOLOGY ON UPLIFT AND DAM STABILITY

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## INTRODUCTION

Geology and water in rock masses can be major sources of problems in dam safety. Water seeping in rock masses can affect the safety of dams in essentially two ways: erosion and uplift. Several dam failures have been attributed to excessive uplift. For instance, the Austin dam in Pennsylvania is believed to have failed in 1910 (Hatton, 1912) due to a combination of high uplift pressure and low shear strength (reduced due to seepage) along some beds in the dam's sandstone foundation. Terzaghi in 1929 cites several examples of gravity dam foundation failures dating back to 1912. More recent examples include the failure of the foundation of the Malpasset dam in 1959. Dam foundation stability is still an ongoing problem as illustrated with some recent problems with the Morris Shepard dam near Austin, Texas (Pullen and Thompson, 1989).

The current design practice relies heavily on simple empirical rules when accounting for the effect of water on dam stability. For instance, it is assumed that uplift pressure at the base of a dam without drains varies linearly from full reservoir pressure at the heel to tailwater at the toe. For dams with foundation drains, the pressure is assumed to follow a bi-linear distribution from full reservoir pressure at the heel to tailwater plus some fraction of the difference between headwater and tailwater at the line of drains, to tailwater at the toe. These approximations are based on the assumption that rock masses behave like porous continua (e.g. soils) with respect to seepage and ignore the influence that geology could have on uplift. It is noteworthy that in the recent FERC guidelines (FERC, 1991), it is suggested that the geology of dam foundations be fully understood prior to selection of an uplift distribution. Other assumptions used in current design practice are (1) that uplift acts over the whole dam base area, (2) that drains control uplift pressure ,and, (3) that grouting controls mostly seepage and helps in reducing large fluctuations in uplift with changing headwater and tailwater levels.

The importance of geology in controlling uplift and dam stability has been emphasized by several authors over the past eighty years and a good literature review on this subject can be found in Grenoble (1989). For instance, Terzaghi (1929) questioned why one of two apparently identical concrete dams on apparently identical foundation rock would fail while the other would not. He found that this could be attributed to minor geological details. Casagrande (1961) also emphasized how unfavorable geology could lead to unusual high uplift. He found that problems with excessive uplift pressures could be attributed to isolated, highly pervious geological features such as faults, seams and shear zones which are located in the foundation near the base of the dam.

Despite the concerns raised by Terzaghi, Casagrande and others and an overall effort of current dam owners to pay more attention to dam site exploration and monitoring, the possible detrimental effects of geology on dam safety are still often misunderstood or overlooked by designers. At the University of Colorado at Boulder, we are investigating several effects of geology on uplift and dam stability in order to identify the limitations of the assumptions used in the current design practice. More specific areas of study include (1) the effect of rock mass discontinuities, anisotropy and block movement on dam stability, and (2) the effect of drains and grouting on uplift, under both static (normal and PMF) and dynamic conditions. These studies are conducted using a combination of physical and numerical models. Some results of the numerical study are presented in this paper.

## NUMERICAL MODELING OF ROCK MASSES

The mechanics and hydraulic properties of a rock mass are mainly determined by macro discontinuities such as joints, seams and faults. Discontinuity planes separate rock masses into blocks. Hence, a continuum model of a rock mass is rarely useful when assessing the stability of dams on rock.

Predicting the stability of a dam on jointed rock must be done using a combination of hydraulic and mechanical models. Indeed, as a jointed rock mass deforms under gravity, reservoir and seismic loads and seepage forces, rock discontinuities open or close and their permeabilities change. This, in turn, creates a new distribution of water pressure in the rock mass and induces new deformations and stresses in the dam-foundation rock system. Two types of numerical models can be used to study the stability of concrete dams on jointed rock; discrete models and equivalent continuum models. Note that most of these models have been developed for the design of waste disposal sites and have only been used for dam foundations in very few cases.

### Discrete Models

In the discrete models, a rock mass is modeled as a network of finite planar hydraulic conduits which are allowed to deform in directions normal and parallel to their planes. The discontinuities have zero tensile strength and therefore can open when subjected to tensile stresses. Also, they are allowed to shear and their shear strength can be mobilized. Opening and sliding of discontinuities change their hydraulic properties and the pressure distribution in the rock mass. The new pressure distribution creates more opening and sliding. Interactive discrete models for flow and stress have been reported by several authors using different numerical methods.

