DYNAMIC PERFORMANCE OF CONCRETE SLIDING INTERFACES

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ABSTRACT

Several shaking table tests were carried out on two concrete blocks where one was fixed to the shaking table and the other was resting on top of the inferior block. The static friction of the concrete in the interface was determined for undisturbed conditions. Then 2000-loading cycles were applied to the blocks and the kinetic friction was determined from the interpretation of the acceleration time histories recorded on the top block. This process was repeated nine times to assess its effect on both the static and kinetic friction coefficients. Furthermore, by comparing the input (motion in shaking table) with the output (motion on the upper block) the amount of energy transmitted across the interface was determined for each experimental stage (every 2000 cycles). The results show that static and kinetic friction coefficients vary significantly with repeated loading, thus modifying the energy transmission across the sliding interface. Accordingly, the response characteristics of the upper block changes with time.

Keywords: Concrete, interface, friction, sliding

INTRODUCTION

The seismic behavior of concrete arch dams and concrete rolled compacted (CRC) dams is affected by concrete ageing and the number of earthquakes they have endured throughout their life. Several structures of this type have suffered damage when subjected to strong seismic events (Pekau and Yuzhu, 2004). Damage is developed mainly in the zones influenced by a significant slope change because dynamic shear stress concentrations lead to severe cracking.

When a future seismic event hits a dam that contains cracks, its response is affected by potential sliding along crack interfaces. The back and forth displacement (however small) wears out the material polishing the interface, which leads to a continuous friction change while shaking lasts. Thus additional cracking can be induced and relative displacements among dam blocks develop. To study the seismic response of a damaged concrete dam, it is necessary to characterize the dynamic frictional properties of concrete to concrete sliding interface, under seismic conditions, i.e., under continuously varying sliding velocity. It is imperative to stress the fact that sliding under seismic excitation develops under non-constant velocity conditions. However it is a common practice to simplify the phenomenon by studying dynamic friction under constant velocity conditions, in spite of shaking table tests carried out do not support this assumption (Constantinou et al., 1987; Mokha et al., 1990; Yegian and Lahlaf, 1992; Yegian and Kadakal, 2004).

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Furthermore, the dynamic behavior of concrete to concrete interfaces has been granted little attention (Theodossius et. al., 1987), thus forcing practitioners to deal with concrete interface-dynamics, as when analyzing the dynamic response of cracked concrete dams, to assume that Coulomb’s friction law is valid under seismic conditions (i.e., velocity independency of friction).

To shed some light on this problem, an experimental program using a shaking table was carried out to study the dynamic response of concrete-concrete sliding interfaces under controlled seismic conditions and the corresponding change in its static friction coefficient ($\mu_s$).

**LABORATORY EQUIPMENT AND EXPERIMENTAL PROGRAM**

To capture the frictional characteristics of the concrete interface under consideration, both static and dynamic tests were performed. Tests were carried out using a unidirectional shaking table driven by a pneumatic actuator. The shaking table pad consisted of a hinged hard wood plate supported by four vertical uprights (Fig. 1) so that it could be inclined to perform tests under several sloping angles, as depicted in Fig 1a. Two concrete blocks were stacked on the support plate. The dimensions of the bottom concrete block (fixed to this pad) were 0.25 m x 0.07 m x 0.07 m (length, height and width), and a top concrete block with mass and dimensions of 1.557 kg and 0.12 m x 0.07 m x 0.07 m, was allowed to freely slide relative to the former. Herein, the concrete block fixed to the table will be referred to as *bottom block* and the upper one will be called *top block*. The details of the experiment set up are presented in Fig. 1.

![Figure 1](image_url)  
**Figure 1.** Apparatus used for the experiments. Static (a) and dynamic tests (b) configuration

During the static tests the shaking table remained still while the inclination of the pad was increased to a value up to the onset of sliding of the top block (see Fig. 1a). This angle was regarded as the concrete-interface static friction angle: $\phi_s$. The angle was computed as the average of the set of three measurements.

The dynamic experiments included monitoring the sliding response of the top block under a harmonic excitation with frequency and amplitude of 2 Hz and 6 cm, respectively. The friction coefficients, both static and dynamic, were computed for undisturbed conditions and then every 2000 loading cycles of the 18000 shearing cycles applied.

