REMR Technical Note CS-ES-4.4

Variation in Uplift Pressures With Changes in Loadings Along a Single Rock Joint Below a Gravity Dam

Objective

This technical note presents the results of a study that show the impact of deformations on the resulting uplift distributions along a single joint located directly below a concrete dam monolith during and after construction and for subsequent initial filling of the reservoir.

Introduction

Navigation and flood-control structures are constantly being examined to determine if they meet stability criteria. A common procedure for evaluating the safety of these structures is the conventional equilibrium method of analysis coupled with a prescribed uplift distribution as given, for example, in an engineering manual specific to that particular hydraulic structure. Many of these types of analyses are conducted without regard to how deformations impact the results. Today, analytical tools such as the finite element method (FEM) are available which can consider the manner in which loads and resistance are developed as a function of the stiffness of the foundation rock (or soil), the structure, and the structure-to-foundation interface.

Modeling Joint Flow: The Cubic Law

Flow within a rock joint can be characterized in a simplistic form as flow between a pair of smooth parallel plates separated by a constant distance. This distance is the joint opening or aperture, e. The flow rate per unit width is given by

$$Q = \frac{\gamma \; e^2}{12 \; \mu} \cdot \left[- \frac{\partial h}{\partial l} \right] \cdot e \qquad (1)$$

where γ is the unit weight of water, e is the conducting aperture, and μ is the dynamic viscosity. The quantity of flow varies with the cube of the aperture e, hence the name "the cubic law." By analogy with Darcy's law, the equation for a single joint may be rewritten as

$$Q = K_{joint} \cdot [\, i \,] \cdot AREA_{flow} \tag{2}$$

where K_{joint} is the permeability, i is the hydraulic gradient, and $AREA_{flow}$ (e times unit width) is the area of flow at any point along the single joint. The above equation can be used to compute the steady-state quantity of flow and distribution of uplift pressures (given known values for γ and μ), the heads at each end of the joint, and the variation in aperture e with distance along the joint. Conventional one-dimensional steady-state seepage computer program packages that are commercially available can be used to perform the seepage analysis.

Modeling Joint Deformation

Laboratory studies have shown that joint aperture is not constant but varies with the stress applied normal to the joint. A mathematical relationship between the deformation of joints and the applied loading (or unloading) has been established based on laboratory tests on several different rocks and joint types. The deformation of a joint with applied normal stress is commonly referred to as joint closure/opening and is modeled for many types of joints and rocks as a hyperbolic function (as described in Bandis, Lumsden, and Barton (1983)). Figure 1 shows the hyperbolic relationship between joint closure/opening with normal stress for initial loading and unloading of a single joint in moderately weathered sandstone using the model parameters given in Bandis, Lumsden, and Barton (1983). The size of the joint is described in terms of the mechanical aperture, E. Mechanical aperture E is distinguished from the conducting aperture e that is used in the cubic equation. The mechanical aperture of the joint is assumed to have an initial value of E_o equal to 8.2×10^{-4} ft (250 μm or 0.25 mm) at zero stress normal to the joint, which is consistent with values typical of moderately weathered sandstone (Bandis, Lumsden, and Barton 1983). A value of 8.2×10^{-4} ft (250 μm) for E_o is classified as a tight to partly open aperture according to the Barton (1973) classification scale for apertures. The changes in the mechanical aperture E with normal stresses shown in the upper portion of Figure 2 are computed as E_o minus the joint closure of Figure 1.

An interrelationship between e and E in Barton, Bandis, and Bakhtar (1985) was used to construct the relationship between conducting joint aperture e and normal stress shown in the lower portion of Figure 2 for a moderately weathered sandstone joint of typical joint roughness. The initial conducting joint aperture e at zero stress normal to the joint is equal to 2.75×10^{-4} ft (84 μm or 0.084 mm). Note that the conducting aperture e will always be less than the mechanical aperture E.

With the relationship between conducting aperture e and the normal stress shown in Figure 2, the relationship between permeability along a single joint and normal stress can be established by

$$K_{joint} = \frac{\gamma\ e^2}{12\ \mu} \qquad (3)$$

Figure 3 shows the resulting relationship.

