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EVALUATION OF EARTHQUAKE INDUCED SLIDING IN GRAVITY DAMS

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ABSTRACT

The stability of a concrete gravity dam against excessive sliding at the dam base must be assured during an earthquake. Sliding refers to concentrated deformation at the interface between the dam and the foundation rock. The objective of a sliding evaluation procedure is to first guarantee stability, and second estimate the deformation at the base. Current evaluation techniques for sliding are either empirical, based on an equivalent static equilibrium model, or involve very simplified assumptions. The present work applies a novel modeling and solution procedure (hybrid frequency-time domain analysis) which accounts for the dynamics of the dam, foundation rock flexibility, compressible water, and a Mohr-Coulomb model for base sliding. The results of an extensive parametric study of gravity dams illustrate the important factors affecting the earthquake induced base sliding displacement. The foremost factor is foundation rock flexibility: estimates of base sliding assuming rigid foundation rock are much larger than when foundation rock flexibility is included. The sliding is also sensitive to the coefficient of friction and cohesion of the interface zone. A framework for evaluation sliding stability is proposed.

KEYWORDS

Dam; gravity dam; concrete; sliding; stability; friction; nonlinear analysis.

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INTRODUCTION

The stability of concrete gravity dams with respect to large rigid-body displacements in the downstream direction must be assessed in a seismic safety evaluation. Sliding can occur when the forces on the interface zone between the dam and foundation rock exceed the strength of the zone. The traditional check of sliding stability involves computing a factor of safety (*FS*) against sliding using a Mohr-Coulomb model of the concrete and foundation materials in the interface zone and equivalent static loads on the dam that represent the dynamic effects of an earthquake. The *FS* is defined for a postulated failure surface as:

$$FS = \frac{C + \mu N_{st}}{V + V_{st}} \tag{1}$$

where N_{st} and V_{st} are the gravity normal and tangential forces (self weight, hydrostatic, and uplift) on the interface zone, V is the maximum dynamic tangential force. The properties of the interface zone are represented by the coefficient of friction, μ, and total cohesion force, C. The cohesion force is $C = cA$, where c is the unit cohesion stress of the interface (force/area) and A is the area of the interface zone developing cohesion. The latter is typically assumed to be the portion of the interface plane with compressive normal stresses due to the forces N_{st}, V_{st}, and V. The typical evaluation procedure involves investigating various interface zones to find the lowest *FS* (according to the upper bound theorem). For extreme loads such as an earthquake an *FS* greater than unity is considered acceptable.

A consistent definition of the equivalent static loads, recognizing all the dynamic effects in the force, can be used to determine if a dam will slide using Eq. 1. Fenves and Chopra (1987) have presented a simplified analysis procedure that can be used to compute V including the characteristics of the earthquake, and the effects of dam-water interaction, dam-foundation rock interaction, and reservoir bottom absorption.

However, a strength criterion based on equivalent static earthquake forces, such as Eq. 1, cannot give information about the magnitude of the rigid-body displacement once sliding commences. The earthquake induced sliding displacement of a dam can be rationally estimated by a dynamic analysis of the system which accounts for the frequency-dependent effects of dam-water and dam-foundation rock interactions and the nonlinear sliding behavior at the dam-foundation rock interface. Although several investigators have examined the earthquake response of gravity dams including sliding (Leger and Katsouli, 1989; Chopra and Zhang, 1991; Hall, Dowling, and El-Aidi, 1991), the studies were limited by assumptions about the dam system.

Chávez and Fenves (1995a, 1995b) have presented an analysis method based on the hybrid frequency-domain procedure (Darbre and Wolf, 1988) for analysis of gravity dam monoliths including sliding. The analysis rationally accounts for the frequency-dependent characteristics of the system and the nonlinear behavior of a sliding on a possibly sloped interface between the dam and foundation rock.

The objectives of this paper are to summarize the model used for dynamic analysis of gravity dams including sliding, illustrate the important factors affecting the sliding displacement, examine a case study to show the relationship between the static factor of safety and the sliding displacement, and finally propose a framework for evaluating the sliding stability of gravity dams.