## Finite Element Method

The Finite Element Method has been used for modeling the interaction between flow and stress by Brekke et al (1972). Chinnaswamy (1986) conducted an extensive finite element study on the effect of a seam (or fault) on the seepage and stability of a dam. Parameters included seam location, seam orientation and seam permeability. The relative permeability of the seam with respect to the rest of the rock mass was defined using a permeability ratio $P_r = (k_s.t)/k_r$ where $k_s$ and $k_r$ are the permeabilities of the seam and intact rock, respectively and t is the seam thickness. Chinnaswamy found that a seam could have a major effect on the flow pattern and the pressure distribution at the base of a dam. In general, because of a seam, the pressure distribution at the base of a dam can no longer be taken as linear. Conclusions reached with that study are as follows:

- for horizontal seams, as the permeability ratio $P_r$ increases, the flow becomes more concentrated in the seam. The pressure distribution at the base of the dam changes. An increase in $P_r$ results in a decrease in pressure on the upstream side and an increase on the downstream side, thus resulting in a shift of the point of action of the uplift force toward the downstream side of the dam. This effect decreases rapidly as the depth of the seam increases and becomes essentially negligible for seams located at depths larger than the base width of the dam.

- Figure 1 shows the flow and equipotential lines below a dam with a seam dipping at an angle of 30 degrees downstream for $P_r$ = 2000. Most of the flow is along the seam and the equipotential lines are closer in the domain above the seam thus affecting the pressure distribution, hydraulic gradient and uplift force at the base of the dam. In general, it was found that for seams that intersect the dam reservoir, the seams create larger uplift than when the rock mass is homogeneous. For seams that intersect the tailwater, the opposite was found to apply. For seams that dip upstream and intersect the base of the dam, larger uplift can be induced except for seams intersecting a region near the heel of the dam for which the opposite is true. For seams that dip downstream and intersect the base of the dam, uplift is reduced except when the seams intersect a region near the toe of the dam. Also, it was found that the effect of a seam on the pressure distribution decreases as its point of intersection with the ground surface is further away from the dam. This effect is essentially negligible at distances larger than 7.5 times the dam base width on either side of the dam.

Coupling between flow and stress was also conducted by Chinnaswamy (1986) to assess the stability of a dam founded on a rock mass with a horizontal seam. Using an elasto-plastic analysis, it was found that any horizontal seam (or fault) located at depths greater than 0.25 times the dam base width are safe (against sliding) irrespective of the weakness of the seam (or fault) (see Chinnaswamy and Amadei, 1991).

Another extensive finite element flow analysis (without the effect of stresses) of jointed rock was conducted by Grenoble (1989). The main emphasis of that study was to assess the influence of variations in geology on uplift calculations. Using a Monte Carlo approach and data on the statistics of joint orientation, location, length, spacing and aperture, several statistical realizations of a joint network below a dam could be generated. For each network, a discrete finite element mesh could be constructed, a seepage analysis carried out and the uplift calculated. Among the conclusions reached in the study of Grenoble (1989), it was found that the distribution of uplift pressure in jointed rock masses is, **on average**, well represented by the conventional linear and bi-linear approximations. However, because of the intrinsic heterogeneous nature of rock masses, it was found that large scatters of uplift values around the average linear and bi-linear pressure distributions were possible. Minor geological details could indeed create larger or smaller uplift forces than those calculated with the conventional approach as suggested by Terzaghi (1929) and Casagrande (1961). Other recommendations on the effect of the variability of geology on uplift can be found in Grenoble and Amadei (1990).

## Distinct Element Method

The Distinct Element Method is similar to the finite element method in that the domain of interest (here the dam and the rock mass) is divided into a system of solid elements (or blocks). The main difference between the two methods is that the distinct element method allows blocks to move (translate and rotate) with respect to one another and large block movements are possible. As blocks move, the gaps between the blocks change and seepage in the jointed rock mass changes. Examples of coupling between the distinct element method and flow can be found in Cundall (1982), Lemos (1987), Asgian (1988) and Kafritsas and Einstein (1988), among others. Figure 2 shows an example of application of the method conducted by the authors. Note the opening of the joints in the rock mass near the heel of the dam.

A distinct element program called UDEC ( Itasca Consulting Group, 1991) was used to determine the effect of the ratio between concrete and rock Young's moduli on the state of stress along a dam-rock interface. In this example, the rock mass was homogeneous with a modulus $E_r$ and a Poisson's ratio equal to 0.25. The concrete had a modulus $E_c$ = 30,000 MPa and a Poisson's ratio equal to 0.2. Two dam geometries were analyzed with heights of 100 and 120 m and a base width of 80 m. This corresponds to dams with slopes of 0.8 and 0.67, respectively. The interface rock-concrete (between the blocks of rock and concrete) was modeled using a joint element with constant normal and shear stiffnesses of 1000 MPa/m, zero cohesion and tensile strength and a friction angle of 45 degrees. The interface was allowed to open and shear (partially or fully). The dams were subjected to gravity and reservoir loads. Figures 3 shows the distribution of normal stresses along the interface for the two dam geometries and for values of $E_r/E_c$ ranging between 0.5 and 10, thus simulating the stability of a dam on rock masses ranging from very soft to very hard. Figure 3 shows that for the dam with a slope of 0.8, compression prevails over the whole interface regardless of the value of $E_r/E_c$. However, as $E_r/E_c$ increases, the amount of compression decreases at the heel and at the toe of the dam and increases in between those extremes. For the dam with a slope of 0.67, tension and therefore opening of the interface occurs at the heel of the dam with more tension and interface separation as the rock foundation becomes stiffer. Figure 4 shows the variation of the horizontal crest displacement with $E_r/E_c$ for the two dam geometries. The amount of displacement is very much affected by the deformability of the foundation rock for values of $E_r/E_c$ less than 2.