**LABORATORY RESULTS**

The acceleration histories recorded during the experiments are presented in this section. These records are periodic as the input signal was harmonic. Therefore, only one acceleration cycle is enough to represent the overall behaviour of the problem being analyzed.
In Fig. 2, acceleration records of the input signal (bottom block) and sliding block (top block) are presented for an intact concrete to concrete interface (initial cycle). Fig. 2 clearly shows the difference between stick and slip phases of the model by the coincidence and separation, respectively, of the acceleration records of the input motion and the top block response. Between points A and B in Fig. 2 both the input motion and the top block acceleration histories coincide thus indicating no relative displacement in the sliding interface develops. At point B, the forces at the sliding interface are at limit equilibrium, i.e., the model is at the onset of sliding, meaning that the yield acceleration has been reached (Newmark, 1965). Once the yield acceleration has been attained, it is generally assumed that no further acceleration will be transferred through the sliding interface (Newmark, 1965; Yegian and Lahlaf, 1992; Jangid, 2000; Yegian and Kadakal, 2004). However, it is observed in Fig. 2 that some percentage of the input acceleration keeps on being transferred (Botero, Mendez and Romo, 2005). Acceleration up to 66% higher than the yield acceleration were transmitted throughout the interface for this test conditions (intact interface). This is easily seen in the Fig. 2 by comparing the horizontal broken line (yield acceleration value) with the continuous thin line (top block acceleration). This behaviour is attributed to the gradual decrease of friction coefficient when sliding starts: the decreasing shear strength at the interface allows that some of the input energy keeps on transferring as the friction coefficient decreases. This transition from stick to slip conditions has been documented by Rabinowicz (1951) and Chaudhuri and Hutchinson (2005) under static tilt tests and by Méndez (2004) and Méndez and Romo (2006) from shaking table experiments. Note that this does not follow Coulomb’s law, which assumes a sudden friction drop as sliding starts.

![Figure 2. Accelerations measured on the model with an intact concrete interface](image)

A similar behavior is observed in the model acceleration curves when the sliding interface has been subjected to a high number of shear loading cycles: the acceleration in the top block continues to rise after the yield value has been reached. This behavior held for all the tests carried out during the experimental program, even when the surface sliding conditions of the top block was modified by the increase of concrete fines present in the sliding interface, as observed in Fig. 3 where the acceleration curves for the concrete to concrete interface during cycle 10,000 are shown. Fig. 3a depicts the

![Figure 3. Accelerations measured on the model cycle 10,000 (a) with fines in the interface, (b) without fines in the interface](image)
acceleration time histories for the interface with fines in it, and Fig. 3b presents the acceleration records for the same 10,000-cycles-sheared interface but without fines in it. Both curves show the same trend observed for the intact interface regarding the increase of the top block’s acceleration over the yield acceleration. However, as Fig. 3a shows the fines present in the interface modify the sliding pattern of the top block. On the other hand, after the fines are removed, the sliding pattern of the top block during cycle 10,000 is very similar to that of cycle zero (intact interface). This shows the importance of the fines. Their presence in the interface tend to increase the energy transferred through the concrete-concrete contact, as shown in the next section of the paper by the energy index plot (Botero, 2004; Botero, Mendez and Romo 2005) as well as the static friction angle graph. These results seem to indicate that the frictional characteristics of these interfaces improve with cycling. This goes against the hypothesis generally adopted for concrete to concrete sliding problems, which assumes that cycling reduces concrete-concrete interface friction. It is clear that this assumption neglects one of the principal tribological characteristics of a sliding interface: wear.

WEAR DEPENDANCY OF STATIC FRICTION AND ENERGY ANALYSIS

The complete laboratory test consists of 18,000 sliding cycles of the top block. From 0 to 10,000 cycles, the accumulation of fine materials produced by wear of the surfaces in contact at the interface is allowed. Later, from 10,000 to 18,000 cycles the fines are removed.

Fig. 4 presents the static friction coefficient variation with the number of cycles. The sliding plane was slowly inclined until the angle corresponding to the static friction coefficient was reached (e.g. beginning of block sliding). Then, the sliding plane was set down horizontally and the test continued again for other 2,000 cycles. In this figure, it is possible to observe that the initial static friction coefficient is 26°, and it progressively-increases until a horizontal asymptotic tendency starts after 6,000 cycles were applied. The initial friction value (cycle zero), corresponds to intact interface materials. At the first 4,000 cycles, the surface smoothing process (trimming of surface irregularities) generates an important amount of fine materials that remain in the sliding interface. Consequently as the fine materials production increases, the static coefficient becomes higher. This may be caused by the fact that as the fine material fills in the cavities of the intact materials, the effective contact area increases, and so does the friction coefficient. This is consistent with the observed behaviour (value of static friction) in Fig. 4, where it is seem that after the cycle 6,000 the friction angle, \( \phi_s \), remains practically constant.