DYNAMIC ANALYSIS FOR SLIDING

Modeling

The idealized concrete gravity dam, shown in Fig. 1, is a two-dimensional monolith (height=H_s), with rigid base supported by flexible foundation rock and impounding a reservoir of compressible water (depth=H). The dam may slide along the interface between the dam base and the foundation rock. Rocking of the dam about the base is not represented in the model. The system is subjected to horizontal and vertical components of free-field earthquake ground motion at the base of the dam.

The monolith is modeled using plane stress finite elements with linear elastic material properties. The water impounded in the reservoir is idealized as a two-dimensional domain extending to infinity in the upstream direction. The water is treated as an inviscid and compressible fluid that produces hydrodynamic pressures that are dependent on the excitation frequency. The foundation rock is idealized as a homogeneous, isotropic and viscoelastic half-plane.

The interface between the dam monolith and the foundation rock is assumed to be a straight surface with the resistance to sliding governed by the Mohr-Coulomb law. This friction model allows quantification of the deformation in the interface zone without requiring detailed modeling of the complex region that consists of shear keys, grout curtains, and roughened surfaces. The sliding resistance at the interface depends on a cohesion force, the coefficient of friction, and the time varying normal force. Although degradation of the friction parameters and rate-dependent effects could be included, there is not sufficient experimental data to develop such as refined model. The model assumes that sliding occurs along the entire interface.

Solution Procedure

The equations of motion for the dam-water-foundation rock system include the frequency-dependent hydrodynamic forces acting on the dam, the dam-foundation rock interaction forces, and the nonlinear inertia forces at the base due to sliding of the dam along the interface. A Rayleigh-Ritz transformation reduces the degrees-of-freedom for the dam to a small number of generalized coordinates.

The hybrid-frequency time domain procedure (Darbre and Wolf, 1988) is used to solve the nonlinear and frequency-dependent equations of motion. The detailed solution procedure for dams is described by Chávez and Fenves (1995a). The procedure iterates over segments of time in three major steps:

1. Linearization of the equations of motion. The nonlinear inertia forces due to sliding are estimated using the current sliding acceleration history.
2. Solution of the linearized equations of motion. The linearized equations of motion are solved in the frequency domain to account for the frequency dependency of the interaction forces. The resultant forces due to dynamic loads at the base of the dam, that includes the shear force $V(t)$ and normal force $N(t)$ are computed at this stage.
3. Determination of sliding state in time domain. The dam slides when the the total shear force at the base, according to Mohr-Coulomb law, exceeds the strength at the interface:

$$|V(t) + V_{st}| \geq |C + \mu\,[N(t) + N_{st}]| \tag{2}$$

Convergence for a segment of time is achieved when the maximum difference between successive iterations of the response quantities is less than a tolerance at every time step in the segment.

The earthquake analyses are performed using the computer program EAGD-SLIDE, which implements the solution procedure (Chávez and Fenves, 1994).

