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Yucca Mountain Site Characterization Project

Effect of Boundary Conditions on the Strength and Deformability of Replicas of Natural Fractures in Welded Tuff: Comparison Between Predicted and Observed Shear Behavior Using a Graphical Method

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**EFFECT OF BOUNDARY CONDITIONS
ON THE STRENGTH AND DEFORMABILITY OF REPLICAS
OF NATURAL FRACTURES IN WELDED TUFF:
COMPARISON BETWEEN PREDICTED AND OBSERVED SHEAR
BEHAVIOR USING A GRAPHICAL METHOD**

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ABSTRACT

Four series of cyclic direct-shear experiments were conducted on several replicas of three natural fractures and a laboratory-developed tensile fracture of welded tuff from Yucca Mountain to test the graphical load-displacement analysis method proposed by Saeb (1989) and Amadei and Saeb (1990). Based on the results of shear tests conducted on several joint replicas under different levels of constant normal load ranging between 0.6 and 25.6 kips (2.7 and 113.9 kN), the shear behavior of joint replicas under constant normal stiffness ranging between 14.8 and 187.5 kips/in. (25.9 and 328.1 kN/cm) was predicted by using the graphical method. The predictions were compared to the results of actual shear tests conducted for the same range of constant normal stiffness. In general, a good agreement was found between the predicted and the observed shear behavior.

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1.0 INTRODUCTION

The response of a rough joint to shear loading depends on its surface properties, as well as the boundary conditions that are applied by the surrounding rock mass. These boundary conditions can exist in a variety of forms and vary between constant normal load (stress), in the case of slope stability problems near the surface, to variable or constant normal stiffness in the vicinity of underground excavations. The normal stiffness applied across joint surfaces is defined as the ratio between increments in normal load and increments in normal displacement. It varies between zero for constant normal load conditions and infinity for constant normal displacement conditions. In general, the joint shear strength under constant or variable normal stiffness (non zero) is higher than the joint shear strength under constant normal load (stress). The main reason for the increase in shear strength is that under constant or variable normal stiffness boundary conditions, joint dilatancy created by joint surface roughness is inhibited and joint normal load (stress) increases as shear takes place. The effect of normal stiffness boundary conditions on the shear behavior of rock joints has been investigated theoretically or experimentally by Obert et al. (1976), Lechnitz (1985), Goodman and Boyle (1985), and Hutson (1987), and more recently by Archambault et al. (1990), Bandis (1990), Benmokrane et al. (1991), Ohnishi and Dharmaratne (1990) and Skinas et al. (1990).

In two recent publications, Saeb (1989) and Amadei and Saeb (1990) proposed mathematical and graphical methods to predict the behavior of a rock joint under any normal stiffness boundary condition from the results of conventional constant normal load (or stress) direct shear tests. An experimental research program was initiated to test these methods using the data collected on several fractures of welded tuff from Yucca Mountain in the southwest corner of the Nevada test site in southern Nevada, and on one fracture from Rainer Mesa. Cyclic direct shear and normal compression tests were conducted on replicas of three natural fractures and a laboratory developed tensile fracture of welded tuff. The direct shear tests

were carried out under constant normal loads ranging between 0.6 and 25.6 kips (2.7 and 113.9 kN) and constant normal stiffnesses ranging between 14.8 and 187.5 kips/in. (25.9 and 328.1 kN/cm) with different initial normal loads. Each test consisted of five cycles of forward and reverse shear motion. The complete set of experimental results can be found in the data report by Wibowo et al. (1993).

Based on the results of the direct shear experiments performed on the replicas of fractures of welded tuff under constant normal load, the shear behavior of the replicas tested under constant normal stiffness was predicted by using the above mentioned graphical method. The predictions are presented in this report and are compared to the actual shear test results with three statistical parameters for all five cycles of forward and reverse shear motion.

2.0 PREDICTION OF FRACTURE BEHAVIOR UNDER CONSTANT NORMAL STIFFNESS

2.1 Graphical method of Amadei and Saeb

The graphical method proposed by Saeb (1989) and Amadei and Saeb (1990) relies on the coupling that exists between the normal load versus displacement and shear load versus displacement response of a rough fracture. In order to use the graphical method, it is necessary to know the normal load versus normal displacement, shear load versus shear displacement and dilatancy versus shear displacement response curves of a given fracture at different levels of constant normal load (or stress). Using these three sets of curves, normal load versus normal displacement diagrams at different levels of shear displacement are constructed. These curves can then be used to predict the shear strength of the fracture for any selected load path with constant or variable controlled stiffness, K . The applied stiffness, K , is defined as the ratio between an increment in normal load, dN , and an increment

in normal displacement, dv . The stiffness can vary between $K = 0$ for the constant normal load path ($dN = 0$) and $K = \infty$ for the constant normal displacement path ($dv = 0$). A fundamental assumption inherent in the graphical method of Saeb (1989) and Amadei and Saeb (1990) is that fracture shear strengths (peak and residual) are independent of the load path. A detailed example of the method applied to hypothetical data can be found in Amadei and Saeb (1990).

2.2 Prediction

The aforementioned method was followed in order to predict the shear and dilatancy response of the replicas of the fractures of welded tuff tested under constant normal stiffness. Predictions were done for the forward and reverse parts of each shear cycle. The predicted response curves were then compared to those measured during the shear experiments. Three sets of response curves presented in the earlier data report (Wibowo et al., 1993) were used in making the prediction: the shear load versus shear displacement curves, the dilatancy versus shear displacement curves, and the normal load versus normal displacement curves. Note that different sets of response curves had to be used for the forward and reverse parts for each one of the five shear cycles.

As an illustrative example, Figures 1a and 1b show, respectively, the first-cycle forward shear load versus shear displacement and dilatancy versus shear displacement curves (solid lines) for the shear tests conducted on the F4 samples under constant normal loads ranging between 0.7 kips (3.2 kN) and 14.4 kips (64.1 kN). Figure 1c shows the normal load versus normal displacement response for fracture F4 tested under normal compression before shear. Note that in Figure 1c, joint closing is assumed to be negative.

Using the curves shown in Figures 1a through 1c, the variation of the normal load with the normal displacement was plotted for different values of the shear displacement, U , ranging between 0 and 0.5 in. (1.27 cm) (see Figure 2). The curves in Figure 2 were

a

b

Figure 1. Sample KR12F4, first-cycle forward shear: (a) Shear load versus shear displacement, (b) Dilatancy versus shear displacement. (Solid lines for constant normal load tests and dashed lines for constant stiffness tests under initial normal load $N_0 = 3.6$ kips [16.0 kN] or $N_0 = 7.2$ kips [32.0 kN]).

Figure 1c. Normal load vs. normal displacement (dilatancy) for RF4 sample, before shear.

Figure 2. Sample KR12F4, first-cycle forward shear: Normal load vs. normal displacement response curves for different levels of shear displacement, U.

constructed using the values of normal load and normal displacement at the points of intersection between the dilatancy curves of Figure 1b and several vertical lines corresponding to arbitrary values of shear displacement. The different constant normal stiffness paths followed during testing of the F4 samples are also shown as straight lines in Figure 2. The bottom three straight lines correspond to constant stiffness experiments conducted at an initial normal load level of $N_0 = 3.6$ kips (16.0 kN) with stiffnesses of 18.8 kips/in. (32.9 kN/cm), 56.3 kips/in. (98.7 kN/cm), and 179.9 kips/in. (314.8 kN/cm). The top two straight lines correspond to tests conducted under an initial normal load of $N_0 = 7.2$ kips (32.0 kN) and for constant normal stiffnesses of 56.3 kips/in. (98.7 kN/cm) and 179.9 kips/in. (314.8 kN/cm). The normal load versus normal displacement response curves at different levels of shear displacement for all joint samples are enclosed in Appendix A. These curves are presented for the forward and reverse parts of each shear cycle.

For each stiffness path, the shear load versus shear displacement and dilatancy versus shear displacement response curves were predicted using Figures 1a, 1b, and 2. This was done by first recording the values of normal load and shear displacement at the points of intersection of each load path with the different curves of Figure 2. Then, these values were transferred to the shear load versus shear displacement and dilatancy versus shear displacement curves in Figures 1a and 1b.

2.3 Comparison between predicted and observed behavior

Predicted shear load versus shear displacement and dilatancy versus shear displacement responses were compared with those measured during shear testing under constant normal stiffness. For the F4 samples, the constant normal stiffness shear test response curves (for the first cycle forward motion) are shown as dashed lines in Figures 1a and 1b. Figures 3a and 3b show examples of comparisons between predicted and measured dilatancy versus shear displacement,

a

b

Figure 3. Specimen KR12F4, first-cycle forward under constant stiffness $K = 179.9 \text{ kips/in.}$ (314.8 kN/cm) and initial normal load $= 7.2 \text{ kips}$ (32.0 kN): (a) Comparison between observed and predicted dilatancy vs. shear displacement curves, (b) Comparison between observed and predicted shear load vs. shear displacement curves.

and shear load versus shear displacement response curves, respectively, for sample KR12F4, tested under an initial load of $N_0 = 7.2$ kips (32.0 kN) and a constant normal stiffness of $K = 179.9$ kips/in. (314.8 kN/cm). It is observed that the agreement between predicted and observed behavior is very good for this particular test. Comparisons between predicted and observed behavior for all joint samples tested under constant normal stiffness can be found in Appendix B. While most comparisons are good, some are not.

In order to quantify the differences between the predicted and observed responses, three statistical parameters were evaluated for each category of response curve: the coefficient of correlation, the standard error, and the coefficient of variation (Ang and Tang, 1975). The parameters are described as follows.

Let X and Y , be the predicted and observed values of shear load or dilatancy respectively. The **coefficient of correlation**, r , between X and Y is defined as

$$r = \frac{\text{Cov}(X, Y)}{(\sigma_X)(\sigma_Y)} \quad (1)$$

where $\text{Cov}(X, Y)$ is the covariance of X and Y , and σ_X and σ_Y are the standard deviations of X and Y , respectively. The values of r range between -1 and $+1$. When $r = \pm 1$, X and Y are linearly related, whereas, when $r = 0$, X and Y are scattered. In other words, the magnitude of the absolute value of the correlation coefficient can be used as a measure of the degree of linear relationship existing between the observed and predicted values of shear load or dilatancy.

If, for a given value of shear displacement, $Y_e = X$ represents the predicted value of Y (shear load or dilatancy), a measure of the scatter about the line $Y = X$ (i.e., predicted value = observed value) is given by the **standard error**, s , such that

$$s^2 = \frac{1}{n - 1} \sum (Y_i - Y_e)^2 \quad (2)$$

where n is the number of data points, and Y_i and Y_e are the observed and predicted values of Y, respectively.

In order to assess whether the dispersion in the X,Y space is large or small, the measure of dispersion relative to the central value is more useful. For this reason, the **coefficient of variation**, v, is used and is defined as follows:

$$v = \frac{s}{\bar{Y}} \quad (3)$$

where s is the standard error defined in equation (2), and $\bar{Y}$ is the mean value of the observed data, Y. The coefficient of variation is a convenient nondimensional measure of dispersion or variability. A disadvantage of this coefficient is that its usefulness diminishes when $\bar{Y}$ is close to zero.