Modeling Joints Using the FEM of Analysis

The reactions of joints in rocks to changes in loadings can be modeled using a type of interface element developed by Goodman, Taylor, and Breeke (1968) to model the behavior of joints. This interface element is incorporated within the FEM program SOILSTRUCT (Ebeling, Peters, and Clough 1992). SOILSTRUCT is a general-purpose FEM program for two-dimensional (2-D) plane strain analysis of soil-structure interaction problems. SOILSTRUCT is capable of modeling the incremental construction and incremental loading of hydraulic structures. SOILSTRUCT calculates displacements and stresses due to incremental construction and/or load application and can model nonlinear stress-strain material behavior. Two types of finite elements are used to represent the behavior of different materials comprising the monolith, its rock foundation, and the interface between them: (a) a 2-D continuum element and (b) an interface element.

Example Problem: Incremental Construction and First Flooding of a Gravity Dam Founded on Sandstone

The case of a concrete gravity dam constructed on weathered sandstone is used to show the impact of joint closure and opening on uplift pressures. Figure 4 shows the hypothetical dam to be 300 ft high and 235 ft wide. It was assumed that jointing within the sandstone foundation was simplistic, a single rock joint parallel to and immediately below the dam-to-foundation interface. Changes in joint aperture in this problem are a result of the construction of the dam and subsequent filling of the reservoir.

The model dam was constructed, and the pool was raised from the base to the crest of the dam in 19 incremental steps using SOILSTRUCT. The dam and the sandstone foundation were assumed to be impervious, while all flow below the dam was assumed to be confined to within the single sandstone joint. Twenty-nine interface elements were used to model the sandstone joint in the finite element analysis, while 1,775 linear elastic, 2-D continuum elements were used to model the concrete dam and the foundation sandstone.

The constitutive model used for all 29 sandstone joint interface elements is shown in Figure 1. Figure 2 shows the resulting relationship between values for effective normal stresses and values for both mechanical and conducting apertures for the sandstone joint. Figure 3 shows the resulting permeability of the rock joint based on the normal stresses. The variation of joint apertures (both E and e) due to changes in normal stresses resulting from the construction of the dam and subsequent raising of the pool is shown in Figure 5. The initial joint aperture (prior to construction) was assumed to be uniform along the joint. The initial values for both the mechanical and conducting joint apertures ($E = 8.2 \times 10^{-4}$ ft and $e = 2.75 \times 10^{-4}$ ft) at two points along the joint are given in Figure 5. Loading or unloading of the sandstone joint is also identified in this figure at each end of the joint and for the four stages of loading reported in this figure.

Figure 6 shows the resulting distribution of uplift pressures along the single sandstone joint for pool elevations of 52, 170, and 300 ft. The results in this figure show that for the low and intermediate pool elevations, the distribution of uplift pressures along the sandstone joint is distinctly nonlinear from the heel to the toe. In fact, each of these two computed distributions is less than the linear distribution of uplift pressures which are typically assumed in equilibrium analyses. The distribution of nonlinear uplift pressures reflects the impact of changes of the distribution in conducting aperture with changes in loading/unloading along the sandstone joint.

Base separation was computed along nearly 50 ft of the base after the pool was raised to 300 ft. Full uplift pressure was assigned in this portion of the sandstone joint, as shown in Figure 6. Changes in joint aperture with this additional loading result in a change in uplift distribution as compared to the results from the intermediate and lower pool cases. Specifically, the distribution of uplift pressure is computed to be *greater than* that corresponding to a linear distribution of uplift pressure as shown in this figure.

Figure 7 shows the variation of uplift head computed at the heel, at the toe, and at four points along the sandstone joint versus height of headwater. The nonlinear variation in uplift head with height of headwater at the four quarter-points along the joint reflects the changes in aperture with loading/unloading along the joint. It is interesting to note that a nonlinear variation in uplift with changes in pool elevations has been observed at several instrumented dam sites, typically in foundations comprising "tight" joints. The joint size used in this analysis would be characterized as a tight sandstone joint.

The results of a finite element analysis of an idealized dam founded on a sandstone foundation with a single tight joint illustrate the interrelationship between changes in joint aperture with loading/unloading of the joint. The changes in joint aperture result in changes in the distribution of uplift pressures along the joint. This key aspect of the behavior of tight joints and corresponding uplift pressures as observed in this idealized problem is likely to be present in more complex, tight rock joint foundations found at some dam sites.

