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Safety evaluation of concrete gravity dams founded on inhomogeneous rock media due to static loads

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Abstract

Dams are mega structures which their safety is of great importance. One of the vague points for engineers during design process is the uncertainty in mechanical and geological form of their massive foundation which inhomogeneity is an inevitable part of them. Large fissures and joints in this media are one of the reasons that would lead to inhomogeneity. Therefore, rock foundation would be divided into many parts which can have different mechanical properties. In this study, static performance of Pine Flat dam is studied by modeling more than 1000 different FE models with different mechanical and geological situations. In specific, the effect of seepage loading is studied in all models. By looking to the results, it has been demonstrated that geological figure in many cases is more important than mechanical properties. In addition, existence of joints in some specific points of foundation would lead to critical responses, the mechanical properties be that as it may.

Keywords: Concrete Gravity Dams, Inhomogeneous Rock Foundation, Static Loading, Safety Indices, Seepage.

1. INTRODUCTION

Large concrete gravity dams are among the most important national infrastructures playing key role in world’s economy. Due to catastrophic consequences of failure of concrete dams, their structural stability is of great concern. The structure of gravity dams mostly performs very well, but there is always doubt and uncertainty in rock mass foundation [1]. A rock mass is a set of individual integral rock blocks, which are separated by systems of differently oriented joints. The foundation situation can significantly affect the safety and stability of gravity dams; one of the most prone areas is the dam-foundation interface plane. The foundation failure has been the case of significant catastrophes such as experiences at St. Francis, Malpasset and Vajont Dams. Geological conditions of concrete dams' foundation are usually complicated due to: (1) variety of rock materials which leads to different mechanical properties from one place to another, and (2) presence of discontinuities such as faults, joints and fissures. These discontinuities can be assumed to be tied to each other or they can slide against each other. They may be parallel or interrupt each other in any depth of foundation [2]. Although the foundation is often assumed to be a homogeneous unbounded medium, critical situations of concrete dams founded on inhomogeneous multi-layered rocks have forced researchers to study the foundation’s inhomogeneity [3-5]. Almost these studies dealt with a real project along with its specific foundation's geometry and geological conditions [6-8].

The history has taught engineers that concrete dams often fail under the action of static loads such as the gravity, hydrostatic and uplift forces [9]. The tragic events have forced designers to make accurate model of seepage regime and the static performance of concrete dams and their rock beds. Hence, a variety of researches have been carried out in this field which led to this conclusion that two most probable failure modes, which should be considered in stability analysis and safety evaluation of each gravity dam, are [10]: (a) overstressing in tension or compression as well as (b) sliding of the monolith along the dam-foundation interface, or with part of foundation, along a failure surface within the foundation. Another potential failure mode is overturning; however, in the usual operating conditions, it is not as possible as the two above-mentioned failure modes [10].

In this paper, the safety of gravity dams located on heterogeneous rock foundations is evaluated under the static loads. For this goal, tallest monolith of Pine Flat dam is utilized for a case study. In addition, the configuration of foundation would change by considering a single large joint within it. The effects of the position of foundation joint, mechanical properties of the rock, and presence of uplift forces are assessed on the safety and stability of the dam through a detailed parametric study.

2. INHOMOGENEITY OF GRAVITY DAMS' FOUNDATION

Typically, there are many geological structures in massive rock foundations. The rock masses inevitably include various kinds of discontinuities, so the geological conditions of dam-sites are complicated and determined by the geometry of their structure and the properties of the blocks and discontinuities [2]. The mechanical properties of the rock masses are the basic input for analysis of dam-foundation systems [8].

It is practically impossible to model all discontinuities of a rock foundation. Therefore, only the major ones can be taken into account for mechanical analysis. The ratio of the elastic modulus of the dam and various parts of the foundation represents the impedance contrast between them. This ratio along with their Poisson's ratios can considerably affect the response of the dam-foundation system [11]. For the seepage analysis, in spite of complicated shapes and different directions of small discontinuities, their effects can be simply considered by changing the rock material behavior [12]. This assumption is valid for large dam foundations [2]. The seepage pattern and the pore pressures within the foundation depend on its stress-strain state. The distribution of pore pressures determines, in turn, the magnitude of seepage forces which affect the stress-strain state of the foundation. Therefore, the coupled problem of stress-seepage analysis requires iterative solution.