The three statistical parameters were calculated for all normal displacement versus shear displacement and shear load versus shear displacement response curves for fractures G2, F2, F3, and F4. This was done for the forward and reverse parts of each of the five shear cycles. As an example, the values of the coefficient of correlation, standard error, and coefficient of variation for sample KR12F4 are given in Figures 3a and 3b for the first shear cycle forward motion. Values of those three statistical parameters for the other cycles and reverse motion can be found in Tables 1a and 1b for dilatancy and shear load, respectively. The complete set of values for all samples can be found in Appendix C.

Tables 2a through 5b give the minimum, maximum, and average values of the coefficient of correlation, the standard error, and the coefficient of variation for the forward and reverse parts of the

Table 1a

Coefficient of Correlation, Standard error, and Coefficient of Variation for Dilatancy. Sample KR12F4 tested under initial normal load 7.2 kips (32.0 kN) and applied stiffness 179.9 kips/in. (314.8 kN/cm).

Sample KR12F4	Coefficient of Correlation (r)	Standard Error (s) (10 ⁻³ in.)	Coefficient of Variation (v)
Forward			
1st cycle	1.00	4.0	0.28
2nd cycle	1.00	1.8	0.70
3rd cycle	1.00	2.0	3.42
4th cycle	1.00	2.5	1.05
5th cycle	-	-	-
Reverse			
1st cycle	1.00	0.7	0.21
2nd cycle	1.00	0.8	0.25
3rd cycle	1.00	0.7	0.12
4th cycle	1.00	0.9	0.12
5th cycle	-	-	-

Table 1b

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Shear Load. Sample KR12F4 tested under initial normal load 7.2 kips (32.0 kN) and applied stiffness 179.9 kips/in. (314.8 kN/cm).

Sample KR12F4	Coefficient of Correlation (r)	Standard Error (s) (kips)	Coefficient of Variation (v)
Forward			
1st cycle	0.99	0.29	0.03
2nd cycle	1.00	0.18	0.03
3rd cycle	0.99	0.30	0.06
4th cycle	0.99	0.39	0.07
5th cycle	-	-	-
Reverse			
1st cycle	0.94	1.25	0.18
2nd cycle	1.00	1.14	0.21
3rd cycle	1.00	0.97	0.19
4th cycle	1.00	0.94	0.19
5th cycle	-	-	-

dilatancy versus shear displacement and shear load versus shear displacement curves for samples F4, F3, F2, and G2, respectively.

2.3.1 Comparison for F4 samples.

For the F4 samples, the coefficient of correlation for dilatancy is very large and the average values range between 0.99 and 1.00 (see Table 2a). The average values of the standard error for dilatancy vary between 0.8 and 8.0×10^{-3} in. (0.02 and 0.20 mm), and the average values of the coefficient of variation for dilatancy vary between 0.15 and 3.68. This large value of the coefficient of variation is due to a mean value of observed dilatancy ($\bar{Y}$ in equation [3]) that is close to zero for sample KR11F4. Analysis of the individual dilatancy versus shear displacement response curves for each F4 sample shows an increase in the values of the standard error and the coefficient of variation with the number of shear cycles for forward and reverse motion.

For the F4 samples, the average values of the coefficient of correlation for the shear load varies between 0.71 and 0.99 (see Table 2b). Minimum values as low as 0.41 were also found for samples KR7F4 and KR9F4. These small values occurred because the observed and predicted shear load versus shear displacement curves are essentially parallel to the shear displacement axis. Therefore, low values of the coefficient of correlation do not always reflect poor predictions. In fact, for samples KR7F4 and KR9F4, small values of the standard error and the coefficient of variation were found, indicating that the predictions are good. In general, the average values of the standard error for the shear load vary between 0.38 and 1.53 kips (1.7 and 6.8 kN), and the average values of the coefficient of variation for the shear load vary between 0.05 and 0.27. As for the dilatancy, analysis of the individual shear load versus shear displacement response curves for each F4 sample shows an increase in the values of the standard

Table 2a

Maximum, Minimum, and Average Values of the Coefficient of Correlation, Standard Error, and Coefficient of Variation for Dilatancy. F4 samples tested under constant normal stiffness. (F = forward motion and R = reverse motion for all shear cycles.)

Sample		Coefficient of Correlation			Standard Error (10^{-3} in.)			Coefficient of Variation		
		Max.	Min.	Av.	Max.	Min.	Av.	Max.	Min.	Av.
KR7F4	F	1.00	1.00	1.00	4.0	0.9	2.6	0.44	0.05	0.23
	R	1.00	1.00	1.00	1.9	1.2	1.5	0.23	0.10	0.15
KR9F4	F	1.00	1.00	1.00	3.6	2.6	3.1	0.35	0.12	0.24
	R	1.00	1.00	1.00	2.6	1.9	2.2	0.41	0.16	0.28
KR10F4	F	1.00	0.99	1.00	4.1	2.6	3.1	0.87	0.17	0.46
	R	1.00	0.99	1.00	9.9	7.1	8.0	1.35	0.47	0.92
KR11F4	F	1.00	1.00	1.00	7.4	5.3	6.2	2.88	0.28	1.28
	R	1.00	0.97	0.99	7.2	3.4	5.7	8.94	0.39	3.68
KR12F4	F	1.00	1.00	1.00	4.0	0.9	2.6	3.42	0.28	1.36
	R	1.00	1.00	1.00	0.9	0.7	0.8	0.25	0.12	0.18

Table 2b

Maximum, Minimum, and Average Values of the Coefficient of Correlation, Standard Error, and Coefficient of Variation for Shear Load. F4 samples tested under constant normal stiffness. (F = forward motion and R = reverse motion for all shear cycles.)

Sample		Coefficient of Correlation			Standard Error (kips)			Coefficient of Variation		
		Max.	Min.	Av.	Max.	Min.	Av.	Max.	Min.	Av.
KR7F4	F	0.98	0.67	0.88	0.95	0.62	0.80	0.35	0.15	0.27
	R	0.95	0.55	0.71	0.67	0.58	0.61	0.21	0.18	0.20
KR9F4	F	0.99	0.41	0.86	0.89	0.36	0.67	0.30	0.09	0.21
	R	0.99	0.87	0.96	0.67	0.71	0.69	0.24	0.17	0.21
KR10F4	F	1.00	0.98	0.99	0.67	0.23	0.38	0.14	0.07	0.10
	R	1.00	0.96	0.99	1.07	0.95	0.99	0.30	0.22	0.27
KR11F4	F	0.98	0.90	0.94	1.80	1.25	1.53	0.31	0.21	0.25
	R	0.94	0.70	0.85	0.62	0.30	0.52	0.11	0.05	0.09
KR12F4	F	1.00	0.99	0.99	0.39	0.18	0.29	0.08	0.03	0.05
	R	1.00	0.94	0.98	1.25	0.97	1.08	0.21	0.18	0.19

error and the coefficient of variation with the number of shear cycles for forward and reverse motion.

2.3.2 Comparison for F3 Samples

For the F3 samples, the coefficient of correlation for dilatancy is very large and the average values range between 0.98 and 1.00 (see Table 3a). The average values of the standard error for dilatancy vary between 3.4 and 12.2×10^{-3} in. (0.1 and 0.3 mm), and the average values of the coefficient of variation for dilatancy vary between 0.14 and 6.77. This large value of the coefficient of variation is due to a mean value of observed dilatancy ($\bar{Y}$ in equation [3]) close to zero for sample KR11F3. Like the F4 sample, analysis of the individual dilatancy versus shear displacement response curves for each F3 sample shows an increase in the value of the standard error and the coefficient of variation with the number of shear cycles for forward and reverse motion.

The average values of the coefficient of correlation for the shear load varies between 0.55 and 0.99 (see Table 3b). Minimum values as low as 0.04 were also found for samples KR7F3 and KR10F3. These very small values occurred because the observed or predicted shear load versus shear displacement response curve is essentially parallel to the shear displacement axis. For samples KR7F3 and KR10F3, relatively small values of the standard error and the coefficient of variation were found, indicating that the predictions are quite good, although the coefficients of correlation were very small. In general, the average values of the standard error for the shear load vary between 0.23 and 1.88 kips, (1.0 and 8.4 kN) and the average values of the coefficient of variation for the shear load vary between 0.06 and 0.55. As for the dilatancy, analysis of the individual shear load versus shear displacement response curves for each F3 sample shows an increase in the values of the standard error and the coefficient of variation with the number of shear cycles for forward and reverse motion.

Table 3a

Maximum, Minimum, and Average Values of the Coefficient of Correlation, Standard Error, and Coefficient of Variation for Dilatancy. F3 samples tested under constant normal stiffness. (F = forward motion and R = reverse motion for all shear cycles.)

Sample		Coefficient of Correlation			Standard Error (10 ⁻³ in.)			Coefficient of Variation		
		Max.	Min.	Av.	Max.	Min.	Av.	Max.	Min.	Av.
KR7F3	F	1.00	0.99	1.00	6.2	5.1	5.8	0.27	0.19	0.24
	R	1.00	1.00	1.00	5.7	3.1	4.7	0.32	0.12	0.24
KR8F3	F	1.00	1.00	1.00	5.1	1.4	3.4	0.23	0.06	0.14
	R	1.00	0.99	1.00	4.2	2.4	3.5	0.28	0.09	0.21
KR9F3	F	1.00	0.99	0.99	4.3	3.2	3.5	0.27	0.19	0.23
	R	0.99	0.97	0.98	5.0	3.5	4.5	0.81	0.22	0.58
KR10F3	F	1.00	1.00	1.00	12.6	12.0	12.2	6.98	0.65	2.76
	R	1.00	0.99	1.00	11.1	9.7	10.3	11.08	0.76	4.88
KR11F3	F	1.00	0.99	0.99	5.1	4.3	4.6	1.07	0.26	0.68
	R	0.99	0.99	0.99	6.5	5.4	5.9	26.38	0.49	6.77

Table 3b

Maximum, Minimum, and Average Values of the Coefficient of Correlation, Standard Error, and Coefficient of Variation for Shear Load. F3 samples tested under constant normal stiffness. (F = forward motion and R = reverse motion for all shear cycles.)

Sample		Coefficient of Correlation			Standard Error (kips)			Coefficient of Variation		
		Max.	Min.	Av.	Max.	Min.	Av.	Max.	Min.	Av.
KR7F3	F	0.92	0.04	0.57	0.61	0.36	0.49	0.31	0.12	0.23
	R	0.80	0.34	0.62	0.53	0.09	0.23	0.15	0.03	0.07
KR8F3	F	1.00	0.98	0.99	0.71	0.49	0.56	0.22	0.20	0.21
	R	0.96	0.92	0.95	0.94	0.53	0.67	0.25	0.20	0.23
KR9F3	F	1.00	0.94	0.98	2.12	1.22	1.54	0.55	0.47	0.51
	R	0.99	0.91	0.96	2.69	1.33	1.77	0.64	0.47	0.55
KR10F3	F	0.93	0.27	0.57	0.71	0.11	0.36	0.10	0.02	0.06
	R	0.83	0.05	0.55	2.36	1.67	1.88	0.28	0.25	0.26
KR11F3	F	1.00	0.97	0.99	0.79	0.68	0.73	0.12	0.09	0.11
	R	1.00	0.98	0.98	0.79	0.38	0.52	0.09	0.07	0.08

2.3.3 Comparison for F2 Samples

The coefficient of correlation for dilatancy is very large and the average values range between 0.92 and 1.00 (see Table 4a). The average values of the standard error for dilatancy vary between 4.3 and 12.6×10^{-3} in. (0.1 and 0.3 mm) and the average values of the coefficient of variation for dilatancy vary between 0.19 and 7.70. As in the case of the previous samples, this large value of the coefficient of variation is due to a mean value of observed dilatancy ($\bar{Y}$ in equation [3]) close to zero for sample KR8F2. The values of the standard error and the coefficient of variation for dilatancy were found to increase markedly with the number of shear cycles for forward and reverse motion.