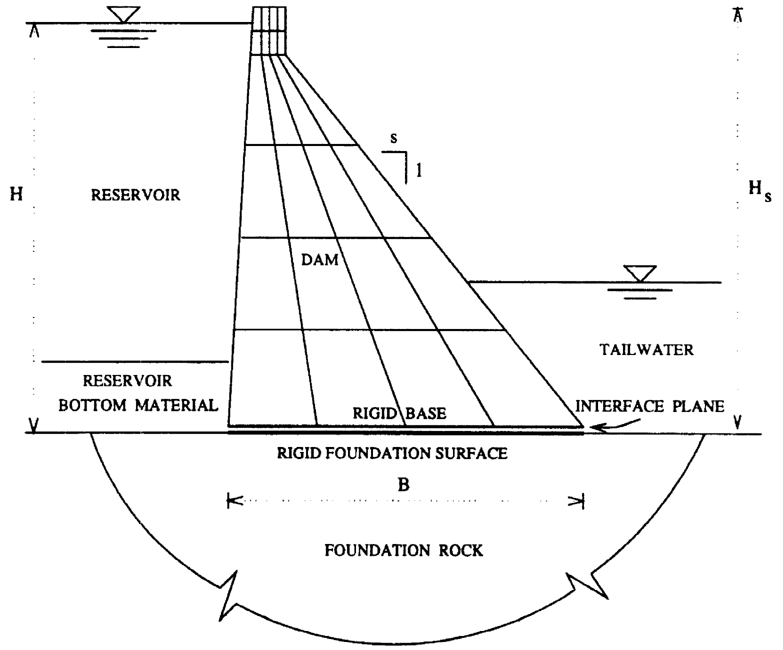


Fig. 1. Dam-reservoir-foundation rock system with interface plane for sliding at the base.

IMPORTANT EFFECTS ON SLIDING

A typical concrete gravity dam monolith with full reservoir is used to investigate the effects peak ground acceleration, foundation rock flexibility, coefficient of friction, and water compressibility on the sliding displacement at the base.

The height of the dam is varied from 25 m (82 ft) to 175 m (574 ft). The modulus of elasticity of concrete, E_{cd}, is 27.6 GPa (4 million psi). The modulus of elasticity of the foundation rock, E_{fr}, varies according to the moduli ratio $E_{fr}/E_{cd} = \infty, 1.0, 0.25$. The first case corresponds to a rigid foundation rock, and the third case corresponds to a very flexible foundation rock. A hysteretic damping coefficient of 0.10 is assumed for the dam and foundation rock. The cohesion force at the base is assumed to be zero and the coefficient of friction varies from 0.8 to 1.2. The monolith is subjected to the S69E horizontal component of the 1952 Taft ground motion, scaled to 0.3g, 0.4g, 0.5g, and 0.6g.

The analysis is simplified by using one generalized coordinate to represent the motion of the dam in its fundamental vibration mode. The sliding displacements computed using the simplified model are a good approximation of the displacements obtained by using a finite element discretization of the dam. An extensive parametric study using this simplified analysis is presented by Chávez and Fenves (1995b).

Influence of Peak Ground Acceleration

The maximum sliding displacement increases substantially with increasing peak ground acceleration, as shown in Fig. 2(a). The sliding increase by a factor of five times when the peak ground acceleration increases from 0.3g (moderate earthquake) to 0.6g (strong earthquake). Dams taller than 50 m (164 ft) subjected to the same peak ground acceleration have more base sliding as the foundation rock becomes more rigid.

Influence of Foundation Rock Flexibility

Foundation rock flexibility affects the value of sliding displacement because the vibration period of the system lengthens and the damping increases. As shown in Fig. 2(a), the peak of the sliding spectrum decreases as the foundation rock flexibility increases. The shorter dams are shifted into the amplified region of the response spectrum for the ground motion, because the period of the system lengthens as the foundation rock flexibility increases.

Another view of how the effects of foundation rock flexibility depend on dam height is shown in Fig. 2(b). For short dams, height less than 50 m (164 ft), the flexible foundation rock has almost no effect on the sliding displacement. For taller dams, height 150 m (492 ft), the sliding displacement decreases as the foundation rock becomes more flexible.

The base sliding displacements computed using the regression equation by Danay and Adeghe (1993) for a dam on rigid foundation rock are also shown in Fig. 2(b). There is a good agreement between the sliding displacements computed using the present model and the regression equation for the mean plus two standard deviations for 50 m (146 ft) dams. For taller dams, the present results fall between the expression for the mean and the mean plus two standard deviations. The regression equation overestimates the sliding displacement when dam-foundation rock interaction effects are important since such effects were not included in the development of the approximate expression.

Influence of Coefficient of Friction

The maximum sliding displacement increases nonlinearly as the coefficient of friction decreases, as shown in Fig. 2(c). For the same value of μ, a dam on rigid foundation rock slides more than a dam on flexible foundation rock. The location of peaks of maximum sliding shift from tall dams, H_s=125 m (410 ft), on rigid foundation rock, to short dams, H_s=75 m (246 ft), on flexible foundation rock with $E_{fr}/E_{cd} = 0.25$, due to the lengthening of the period of the dam system as the dam height increases and the foundation rock flexibility increases.