**Equivalent Continuum Models**

In general, the discrete models discussed above are used in dam stability analysis for rock masses with a limited number of discontinuities and blocks. That number varies with the computer memory size. Furthermore, discrete models require a complete understanding of the foundation joint network. Such an understanding would be extremely expensive, if even possible, to develop.

Unlike discrete element models, equivalent continuum models can be used for heavily jointed rock masses, i.e. rock masses which joint spacings that are much smaller than the base width of the dam (less than 10% of the base width as a rule of thumb). Here, the jointed rock mass is replaced by a equivalent continuum with anisotropic deformability and flow properties. The permeability coefficients and the deformability properties of the equivalent continuum depend on the spacing, orientation and aperture of the different joint sets but not on their exact location. Such an an approach has been used for dams by Gell and Wittke (1986) and Erban and Gell (1988). In an ongoing study, the authors are using an equivalent continuum approach in the stability analysis of an arch dam founded on argillite. The rock mass contains three well defined joint sets, one set of bedding joints and two sets are right angles to the first set. Joint spacing varies between several inches and 7 feet. The stability analysis requires coupling between stress, flow and temperature as the safety factor against sliding along the rock concrete interface in the left thrust block of the dam was found to be less than 3 in the summer months. Results of this study will be presented in the near future.

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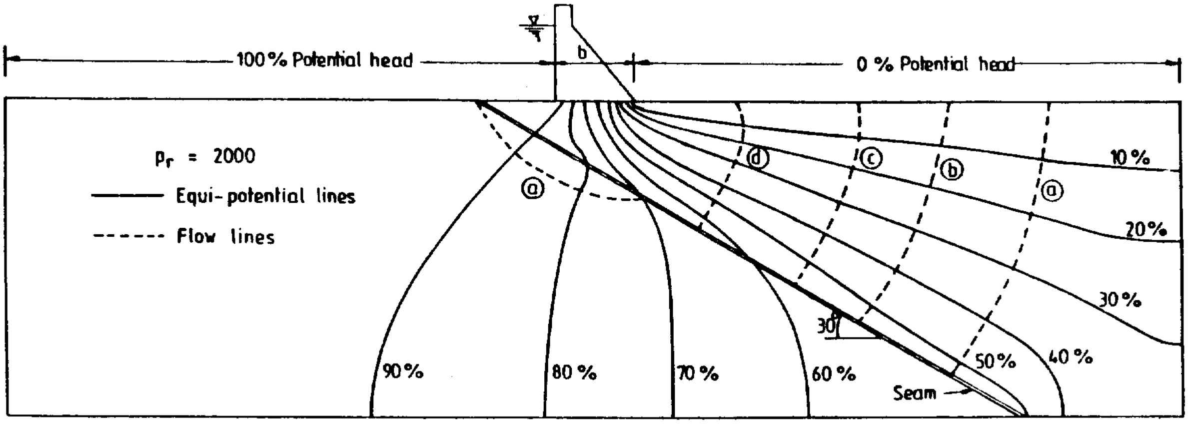


Figure 1. Flow and Equipotential Lines Below a Dam with a Seam Dipping 30° Downstream and Intersecting the Dam Reservoir (after Chinnaswamy, 1986).

