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DISCUSSION

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ABSTRACT

In this paper, the authors criticize the fully softened strength (FSS) correlation by Stark and Eid (Stark, T. D. and Eid, H. T., 1997, "Slope Stability Analyses in Stiff Fissured Clays," *J. Geotech. Geoenviron. Eng.*, Vol. 123, No. 4, pp. 335–343) and subsequent updates (Stark, T.D., Choi, H., and McCone, S., 2005, "Shear Strengths for Analysis of Landslides," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 131, No. 5, pp. 575–588; Stark, T. D. and Hussain, M., 2010, "Shear Strength in Preexisting Landslides," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 136, No. 7, pp. 957–962; Gamez, J. and Stark, T. D., 2014, "Fully Softened Shear Strength at Low Stresses for Levee and Embankment Design," *Geotech. Geoenviron. J.*, Vol. 140, No. 9) in the following five areas: (1) use of a torsional ring shear device, (2) converting the ring shear results to the triaxial compression mode of shear, (3) sample processing, (4) a non- continuous strength envelope, and (5) use of three distinct clay-size fraction groups even though admitting that the Stark and Eid (Stark, T.D. and Eid, H.T., 1997, "Slope Stability Analyses in Stiff Fissured Clays," *J. Geotech. Geoenviron. Eng.*, Vol. 123, No. 4, pp. 335–343) correlation "is used widely and has been generally accepted in practice." The authors also use questionable direct shear test data from Castellanos (2014, "Use and Measurement of Fully Softened Shear Strength," Ph.D. dissertation, Virginia Tech, Blacksburg, VA, p. 805, https://www.dropbox.com/s/0k0ym51d8jdmn4v/Castellanos-FSS-Thesis-2014.pdf?dl=0.) to develop a fully softened

strength correlation based on index properties, i.e., clay-size fraction (CF) and plasticity index (PI). The following paragraphs address these five criticisms, the questionable ring shear and direct shear testing presented in Castellanos (2014, "Use and Measurement of Fully Softened Shear Strength," Ph.D. dissertation, Virginia Tech, Blacksburg, VA, p. 805, https://www.dropbox.com/s/0k0ym51d8jdmn4v/Castellanos-FSS-Thesis-2014.pdf?dl=0.), and the proposed FSS correlation.

Keywords

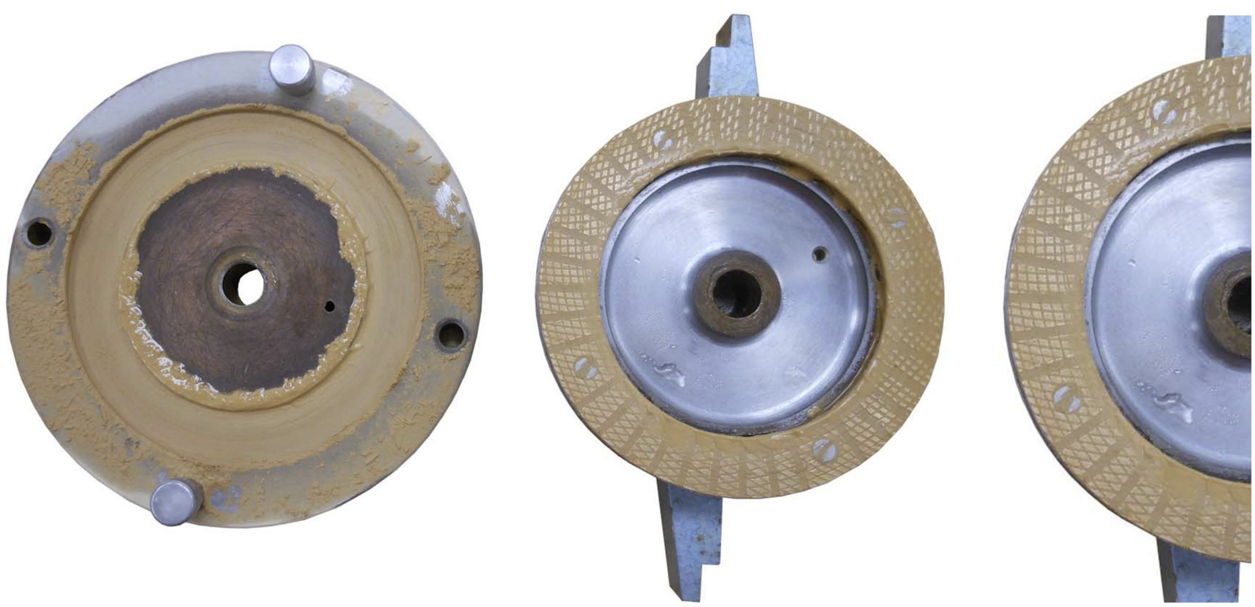
shear strength, fully softened strength, direct shear, ring shear, stiff clay, compacted clay, Atterberg limits, correlation