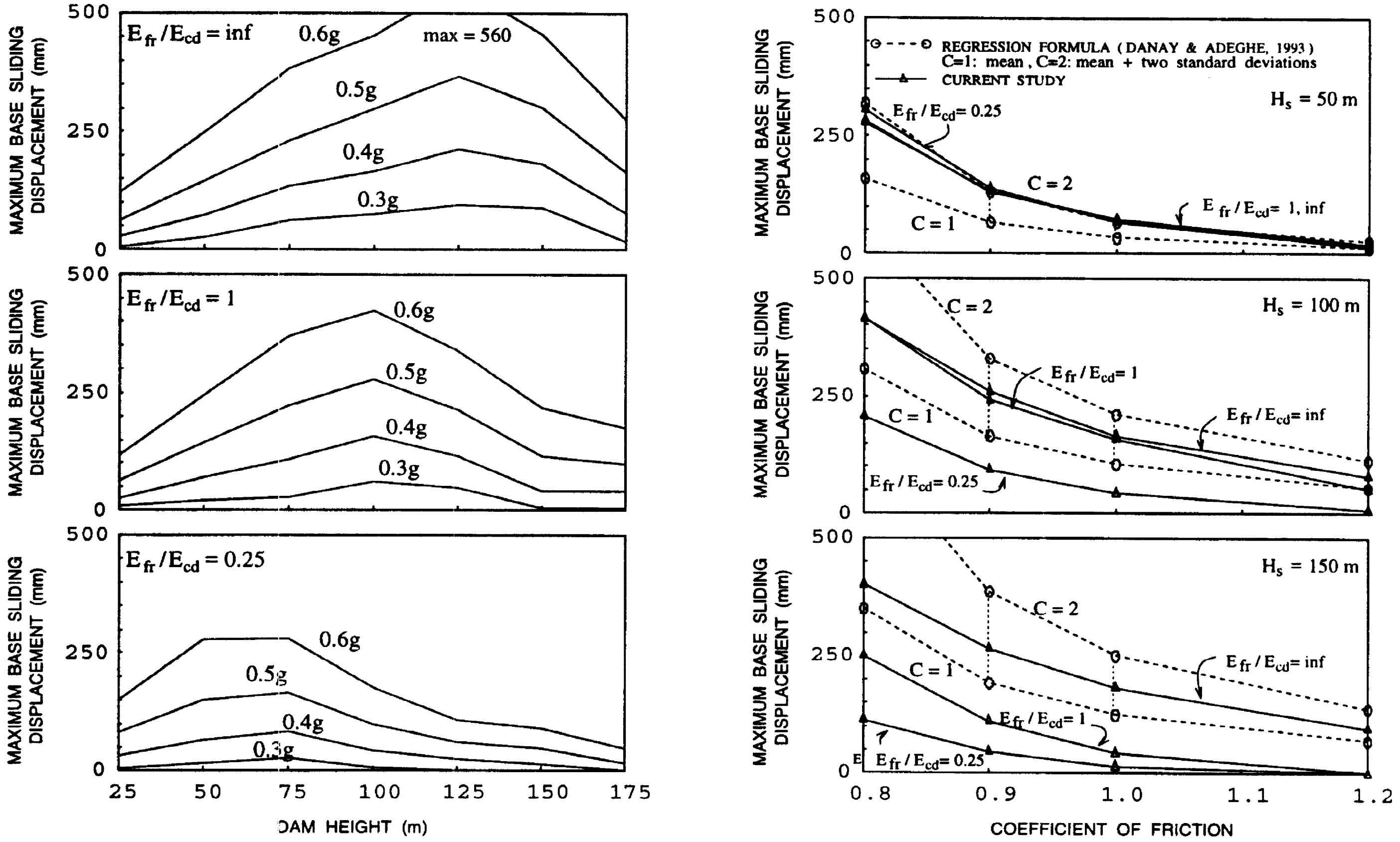
Influence of Water Compressibility

The sliding displacement for a dam is greater when the water is considered to be compressible compared with the case of incompressible water, as shown in Fig. 2(d). Water compressibility has the largest effect when the dam is on rigid foundation rock, especially for dams less than 150 m (492 ft) tall. In this range of dam heights, the sliding displacement obtained with incompressible water is as much as 40% less than the displacement with compressible water. The effects of compressibility are smaller for dams on flexible foundation rock because the foundation rock damping generally reduces the importance of dam-water interaction.

