DYNAMIC BEHAVIOR OF JOINTED ROCK

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SUMMARY

This paper discusses recent investigation into the behavior of rock joints, and rock masses bounded by joints, subjected to dynamic or earthquake loading. Previous work is examined and a program of laboratory dynamic direct shear testing is discussed. The theoretical and practical implications of the laboratory results are examined with respect to design using an example dynamic analysis of a dam foundation.

INTRODUCTION

Numerous cases of foundation and slope failures caused by liquefaction or cyclic mobility of soils under earthquake loading have been documented. Motivated by these catastrophic failures, research needs in soil dynamics were established early, and much effort has gone into seeking an understanding of the behavior and response of soils subjected to cyclic loading. On the other hand, few rock mass failures are known to have resulted from seismic activity, and until recently little emphasis has been placed on understanding the dynamic behavior of jointed rock. The Madison Canyon landslide, triggered by the 1959 Hebgen Lake earthquake, represents one such event. An outcrop of dolomite acted as a buttress, preventing a weak schist above from sliding on foliation dipping about 50° into the canyon. The dolomite collapsed due to the shaking and 33 million m^3 of rock material slid into the canyon, damming the river and killing 27 people (Ref. 1). This event indicates that it may be possible for a rock mass to exhibit changes in behavior when subjected to dynamic loading. Since many slopes and dams in seismically active areas are dependent on jointed rock for stability, it is important to understand the changes in rock mass behavior that might occur under dynamic loading.

It is well established that the behavior of a rock mass is controlled to a large extent by the presence of discontinuities such as joints, bedding seams, foliation, and shear zones. It is, therefore, appropriate that initial research efforts should concentrate on the dynamic behavior of such discontinuities.

PREVIOUS LABORATORY INVESTIGATIONS

Hencher (Ref. 2) used shaking table tests to examine rock slope stability under dynamic loading. Sliding blocks of four rock types on

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smooth and dry tilted surfaces were studied under damped harmonic motion at various frequencies. Back calculated displacements, from double integration of measured accelerations, were compared to measured displacements to estimate dynamic friction angles. The latter were in turn compared to static friction angles. The main conclusions from the studies are: (1) the dynamic friction angle just prior to sliding is higher than the same friction angle under static conditions, and is higher for higher rates of loading and (2) the dynamic friction angle during sliding is lower than the same friction angle under static loading, resulting in larger displacements than would be predicted using friction angles obtained from static tests.

Crawford and Curran (Ref. 3) studied the effects of relative velocity on the shear resistance of rock discontinuities. A servo-controlled dynamic direct shear machine was developed for the experimental program. The machine has independently controlled horizontal and vertical actuators. Artificial saw cut joints in four rock types, approximately 200 mm square, were lapped with silicon carbide grit and tested under dry conditions. The samples were displaced at various shear velocities under constant normal loads. It was found that, beyond a critical threshold velocity, the shear strength of the discontinuities changed with increasing velocity. The shear strength of harder rocks was found to decrease, and the shear resistance of softer rocks was found to increase, varying approximately linearly with the logarithm of velocity. An example for a hard rock is shown in Figure 1. Here, the shear strength at a given velocity is normalized with respect to the strength at a very low shearing velocity.For all rock types studied except one, the behavior was found to be approximately independent of normal stress.

CURRENT LABORATORY INVESTIGATIONS

The following is a summary of the laboratory experiments conducted for the research program reported herein. Additional details are discussed by Gillette et al. (Ref. 4).

Dynamic Direct Shear Equipment

Direct shear experiments were conducted in the high capacity direct shear apparatus illustrated in Figure 2. The apparatus consists of independent horizontal and vertical servo-controlled loading actuators, reaction frames, and shear box fixtures. The upper shear box compartment is restrained against horizontal motion by roller bearings on the top support plate, which bear against hardened steel plates set into the vertical faces of the specimen reaction frames. The bottom support plate rests on two rows of roller bearings. Shear forces are applied co-linear to the shear surface to reduce moments applied to the specimen. Several loading patterns are possible through the use of a digital function generator. Each actuator can be operated in the load controlled or displacement controlled mode. The normal force actuator has a capacity of 736 kN and the shear force actuator has a capacity of 156 kN. Loads are monitored by load cells on each actuator, and normal displacements are monitored by an LVDT internal to the normal load actuator. Shear displacements are monitored by subtracting the signals of two LVDTs, one attached to the upper half of the sample and the other attached to the lower half.