Torsional Ring Shear Device

Castellanos et al. (2016) claim the torsional ring shear device "results in very conservative fully softened shear strength envelopes." Fig. 1a shows a typical photograph of a ring shear specimen after testing performed by Castellanos (2014). The low and "very conservative" ring shear values reported by Castellanos (2014) are a result of, among other things, sliding of the upper porous disc over the small amount of soil remaining in the specimen container and/or sliding between the upper and lower porous discs. The close-up of the upper porous disc from this test in Fig. 1b shows an insufficient serration or texture pattern to create a strong interlock between the soil and upper porous disc to prevent the soil-on-porous disc and/or porous disc-on-porous disc sliding. In particular, Fig. 1b shows that most of the surface area of the upper porous disc consists of smooth flat surfaces, which do not allow sufficient soil to interlock within the upper porous disc and create a shear surface within the soil instead of at the upper porous disc/soil interface (see Fig. 1a). The horizontal slots cut by the authors in the upper porous disc (Fig. 1b) are also not sufficient to force shearing to occur in the soil specimen as previously reported by Stark and Eid (1993). This lack of interlocking and the limited amount of soil in the specimen container contributed to the low FSS values reported by Castellanos et al. (2013) and Castellanos (2014) and is an artifact of Castellanos' (2014) testing. This conclusion is reinforced below with comparison testing of the Northern Virginia (NOVA) clay tested by Castellanos (2014).

A more aggressive serration pattern (see Fig. 2) than the manufacturer-provided pattern (see Fig. 1b) was developed at the University of Illinois at Urbana-Champaign (UIUC) to promote sufficient interlocking between the soil and upper porous disc. Thus, shearing occurs within the soil specimen and not at the upper porous disc/soil interface as shown in Fig. 1a. This serration pattern results in only about 25 % of the soil area being in contact with the tips of the upper porous disc serration instead of about 80 % with the manufacturer provided porous discs (see Fig. 1b). The serration pattern in Fig. 2 and the test procedures in ASTM D7608-10 (2010) and D6467-13 (2013) are being used by commercial and governmental laboratories to

FIG. 1 Photographs of Alabama 1 non-blenderized ring shear specimen after (a) shearing at an effective normal stress of 167.0 kPa (3489 psf) at a shear displacement of about 37.6 cm (1.48 in.), and (b) close-up of top porous disc after shearing of Alabama 1 showing the smooth and large flat areas on the top porous disc in dashed circle (Castellanos 2014, p. 536).



(a) (b)