Conclusions

The principal results of this study are as follows:

a. Joint aperture and permeability vary with normal stress.

b. The distribution of uplift pressure along tight joints changes with the applied load and can be nonlinear.

c. The change in piezometric head at any point along a tight rock joint can vary nonlinearly when compared with changes in reservoir head.

References

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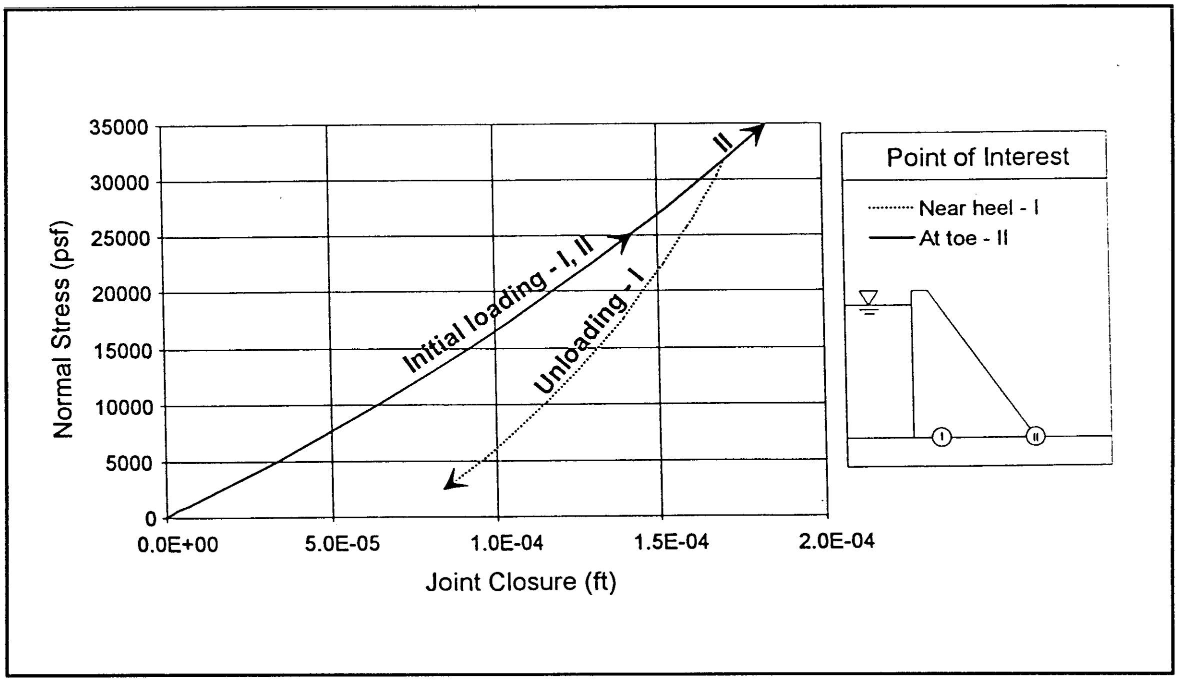