3. STABILITY ANALYSIS AND SAFETY EVALUATION

A gravity dam maintains its stability relying on its large weight. There are two risky potential failure modes which may jeopardize the stability of gravity dams. The first one is the tensile or compressive overstressing. Because the tensile strength of brittle materials like mass concrete or rock is lower than 10% of their compressive strength [13], the tensile failure is more probable. The safety factor against overstressing can be defined as:

$$SF_{\sigma,i} = \frac{\sigma_{S,i}}{\sigma_{P,i}} \quad , \quad i = T \ \ or \ \ C \tag{1}$$

Where σ_P is the peak principal stress within the considered domain, and σ_S is the material uniaxial strength. Subscripts T and C represent the tension and compression conditions, respectively.

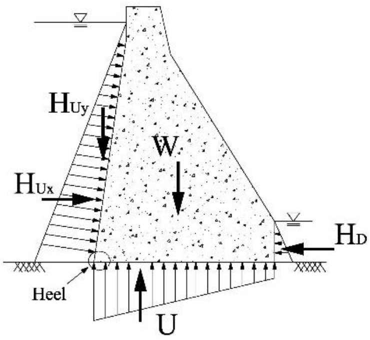
The second failure mode is sliding along the dam base or a potential failure surface within the foundation. The sliding stability can be studied by numerical methods such as limit equilibrium method and finite element method [6, 7]. However, this study concerns the sliding mechanism along predefined planes considering motion in the upstream-downstream direction. For the dam-foundation interface plane, considering the equilibrium of forces shown in Figure 1. (a), the global safety factor against sliding for entire dam's body is defined by utilizing the Mohr-Coulomb criterion as:

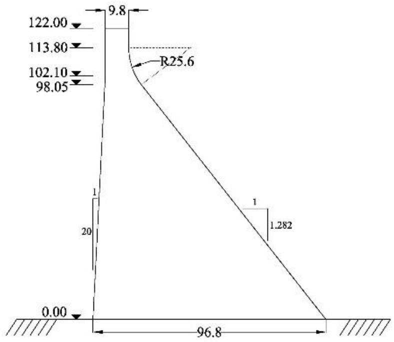
$$SF_{GS} = \frac{F_R}{F_S} = \frac{\mu_s F_n + cA}{F_s} = \frac{\mu_s\left(W + H_{Uy} - U\right) + cA}{H_{Ux} - H_D} \tag{2}$$

Where F_R, F_S and F_n are the resisting, shear and normal forces, respectively. W and U are dam weight and uplift force, c and μ_s are the cohesion and the friction coefficient of the dam-foundation interface, A is the base length (area), H_U and H_D are the hydrostatic forces acting on dam's upstream and downstream faces, respectively. The global dominant forces (i.e. F_R and F_S) and hence the global safety factor, will not considerably change due to inhomogeneity of the foundation, if the shear resistance parameters c and μ_s are assumed to be constant. But the distribution of the normal and shear stresses on the base interface plane may locally change significantly. Therefore, it is better to compute local safety factors against sliding (SF_{LS}) in the sliding-prone regions along the dam base using the local normal and shear forces.

4. NUMERICAL EXAMPLE

The tallest monolith of Pine Flat dam is selected for the purpose of analysis as it is shown in Figure 1. (b). The inhomogeneity of rock foundation is considered by changing the properties of the rock through major discontinuities of the foundation. In this paper, these discontinuities are assumed as one single large joint/fault plane with varying position within the foundation (Figure 2). This joint/fault is assumed to behave linear, and there is no sliding or opening across its interfaces. Therefore, the foundation is a continuous and heterogeneous medium. As it is illustrated in Figure 2, joint/fault orientation is fully defined by two parameters: l which is measured from the foundation domain corner, and α which measures the dip angle of the fault. In all models, based on the previous practical observations, the main geometric parameters of the foundation discontinuities independently vary in the following ranges: $1B \le l \le 4B$, and $30º \le \alpha \le 150º$.