EVALUATION OF SLIDING

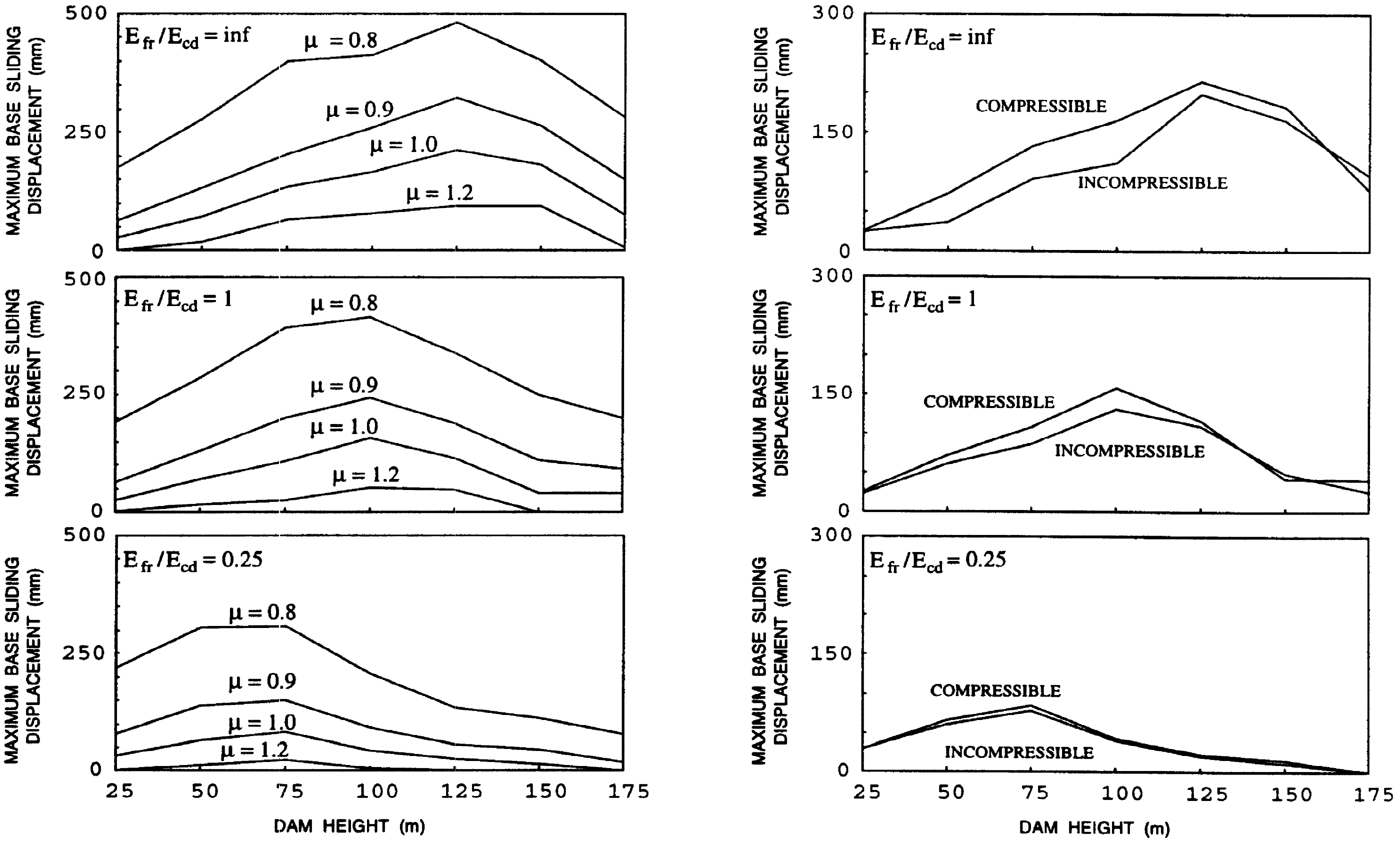
This section examines the earthquake earthquake sliding response of a typical concrete gravity dam. The static procedure using a *FS* and the dynamic analysis to compute the sliding displacement are investigated and the results are compared.