Figure 1. Joint closure and opening versus normal stress

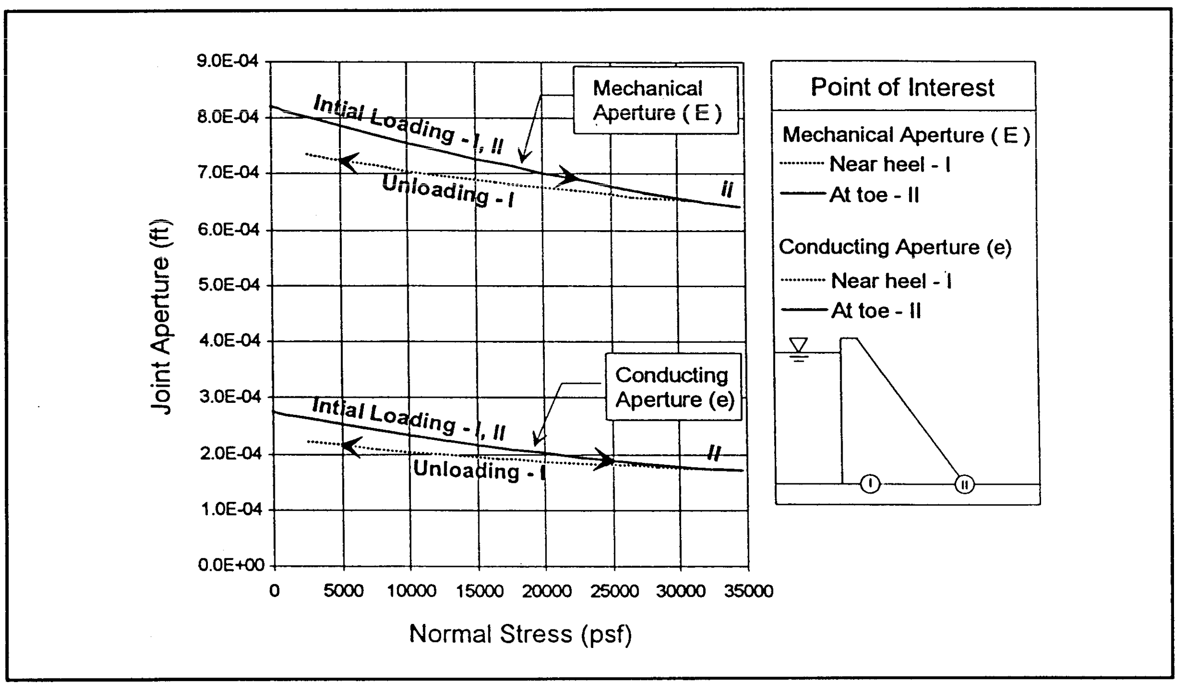

Figure 2. Joint aperture versus normal stress