The average value of the coefficient of correlation for the shear load varies between 0.55 and 0.99 (see Table 4b). A value as low as 0.07 was found for sample KR6F2. This very small value occurred because the observed or predicted shear load versus shear displacement response curve is essentially parallel to the shear displacement axis. For this particular sample, the small values found for the standard error and the coefficient of variation indicate that the predictions are quite good, even though the coefficient of correlation is very small. The average values of the standard error for the shear load vary between 0.18 and 0.42 kips (0.8 and 1.9 kN) and the average values of the coefficient of variation for the shear load vary between 0.12 and 0.19. Analysis of the individual shear load versus shear displacement response curves for each F2 sample shows an increase in the values of the standard error and the coefficient of variation for the shear load with the number of shear cycles for forward and reverse motion.

2.3.4 Comparison for G2 Samples

The coefficient of correlation for dilatancy is quite large and the average values range between 0.43 and 1.00 (see Table 5a). The

Table 4a

Maximum, Minimum, and Average Values of the Coefficient of Correlation, Standard Error, and Coefficient of Variation for Dilatancy. F2 samples tested under constant normal stiffness. (F = forward motion and R = reverse motion for all shear cycles.)

Sample		Coefficient of Correlation			Standard Error (10 ⁻³ in.)			Coefficient of Variation		
		Max.	Min.	Av.	Max.	Min.	Av.	Max.	Min.	Av.
KR6F2	F	1.00	1.00	1.00	8.9	2.7	5.6	0.83	0.09	0.40
	R	0.99	0.98	0.99	18.4	5.7	12.6	3.00	1.28	1.89
KR7F2	F	1.00	0.97	0.99	9.4	1.9	4.3	0.40	0.07	0.19
	R	1.00	0.98	0.99	22.0	2.1	11.5	0.92	0.19	0.62
KR8F2	F	1.00	1.00	1.00	10.6	7.7	8.8	0.66	0.33	0.48
	R	0.96	0.92	0.94	5.6	2.4	4.4	20.23	0.41	7.70

Table 4b

Maximum, Minimum, and Average Values of the Coefficient of Correlation, Standard Error, and Coefficient of Variation for Shear Load. F2 samples tested under constant normal stiffness. (F = forward motion and R = reverse motion for all shear cycles.)

Sample		Coefficient of Correlation			Standard Error (kips)			Coefficient of Variation		
		Max.	Min.	Av.	Max.	Min.	Av.	Max.	Min.	Av.
KR6F2	F	0.78	0.07	0.52	0.41	0.15	0.27	0.19	0.10	0.16
	R	0.97	0.89	0.95	0.22	0.16	0.19	0.16	0.11	0.13
KR7F2	F	0.97	0.32	0.75	0.55	0.18	0.34	0.40	0.09	0.19
	R	0.96	0.60	0.78	0.56	0.16	0.26	0.32	0.10	0.16
KR8F2	F	1.00	0.91	0.98	0.73	0.17	0.42	0.28	0.04	0.16
	R	0.84	0.42	0.65	0.21	0.15	0.18	0.14	0.08	0.12

Table 5a

Maximum, Minimum, and Average Values of the Coefficient of Correlation, Standard Error, and Coefficient of Variation for Dilatancy. G2 samples tested under constant normal stiffness. (F = forward motion and R = reverse motion for all shear cycles.)

Sample		Coefficient of Correlation			Standard Error (10 ⁻³ in.)			Coefficient of Variation		
		Max.	Min.	Av.	Max.	Min.	Av.	Max.	Min.	Av.
KR5G2	F	1.00	1.00	1.00	17.2	5.9	11.6	0.88	0.21	0.55
	R	0.99	0.93	0.96	56.7	37.6	47.2	4.59	3.54	4.06
KR6G2	F	1.00	0.83	0.91	19.4	4.6	12.0	8.84	0.23	4.53
	R	0.64	0.23	0.43	27.6	22.4	25.0	1.12	0.91	1.02

Table 5b

Maximum, Minimum, and Average Values of the Coefficient of Correlation, Standard Error, and Coefficient of Variation for Shear Load. G2 samples tested under constant normal stiffness. (F = forward motion and R = reverse motion for all shear cycles.)

Sample		Coefficient of Correlation			Standard Error (kips)			Coefficient of Variation		
		Max.	Min.	Av.	Max.	Min.	Av.	Max.	Min.	Av.
KR5G2	F	0.99	0.98	0.99	0.56	0.29	0.43	0.28	0.16	0.22
	R	0.99	0.76	0.88	0.36	0.30	0.33	0.39	0.39	0.39
KR6G2	F	0.99	0.71	0.85	0.91	0.34	0.62	0.15	0.05	0.10
	R	0.99	0.73	0.86	1.62	1.22	1.42	0.38	0.31	0.35

average values of the standard error for dilatancy vary between 11.6 and 47.2×10^{-3} in. (0.3 and 1.2 mm) and the average values of the coefficient of variation for dilatancy vary between 0.55 and 4.53. The values of the standard error and the coefficient of variation for dilatancy were found to increase notably with the number of shear cycles for forward and reverse motion. Because of extensive damage to the joint surfaces observed at the end of the fifth cycles, comparisons between predicted and observed behavior were done for the first and second cycles only. As observed by Wibowo et al. (1993), the extensive damage can be attributed to the absence of confinement embankments along the sample periphery and the extreme roughness of the joint surfaces.

The average values of the coefficient of correlation for the shear load vary between 0.85 and 0.99 (see Table 5b). The average values of the standard error for the shear load vary between 0.33 and 1.42 kips (1.5 and 6.3 kN), and the average values of the coefficient of variation for the shear load vary between 0.10 and 0.39. Analysis of the individual shear load versus shear displacement response curves for each G2 sample shows an increase in the values of the standard error and the coefficient of variation for the shear load with the number of shear cycles for forward and reverse motion.

3.0 CONCLUSIONS

Based on the results of direct shear experiments performed on replicas of four fractures of welded tuff under constant normal load boundary conditions, the shear behavior of replicas tested under constant normal stiffness boundary conditions was predicted by using the graphical method of Saeb (1989) and Amadei and Saeb (1990). The predictions were compared to the actual shear test results from constant normal stiffness experiments. Two hundred and sixty eight comparisons between predicted and observed dilatancy and shear load responses were analyzed. Three

statistical parameters were evaluated for each type of response curve: the coefficient of correlation, the standard error, and the coefficient of variation. Several important observations can be made:

1. In general, a good agreement was found between joint the response predicted using the Amadei and Saeb graphical method and the observed response.
2. The graphical method is straightforward and simple, and can be used to predict joint behavior under cyclic loading for a variety of loading paths and boundary conditions.
3. Differences between predictions and observations do sometimes occur. There are several possible sources for such differences.
 - In constructing the normal load versus dilatancy curves for different values of shear displacement, a linear interpolation was made.
 - In constructing the shear load versus shear displacement and dilatancy versus shear displacement curves for the joints under constant normal stiffness, linear interpolation was made between the shear load curves and between the dilatancy curves obtained under constant normal load.
 - In making predictions using the normal load versus dilatancy curves, it was assumed that the load path had no effect on the predicted values of joint shear strength and dilatancy.
 - Additional errors that have been explored in the report by Wibowo et al. (1993) may have contributed to the differences between predictions and observations (i.e., reproducibility and specimen installation); however, in most cases, the differences between observed and predicted shear load and dilatancy seem to be within the

reported experimental error of 0.8 kips (3.6 kN) for the shear load and 0.005 in. (0.13 mm) for the dilatancy.

4. The values of standard error and coefficient of variation were found to increase systematically with the number of cycles. The cumulative damage that occurred during shear was not accounted for in the current version of the graphical method.

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APPENDICES

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B	Comparison Between Prediction and Observed of Dilatancy and Shear Load	B-1 to B-134
C	Coefficient of Correlation, Standard Error, and Coefficient of Variation	C-1 to C-15

APPENDIX A

Normal Load Versus Dilatancy for Different Levels of Shear Displacement

SAMPLE	DESCRIPTION	PAGE
RF4	First cycle forward	A-1
RF4	First cycle reverse	A-1
RF4	Second cycle forward	A-2
RF4	Second cycle reverse	A-2
RF4	Third cycle forward	A-3
RF4	Third cycle reverse	A-3
RF4	Forth cycle forward	A-4
RF4	Forth cycle reverse	A-4
RF4	Fifth cycle forward	A-5
RF4	Fifth cycle reverse	A-5
RF3	First cycle forward	A-6
RF3	First cycle reverse	A-6
RF3	Second cycle forward	A-7
RF3	Second cycle reverse	A-7
RF3	Third cycle forward	A-8
RF3	Third cycle reverse	A-8
RF3	Forth cycle forward	A-9
RF3	Forth cycle reverse	A-9
RF3	Fifth cycle forward	A-10
RF3	Fifth cycle reverse	A-10
RF2	First cycle forward	A-11
RF2	First cycle reverse	A-11
RF2	Second cycle forward	A-12
RF2	Second cycle reverse	A-12
RF2	Third cycle forward	A-13
RF2	Third cycle reverse	A-13
RF2	Forth cycle forward	A-14

SAMPLE	DESCRIPTION	PAGE
RF2	Forth cycle reverse	A-14
RF2	Fifth cycle forward	A-15
RF2	Fifth cycle reverse	A-15
RG2	First cycle forward	A-16
RG2	First cycle reverse	A-16
RG2	Second cycle forward	A-17
RG2	Second cycle reverse	A-17