The tallest monolith, 122 m (400 ft) high, of Pine Flat dam is selected for the evaluation. Two cases are considered: dam on rigid foundation rock, and dam on flexible foundation rock with $E_{fr}/E_{cd} = 1$. The impounded compressible water has a depth of 116.2 m (381 ft). The unit cohesion stress at the base varies



(a) Effect of peak ground acceleration

(b) Effect of foundation rock flexibility (PGA=0.4g)



(c) Effect of coefficient of friction (PGA=0.4g)

(d) Effect of water compressibility (PGA=0.4g, μ=1)

Fig. 2. Important effects on the maximum base sliding displacement of a typical dam with full reservoir, $C = 0$, subjected to the Taft S69E ground motion.

from 0 to 800 kPa, and the coefficient of friction varies from 0.75 to 1.25. The dam is subjected to the S69E horizontal component of the 1952 Taft ground motion, scaled to a peak ground acceleration of 0.6g.

Static Procedure

The equivalent static analysis for stability uses Eq. 1 to compute a factor of safety against sliding. The area developing cohesion is $A = rA_g$, where A_g is the gross section area at the base and r is a reduction factor that accounts for cracking of the concrete at the base (Bureau of Reclamation, 1976). The factor r is 0.66 for the dam on rigid foundation rock, and 0.85 for the dam on flexible foundation rock, using the static and maximum earthquake forces for Pine Flat dam. The equivalent static loads are computed using the simplified analysis procedure by Fenves and Chopra (1987) that includes the characteristics of the earthquake, the effects of the dam-water interaction, dam-foundation rock interaction, and reservoir bottom absorption. Computed values of *FS* are shown in Fig. 3(a) for rigid foundation rock and in Fig. 4(a) for flexible foundation rock. The *FS* for the dam on flexible foundation rock is larger than the *FS* for the dam on flexible foundation rock. For the cases when *FS* is much less than unity, large sliding displacements can be expected.

Dynamic Analysis

The dynamic analysis, using EAGD-SLIDE (Châvez and Fenves, 1994), is performed to compute the base sliding displacements of Pine Flat dam for the cases considered. The results are shown in Fig. 3(b) for rigid foundation rock and in Fig. 4(b) for flexible foundation rock. For both cases the sliding displacement decreases substantially with an increase of the coefficient of friction and unit cohesion stress. The dam on rigid foundation rock slides more than the dam on flexible foundation rock.

Comparison

Figure 5 shows the comparison between *FS* and the sliding displacement for the Pine Flat dam for the different cases of coefficient of friction and unit shear stress. The dam slides when the safety factor is less than unity and sliding increases as the safety factor decreases.