(a) (b)

Figure 1. (a) Schematic representation of dominant static loadings applied on a gravity dam's section; (b) the tallest non-over-flow monolith of Pine Flat dam (all dimensions are in meter).

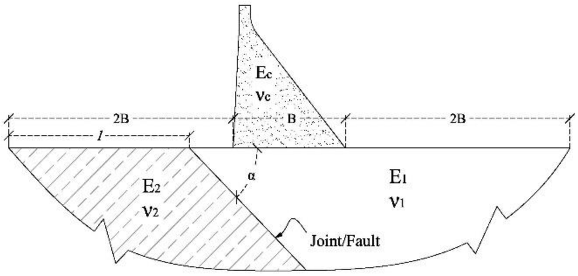


Figure 2. Inhomogeneity of the foundation

The concrete's behavior is assumed to be isotropic linear elastic with the Young's modulus of 27.58 GPa, Poisson's ratio is 0.2, and density is considered to be 2400 kg/m3. The foundation rock behavior is also linear elastic, but with various stiffness through the joint/fault to investigate the effects of foundation inhomogeneity. Seeking this goal, in all models, it is assumed that $E_1 = E_c$, ν_1=ν_2=0.33, and $\overline{E}$ which denotes the ratio of E_2/E_1 is 0.25, 0.33, 0.5, 1.5, and 2. The case in which $\overline{E}$ =1, represents the homogenous foundation which is named as the base-case model.

Two loading combinations are studied: LC1 and LC2. The LC1 consists of the dead weight of the dam and the hydrostatic force of the full reservoir on the upstream face of the dam. In addition to these forces, the seepage load through the foundation is also added in the LC2. The dam body is assumed to be impermeable. The steady-state seepage in the foundation follows the Darcy's law assuming isotropic permeability (i.e. the same permeability coefficient in any direction). Moreover, the foundation is assumed to be fully saturated with the permeability coefficient of $k = 4*10^{-7}$ m/s for all of the models. The same permeability coefficient is assumed across the joint/fault. The full reservoir and zero head are assigned to the upstream (US) and downstream (DS) horizontal surfaces of the foundation, respectively. No grout curtain or drainage system is modelled in the analysis. The in-situ stresses of the rock mass are neglected.

A potential sliding path along the dam-foundation interface plane is assumed in all models to assess the local sliding stability of the entire dam body using equation (2). For this aim, zero cohesion and unit friction coefficient are assumed for shear resistance parameters (i.e. c=0 and μ_s =1). The effects of the foundation inhomogeneity including various geometries and stiffness as well as the effects of the seepage within the foundation are studied by generating and analyzing more than 1000 models. The results are presented in the next section.

5. RESULTS AND DISCUSSION

The analysis results of various geometries and mechanical properties which are made up due to existence of a discontinuity in the foundation are presented in this section. The results include the relative displacement of the dam crest with respect to the base (i.e. U_{rel}), which is always into the DS direction; the peak minimum (compressive) principal stress of the dam's body (i.e. PS_{CD}), which is always at the dam's toe; and the peak maximum (tensile) principal stress of the dam's heel (i.e. PS_{TD}). The stresses are positive in tension. It is observed from results for base-case model under the load combination LC1 that U_{rel} , PS_{CD} and PS_{TD} would be respectively 1.57cm, -3.37MPa and -0.33MPa. Moreover, under hydrostatic loading, the dam heel is the most prone location to slide, so the local sliding safety factor (i.e. SF_{LS}) is computed for this area. It is illustrated that this parameter around the heel area of base-case model is 2.84 and 1.20 under the load combinations LC1 and LC2, respectively. The global safety factor (i.e. SF_{GS}), is approximately the same for all models along the dam-foundation interface plane. This parameter for all models is almost 1.9 and 1.2 under the load combinations LC1 and LC2, respectively Figure 3 represents U_{rel} , PS_{TD} , and PS_{CD} in terms of l/B , α , and $\overline{E}$. The ratio of l/B between 2 and 3 represents the fault intersecting with the dam base. As it is observed in Figure 3, reducing $\overline{E}$ ratio, i.e. the softer foundation, increases the variation of the results and also increases the difference between results of similar models while seepage is included or excluded. The results of the models with $\overline{E}$ < 1 oppose to the models with $\overline{E}$ > 1, as it was expected.