JOINT - DEFORMATION

RF4 SPECIMEN - 1ST CYCLE FORWARD

JOINT - DEFORMATION

RF4 SPECIMEN - 1ST CYCLE REVERSE

JOINT - DEFORMATION

RF4 SPECIMEN - 2ND CYCLE FORWARD

JOINT - DEFORMATION

RF4 SPECIMEN - 2ND CYCLE REVERSE

JOINT - DEFORMATION

RF4 SPECIMEN - 3RD CYCLE FORWARD

JOINT - DEFORMATION

RF4 SPECIMEN - 3RD CYCLE REVERSE

JOINT - DEFORMATION

RF4 SPECIMEN - 4TH CYCLE FORWARD

JOINT - DEFORMATION

RF4 SPECIMEN - 4TH CYCLE REVERSE

JOINT - DEFORMATION

RF4 SPECIMEN - 5TH CYCLE FORWARD

JOINT - DEFORMATION

RF4 SPECIMEN - 5TH CYCLE REVERSE

JOINT - DEFORMATION

RF3 SPECIMEN - 1ST CYCLE FORWARD

JOINT - DEFORMATION

RF3 SPECIMEN - 1ST CYCLE REVERSE

JOINT - DEFORMATION

RF3 SPECIMEN - 2ND CYCLE FORWARD

JOINT - DEFORMATION

RF3 SPECIMEN - 2ND CYCLE REVERSE

JOINT - DEFORMATION

RF3 SPECIMEN - 3RD CYCLE FORWARD

JOINT - DEFORMATION

RF3 SPECIMEN - 3RD CYCLE REVERSE

JOINT - DEFORMATION

RF3 SPECIMEN - 4TH CYCLE FORWARD

JOINT - DEFORMATION

RF3 SPECIMEN - 4TH CYCLE REVERSE

JOINT - DEFORMATION

RF3 SPECIMEN - 5TH CYCLE FORWARD

JOINT - DEFORMATION

RF3 SPECIMEN - 5TH CYCLE REVERSE

JOINT - DEFORMATION

RF2 SPECIMEN - 1ST CYCLE FORWARD

JOINT - DEFORMATION

RF2 SPECIMEN - 1ST CYCLE REVERSE

JOINT - DEFORMATION

RF2 SPECIMEN - 2ND CYCLE FORWARD

JOINT - DEFORMATION

RF2 SPECIMEN - 2ND CYCLE REVERSE

JOINT - DEFORMATION

RF2 SPECIMEN - 3RD CYCLE FORWARD

JOINT - DEFORMATION

RF2 SPECIMEN - 3RD CYCLE REVERSE

JOINT - DEFORMATION
RF2 SPECIMEN - 4TH CYCLE REVERSE

JOINT - DEFORMATION
RF2 SPECIMEN - 4TH CYCLE FORWARD

JOINT - DEFORMATION

RF2 SPECIMEN - 5TH CYCLE FORWARD

JOINT - DEFORMATION

RF2 SPECIMEN - 5TH CYCLE REVERSE

JOINT - DEFORMATION
RG2 SPECIMEN - 1ST CYCLE REVERSE

JOINT - DEFORMATION
RG2 SPECIMEN - 1ST CYCLE FORWARD

JOINT - DEFORMATION

RG2 SPECIMEN - 2ND CYCLE FORWARD

JOINT - DEFORMATION

RG2 SPECIMEN - 2ND CYCLE REVERSE

APPENDIX B

Comparison Between Prediction and Observation of Dilatancy and Shear Load

SAMPLE	DESCRIPTION	PAGE
KR7F4	Dilatancy comparison of 1st cycle forward, Normal Load = 3.6 kips; K = 18.0 kips/in	B-1
KR7F4	Shear load comparison of 1st cycle forward, Normal Load = 3.6 kips; K = 18.0 kips/in	B-1
KR7F4	Dilatancy comparison of 1st cycle reverse, Normal Load = 3.6 kips; K = 18.0 kips/in	B-2
KR7F4	Shear load comparison of 1st cycle reverse, Normal Load = 3.6 kips; K = 18.0 kips/in	B-2
KR7F4	Dilatancy comparison of 2nd cycle forward, Normal Load = 3.6 kips; K = 18.0 kips/in	B-3
KR7F4	Shear load comparison of 2nd cycle forward, Normal Load = 3.6 kips; K = 18.0 kips/in	B-3
KR7F4	Dilatancy comparison of 2nd cycle reverse, Normal Load = 3.6 kips; K = 18.0 kips/in	B-4
KR7F4	Shear load comparison of 2nd cycle reverse, Normal Load = 3.6 kips; K = 18.0 kips/in	B-4
KR7F4	Dilatancy comparison of 3rd cycle forward, Normal Load = 3.6 kips; K = 18.0 kips/in	B-5
KR7F4	Shear load comparison of 3rd cycle forward, Normal Load = 3.6 kips; K = 18.0 kips/in	B-5
KR7F4	Dilatancy comparison of 3rd cycle reverse, Normal Load = 3.6 kips; K = 18.0 kips/in	B-6
KR7F4	Shear load comparison of 3rd cycle reverse, Normal Load = 3.6 kips; K = 18.0 kips/in	B-6
KR7F4	Dilatancy comparison of 4th cycle forward, Normal Load = 3.6 kips; K = 18.0 kips/in	B-7
KR7F4	Shear load comparison of 4th cycle forward, Normal Load = 3.6 kips; K = 18.0 kips/in	B-7
KR7F4	Dilatancy comparison of 4th cycle reverse, Normal Load = 3.6 kips; K = 18.0 kips/in	B-8

SAMPLE	DESCRIPTION	PAGE
KR7F4	Shear load comparison of 4th cycle reverse, Normal Load = 3.6 kips; K = 18.0 kips/in	B-8
KR7F4	Dilatancy comparison of 5th cycle forward, Normal Load = 3.6 kips; K = 18.0 kips/in	B-9
KR7F4	Shear load comparison of 5th cycle forward, Normal Load = 3.6 kips; K = 18.0 kips/in	B-9
KR7F4	Dilatancy comparison of 5th cycle reverse, Normal Load = 3.6 kips; K = 18.0 kips/in	B-10
KR7F4	Shear load comparison of 5th cycle reverse, Normal Load = 3.6 kips; K = 18.0 kips/in	B-10
KR9F4	Dilatancy comparison of 1st cycle forward, Normal Load = 3.6 kips; K = 54.0 kips/in	B-11
KR9F4	Shear load comparison of 1st cycle forward, Normal Load = 3.6 kips; K = 54.0 kips/in	B-11
KR9F4	Dilatancy comparison of 1st cycle reverse, Normal Load = 3.6 kips; K = 54.0 kips/in	B-12
KR9F4	Shear load comparison of 1st cycle reverse, Normal Load = 3.6 kips; K = 54.0 kips/in	B-12
KR9F4	Dilatancy comparison of 2nd cycle forward, Normal Load = 3.6 kips; K = 54.0 kips/in	B-13
KR9F4	Shear load comparison of 2nd cycle forward, Normal Load = 3.6 kips; K = 54.0 kips/in	B-13
KR9F4	Dilatancy comparison of 2nd cycle reverse, Normal Load = 3.6 kips; K = 54.0 kips/in	B-14
KR9F4	Shear load comparison of 2nd cycle reverse, Normal Load = 3.6 kips; K = 54.0 kips/in	B-14
KR9F4	Dilatancy comparison of 3rd cycle forward, Normal Load = 3.6 kips; K = 54.0 kips/in	B-15
KR9F4	Shear load comparison of 3rd cycle forward, Normal Load = 3.6 kips; K = 54.0 kips/in	B-15
KR9F4	Dilatancy comparison of 3rd cycle reverse, Normal Load = 3.6 kips; K = 54.0 kips/in	B-16
KR9F4	Shear load comparison of 3rd cycle reverse, Normal Load = 3.6 kips; K = 54.0 kips/in	B-16

SAMPLE	DESCRIPTION	PAGE
KR9F4	Dilatancy comparison of 4th cycle forward, Normal Load = 3.6 kips; K = 54.0 kips/in	B-17
KR9F4	Shear load comparison of 4th cycle forward, Normal Load = 3.6 kips; K = 54.0 kips/in	B-17
KR9F4	Dilatancy comparison of 4th cycle reverse, Normal Load = 3.6 kips; K = 54.0 kips/in	B-18
KR9F4	Shear load comparison of 4th cycle reverse, Normal Load = 3.6 kips; K = 54.0 kips/in	B-18
KR9F4	Dilatancy comparison of 5th cycle forward, Normal Load = 3.6 kips; K = 54.0 kips/in	B-19
KR9F4	Shear load comparison of 5th cycle forward, Normal Load = 3.6 kips; K = 54.0 kips/in	B-19
KR9F4	Dilatancy comparison of 5th cycle reverse, Normal Load = 3.6 kips; K = 54.0 kips/in	B-20
KR9F4	Shear load comparison of 5th cycle reverse, Normal Load = 3.6 kips; K = 54.0 kips/in	B-20
KR10F4	Dilatancy comparison of 1st cycle forward, Normal Load = 3.6 kips; K=179.9 kips/in	B-21
KR10F4	Shear load comparison of 1st cycle forward, Normal Load = 3.6 kips; K=179.9 kips/in	B-21
KR10F4	Dilatancy comparison of 1st cycle reverse, Normal Load = 3.6 kips; K = 179.9 kips/in	B-22
KR10F4	Shear load comparison of 1st cycle reverse, Normal Load = 3.6 kips; K = 179.9 kips/in	B-22
KR10F4	Dilatancy comparison of 2nd cycle forward, Normal Load = 3.6 kips; K = 179.9 kips/in	B-23
KR10F4	Shear load comparison of 2nd cycle forward, Normal Load = 3.6 kips; K = 179.9 kips/in	B-23
KR10F4	Dilatancy comparison of 2nd cycle reverse, Normal Load = 3.6 kips; K = 179.9 kips/in	B-24
KR10F4	Shear load comparison of 2nd cycle reverse, Normal Load = 3.6 kips; K = 179.9 kips/in	B-24
KR10F4	Dilatancy comparison of 3rd cycle forward, Normal Load = 3.6 kips; K = 179.9 kips/in	B-25

SAMPLE	DESCRIPTION	PAGE
KR10F4	Shear load comparison of 3rd cycle forward, Normal Load = 3.6 kips; K = 179.9 kips/in	B-25
KR10F4	Dilatancy comparison of 3rd cycle reverse, Normal Load = 3.6 kips; K = 179.9 kips/in	B-26
KR10F4	Shear load comparison of 3rd cycle reverse, Normal Load = 3.6 kips; K = 179.9 kips/in	B-26
KR10F4	Dilatancy comparison of 4th cycle forward, Normal Load = 3.6 kips; K = 179.9 kips/in	B-27
KR10F4	Shear load comparison of 4th cycle forward, Normal Load = 3.6 kips; K = 179.9 kips/in	B-27
KR10F4	Dilatancy comparison of 4th cycle reverse, Normal Load = 3.6 kips; K = 179.9 kips/in	B-28
KR10F4	Shear load comparison of 4th cycle reverse, Normal Load = 3.6 kips; K = 179.9 kips/in	B-28
KR10F4	Dilatancy comparison of 5th cycle forward, Normal Load = 3.6 kips; K = 179.9 kips/in	B-29
KR10F4	Shear load comparison of 5th cycle forward, Normal Load = 3.6 kips; K = 179.9 kips/in	B-29
KR10F4	Dilatancy comparison of 5th cycle reverse, Normal Load = 3.6 kips; K = 179.9 kips/in	B-30
KR10F4	Shear load comparison of 5th cycle reverse, Normal Load = 3.6 kips; K = 179.9 kips/in	B-30
KR11F4	Dilatancy comparison of 1st cycle forward, Normal Load = 7.2 kips; K = 54.0 kips/in	B-31
KR11F4	Shear load comparison of 1st cycle forward, Normal Load = 7.2 kips; K = 54.0 kips/in	B-31
KR11F4	Dilatancy comparison of 1st cycle reverse, Normal Load = 7.2 kips; K = 54.0 kips/in	B-32
KR11F4	Shear load comparison of 1st cycle reverse, Normal Load = 7.2 kips; K = 54.0 kips/in	B-32
KR11F4	Dilatancy comparison of 2nd cycle forward, Normal Load = 7.2 kips; K = 54.0 kips/in	B-33
KR11F4	Shear load comparison of 2nd cycle forward, Normal Load = 7.2 kips; K = 54.0 kips/in	B-33