A FRAMEWORK FOR EVALUATING SLIDING STABILITY

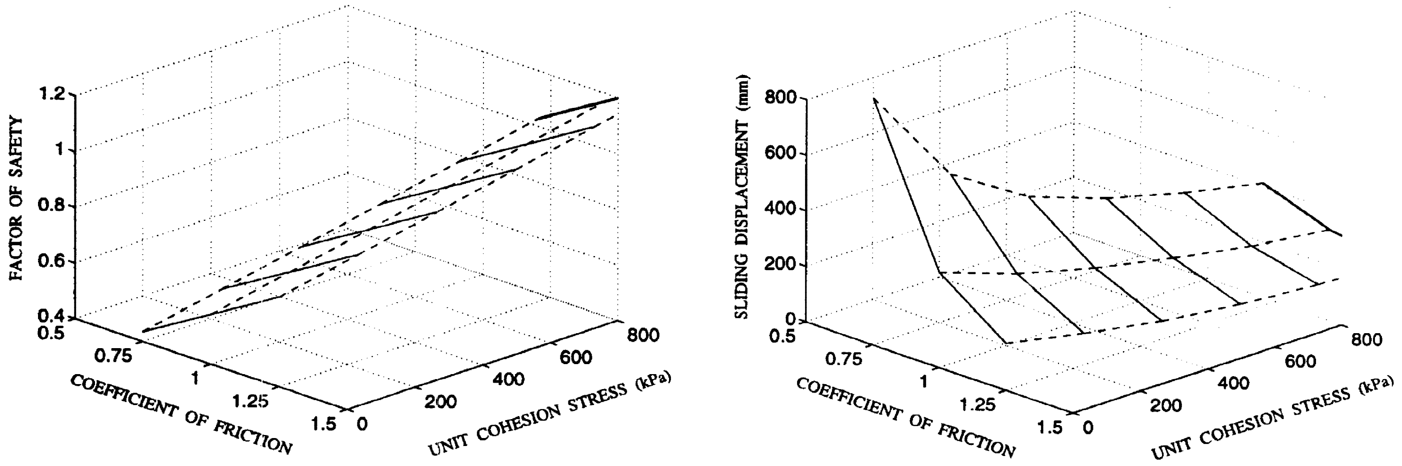
The previous results show that the static procedure (Eq. 1) for determining the sliding factor of safety, with a rational definition of the equivalent lateral earthquake load, can be used to determine when sliding is prevented from cases when sliding will occur. If the static procedure shows that sliding will not occur ($FS > 1$), then no further analysis is required.

For cases when *FS* is less than unity, the proper question is not whether the dam is stable, but rather what is the magnitude of the sliding displacement. The dynamic analysis procedure described in this paper can be used to evaluate sliding displacement. An important parameter for the sliding analysis is the value of the cohesion force. Based on the results in the previous section, the cohesion force may be selected as $C = cA$, where A is the area of the interface under compression as determined from the static analysis with the equivalent lateral forces. Of course an upper bound on the sliding displacement can be obtained by assume zero cohesion, $C = 0$. Although it could be argued that zero cohesion is appropriate once sliding commences, it is believed that zero cohesion is overly conservative because the materials do not necessarily lose all cohesive properties under small deformations.

In the current version of the analysis procedure, the cohesion force is a constant (Eq. 2), hence requiring an assumption on the value of A. A future modification of the program would be to determine the time varying value of area under compression and hence the area providing cohesion.

A dynamic analysis accounting for all the factors effecting sliding provides a rational estimate for the sliding displacement. Although there have been attempts to approximate sliding displacements by sliding block analysis or definition of a critical acceleration causing sliding, they can produce substantial errors (Chopra and Zhang, 1991).

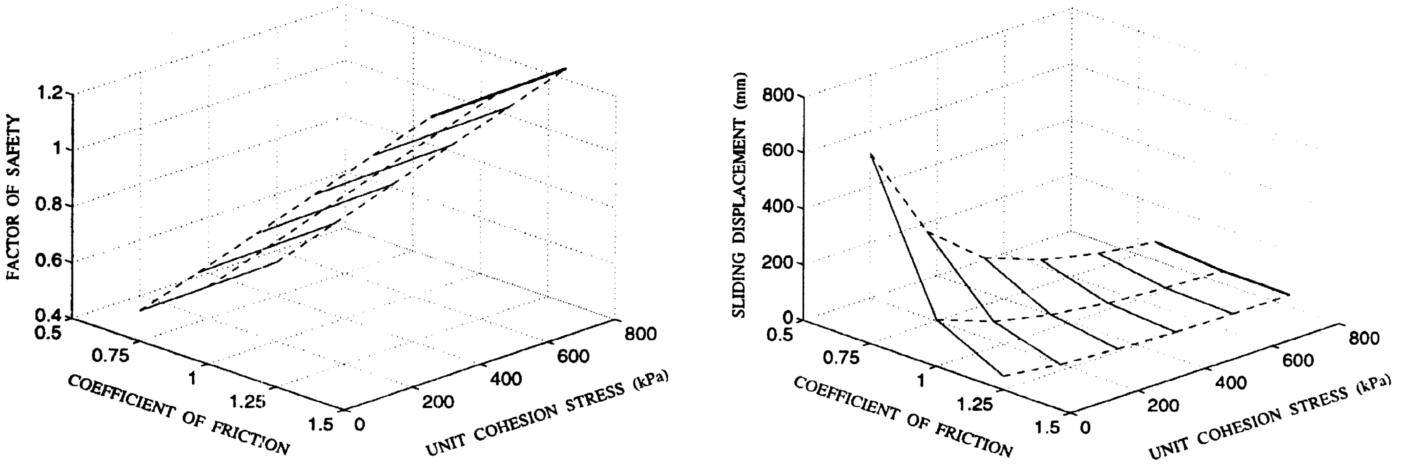
The magnitude of the sliding displacement from a dynamic analysis must be compared with a criterion for the maximum allowable displacement. This is a difficult question to answer because sliding may cause damage to joints, grout curtains, and drains, and the possibility of water intrusion into a damaged interface zone must be considered. However, for an extreme earthquake with low probability of occurrence (such as a maximum