In the models without seepage (i.e. under the load combination LC1), if $\overline{E}$ < 1, minimum and maximum values of U_{rel} will be observed when the fault respectively passes through the dam base and the DS side. It would be opposite for the models with $\overline{E}$ > 1, where maximum U_{rel} is obtained when the fault intersects with the dam base. The highest value of U_{rel} is 2.7cm which occurs for the most flexible foundation, i.e. $\overline{E}$ =0.25, α =30º, and l/B =4. The lowest value of U_{rel} belongs to the model with $\overline{E}$ =0.25, α =90°, l/B =2.75 with the value of 0.4cm. The lowest value of U_{rel} when seepage is included in the models is 1.6cm for the model with the most stiff foundation, i.e. $\overline{E}$ =2, α =30º, and l/B =4. The highest value of U_{rel} occurs again for the most flexible foundation with the value of 4.1cm.

About PS_{TD} , when seepage is excluded and $\overline{E}$ < 1, whole dam body is in compression, so it is negative. Increasing the $\overline{E}$ ratio, i.e. the stiffer foundation, increases the tension within the dam body. In the models with $\overline{E}$ > 1, if the fault intersects with the dam base while it is oriented into the DS side (α <90º), then the dam heel would be in tension. If the fault does not pass through the dam base, the heel would be in compression specifically when it is oriented into the US side (α >90º). The highest value of PS_{TD} belongs to the model with $\overline{E}$ =2, l/B =2.5 (fault passing middle of the dam base), α =60º with the value of 0.26MPa. By considering seepage and in the cases which $\overline{E}$ < 1, the minimum tension in the dam heel will be observed when the fault passes near it. The models with l/B =4, exposes the maximum value of PS_{TD} . For the stiffer foundations with $\overline{E}$ > 1, the heel is completely in tension. The maximum tension is observed when the fault passes near the heel, and the peak PS_{TD} belongs to the model with $\overline{E}$ =2 and α =120º, with the value of 0.71MPa, however, most of the dam body undergoes compression again.