![Figure 4. Relation between static friction coefficient and number of cycles (first 10,000 cycles)](image)

The results of whole set of cycles applied are shown in Fig. 5 with the purpose of highlighting the influence of the fine materials. The results included correspond to specific cycles: 10,000, 14,000, 16000 and 18,000. It should be mentioned that \( \phi_s \) was measured before and after the fines were removed. Thus the influence of the fines was assessed. At cycle 10,000, after fines removal, the static
The coefficient is similar to the registered at the test beginning of the experiment (cycle zero). Then, after 4,000 cycles the friction increases, due to the larger contact area caused by the presence of the fine material as mentioned above. When cycle 14,000 is reached, the friction coefficient is similar to the one registered at cycle 2,000, as shown in Fig. 5 for the “unclean” interface.

The above results can be interpreted in terms of energy. To this end an energy index was proposed: Energy Index \( (EI) = \frac{\text{Output Energy}}{\text{Input Energy}} \), where the Input Energy (for the input conditions of the test) is the energy content in one excitation cycle and the Output Energy is the energy content of the top block response for the same cycle (Botero, 2004 and Botero, Mendez and Romo 2005). The \( EI \) definition can be easily generalized for random inputs.

Fig. 6 depicts the variation of \( EI \) versus the number of cycles. When the Energy Index is equal to one, it means that the top and lower block are coupled and energy loss at the sliding interface is null. When uncoupled conditions develop (top block slides) \( EI \) mainly changes for two principal causes: 1) due to the energy dissipation at the sliding interface thus decreasing \( E \); and 2) due to the contribution of the inertial forces, generated at the top block by its relative velocity with respect to the bottom block, causing an increase on \( EI \).

Figure 6 shows that for the first 6,000 cycles \( EI \) remains almost constant because it is not affected by the fine material accumulation but between cycles 6,000 to 10,000 the increase of fine material concentration at the interface produces a decrease of the kinetic acceleration of the top block due to the
friction increase. In the next 8,000 cycles, it is possible to observe clearly this situation. The EI increases after each time the fines are removed accordingly, the static friction coefficient drops and thus the top block displaces more freely, which spurs up the inertial forces of the top block.

LABORATORY DETERMINATIONS OF SLIDING FRICTION

It is common practice to determine kinetic friction coefficient ($\mu_k$) by measuring the average force when a body is moving at constant velocity. This procedure does not account for inertial effects and results in an average kinetic friction coefficient which is likely to be influenced by the stiffness of the force measuring device (Tolstoi, 1967; Cambou, 1974). In this research, a simple approach is proposed to determine the instantaneous friction coefficient either in static ($\mu_s = \tan \phi$) or kinetic conditions ($\mu_k$), by considering the equations of dynamic equilibrium under an approximately constant force, hence inertial effects under any acceleration condition are accounted for. For a full discussion on the procedure details refer to the work of Méndez (2004) and Méndez and Romo (2006). The reader is also encouraged to consult Chaudhuri and Hutchinson (2005).

Figure 7: (a) Free body diagram of top block subjected to shaking table acceleration $\ddot{U}_g$. (b) Normalized friction coefficient variation computed with equation (3)

Consider Fig. 7a, where the top block is subjected to an acceleration pulse $\ddot{U}_g$ at a given time interval, $\Delta t$, is shown. Applying Newton’s second law of motion to the resultant force in the sliding interface we get

$$m\ddot{U} = m\ddot{U}_g - mg\mu$$

where $m$ is the mass of the top block and $\ddot{U}$ its acceleration, $g$ is the gravity acceleration and $\mu$ the friction coefficient variation in every $\Delta t$. By solving Eq. 1 for $\mu$ and taking the absolute value of the accelerations, the friction coefficient variation under dynamic conditions is obtained:

$$\Delta \mu(t) = \frac{|\ddot{U}_g(t)| - |\ddot{U}(t)|}{g}$$

In Eq. 2 we use the delta symbol in $\mu$ to stress the fact that this equation yields the friction coefficient variation in every $\Delta t$ by which the total available static friction coefficient ($\mu_s$) during stick conditions is modified by relative displacement (Méndez, 2004; Méndez and Romo, 2006). The absolute value of the accelerations is used to consider only their magnitude because the algebraic sign is meaningless in the interpretation of friction coefficient variation. The real effect in friction is only given by the change in relative acceleration, not by its direction, which only indicates that the top block has moved to a different zone of the interface. This conforms to the fact that the friction force is non-conservative and thus path dependant [op. cit.].
To consider this change in $\mu$, the static term is added to Eq. 2 to obtain the continuous friction coefficient variation, $\mu$, at any time (Méndez, 2004; Méndez and Romo, 2006):

$$\mu(t) = \mu_S - \Delta \mu(t) = \mu_S - \frac{\ddot{u}_g(t) - \ddot{u}(t)}{g}$$  \hspace{1cm} (3)

The approach given in Eq. 3 was proposed by Méndez (2004), and a similar expression was proposed by Chaudhuri and Hutchinson (2005).