(a) Static procedure

(b) Dynamic analysis

Fig. 3. Static solution and dynamic evaluation of sliding for Pine Flat dam on rigid foundation rock.



(a) Static procedure

(b) Dynamic analysis

Fig. 4. Static solution and dynamic evaluation of sliding for Pine Flat dam on flexible foundation rock.

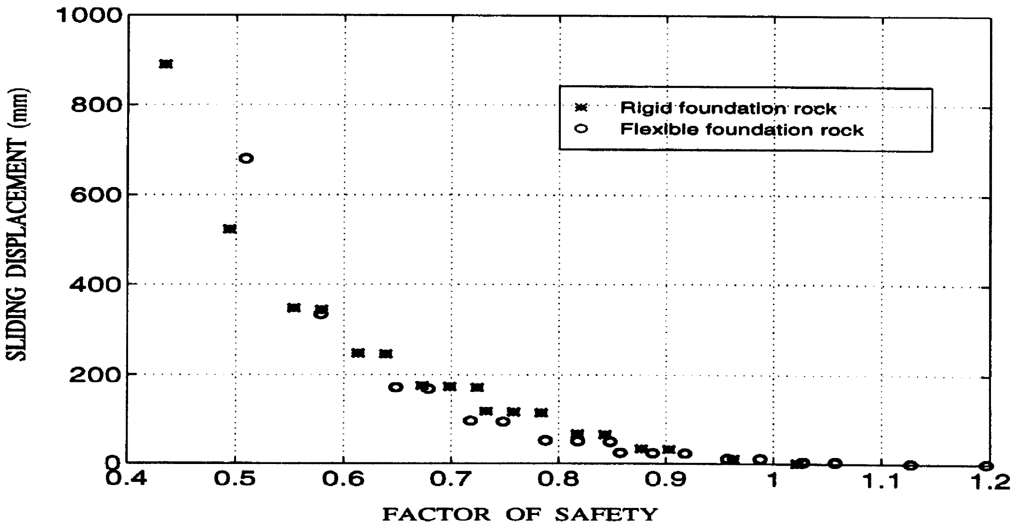


Fig. 5. Comparison between factor of safety and sliding displacement.

credible event), allowing sliding displacements of less than 50 mm appears to be reasonable.

Finally, there may be an intermediate range of the factor of safety near unity, $FS_{cr} < FS < 1$, where it can be expected that sliding displacements are small enough to not require a dynamic analysis. The previous results indicate that an $FS_{cr} = 0.90$, for which the maximum forces exceed the interface strength by only 10% for a short duration, correlates with limited sliding displacement. Again it must emphasized that the factor of safety should be computed using a rational procedure for the earthquake forces, such as by Fenves and Chopra (1987). It is very important that the effects of dam-foundation rock interaction be included in the static evaluation procedure. Otherwise, the sliding determination will be based on unrealistically small factors of safety or large sliding displacements.

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