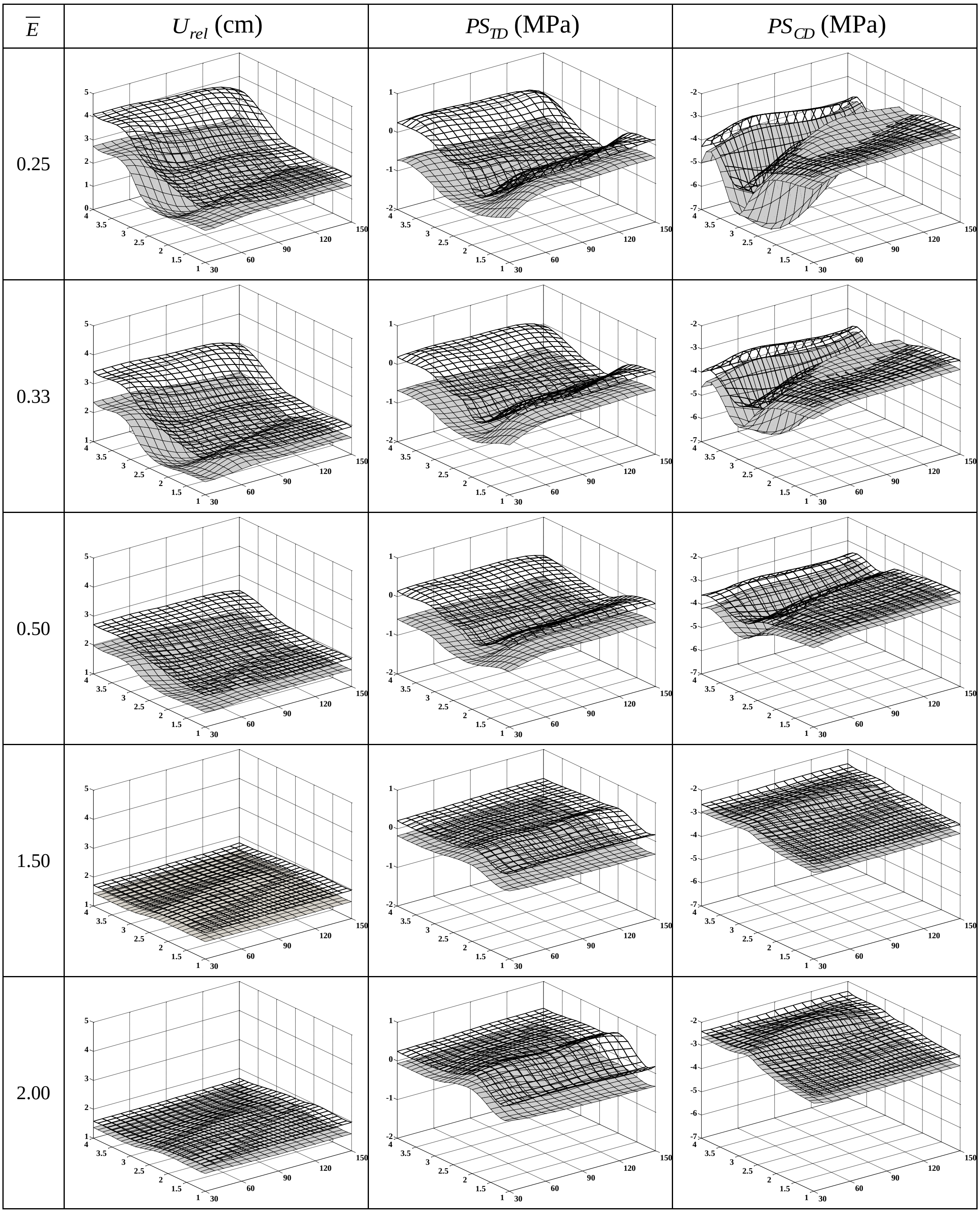
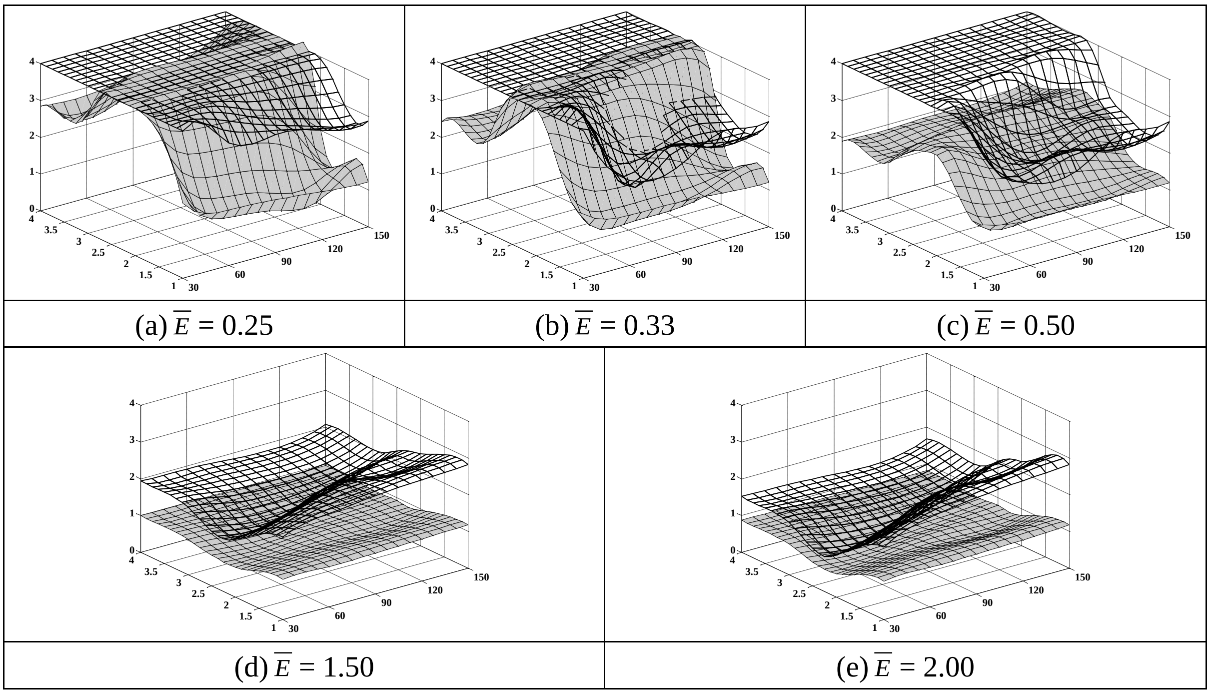