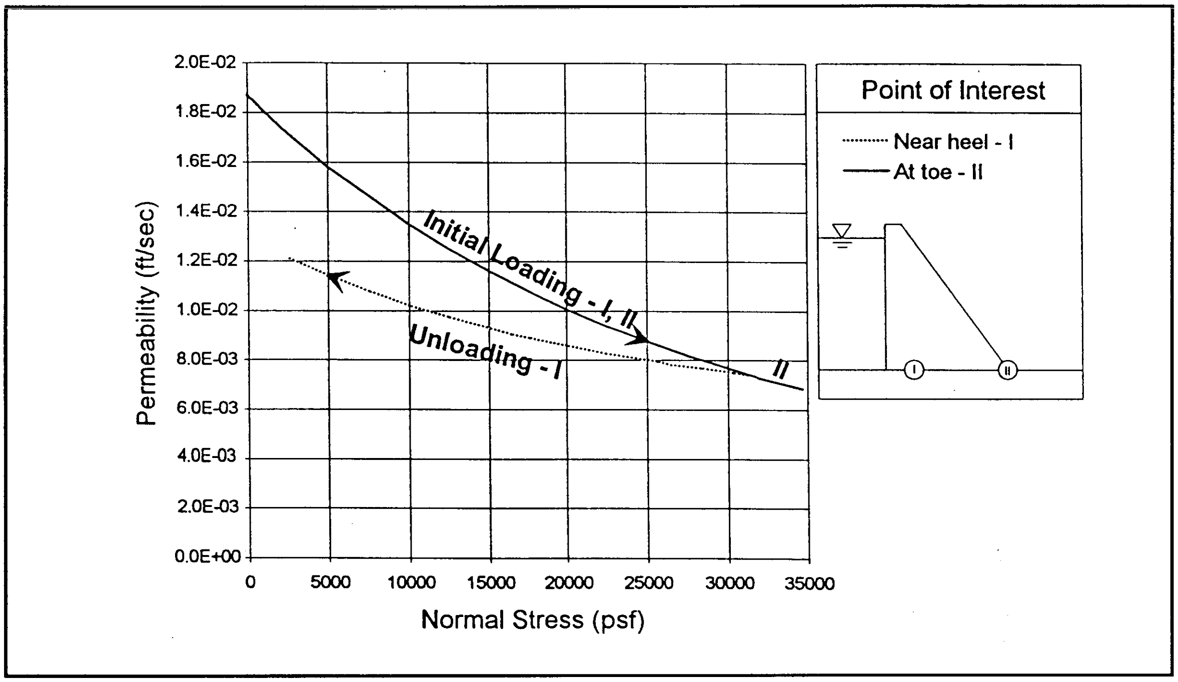

Figure 3. Permeability versus effective normal stress

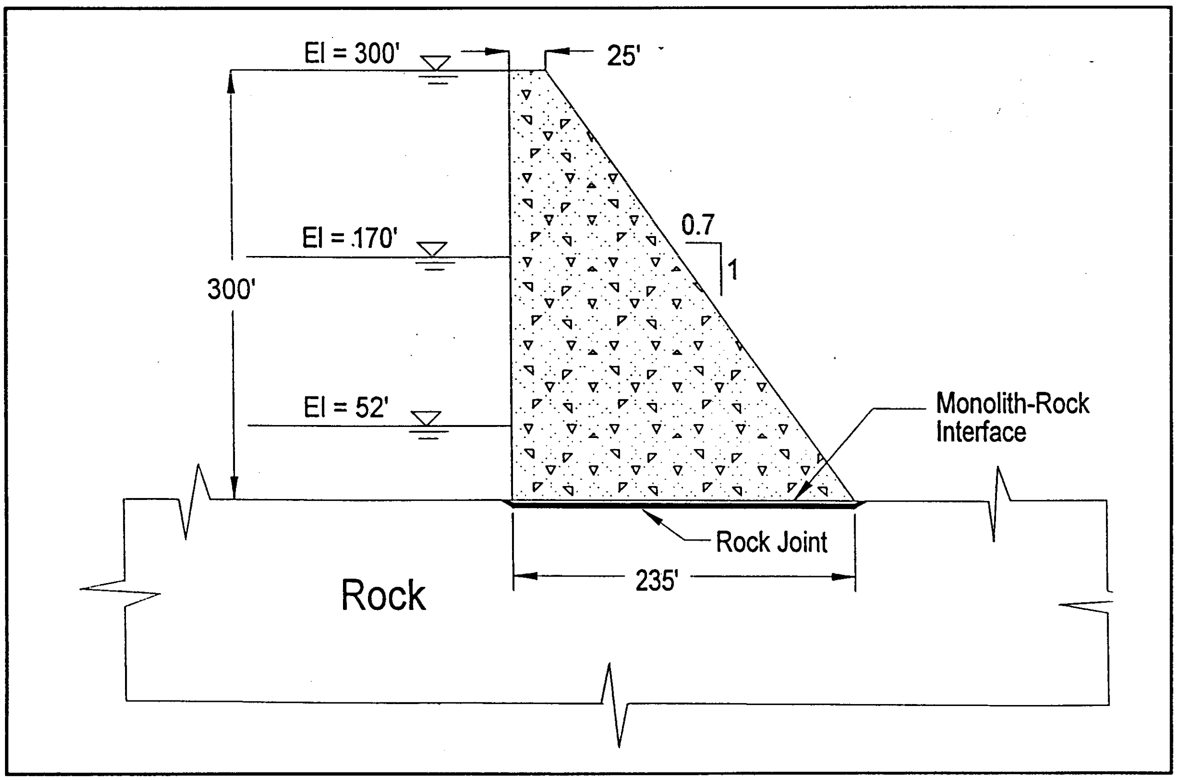