SAMPLE	DESCRIPTION	PAGE
KR11F4	Dilatancy comparison of 2nd cycle reverse, Normal Load = 7.2 kips; K = 54.0 kips/in	B-34
KR11F4	Shear load comparison of 2nd cycle reverse, Normal Load = 7.2 kips; K = 54.0 kips/in	B-34
KR11F4	Dilatancy comparison of 3rd cycle forward, Normal Load = 7.2 kips; K = 54.0 kips/in	B-35
KR11F4	Shear load comparison of 3rd cycle forward, Normal Load = 7.2 kips; K = 54.0 kips/in	B-35
KR11F4	Dilatancy comparison of 3rd cycle reverse, Normal Load = 7.2 kips; K = 54.0 kips/in	B-36
KR11F4	Shear load comparison of 3rd cycle reverse, Normal Load = 7.2 kips; K = 54.0 kips/in	B-36
KR11F4	Dilatancy comparison of 4th cycle forward, Normal Load = 7.2 kips; K = 54.0 kips/in	B-37
KR11F4	Shear load comparison of 4th cycle forward, Normal Load = 7.2 kips; K = 54.0 kips/in	B-37
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KR6F2	Normal load = 3.0 kips; K = 14.8 kips/in	B-105
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DILATANCY PREDICTION F41F