Figure 3. The results of the one-fault models. The second, third and fourth column respectively show the U_{rel} , PS_{TD} and PS_{CD} for the dam body in terms of l/B (left horizontal axis), α (right horizontal axis) and $\overline{E}$. The filled and un-filled curves are representing the models under the loading combination LC1 and the LC2, respectively.

Increasing the $\overline{E}$ ratio totally decreases the value of compressive stresses in the dam body. With and without seepage, if $\overline{E} < 1$, the maximum and minimum compression in the dam toe will occur when the fault passes through the toe and US side, respectively. Opposite trend is observed for the models with $\overline{E} > 1$. The

PS_{CD} in the dam toe is almost the same when the fault passes the US side. The peak value of PS_{CD} , which is -7.25 MPa, belongs to the model with flexible foundation of $\overline{E}$ =0.25, fault passing the dam toe (l/B =3) and orienting into the DS direction (α =45º). When seepage is included in loading, the maximum PS_{CD} again belongs to the above-mentioned model with the value of -6.044 MPa. The peak compressive stress of the dam body is totally lower than the common compressive strength of concrete, say 30 MPa, so, the dam remains in the elastic mode. Furthermore, $SF_{\sigma C}$ is higher than 4 and 4.9 for the models without and with seepage, respectively.



(a) $\overline{E}$ = 0.25 (b) $\overline{E}$ = 0.33 (c) $\overline{E}$ = 0.50

(d) $\overline{E}$ = 1.50 (e) $\overline{E}$ = 2.00

Figure 4. The local sliding safety factor at the dam heel in terms of l/B (left horizontal axis), α (right horizontal axis) and $\overline{E}$ ratio. The filled and un-filled curves are representing the models under the loading combination LC2 and the LC1, respectively.

As it was explained, the local sliding safety factor (i.e. SF_{LS}), is computed for the dam heel region and is presented in Figure 4. To better plot the obtained results, the local safety factors more than 4 are constantly shown as four. Increasing the $\overline{E}$ ratio, i.e. the stiffer foundation, generally leads to decrease of SF_{LS} . Without seepage, if $\overline{E}$ < 1, then generally SF_{LS} > 2.0. If the fault passes the DS side, i.e. the foundation beneath the dam is softer than the dam concrete, then SF_{LS} > 4. For the models with $\overline{E}$ =0.25 or 0.33, if the fault intersects with the dam base oriented into the US side ($\alpha \leq 90$º), then the horizontal force in the heel region may be into the US direction. In the models of $\overline{E}$ > 1, minimum SF_{LS} is observed when the fault passes exactly through middle of the dam base. If $\overline{E}$ =2 (Figure 4.(e)), then SF_{LS} <1 when the fault passes through the dam base oriented into the DS side (α<90º). The lowest SF_{LS} value occurs for the model with l/B =2.5 and α =60º which is 0.823.