Figure 4. Geometry of dam used in study

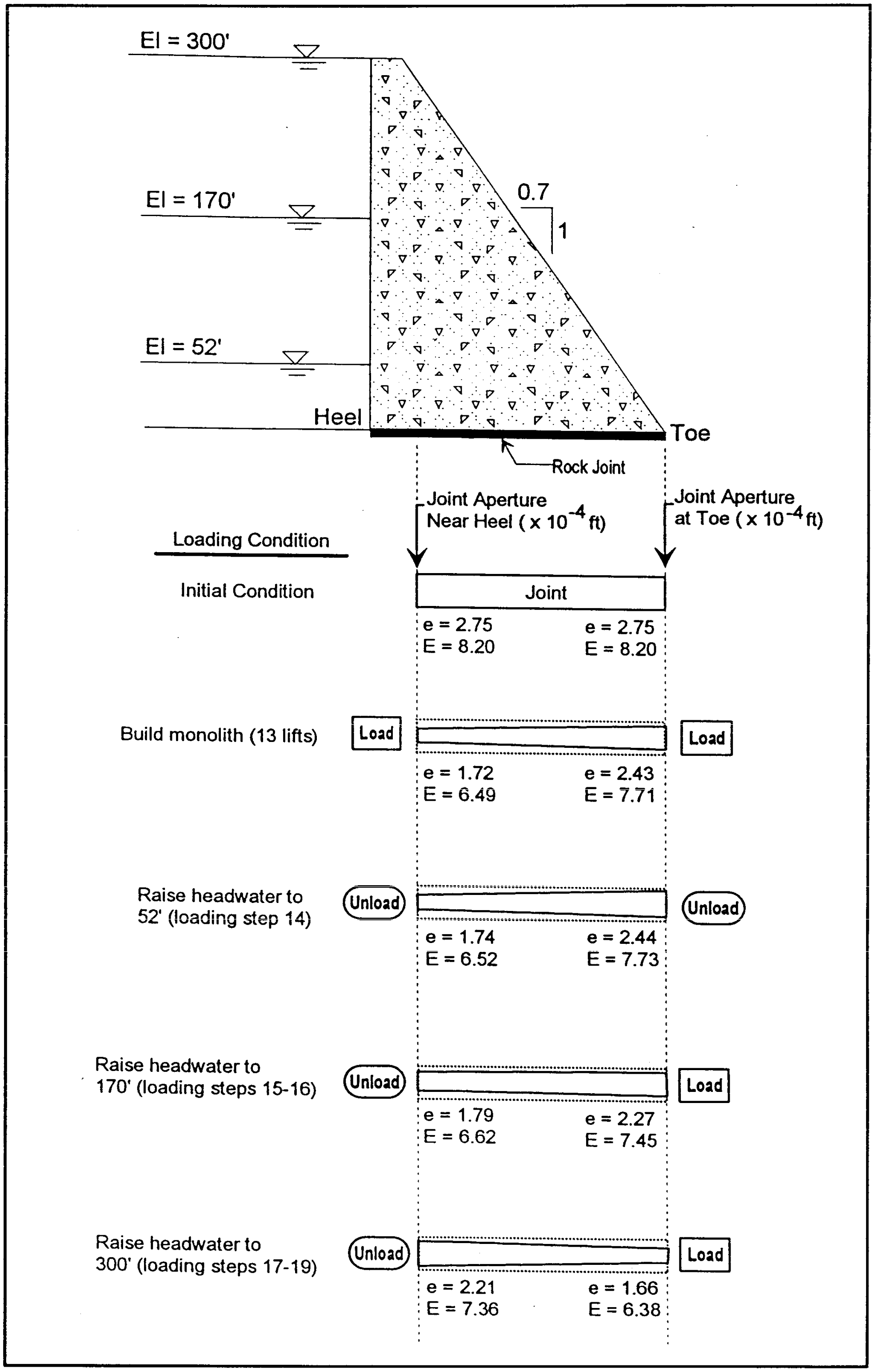

Figure 5. Effects of construction and water loading of monolith on joint aperture