Undrained dynamic shear experiments on rock joints were performed utilizing the membrane system illustrated in Figure 3. A 5 mm thick silicone rubber membrane was made to fit into grooves surrounding the shear box compartments. Glass fiber reinforced adhesive tape was wrapped around the membrane to prevent tearing, and the membrane was secured and sealed by clamping bars bolted to the shear box compartments. Sliding steel confinement hoops were stacked outside the specimen to prevent bulging of the membrane during pressurization and shear displacements. Several fluid inlet and outlet ports were provided for saturation and pressurization of the specimen. Pressure transducers were used to monitor water pressure within the joint plane. Pressure changes were found to be very small during shearing of smooth metal calibration surfaces.

Test Program and Results

Rough artificial joints were created for testing by tensile splitting cores of Loveland sandstone. Smooth samples in the same rock were prepared by sawing blocks and grinding smooth the cut surfaces. Specimens with a nominal shear area of 360 cm^2 were prepared and placed in the shear box compartment with sulphur capping compound. The top sample edges were bevelled to prevent tensile spalling and maintain a constant nominal shear area.

An initial series of dry tests was performed with sinusoidally imposed shear displacements of approximately $\pm$ 1.3 and $\pm$ 2.5 mm, at frequencies of 0.01, 0.1, and 1.0 Hz. Nominal normal stress levels were maintained nearly constant at 0.21, 0.69, and 3.45 MPa. Tests were also conducted at a normal stress of 0.07 MPa, although large fluctuations in the normal load were observed. A few tests were conducted at frequencies of 0.001 and 10 Hz. The complete shear stress-displacement behavior was monitored, and the strength at maximum velocity was determined for each test. An increase in shear strength with increasing relative shearing velocity was observed for both rough and smooth samples. This change in strength was found to be relatively independent of normal stress and consistent with the conclusions of Crawford and Curran.

A series of dry tests was also performed with load control on rough sandstone specimens. Normal stress levels of 0.21 and 0.69 MPa, and sinusoidal shear load frequencies of 0.01, 0.1 and 1.0 Hz were used. Tests were also conducted at 10 Hz, but at this frequency inertial effects dominated the response and there was no clear point of failure. The magnitude of the cyclic shear stress was small initially for a few cycles, and was gradually increased until failure occurred. Very small displacements were observed to occur in the few cycles just prior to failure. Failure was catastrophic and resulted in a sudden drop in shear strength, supporting the conclusions of Hencher (Ref. 2).

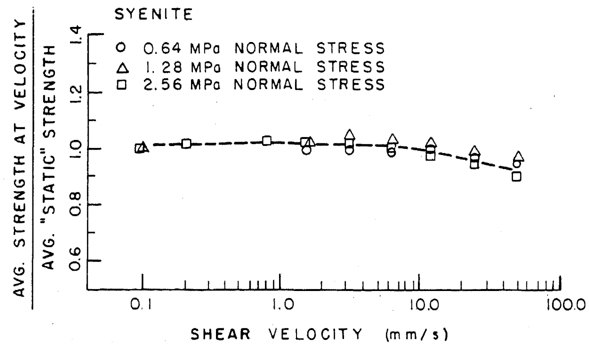

Figure 1. Normalized Shear Strength vs. Shear Velocity for Tests on Syenite (Ref. 3)