K=18.0 KIPS/IN, NORMAL LOAD=3.6 KIPS

SHEAR LOAD PREDICTION F41F

K=18.0 KIPS/IN, NORMAL LOAD=3.6 KIPS

DILATANCY PREDICTION F41R

K=18.0 KIPS/IN, NORMAL LOAD=3.6 KIPS

SHEAR LOAD PREDICTION F41R

K=18.0 KIPS/IN, NORMAL LOAD=3.6 KIPS

DILATANCY PREDICTION F42F

K=18.0 KIPS/IN, NORMAL LOAD=3.6 KIPS

SHEAR LOAD PREDICTION F42F

K=18.0 KIPS/IN, NORMAL LOAD=3.6 KIPS

DILATANCY PREDICTION F42R

K=18.0 KIPS/IN, NORMAL LOAD=3.6 KIPS

SHEAR LOAD PREDICTION F42R

K=18.0 KIPS/IN, NORMAL LOAD=3.6 KIPS

DILATANCY PREDICTION F43F

K=18.0 KIPS/IN, NORMAL LOAD=3.6 KIPS

SHEAR LOAD PREDICTION F43F

K=18.0 KIPS/IN, NORMAL LOAD=3.6 KIPS

DILATANCY PREDICTION F43R

K=18.0 KIPS/IN, NORMAL LOAD=3.6 KIPS

SHEAR LOAD PREDICTION F43R

K=18.0 KIPS/IN, NORMAL LOAD=3.6 KIPS

DILATANCY PREDICTION F44F

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SHEAR LOAD PREDICTION F44F

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DILATANCY PREDICTION F44R

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SHEAR LOAD PREDICTION F44R

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DILATANCY PREDICTION F45F

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SHEAR LOAD PREDICTION F45F

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DILATANCY PREDICTION F45R

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SHEAR LOAD PREDICTION F45R

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DILATANCY PREDICTION F41F

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SHEAR LOAD PREDICTION F41F

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DILATANCY PREDICTION F41R

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SHEAR LOAD PREDICTION F41R

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DILATANCY PREDICTION F42F

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SHEAR LOAD PREDICTION F42F

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DILATANCY PREDICTION F42R

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SHEAR LOAD PREDICTION F42R

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DILATANCY PREDICTION F43F

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SHEAR LOAD PREDICTION F43F

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DILATANCY PREDICTION F43R

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SHEAR LOAD PREDICTION F43R

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DILATANCY PREDICTION F44F

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SHEAR LOAD PREDICTION F44F

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DILATANCY PREDICTION F44R

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SHEAR LOAD PREDICTION F44R

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DILATANCY PREDICTION F45F

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SHEAR LOAD PREDICTION F45F

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DILATANCY PREDICTION F45R

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SHEAR LOAD PREDICTION F45R

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DILATANCY PREDICTION F41F

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SHEAR LOAD PREDICTION F41F

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DILATANCY PREDICTION F41R

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SHEAR LOAD PREDICTION F41R

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DILATANCY PREDICTION F42F

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SHEAR LOAD PREDICTION F42F

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DILATANCY PREDICTION F42R

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SHEAR LOAD PREDICTION F42R

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DILATANCY PREDICTION F43F

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SHEAR LOAD PREDICTION F43F

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DILATANCY PREDICTION F43R

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DILATANCY PREDICTION F44F

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SHEAR LOAD PREDICTION F44F

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DILATANCY PREDICTION F44R

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SHEAR LOAD PREDICTION F44R

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DILATANCY PREDICTION F45F

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SHEAR LOAD PREDICTION F45F

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DILATANCY PREDICTION F45R

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SHEAR LOAD PREDICTION F45R

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DILATANCY PREDICTION F41F

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SHEAR LOAD PREDICTION F41F

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DILATANCY PREDICTION F41R

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SHEAR LOAD PREDICTION F41R

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DILATANCY PREDICTION F42F

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SHEAR LOAD PREDICTION F42F

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DILATANCY PREDICTION F42R

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SHEAR LOAD PREDICTION F42R

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DILATANCY PREDICTION F43F

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SHEAR LOAD PREDICTION F43F

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DILATANCY PREDICTION F43R

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SHEAR LOAD PREDICTION F43R

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DILATANCY PREDICTION F44F

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SHEAR LOAD PREDICTION F44F

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DILATANCY PREDICTION F44R

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SHEAR LOAD PREDICTION F44R

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DILATANCY PREDICTION F45F

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SHEAR LOAD PREDICTION F45F

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DILATANCY PREDICTION F45R

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SHEAR LOAD PREDICTION F45R

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DILATANCY PREDICTION F41F

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SHEAR LOAD PREDICTION F41F

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DILATANCY PREDICTION F41R

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SHEAR LOAD PREDICTION F41R

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DILATANCY PREDICTION F42F

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SHEAR LOAD PREDICTION F42F

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DILATANCY PREDICTION F42R

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SHEAR LOAD PREDICTION F42R

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DILATANCY PREDICTION F43F

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SHEAR LOAD PREDICTION F43F

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DILATANCY PREDICTION F43R

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SHEAR LOAD PREDICTION F43R

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DILATANCY PREDICTION F44F

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SHEAR LOAD PREDICTION F44F

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DILATANCY PREDICTION F44R

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SHEAR LOAD PREDICTION F44R

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DILATANCY PREDICTION F31F

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SHEAR LOAD PREDICTION F31F

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DILATANCY PREDICTION F31R

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SHEAR LOAD PREDICTION F31R

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DILATANCY PREDICTION F32F

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SHEAR LOAD PREDICTION F32F

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DILATANCY PREDICTION F32R

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SHEAR LOAD PREDICTION F32R

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DILATANCY PREDICTION F33F

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DILATANCY PREDICTION F33R

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SHEAR LOAD PREDICTION F33R

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DILATANCY PREDICTION F34F

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DILATANCY PREDICTION F34R

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SHEAR LOAD PREDICTION F34R

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DILATANCY PREDICTION F35F

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SHEAR LOAD PREDICTION F35F

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DILATANCY PREDICTION F35R

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SHEAR LOAD PREDICTION F35R

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DILATANCY PREDICTION F31F

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SHEAR LOAD PREDICTION F31F

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DILATANCY PREDICTION F31R

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SHEAR LOAD PREDICTION F31R

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DILATANCY PREDICTION F32F

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SHEAR LOAD PREDICTION F32F

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DILATANCY PREDICTION F32R

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SHEAR LOAD PREDICTION F32R

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DILATANCY PREDICTION F33F

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SHEAR LOAD PREDICTION F33F

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DILATANCY PREDICTION F33R

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SHEAR LOAD PREDICTION F33R

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DILATANCY PREDICTION F34F

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SHEAR LOAD PREDICTION F34F

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DILATANCY PREDICTION F34R

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SHEAR LOAD PREDICTION F34R

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DILATANCY PREDICTION F35F

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SHEAR LOAD PREDICTION F35F

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DILATANCY PREDICTION F35R

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SHEAR LOAD PREDICTION F35R

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DILATANCY PREDICTION F31F

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SHEAR LOAD PREDICTION F31F

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DILATANCY PREDICTION F31R

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SHEAR LOAD PREDICTION F31R

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DILATANCY PREDICTION F32F

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SHEAR LOAD PREDICTION F32F

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DILATANCY PREDICTION F32R

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SHEAR LOAD PREDICTION F32R

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DILATANCY PREDICTION F33F

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SHEAR LOAD PREDICTION F33F

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DILATANCY PREDICTION F33R

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SHEAR LOAD PREDICTION F33R

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DILATANCY PREDICTION F34F

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SHEAR LOAD PREDICTION F34F

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DILATANCY PREDICTION F34R

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SHEAR LOAD PREDICTION F34R

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DILATANCY PREDICTION F35F

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SHEAR LOAD PREDICTION F35F

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DILATANCY PREDICTION F35R

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SHEAR LOAD PREDICTION F35R

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DILATANCY PREDICTION F31F

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SHEAR LOAD PREDICTION F31F

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DILATANCY PREDICTION F31R

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SHEAR LOAD PREDICTION F31R

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DILATANCY PREDICTION F32F

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SHEAR LOAD PREDICTION F32F

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DILATANCY PREDICTION F32R

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SHEAR LOAD PREDICTION F32R

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DILATANCY PREDICTION F33F

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SHEAR LOAD PREDICTION F33F

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DILATANCY PREDICTION F33R

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SHEAR LOAD PREDICTION F33R

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DILATANCY PREDICTION F34F

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SHEAR LOAD PREDICTION F34F

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DILATANCY PREDICTION F34R

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SHEAR LOAD PREDICTION F34R

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DILATANCY PREDICTION F35F

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SHEAR LOAD PREDICTION F35F

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DILATANCY PREDICTION F35R

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SHEAR LOAD PREDICTION F35R

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DILATANCY PREDICTION F31F

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SHEAR LOAD PREDICTION F31F

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DILATANCY PREDICTION F31R

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SHEAR LOAD PREDICTION F31R

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DILATANCY PREDICTION F32F

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SHEAR LOAD PREDICTION F32F

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DILATANCY PREDICTION F32R

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SHEAR LOAD PREDICTION F32R

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DILATANCY PREDICTION F33F

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SHEAR LOAD PREDICTION F33F

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DILATANCY PREDICTION F33R

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SHEAR LOAD PREDICTION F33R

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DILATANCY PREDICTION F34F

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SHEAR LOAD PREDICTION F34F

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DILATANCY PREDICTION F34R

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SHEAR LOAD PREDICTION F34R

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DILATANCY PREDICTION F35F

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SHEAR LOAD PREDICTION F35F

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DILATANCY PREDICTION F35R

K=187.5 KIPS/IN, NORMAL LOAD=7.5 KIPS

SHEAR LOAD PREDICTION F35R

K=187.5 KIPS/IN, NORMAL LOAD=7.5 KIPS

DILATANCY PREDICTION F21F **K=14.8 KIPS/IN, NORMAL LOAD=3.0 KIPS**

SHEAR LOAD PREDICTION F21F **K=14.8 KIPS/IN, NORMAL LOAD=3.0 KIPS**

DILATANCY PREDICTION F21R K=14.8 KIPS/IN, NORMAL LOAD=3.0 KIPS

SHEAR LOAD PREDICTION F21R K=14.8 KIPS/IN, NORMAL LOAD=3.0 KIPS

DILATANCY PREDICTION F22F **K=14.8 KIPS/IN, NORMAL LOAD=3.0 KIPS**

SHEAR LOAD PREDICTION F22F **K=14.8 KIPS/IN, NORMAL LOAD=3.0 KIPS**

DILATANCY PREDICTION F22R K=14.8 KIPS/IN, NORMAL LOAD=3.0 KIPS

SHEAR LOAD PREDICTION F22R K=14.8 KIPS/IN, NORMAL LOAD=3.0 KIPS

DILATANCY PREDICTION F23F **K=14.8 KIPS/IN, NORMAL LOAD=3.0 KIPS**

SHEAR LOAD PREDICTION F23F **K=14.8 KIPS/IN, NORMAL LOAD=3.0 KIPS**

DILATANCY PREDICTION F23R K=14.8 KIPS/IN, NORMAL LOAD=3.0 KIPS

SHEAR LOAD PREDICTION F23R K=14.8 KIPS/IN, NORMAL LOAD=3.0 KIPS

DILATANCY PREDICTION F24F **K=14.8 KIPS/IN, NORMAL LOAD=3.0 KIPS**

SHEAR LOAD PREDICTION F24F **K=14.8 KIPS/IN, NORMAL LOAD=3.0 KIPS**

DILATANCY PREDICTION F24R K=14.8 KIPS/IN, NORMAL LOAD=3.0 KIPS

SHEAR LOAD PREDICTION F24R K=14.8 KIPS/IN, NORMAL LOAD=3.0 KIPS

DILATANCY PREDICTION F25F **K=14.8 KIPS/IN, NORMAL LOAD=3.0 KIPS**

SHEAR LOAD PREDICTION F25F **K=14.8 KIPS/IN, NORMAL LOAD=3.0 KIPS**

DILATANCY PREDICTION F25R
K=14.8 KIPS/IN, NORMAL LOAD=3.0 KIPS

SHEAR LOAD PREDICTION F25R
K=14.8 KIPS/IN, NORMAL LOAD=3.0 KIPS

SHEAR LOAD PREDICTION F21F
 $K=44.3$ KIPS/IN, NORMAL LOAD=3.0 KIPS

DILATANCY PREDICTION F21F
 $K=44.3$ KIPS/IN, NORMAL LOAD=3.0 KIPS

DILATANCY PREDICTION F21R K=44.3 KIPS, NORMAL LOAD=3.0 KIPS

SHEAR LOAD PREDICTION F21R K=44.3 KIPS/IN, NORMAL LOAD=3.0 KIPS

DILATANCY PREDICTION F22F **K=44.3 KIPS/IN, NORMAL LOAD=3.0 KIPS**

SHEAR LOAD PREDICTION F22F **K=44.3 KIPS/IN, NORMAL LOAD=3.0 KIPS**

DILATANCY PREDICTION F22R **K=44.3 KIPS/IN, NORMAL LOAD=3.0 KIPS**

SHEAR LOAD PREDICTION F22R **K=44.3 KIPS/IN, NORMAL LOAD=3.0 KIPS**

DILATANCY PREDICTION F23F **K=44.3 KIPS/IN, NORMAL LOAD=3.0 KIPS**

SHEAR LOAD PREDICTION F23F **K=44.3 KIPS/IN, NORMAL LOAD=3.0 KIPS**

DILATANCY PREDICTION F23R K=44.3 KIPS/IN, NORMAL LOAD=3.0 KIPS

SHEAR LOAD PREDICTION F23R K=44.3 KIPS/IN, NORMAL LOAD=3.0 KIPS

DILATANCY PREDICTION F24F **K=44.3 KIPS/IN, NORMAL LOAD=3.0 KIPS**

SHEAR LOAD PREDICTION F24F **K=44.3 KIPS/IN, NORMAL LOAD=3.0 KIPS**

DILATANCY PREDICTION F24R K=44.3 KIPS/IN, NORMAL LOAD=3.0 KIPS

SHEAR LOAD PREDICTION F24R K=44.3 KIPS/IN, NORMAL LOAD=3.0 KIPS

DILATANCY PREDICTION F21F **K=147.7 KIPS/IN, NORMAL LOAD=3.0 KIPS**

SHEAR LOAD PREDICTION F21F **K=147.7 KIPS/IN, NORMAL LOAD=3.0 KIPS**

DILATANCY PREDICTION F21R K=147.7 KIPS/IN, NORMAL LOAD=3.0 KIPS

SHEAR LOAD PREDICTION F21R K=147.7 KIPS/IN, NORMAL LOAD=3.0 KIPS

DILATANCY PREDICTION F22F **K=147.7 KIPS/IN, NORMAL LOAD=3.0 KIPS**

SHEAR LOAD PREDICTION F22F **K=147.7 KIPS/IN, NORMAL LOAD=3.0 KIPS**

DILATANCY PREDICTION F22R K=147.7 KIPS/IN, NORMAL LOAD=3.0 KIPS

SHEAR LOAD PREDICTION F22R K=147.7 KIPS/IN, NORMAL LOAD=3.0 KIPS

DILATANCY PREDICTION F23F **K=147.7 KIPS/IN, NORMAL LOAD=3.0 KIPS**

SHEAR LOAD PREDICTION F23F **K=147.7 KIPS/IN, NORMAL LOAD=3.0 KIPS**

DILATANCY PREDICTION F23R **K=147.7 KIPS/IN, NORMAL LOAD=3.0 KIPS**

SHEAR LOAD PREDICTION F23R **K=147.7 KIPS/IN, NORMAL LOAD=3.0 KIPS**

DILATANCY PREDICTION F24F **K=147.7 KIPS/IN, NORMAL LOAD=3.0 KIPS**

SHEAR LOAD PREDICTION F24F **K=147.7 KIPS/IN, NORMAL LOAD=3.0 KIPS**

DILATANCY PREDICTION F24R K=147.7 KIPS/IN, NORMAL LOAD=3.0 KIPS

SHEAR LOAD PREDICTION F24R K=147.7 KIPS/IN, NORMAL LOAD=3.0 KIPS

DILATANCY PREDICTION F25F **K=147.7 KIPS/IN, NORMAL LOAD=3.0 KIPS**

SHEAR LOAD PREDICTION F25F **K=147.7 KIPS/IN, NORMAL LOAD=3.0 KIPS**

DILATANCY PREDICTION G21F K=32 KIPS/IN, NORMAL LOAD=1.3 KIPS

SHEAR LOAD PREDICTION G21F K=32 KIPS/IN, NORMAL LOAD=1.3 KIPS

DILATANCY PREDICTION G21R K=32 KIPS/IN, NORMAL LOAD=1.3 KIPS

SHEAR LOAD PREDICTION G21R K=32 KIPS/IN, NORMAL LOAD=1.3 KIPS

DILATANCY PREDICTION G22F K=32 KIPS/IN, NORMAL LOAD=1.3 KIPS

SHEAR LOAD PREDICTION G22F K=32 KIPS/IN, NORMAL LOAD=1.3 KIPS

DILATANCY PREDICTION G22R K=32 KIPS/IN, NORMAL LOAD=1.3 KIPS

SHEAR LOAD PREDICTION G22R K=32 KIPS/IN, NORMAL LOAD=1.3 KIPS

DILATANCY PREDICTION G21F K=64 KIPS/IN, NORMAL LOAD=6.4 KIPS

SHEAR LOAD PREDICTION G21F K=64 KIPS/IN, NORMAL LOAD=6.4 KIPS

DILATANCY PREDICTION G21R K=64 KIPS/IN, NORMAL LOAD=6.4 KIPS

SHEAR LOAD PREDICTION G21R K=64 KIPS/IN, NORMAL LOAD=6.4 KIPS

DILATANCY PREDICTION G22F K=64 KIPS/IN, NORMAL LOAD=6.4 KIPS

SHEAR LOAD PREDICTION G22F K=64 KIPS/IN, NORMAL LOAD=6.4 KIPS

DILATANCY PREDICTION G22R K=64 KIPS/IN, NORMAL LOAD=6.4 KIPS

SHEAR LOAD PREDICTION G22R K=64 KIPS/IN, NORMAL LOAD=6.4 KIPS

APPENDIX C

Coefficient of correlation, standard error, and coefficient of variation load

KR7F4	Dilatancy comparison, Normal Load = 3.6 kips; K = 18.0 kips/in	C-1
KR7F4	Shear load comparison, Normal Load = 3.6 kips; K = 18.0 kips/in	C-1
KR9F4	Dilatancy comparison, Normal Load = 3.6 kips; K = 54.0 kips/in	C-2
KR9F4	Shear load comparison, Normal Load = 3.6 kips; K = 54.0 kips/in	C-2
KR10F4	Dilatancy comparison, Normal Load = 3.6 kips; K=179.9 kips/in	C-3
KR10F4	Shear load comparison, Normal Load = 3.6 kips; K=179.9 kips/in	C-3
KR11F4	Dilatancy comparison, Normal Load = 7.2 kips; K = 54.0 kips/in	C-4
KR11F4	Shear load comparison, Normal Load = 7.2 kips; K = 54.0 kips/in	C-4
KR12F4	Dilatancy comparison, Normal Load = 7.2 kips; K = 179.9 kips/in	C-5
KR12F4	Shear load comparison, Normal Load = 7.2 kips; K = 179.9 kips/in	C-5
KR7F3	Dilatancy comparison, Normal Load = 3.8 kips; K = 18.8 kips/in	C-6
KR7F3	Shear load comparison, Normal Load = 3.8 kips; K = 18.8 kips/in	C-6
KR8F3	Dilatancy comparison, Normal Load = 3.8 kips; K = 56.3 kips/in	C-7
KR8F3	Shear load comparison, Normal Load = 3.8 kips; K = 56.3 kips/in	C-7
KR9F3	Dilatancy comparison, Normal Load = 3.8 kips; K = 187.5 kips/in	C-8

SAMPLE	DESCRIPTION	PAGE
KR9F3	Shear load comparison, Normal Load = 3.8 kips; K = 187.5 kips/in	C-8
KR10F3	Dilatancy comparison, Normal Load = 7.5 kips; K = 56.3 kips/in	C-9
KR10F3	Shear load comparison, Normal Load = 7.5 kips; K = 56.3 kips/in	C-9
KR11F3	Dilatancy comparison, Normal Load = 7.5 kips; K = 187.5 kips/in	C-10
KR11F3	Shear load comparison, Normal Load = 7.5 kips; K = 187.5 kips/in	C-10
KR6F2	Dilatancy comparison, Normal Load = 3.0 kips; K = 14.8 kips/in	C-11
KR6F2	Shear load comparison, Normal Load = 3.0 kips; K = 14.8 kips/in	C-11
KR7F2	Dilatancy comparison, Normal Load = 3.0 kips; K = 44.3 kips/in	C-12
KR7F2	Shear load comparison, Normal Load = 3.0 kips; K = 44.3 kips/in	C-12
KR8F2	Dilatancy comparison, Normal Load = 3.0 kips; K = 147.8 kips/in	C-13
KR8F2	Shear load comparison, Normal Load = 3.0 kips; K = 147.8 kips/in	C-13
KR5G2	Dilatancy comparison, Normal Load = 1.3 kips; K = 32 kips/in	C-14
KR5G2	Shear load comparison, Normal Load = 1.3 kips; K = 32 kips/in	C-14
KR6G2	Dilatancy comparison, Normal Load = 6.4 kips; K = 64 kips/in	C-15
KR6G2	Shear load comparison, Normal Load = 6.4 kips; K = 64 kips/in	C-15

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Dilatancy. Sample KR7F4 Tested under initial normal load 3.6 kips and applied stiffness 18.0 kips/in.

