

CHAPTER 8: CYCLIC SHEAR STRENGTHS OF SLICKENSIDED SURFACES

The results from the laboratory tests conducted on Rancho Solano Clay #1 and the centrifuge tests conducted on Rancho Solano Clay #2 described in previous chapters provide insight into the cyclic strength that can be mobilized along slickensided surfaces.

Results from Laboratory Test Program on Rancho Solano Clay #1

Chapters 4 and 5 outline the results from the ring shear and direct shear tests that were conducted at Virginia Tech on Rancho Solano Clay #1, Rancho Solano Clay #2, and San Francisco Bay Mud test specimens. Of the three soils tested in the direct shear device, only the slickensided surfaces prepared for Rancho Solano Clay #1 gave drained residual strengths that agreed well with those measured in the Bromhead ring shear device. Consequently, rapid loading and cyclic loading direct shear tests were only performed on Rancho Solano Clay #1.

The loading rates that were used for the direct shear tests on Rancho Solano Clay #1 were as follows:

- The displacement rate for the drained direct shear tests was 0.000123 inches/minute.
- The displacement rate for the fast direct shear tests was 0.048 inches/minute.
- The loading frequency for the cyclic direct shear tests was 0.5 cycles/second.

In order to compare the strengths measured in the monotonic strain-controlled tests with the strengths measured in the cyclic loading tests, it is convenient to express the monotonic displacement rates as stress cycle loading rates. To use this approach, it is necessary to assume that failure occurs in one cycle of monotonic loading. The equivalent loading frequency for the monotonic direct shear tests can then be calculated as follows:

$$\text{Equivalent Frequency} = \frac{\# \text{ of Cycles to Failure}}{\text{Time to Failure}} = \frac{1}{\text{Time to Failure}} \quad (8-1)$$

For the four slow direct shear tests that were performed at 14.5 psi on Rancho Solano Clay #1, the average time to failure was 638 minutes. Using Equation 8-1, an equivalent

loading frequency of 2.6×10^{-5} Hz can be used to represent the slow direct shear tests. For the two fast direct shear tests that were performed at 14.5 psi on Rancho Solano Clay #1, the average time to failure was 0.64 minutes. Using Equation 8-1, an equivalent loading frequency of 2.6×10^{-2} Hz can be used to represent the fast direct shear tests. An equivalent loading frequency of 8.4×10^{-6} Hz was calculated for the Bromhead ring shear tests, for which the average time to failure was 1996 minutes.

Table 8-1 lists the strength ratios that were measured for Rancho Solano Clay #1 during the ring shear and direct shear testing programs. Figure 8-1 shows a plot of the measured strength ratios as a function of equivalent loading frequency.

Table 8-1: Strength Ratios Measured for Rancho Solano Clay #1

Type of Test Performed	No. of Tests Performed @ 14.5 psi	Normal Stress (psi)	Equivalent Loading Frequency (Hz)	Average Measured Strength Ratio
Bromhead Ring Shear Tests	4	14.6	8.4×10^{-6}	0.31
Slow Direct Shear Tests	4	14.5	2.6×10^{-5}	0.32
Fast Direct Shear Tests	2	14.5	2.6×10^{-2}	0.31
Cyclic Direct Shear Tests	8	14.9	0.5	0.66