The seepage reduces SF_{LS} . Again, the stiffer foundation shows lower SF_{LS} values. If $\overline{E}$ < 1, then the horizontal forces in the dam heel region are totally into the DS direction. In general SF_{LS} >1.2, but if the fault passes through the dam base or DS side, this parameter will be greater than 1.6. The minimum values of SF_{LS} are observed when the fault intersects with the dam base for the models with $\overline{E}$ > 1. In general in this situation, totally SF_{LS} <1.2; in particular if the fault passes through the dam base or DS side, then SF_{LS} < 1.0. The lowest SF_{LS} is observed in the model with l/B =2.5 and α =60º with the value of 0.749 and 0.547 for $\overline{E}$ = 1.5 and 2, respectively. For these two critical cases, the local sliding safety factors are also computed along the dam base to locally investigate the possibility of base sliding. As it is shown in Figure 5, the local sliding safety factor becomes more than one immediately after the heel region. It is more than 2.5 for the range of 0.3 to 0.7 of the base and reduces to 1.4 at the dam toe.

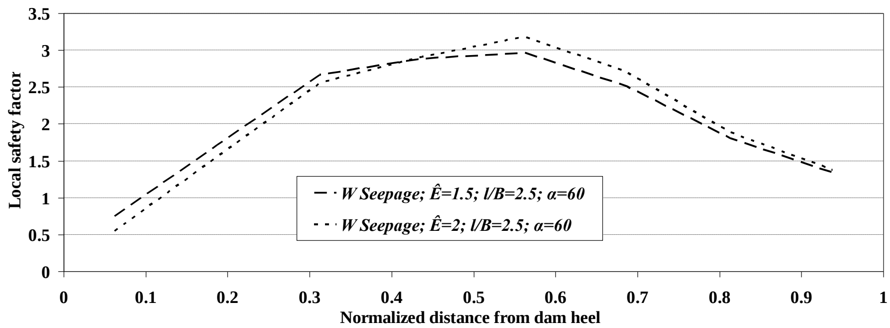


Figure 5. Local sliding safety factor along the dam base for the critical models while seepage is included.

6. SUMMARY AND CONCLUSIONS

In this paper, the structural stability and safety of gravity dams located on inhomogeneous rock foundations is evaluated under dominant static loads by measuring overstressing and sliding safety factor indices. For this purpose, Pine Flat gravity dam is considered as a case study. The spatial configuration of the foundation is changed by inserting one single large joint/fault plane within it. The effects of the position of the foundation joint/fault, mechanical properties of the rock, and presence of the uplift forces on the safety and stability of the dam are assessed through a detailed parametric study using more than 1000 finite element models. It is found that the foundation inhomogeneity may increase or decrease the response results. Therefore, it should be taken into account for the safety assessment of concrete gravity dams. The conclusions of results are presented as follow:

- The presence of softer foundation increases the variation of the results and also increases the difference between results of similar models while seepage is included or excluded.
- The results of the models with weaker foundation oppose to the models with stiffer foundation, as it was expected.
- When the fault passes with a distance of more than 0.5B through DS or US sides of the dam, the trends of responses are smoother. To put it another word, it has been demonstrated that only if the fault passes through a close distant of 0.5B from dam’s body, they will influence in dam’s responses.
- The local sliding at the dam heel is more perilous than the dam body’s overstressing in all models.
- The seepage increases the peak relative displacement and tensile stress of the dam body but decreases the peak compressive stress and local safety factor.
- By comparing responses of the cases which seepage is included with the cases which seepage is excluded, similar trends would be observed.
- The stiffer foundation increases the tension within the dam body but generally decreases local safety factor.

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