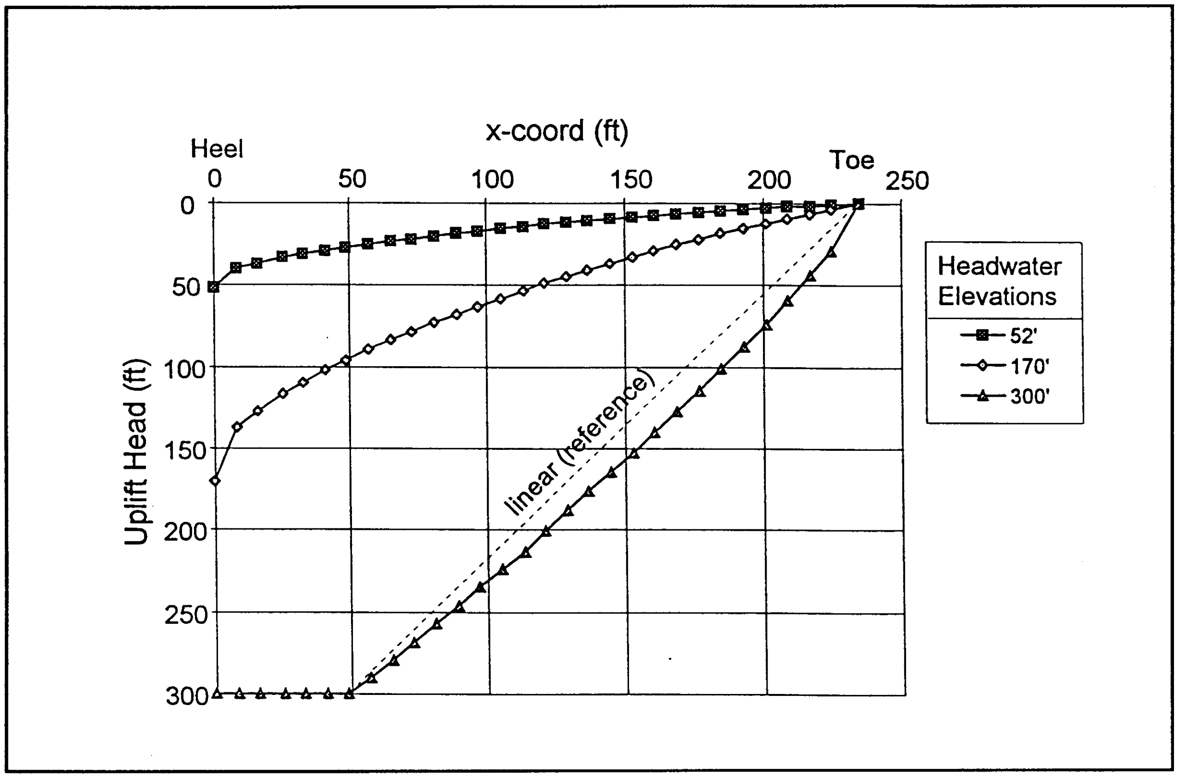

Figure 6. Variation in uplift head along a single joint with three headwater elevations

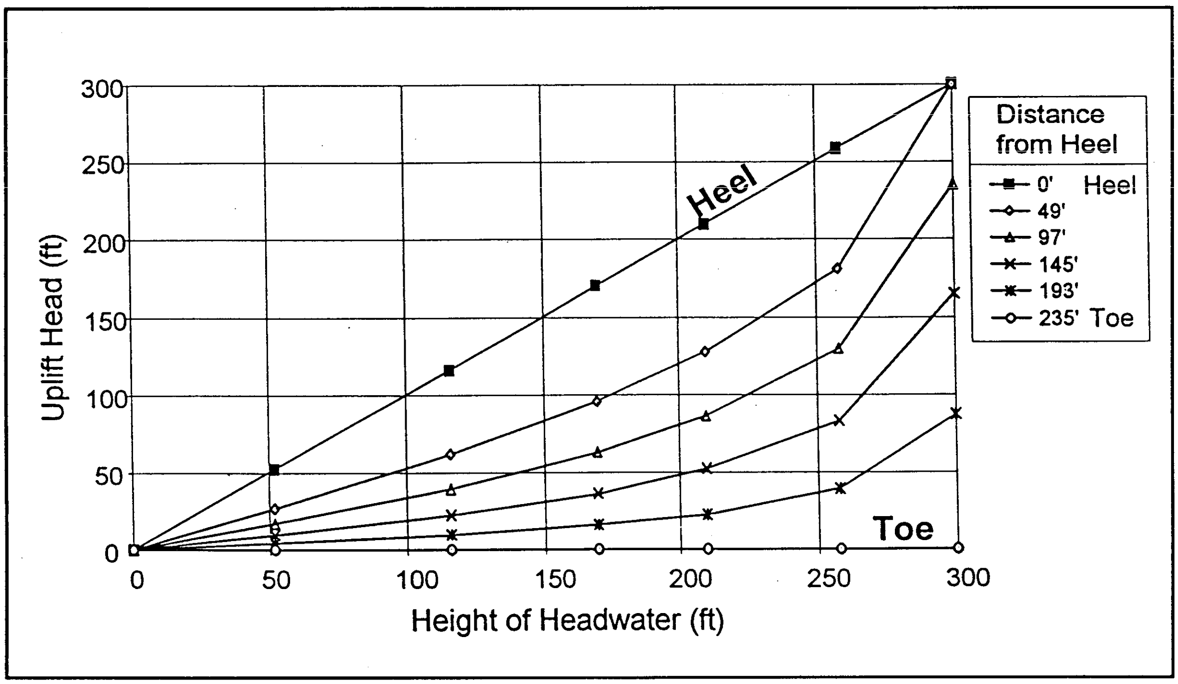

Figure 7. Variation of uplift head at six locations along the joint with headwater elevation