Sample KR7F4	Coefficient of Correlation (r)	Standard Error (s) (10 ⁻³ in.)	Coefficient of Variation (v)
Forward			
1st cycle	1.00	0.9	0.05
2nd cycle	1.00	2.7	0.18
3rd cycle	1.00	1.9	0.15
4th cycle	1.00	3.6	0.34
5th cycle	1.00	4.0	0.44
Reverse			
1st cycle	1.00	1.9	0.11
2nd cycle	1.00	1.2	0.10
3rd cycle	1.00	1.3	0.14
4th cycle	1.00	1.4	0.17
5th cycle	1.00	1.6	0.23

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Shear Load. Sample KR7F4 tested under initial normal load 3.6 kips and applied stiffness 18.0 kips/in.

Sample KR7F4	Coefficient of Correlation (r)	Standard Error (s) (kips)	Coefficient of Variation (v)
Forward			
1st cycle	0.98	0.62	0.15
2nd cycle	0.91	0.79	0.26
3rd cycle	0.88	0.82	0.29
4th cycle	0.67	0.95	0.35
5th cycle	0.96	0.83	0.31
Reverse			
1st cycle	0.95	0.67	0.18
2nd cycle	0.84	0.58	0.19
3rd cycle	0.55	0.61	0.21
4th cycle	0.61	0.59	0.21
5th cycle	0.62	0.60	0.21

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Dilatancy. Sample KR9F4 tested under initial normal load 3.6 kips and applied stiffness 54.0 kips/in.

Sample KR9F4	Coefficient of Correlation (r)	Standard Error (s) (10 ⁻³ in.)	Coefficient of Variation (v)
Forward			
1st cycle	1.00	2.6	0.12
2nd cycle	1.00	3.0	0.20
3rd cycle	1.00	2.9	0.24
4th cycle	1.00	3.2	0.30
5th cycle	1.00	3.6	0.35
Reverse			
1st cycle	1.00	2.3	0.16
2nd cycle	1.00	1.9	0.21
3rd cycle	1.00	2.1	0.28
4th cycle	1.00	2.2	0.33
5th cycle	1.00	2.6	0.41

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Shear Load. Sample KR9F4 tested under initial normal load 3.6 kips and applied stiffness 54.0 kips/in.

Sample KR9F4	Coefficient of Correlation (r)	Standard Error (s) (kips)	Coefficient of Variation (v)
Forward			
1st cycle	0.41	0.36	0.09
2nd cycle	0.99	0.63	0.19
3rd cycle	0.99	0.68	0.22
4th cycle	0.91	0.89	0.30
5th cycle	0.99	0.78	0.27
Reverse			
1st cycle	0.87	0.71	0.17
2nd cycle	0.98	0.67	0.20
3rd cycle	0.98	0.68	0.22
4th cycle	0.98	0.89	0.23
5th cycle	0.99	0.78	0.24

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Dilatancy. Sample KR10F4 tested under initial normal load 3.6 kips and applied stiffness 179.9 kips/in.

Sample KR10F4	Coefficient of Correlation (r)	Standard Error (s) (10 ⁻³ in.)	Coefficient of Variation (v)
Forward			
1st cycle	1.00	2.6	0.17
2nd cycle	1.00	2.9	0.31
3rd cycle	1.00	2.6	0.38
4th cycle	1.00	3.3	0.60
5th cycle	1.00	4.1	0.87
Reverse			
1st cycle	1.00	7.1	0.47
2nd cycle	1.00	7.2	0.73
3rd cycle	1.00	7.6	0.92
4th cycle	1.00	8.2	1.13
5th cycle	0.99	9.9	1.35

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Shear Load. Sample KR10F4 tested under initial normal load 3.6 kips and applied stiffness 179.9 kips/in.

Sample KR10F4	Coefficient of Correlation (r)	Standard Error (s) (kips)	Coefficient of Variation (v)
Forward			
1st cycle	1.00	0.67	0.13
2nd cycle	1.00	0.24	0.07
3rd cycle	0.99	0.23	0.07
4th cycle	0.98	0.42	0.14
5th cycle	1.00	0.33	0.11
Reverse			
1st cycle	0.96	1.07	0.22
2nd cycle	1.00	1.00	0.27
3rd cycle	0.99	0.98	0.29
4th cycle	0.98	0.95	0.29
5th cycle	1.00	0.96	0.30

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Dilatancy. Sample KR11F4 tested under initial normal load 7.2 kips and applied stiffness 54.0 kips/in.

Sample KR11F4	Coefficient of Correlation (r)	Standard Error (s) (10 ⁻³ in.)	Coefficient of Variation (v)
Forward			
1st cycle	1.00	5.6	0.28
2nd cycle	1.00	5.3	0.58
3rd cycle	1.00	5.8	1.01
4th cycle	1.00	6.8	1.64
5th cycle	1.00	7.4	2.88
Reverse			
1st cycle	1.00	3.4	0.39
2nd cycle	1.00	4.4	1.60
3rd cycle	0.97	7.0	3.79
4th cycle	1.00	6.3	8.94
5th cycle	1.00	7.2	3.67

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Shear Load. Sample KR11F4 tested under initial normal load 7.2 kips and applied stiffness 54.0 kips/in.

Sample KR11F4	Coefficient of Correlation (r)	Standard Error (s) (kips)	Coefficient of Variation (v)
Forward			
1st cycle	0.90	1.45	0.17
2nd cycle	0.92	1.25	0.21
3rd cycle	0.95	1.46	0.25
4th cycle	0.95	1.70	0.29
5th cycle	0.98	1.80	0.31
Reverse			
1st cycle	0.70	0.62	0.09
2nd cycle	0.82	0.30	0.05
3rd cycle	0.87	0.52	0.09
4th cycle	0.91	0.58	0.10
5th cycle	0.94	0.58	0.11

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Dilatancy. Sample KR12F4 tested under initial normal load 7.2 kips and applied stiffness 179.9 kips/in.

Sample KR12F4	Coefficient of Correlation (r)	Standard Error (s) (10 ⁻³ in.)	Coefficient of Variation (v)
Forward			
1st cycle	1.00	4.0	0.28
2nd cycle	1.00	1.8	0.70
3rd cycle	1.00	2.0	3.42
4th cycle	1.00	2.5	1.05
5th cycle	-	-	-
Reverse			
1st cycle	1.00	0.7	0.21
2nd cycle	1.00	0.8	0.25
3rd cycle	1.00	0.7	0.12
4th cycle	1.00	0.9	0.12
5th cycle	-	-	-

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Shear Load. Sample KR12F4 tested under initial normal load 7.2 kips and applied stiffness 179.9 kips/in.

Sample KR12F4	Coefficient of Correlation (r)	Standard Error (s) (kips)	Coefficient of Variation (v)
Forward			
1st cycle	0.99	0.29	0.03
2nd cycle	1.00	0.18	0.03
3rd cycle	0.99	0.30	0.06
4th cycle	0.99	0.39	0.07
5th cycle	-	-	-
Reverse			
1st cycle	0.94	1.25	0.18
2nd cycle	1.00	1.14	0.21
3rd cycle	1.00	0.97	0.19
4th cycle	1.00	0.94	0.19
5th cycle	-	-	-

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Dilatancy. Sample KR7F3 tested under initial normal load 3.8 kips and applied stiffness 18.8 kips/in.

Sample KR7F3	Coefficient of Correlation (r)	Standard Error (s) (10 ⁻³ in.)	Coefficient of Variation (v)
Forward			
1st cycle	1.00	5.6	0.19
2nd cycle	1.00	6.1	0.24
3rd cycle	1.00	6.2	0.27
4th cycle	1.00	5.8	0.26
5th cycle	0.99	5.1	0.23
Reverse			
1st cycle	1.00	3.1	0.12
2nd cycle	1.00	4.2	0.20
3rd cycle	1.00	4.9	0.26
4th cycle	1.00	5.7	0.32
5th cycle	1.00	5.7	0.32

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Shear Load. Sample KR7F3 tested under initial normal load 3.8 kips and applied stiffness 18.8 kips/in.

Sample KR7F3	Coefficient of Correlation (r)	Standard Error (s) (kips)	Coefficient of Variation (v)
Forward			
1st cycle	0.04	0.36	0.12
2nd cycle	0.92	0.50	0.23
3rd cycle	0.80	0.61	0.31
4th cycle	0.54	0.53	0.28
5th cycle	0.54	0.46	0.23
Reverse			
1st cycle	0.34	0.53	0.15
2nd cycle	0.80	0.24	0.09
3rd cycle	0.62	0.16	0.06
4th cycle	0.60	0.14	0.05
5th cycle	0.72	0.09	0.03

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Dilatancy. Sample KR8F3 tested under initial normal load 3.8 kips and applied stiffness 56.3 kips/in.

Sample KR8F3	Coefficient of Correlation (r)	Standard Error (s) (10 ⁻³ in.)	Coefficient of Variation (v)
Forward			
1st cycle	1.00	2.2	0.07
2nd cycle	1.00	1.4	0.06
3rd cycle	1.00	3.7	0.16
4th cycle	1.00	4.5	0.20
5th cycle	1.00	5.1	0.23
Reverse			
1st cycle	1.00	2.4	0.09
2nd cycle	1.00	3.3	0.18
3rd cycle	0.99	3.6	0.22
4th cycle	0.99	4.2	0.27
5th cycle	0.99	4.1	0.28

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Shear Load. Sample KR8F3 tested under initial normal load 3.8 kips and applied stiffness 56.3 kips/in.

Sample KR8F3	Coefficient of Correlation (r)	Standard Error (s) (kips)	Coefficient of Variation (v)
Forward			
1st cycle	0.98	0.71	0.20
2nd cycle	0.99	0.55	0.20
3rd cycle	0.98	0.55	0.22
4th cycle	1.00	0.49	0.20
5th cycle	1.00	0.50	0.21
Reverse			
1st cycle	0.92	0.94	0.25
2nd cycle	0.94	0.72	0.24
3rd cycle	0.96	0.63	0.23
4th cycle	0.96	0.54	0.20
5th cycle	0.98	0.53	0.20

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Dilatancy. Sample KR9F3 tested under initial normal load 3.8 kips and applied stiffness 187.5 kips/in.