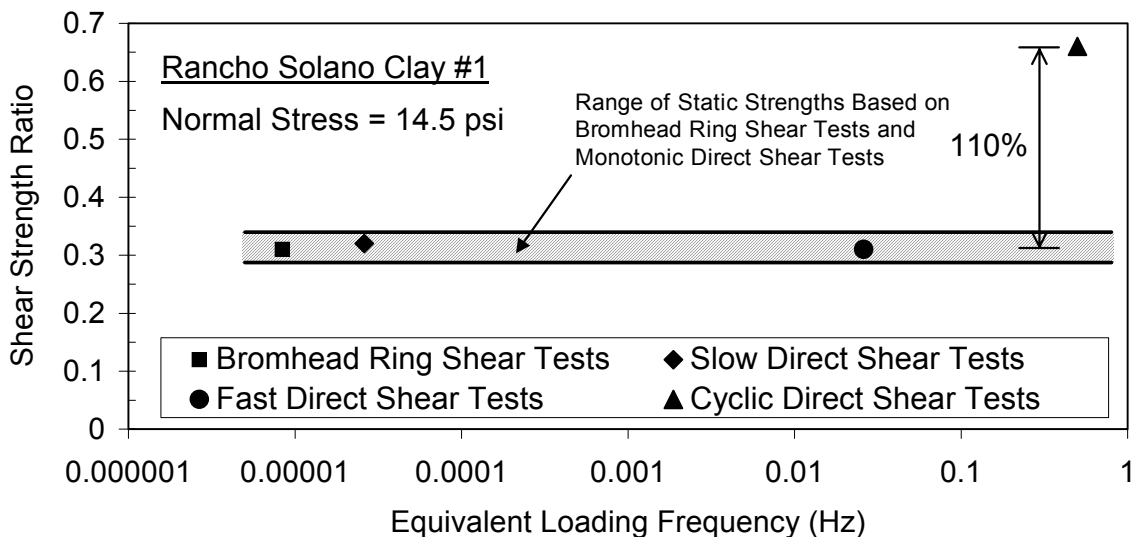


Figure 8-1. Shear strength ratio vs. equivalent loading frequency for Rancho Solano Clay #1.

As shown in Table 8-1 and Figure 8-1, the shear strength ratios measured in the Bromhead ring shear device and in the slow and fast monotonic direct shear tests were essentially the same, indicating that the rate of loading had no effect on the measured strength within the range of loading rates covered in these tests. The cyclic strengths measured in the cyclic direct shear tests were 110% higher than the static strengths measured in the ring shear and direct shear tests, indicating that either the faster rate of loading or the cyclic nature of the loading had a very significant effect on the shearing resistance.

Results from Centrifuge Test Program on Rancho Solano Clay #2

Chapter 6 discusses the results from the centrifuge tests that were conducted at UC Davis on two Rancho Solano Clay #2 test specimens. Chapter 7 describes the Newmark analyses that were performed to determine representative cyclic strengths for Rancho Solano Clay #2 in the centrifuge tests. As discussed in Chapter 6, both slow, static loading and rapid, cyclic loading were performed for the Rancho Solano Clay #2 test specimens during the centrifuge test.

The loading rates used during the centrifuge test are as follows:

- The displacement rate for the slow, static loading events was 0.0005 inches/minute.
- The loading frequency for the rapid, cyclic loading events was 55 cycles/second.

In order to compare the strengths measured in the slow, static loading events with the strengths measured in the rapid, cyclic loading events, equivalent loading frequencies for the static loading events were calculated using Equation 8-1.

For Static Pull #1, the time to failure for the 10.5° slope was 67 minutes, which leads to an equivalent loading frequency of 2.5×10^{-4} Hz. The time to failure for the 12° slope was 18 minutes, which leads to an equivalent loading frequency of 9.3×10^{-4} Hz.

For Static Pull #2, the time to failure for the 12° slope was 7 minutes, which leads to an equivalent loading frequency of 2.4×10^{-3} Hz.

Table 8-2 lists the strength ratios measured for Rancho Solano Clay #2 during centrifuge test CLM02. Figure 8-2 shows a plot of the measured strength ratios as a function of the equivalent loading frequency.

Table 8-2: Strength Ratios Measured for Rancho Solano Clay #2

	No. of Tests Performed Near 10.1 psi Normal Stress	Equivalent Loading Frequency (Hz)	Average Measured Strength Ratio
Bromhead Ring Shear Tests (Interpolated between 7.5 psi & 14.6 psi)	12	8.4×10^{-6}	0.42
Static Pull #1 – 10.5° Slope	1	2.5×10^{-4}	0.46
Static Pull #1 – 12° Slope	1	9.3×10^{-4}	0.42
Shake 3 – 10.5° Slope (from Newmark analysis)	1	55	0.63
Shake 3 – 12° Slope (from Newmark analysis)	1	55	0.69
Static Pull #2 – 12° Slope (after shaking)	1	2.4×10^{-3}	0.55