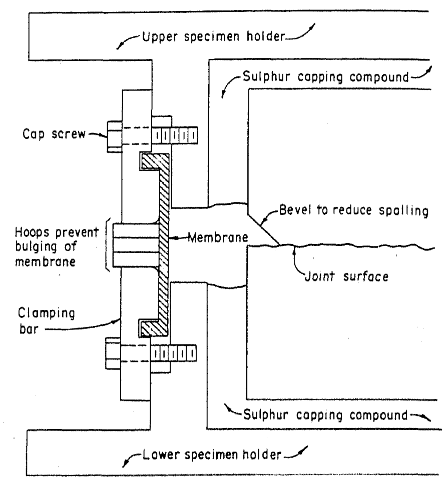

Figure 3. Section Through Specimen Holders and Membrane System

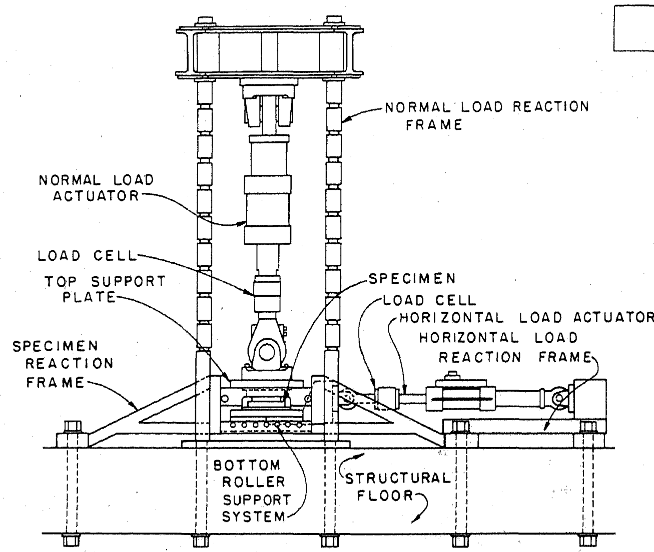

Figure 2. Dynamic Direct Shear Apparatus (Side View Schematic)

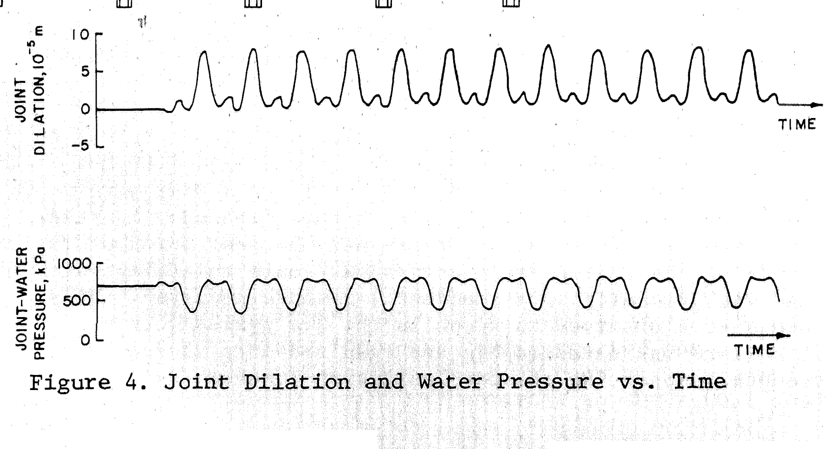

Figure 4. Joint Dilation and Water Pressure vs. Time

However, the effects of frequency and comparisons with strengths from static tests were difficult to assess, since the strengths were quite unpredictable from one test to the next. Geometry of the joint, mating of the surfaces, and localized degradation all contribute to this observed behavior.

A series of undrained tests was conducted on saturated specimens at frequencies of 0.01, 0.1, 1.0, and 10 Hz, under imposed sinusoidal shear displacements of approximately ± 2.5mm. Effective normal stress levels were initially 0.21, 0.69, and 2.07 MPa with joint water pressure initially 0, 0.35 and 0.69 MPa. For cases with an initial joint water pressure, a very close correlation was obtained between joint dilation or contraction, and water pressure as shown in Figure 4. The magnitude of joint water pressure change was found to be larger at higher displacement frequencies. The mean joint water pressure was found to increase gradually at first, but stabilize after the first few cycles, and decrease exponentially to the initial pressure after shearing was stopped. The initial increase was larger for larger initial effective stresses and higher frequencies. Maximum increases in the mean pressure were about 0.1 MPa. The porous nature of the sandstone tested may have contributed to the observed pressure response. The strength of the specimens was found to be governed by the effective stress, even under the fluctuating water pressures. This was determined by comparing results from drained and undrained testing of each specimen, and examination of the strength and joint pressure response curves such as those shown in Figure 5. In this case, the effective normal stress approaches zero and shear strength is essentially lost. However, very little shear displacement is required before the joint dilates enough to regain effective stress and strength. The stresses shown in Figure 4 are not directly additive since the water pressure acts over an area larger than the sample size. It can also be seen from Figure 5 that the joint water pressure increases towards either extreme of the shearing motion without any significant movement of the joint. This is likely due to elastic deformations in the rock.