Fig. 7b shows the friction coefficient variation (normalized by $\mu_s$) computed using Eq. 3 and laboratory acceleration measurements. The variation presented in Fig. 7b complies well with the acceleration histories presented in Fig. 2. Point B in Fig. 2 corresponds to point B in Fig. 7b. This is the point where yield acceleration is reached, i.e., where static friction conditions are about to change because sliding is imminent. Note that after point B, the friction coefficient starts gradually decreasing until it reaches a small value (about half of $\mu_s$). This value depends on input acceleration, excitation frequency and interface materials, among other factors. The decrease in friction coefficient is consistent with the raising values of top block response–acceleration, because, as said before, friction gradually decreases allowing increasing amounts of energy to be transferred through the sliding interface: shear strength in the interface does not drop suddenly. This phenomenon has been reported by other investigators (e.g., Rabinowicz, 1951; Marone, 1998; Naboulsi and Nicholas, 2003). Observe that in Fig. 7b the friction coefficient equals $\mu_s$ at points A and E. This means that there is no displacement of the top block relative to the bottom block. It is interesting to note that the friction coefficient is higher than $\mu_s$ during the kinetic phase (between points D and E), i.e., where the effect of sliding has its greatest influence on the model response and allows the top block to have an acceleration higher than the input motion. This high value of the friction coefficient indicates that a greater force is needed to maintain the motion from D to E than the one needed to initiate the relative displacement (from point A to point C). Other researchers have also measured kinetic friction coefficients higher than $\mu_s$ (Hunt et al., 1965), lending support to present results.

The fact that accelerations higher than the yield acceleration propagate through the sliding interface has important practical implications when analyzing the response of, for example, structures on friction base isolators, cracked gravity dams. This could lead to underestimations of the structure’s dynamic response, because either the coulomb’s friction law and other friction laws that estimate a constant friction coefficient according to a constant sliding velocity (e.g., Constantinou et al., 1990), do not account for the response acceleration increases during sliding.

Eq. 3 was used to assess the dynamic friction coefficient variation in the concrete to concrete sliding interface for different shearing states. The results are presented in Fig. 8 for the case of the intact surface, 10,000 loading cycles with fines (F) and no fines (NF) in the sliding interface, and for the 18,000 cycles stage with no fines in the interface. The values of $\mu$ used in Fig. 8 were taken from Fig. 4. Fig. 8 reveals a strong variation of the friction coefficient, $\mu$, with respect to the static value, $\mu_s$, for the case of the intact surface. It is also observed that for loading cycle 10,000, this variation is reduced when the interface is clean. More reduction is observed for the case of the interface with fines in it. This decrease on the variation of the friction coefficient with respect to $\mu_s$ is due to the wear of the sliding surface. Note that the variation of the $\mu/\mu_s$ relation from cycle 10,000 to 18,000 is not as important as the variation from intact conditions to cycle 10,000. This suggests a strong influence of the concrete surface finish on the frictional characteristics of a concrete to concrete interface. After the surface has been worn down, the interface frictional characteristics tend to stabilize. Of course, this is true for cases where the wear pattern is the same during cycling (i.e. the same input motion used for all tests). It should be stressed that for situations where different input motions are used then the wearing of the surface will follow other patterns than the one induced in the present research.
CONCLUSIONS

From the experimental program carried out with a concrete to concrete frictional interface sliding under seismic conditions, it is possible to withdraw the following basic conclusions:

Coulomb’s friction law does not hold for concrete to concrete sliding interfaces under seismic conditions. Thus, its use in modeling applications should be used consciously.

Mechanisms that account for the effect of concrete wear debris within block interfaces should be implemented in analysis methods.

The initial frictional characteristics of a concrete sliding interface can be very different from those obtained during repeated shearing. Therefore, it is advisable to make estimates of the on-shearing frictional characteristics of a concrete interface while the input motion lasts. A practical procedure to make these evaluations is given by Botero E., Méndez B. and Romo M. P. 2006.

REFERENCES


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