Sample KR9F3	Coefficient of Correlation (r)	Standard Error (s) (10 ⁻³ in.)	Coefficient of Variation (v)
Forward			
1st cycle	0.99	4.3	0.19
2nd cycle	1.00	3.5	0.22
3rd cycle	0.99	3.3	0.22
4th cycle	1.00	3.2	0.24
5th cycle	1.00	3.4	0.27
Reverse			
1st cycle	0.99	3.5	0.22
2nd cycle	0.98	5.0	0.52
3rd cycle	0.98	4.8	0.64
4th cycle	0.97	4.7	0.71
5th cycle	0.99	4.6	0.81

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Shear Load. Sample KR9F3 tested under initial normal load 3.8 kips and applied stiffness 187.5 kips/in.

Sample KR9F3	Coefficient of Correlation (r)	Standard Error (s) (kips)	Coefficient of Variation (v)
Forward			
1st cycle	0.97	2.12	0.50
2nd cycle	0.94	1.62	0.55
3rd cycle	0.97	1.46	0.54
4th cycle	1.00	1.23	0.47
5th cycle	1.00	1.22	0.48
Reverse			
1st cycle	0.96	2.69	0.64
2nd cycle	0.91	1.89	0.61
3rd cycle	0.95	1.59	0.55
4th cycle	0.97	1.34	0.47
5th cycle	0.99	1.33	0.49

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Dilatancy. Sample KR10F3 tested under initial normal load 7.5 kips and applied stiffness 56.3 kips/in.

Sample KR10F3	Coefficient of Correlation (r)	Standard Error (s) (10 ⁻³ in.)	Coefficient of Variation (v)
Forward			
1st cycle	1.00	12.2	0.65
2nd cycle	1.00	12.6	1.31
3rd cycle	1.00	12.0	1.82
4th cycle	1.00	12.0	3.02
5th cycle	1.00	12.2	6.98
Reverse			
1st cycle	1.00	9.7	0.76
2nd cycle	1.00	9.7	2.12
3rd cycle	1.00	10.6	11.08
4th cycle	1.00	10.6	7.26
5th cycle	1.00	11.1	3.17

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Shear Load. Sample KR10F3 tested under initial normal load 7.5 kips and applied stiffness 56.3 kips/in.

Sample KR10F3	Coefficient of Correlation (r)	Standard Error (s) (kips)	Coefficient of Variation (v)
Forward			
1st cycle	0.27	0.71	0.10
2nd cycle	0.93	0.11	0.02
3rd cycle	0.68	0.20	0.04
4th cycle	0.52	0.28	0.06
5th cycle	0.46	0.38	0.08
Reverse			
1st cycle	0.62	2.36	0.25
2nd cycle	0.05	1.76	0.25
3rd cycle	0.50	1.75	0.26
4th cycle	0.73	1.84	0.28
5th cycle	0.83	1.67	0.27

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Dilatancy. Sample KR11F3 tested under initial normal load 7.5 kips and applied stiffness 187.5 kips/in.

Sample KR11F3	Coefficient of Correlation (r)	Standard Error (s) (10 ⁻³ in.)	Coefficient of Variation (v)
Forward			
1st cycle	0.99	4.5	0.26
2nd cycle	0.99	4.6	0.46
3rd cycle	0.99	5.1	0.74
4th cycle	0.99	4.6	0.86
5th cycle	1.00	4.3	1.07
Reverse			
1st cycle	0.99	5.4	0.49
2nd cycle	0.99	5.4	1.68
3rd cycle	0.99	6.2	26.38
4th cycle	0.99	6.2	3.44
5th cycle	0.99	6.5	1.88

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Shear Load. Sample KR11F3 tested under initial normal load 7.5 kips and applied stiffness 187.5 kips/in.

Sample KR11F3	Coefficient of Correlation (r)	Standard Error (s) (kips)	Coefficient of Variation (v)
Forward			
1st cycle	1.00	0.79	0.09
2nd cycle	0.97	0.76	0.12
3rd cycle	0.99	0.68	0.12
4th cycle	0.99	0.70	0.12
5th cycle	0.99	0.68	0.12
Reverse			
1st cycle	0.99	0.79	0.09
2nd cycle	0.93	0.54	0.08
3rd cycle	0.98	0.46	0.08
4th cycle	0.99	0.45	0.08
5th cycle	1.00	0.38	0.07

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Dilatancy. Sample KR6F2 tested under initial normal load 3.0 kips and applied stiffness 14.8 kips/in.

Sample KR6F2	Coefficient of Correlation (r)	Standard Error (s) (10 ⁻³ in.)	Coefficient of Variation (v)
Forward			
1st cycle	1.00	2.6	0.09
2nd cycle	1.00	4.0	0.18
3rd cycle	1.00	4.0	0.19
4th cycle	1.00	8.4	0.68
5th cycle	1.00	8.9	0.83
Reverse			
1st cycle	0.99	5.7	1.28
2nd cycle	0.99	10.3	3.00
3rd cycle	0.99	11.2	2.20
4th cycle	0.99	17.5	1.54
5th cycle	0.99	18.4	1.45

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Shear Load KR6F2 tested under initial normal load 3.0 kips and applied stiffness 14.8 kips/in.

Sample KR6F2	Coefficient of Correlation (r)	Standard Error (s) (kips)	Coefficient of Variation (v)
Forward			
1st cycle	0.76	0.41	0.19
2nd cycle	0.07	0.31	0.18
3rd cycle	0.53	0.28	0.18
4th cycle	0.78	0.21	0.14
5th cycle	0.47	0.15	0.10
Reverse			
1st cycle	0.97	0.22	0.13
2nd cycle	0.94	0.17	0.11
3rd cycle	0.89	0.17	0.12
4th cycle	0.94	0.16	0.12
5th cycle	0.99	0.22	0.16

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Dilatancy. Sample KR7F2 tested under initial normal load 3.0 kips and applied stiffness 44.3 kips/in.

Sample KR7F2	Coefficient of Correlation (r)	Standard Error (s) (10 ⁻³ in.)	Coefficient of Variation (v)
Forward			
1st cycle	1.00	1.9	0.07
2nd cycle	1.00	1.9	0.10
3rd cycle	0.99	3.9	0.19
4th cycle	0.97	9.4	0.40
5th cycle	-	-	-
Reverse			
1st cycle	1.00	2.1	0.19
2nd cycle	0.99	7.2	0.58
3rd cycle	0.98	14.7	0.78
4th cycle	0.98	22.0	0.92
5th cycle	-	-	-

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Shear Load. Sample KR7F2 tested under initial normal load 3.0 kips and applied stiffness 44.3 kips/in.

Sample KR7F2	Coefficient of Correlation (r)	Standard Error (s) (kips)	Coefficient of Variation (v)
Forward			
1st cycle	0.32	0.33	0.13
2nd cycle	0.97	0.18	0.09
3rd cycle	0.96	0.28	0.16
4th cycle	0.76	0.55	0.40
5th cycle	-	-	-
Reverse			
1st cycle	0.96	0.18	0.10
2nd cycle	0.94	0.16	0.10
3rd cycle	0.62	0.16	0.11
4th cycle	0.60	0.56	0.32
5th cycle	-	-	-

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Dilatancy. Sample KR8F2 tested under initial normal load 3.0 kips and applied stiffness 147.8 kips/in.

Sample KR8F2	Coefficient of Correlation (r)	Standard Error (s) (10 ⁻³ in.)	Coefficient of Variation (v)
Forward			
1st cycle	1.00	8.4	0.33
2nd cycle	1.00	7.7	0.39
3rd cycle	1.00	8.9	0.50
4th cycle	1.00	8.5	0.51
5th cycle	1.00	10.6	0.66
Reverse			
1st cycle	0.95	2.4	0.41
2nd cycle	0.96	4.0	2.60
3rd cycle	0.93	4.8	20.23
4th cycle	0.92	5.6	10.83
5th cycle	0.92	5.3	4.45

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Shear load. Sample KR8F2 tested under initial normal load 3.0 kips and applied stiffness 147.8 kips/in.

Sample KR8F2	Coefficient of Correlation (r)	Standard Error (s) (kips)	Coefficient of Variation (v)
Forward			
1st cycle	0.98	0.17	0.04
2nd cycle	1.00	0.21	0.08
3rd cycle	0.99	0.42	0.16
4th cycle	0.91	0.56	0.22
5th cycle	0.99	0.73	0.28
Reverse			
1st cycle	0.84	0.18	0.08
2nd cycle	0.42	0.15	0.10
3rd cycle	0.79	0.18	0.12
4th cycle	0.72	0.21	0.14
5th cycle	0.50	0.18	0.13

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Dilatancy. Sample KR5G2 tested under initial normal load 1.3 kips and applied stiffness 32.0 kips/in.

Sample KR5G2	Coefficient of Correlation (r)	Standard Error (s) (10 ⁻³ in.)	Coefficient of Variation (v)
Forward			
1st cycle	1.00	5.9	0.21
2nd cycle	1.00	17.2	0.88
3rd cycle	-	-	-
4th cycle	-	-	-
5th cycle	-	-	-
Reverse			
1st cycle	0.99	37.6	4.59
2nd cycle	0.93	56.7	3.54
3rd cycle	-	-	-
4th cycle	-	-	-
5th cycle	-	-	-

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Shear Load. Sample KR5G2 tested under initial normal load 1.3 kips and applied stiffness 32.0 kips/in.

Sample KR5G2	Coefficient of Correlation (r)	Standard Error (s) (kips)	Coefficient of Variation (v)
Forward			
1st cycle	0.98	0.56	0.28
2nd cycle	0.99	0.29	0.16
3rd cycle	-	-	-
4th cycle	-	-	-
5th cycle	-	-	-
Reverse			
1st cycle	0.99	0.36	0.39
2nd cycle	0.76	0.30	0.39
3rd cycle	-	-	-
4th cycle	-	-	-
5th cycle	-	-	-

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Dilatancy. Sample KR6G2 tested under initial normal load 6.4 kips and applied stiffness 64.0 kips/in.

Sample KR6G2	Coefficient of Correlation (r)	Standard Error (s) (10 ⁻³ in.)	Coefficient of Variation (v)
Forward			
1st cycle	1.00	4.6	0.23
2nd cycle	0.83	19.4	8.84
3rd cycle	-	-	-
4th cycle	-	-	-
5th cycle	-	-	-
Reverse			
1st cycle	0.23	22.4	1.12
2nd cycle	0.64	27.6	0.91
3rd cycle	-	-	-
4th cycle	-	-	-
5th cycle	-	-	-

Coefficient of Correlation, Standard Error, and Coefficient of Variation for Shear Load. Sample KR6G2 tested under initial normal load 6.4 kips and applied stiffness 64.0 kips/in.

Sample KR6G2	Coefficient of Correlation (r)	Standard Error (s) (kips)	Coefficient of Variation (v)
Forward			
1st cycle	0.99	0.34	0.05
2nd cycle	0.71	0.91	0.15
3rd cycle	-	-	-
4th cycle	-	-	-
5th cycle	-	-	-
Reverse			
1st cycle	0.99	1.62	0.38
2nd cycle	0.73	1.22	0.31
3rd cycle	-	-	-
4th cycle	-	-	-
5th cycle	-	-	-

APPENDIX

Information from the Reference Information Base Used in this Report

This report contains no information from the Reference Information Base.

Candidate Information for the Reference Information Base

This report contains no candidate information for the Reference Information Base.

Candidate Information for the Geographic Nodal Information Study and Evaluation System

This report contains no candidate information for the Geographic Nodal Information Study and Evaluation System.

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