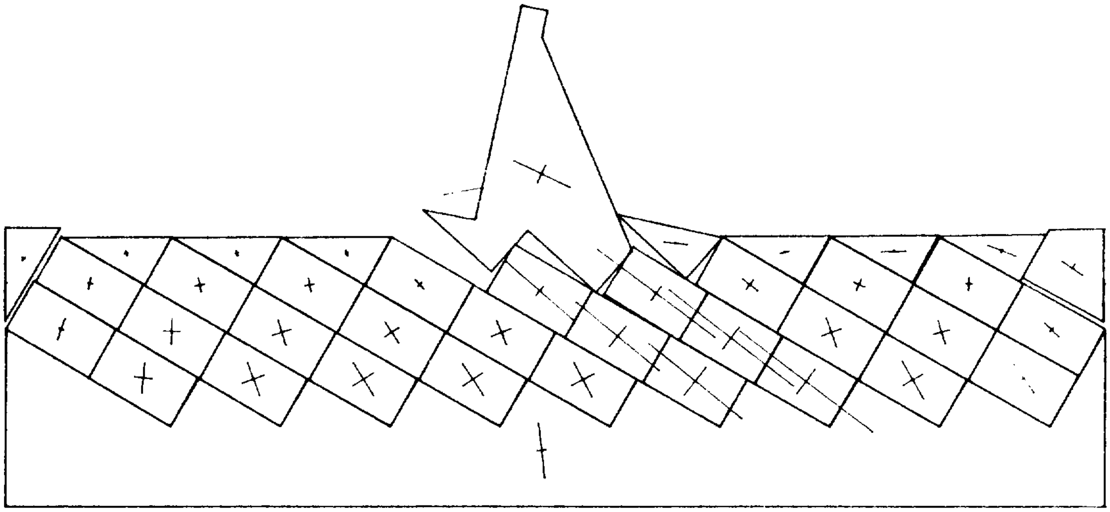

Figure 2. Distinct Element Model of a Dam Resting on Jointed Rock

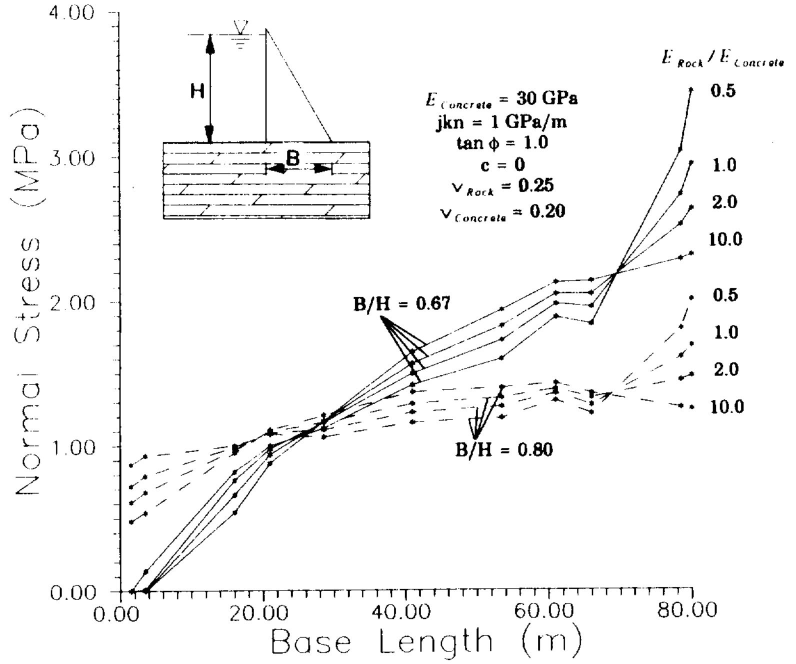


Figure 3. Normal Stress Distribution at Rock-Concrete Interface for Different Values of $E_r/E_c$ and Two Dam Geometries.

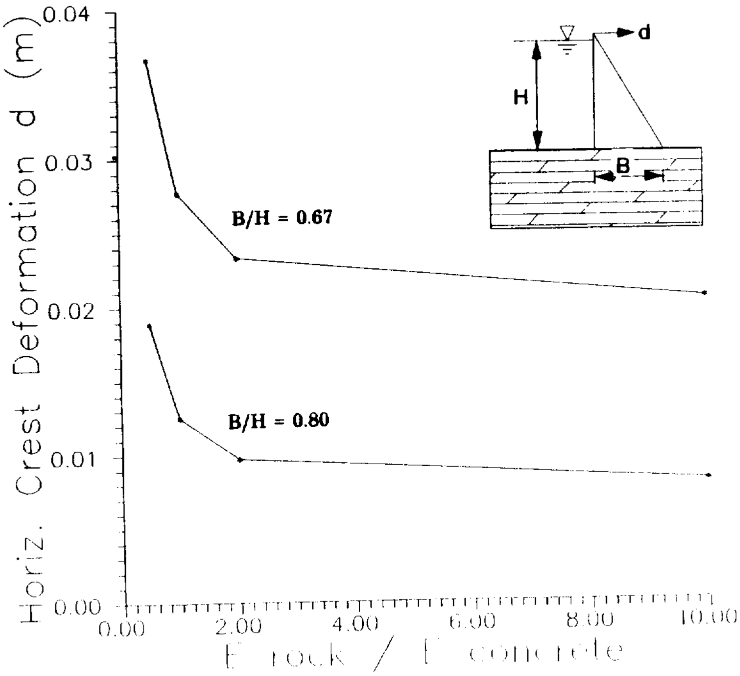


Figure 4. Crest Horizontal Displacement for Different Values of $E_r/E_c$ and Two Dam Geometries.