EXAMPLE DYNAMIC ANALYSIS

The following discussion summarizes results from dynamic analysis of a concrete dam foundation. Additional details of the example problem and methods of analysis are discussed by Scott and Dreher (Ref. 5). Consider a potentially unstable dam foundation block at the base of a 200 m high arch dam, bounded by planar discontinuities, numbered 1 to 6 as shown in Figure 6. For a given earthquake, using digitized records and computer techniques, dynamic forces acting on the block from the dam can be determined from response history structural finite element analyses. Inertia loading on the block can be determined from digitized accelerograms. Static loads acting on the block include static forces from the dam, and water forces acting normal to each plane, assuming no change in water pressures during dynamic loading. Given the shear strengths of the discontinuities, a three-dimensional limit equilibrium analysis can be performed for each time step during the earthquake. The potential mode of instability may change during the earthquake due to time varying forces as shown in Figure 7. A factor of safety against sliding can also be computed for the block at each time step during the earthquake as shown in Figure 8. If the factor of safety drops below 1.0 for short periods of time, cumulative permanent displacements can be computed, assuming rigid - perfect plastic behavior, by double integration of the relative acceleration. The first integration provides a relative shearing velocity. To study velocity effects on calculated permanent displacements, a number of such analyses were performed for the example block, assuming velocity dependent strength for plane 3 only and loading consistent with a local Richter M6.5 earthquake. The results are summarized in Figure 9. Displacement is plotted against the slope of a normalized strength vs. velocity curve (see Figure 1). Points above the dashed line represent increasing strength with increasing velocity, and points below the dashed line represent decreasing strength with decreasing velocity. The calculated displacements are shown to be very sensitive to the velocity dependent behavior.

DISCUSSION AND CONCLUSIONS

Some of the observed dynamic behavior of rock joints can be explained by adhesion theory, which states that frictional resistance is proportional to the true area of contact. The real area of contact may be smaller for surfaces that are only in contact for a short period of time due to a lag in elastic or plastic deformations. Thus, rapidly shearing hard surfaces might exhibit a lower shear strength. The shear strength of rough joints is dependent on the compressive strength of the wall rock material. Materials such as concrete exhibit increased compressive strength under rapid loading. Thus, prior to sliding an increase in strength might occur.

Only in recent years has there been significant research into the dynamic behavior of jointed rock. Although much data has been gathered recently, there are still many uncertainties. Critical slopes and foundations of jointed rock in seismically active areas warrant careful stability assessments.

It is recommended that for such features, response history limit equilibrium analyses be performed utilizing design earthquakes. The factor of safety against sliding should be greater than 1.0 at each time step during the earthquake, assuming reasonably conservative shear strengths determined from static tests. This is necessary because permanent displacements calculated when the factor of safety drops below 1.0 can be grossly underestimated, unless the velocity dependent shear strength behavior of the rock in question is taken into account. Calculated displacements are very sensitive to small changes in velocity dependent behavior.

Water forces determined for static conditions can also be utilized in the analysis if the dynamic factor of safety is always greater than 1.0. Fluctuating dynamic water pressures were found to be related primarily to the normal displacement of discontinuities. This normal displacement should be minimal if no shearing is allowed to occur.

Although in some cases joint water pressure was found to increase without shear displacement, a larger force is also required to initiate sliding under dynamic loads than static loads. These two effects tend to cancel each other. In any case, it appears that very small displacements are required to cause enough dilation for substantial reduction in water pressures.