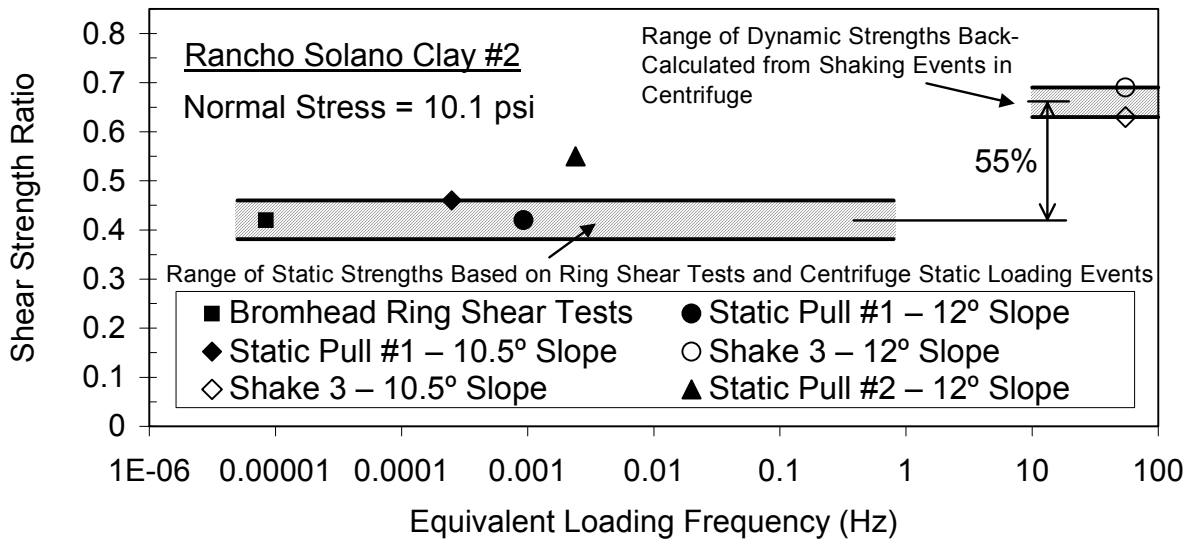


Figure 8-2. Shear strength ratio vs. equivalent loading frequency for Rancho Solano Clay #2.

As shown in Table 8-2 and Figure 8-2, the shear strength ratios measured in the Bromhead ring shear device agreed quite well with the strength ratios measured for both slopes during Static Pull #1. This agreement provides validation for the polishing process

that was used to prepare the centrifuge specimens. The cyclic shear resistances back-calculated from centrifuge test CLM02 were 55% higher than the static strengths measured in the Bromhead ring shear tests and the centrifuge static loading events that were performed before the cyclic loading.

Static Pull #2 was performed after Shake 3, and the measured strength ratio for that loading was 30% higher than the strength ratio that was measured during Static Pull #1. This data indicates that the post-shaking shear strength along the slickensided surface was higher than the shear strength before shaking, indicating that the clay had been stiffened and strengthened by the cyclic loading. This increase in strength may be due to disordering of the slickensided shear plane during cyclic loading, which would be consistent with the mechanism proposed by Skempton (1985), Lemos et al. (1985), and Tika et al. (1996) for the significant strength gains observed during rapid monotonic loading on slickensided shear surfaces.

Implications for Design Practice

Both the laboratory tests conducted on Rancho Solano Clay #1 and the centrifuge tests conducted on Rancho Solano Clay #2 show that the cyclic shear resistance that can be mobilized along slickensided surfaces is significantly higher than the drained shear resistance that is available under static loading conditions. For cyclic loading at frequencies of 0.5 Hz and 55 Hz, the measured cyclic strengths for Rancho Solano Clay #1 and Rancho Solano Clay #2 were 110% and 55% higher, respectively, than the corresponding static drained residual strengths for these soils. This agrees with the results of cyclic ring shear tests performed on 16 different soils by Yoshimine et al. (1999), who reported cyclic strengths 20% to 100% larger than the slow residual strengths, for tests conducted at cyclic load frequencies of 0.5 Hz, 1.0 Hz, and with actual earthquake time histories.

As noted by Blake et al. (2002), the current state of practice is to use drained residual shear strengths when performing dynamic analyses of slopes that contain slickensided slip surfaces. Because the actual dynamic shearing resistance may be significantly larger than the drained residual shear strength, this design approach can result in overly conservative slope designs.

Taken together, the laboratory tests outlined in this dissertation and the dynamic ring shear tests performed by Yoshimine et al. (1999) provide justification for using cyclic strengths that are larger than the drained residual shear strength when performing seismic slope stability analyses of slopes that contain slickensided slip surfaces. To reduce the conservatism that is built into the current state of practice, it seems logical that dynamic slope stability analyses be performed using a cyclic shear resistance that is at least 20% larger than the drained residual shear strength.

The centrifuge tests performed on Rancho Solano Clay #2 also showed that the post-shaking shear strength along the slickensided surface is higher than the shear strength before shaking. This data indicates that post-earthquake stability of slickensided clay slopes should not be an issue of significant concern. This is consistent with what has been observed in the field by other researchers (Pradel et al., 2005).

Further research to develop a better understanding of the factors that influence the magnitude of cyclic shear resistance could be of great value. Of particular utility could be research that would identify a relationship between index properties, clay mineralogy, and the cyclic shear resistance.