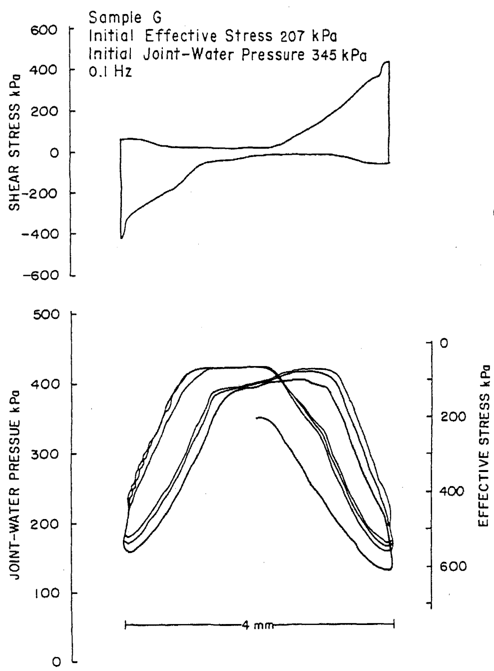

Figure 5. Shear Stress and Joint Water Pressure Showing Complete Loss of Effective Stress

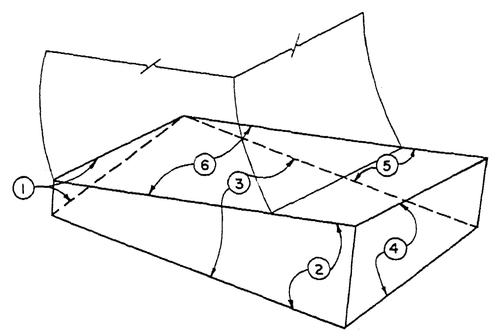

Figure 6. Isometric View of Example Block

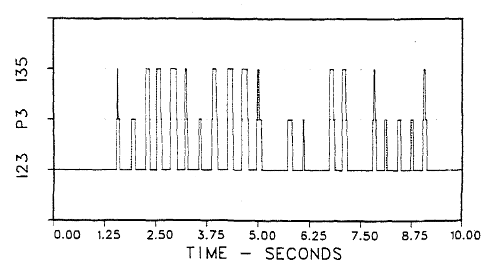

Figure 7. Modes of Potential Instability vs. Time - 123 Represents Sliding on Intersection of Planes 2 and 3, P3 Represents Sliding on Plane 3, 135 Represents Sliding on Intersection of Planes 3 and 5 (See Fig. 6)

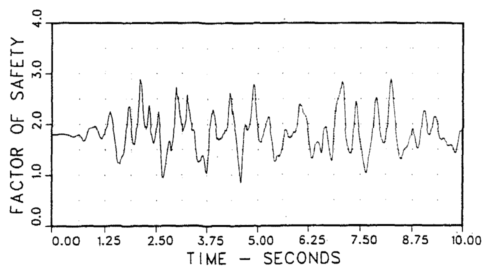

Figure 8. Factor of Safety vs. Time

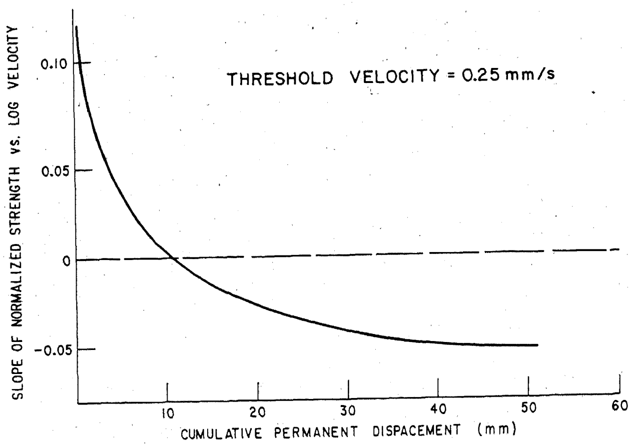

Figure 9. Effects of Velocity-Dependent Behavior on Calculated Displacements

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