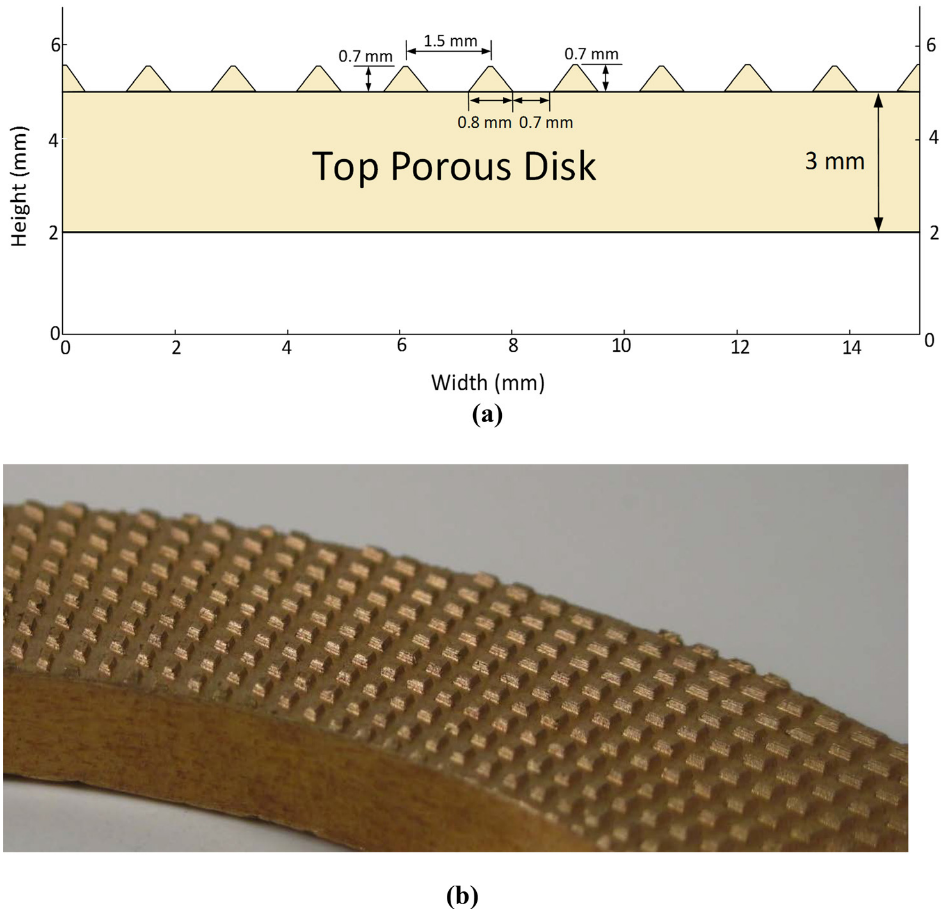


FIG. 2
Serration pattern (a) developed at UIUC to ensure shearing in the ring shear remains in the soil specimen, and (b) photograph of serrated porous disc.

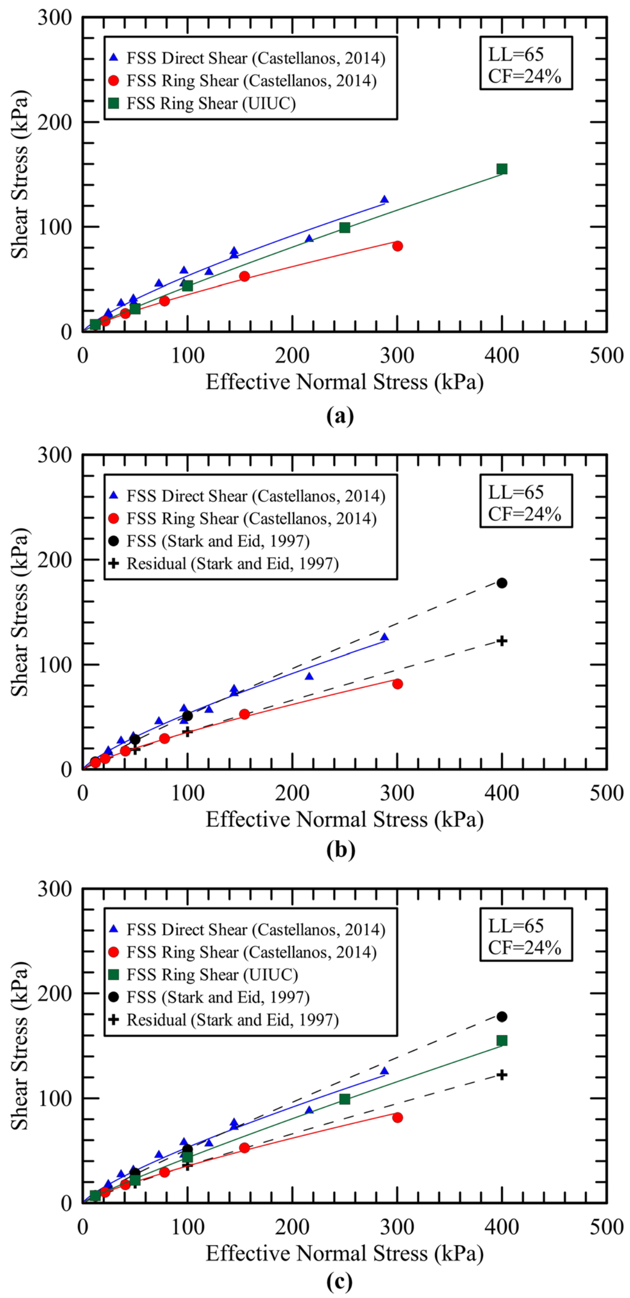
measure values of fully softened strength (FSS) and residual strength, respectively, that are in agreement with the correlations presented by Stark and Eid (1997) and subsequent updates.

Fortunately, the second author provided a split sample of the NOVA clay to the writer for comparison testing before Castellanos (2014) completed his testing. The writer tested this sample in accordance with ASTM D7608-10 (2010) and the upper porous disc shown in **Fig. 2b**. **Fig. 3a** shows that this FSS strength envelope is significantly higher than the ring-shear FSS envelope measured using ring shear tests by Castellanos (2014) but lower than the direct shear–derived FSS envelope from Castellanos (2014), which is discussed below. **Fig. 3b** compares the FSS and residual strength envelopes from the Stark and Eid (1997) correlations with the ring shear FSS values reported by Castellanos (2014) using the liquid limit (LL) and CF of 65 % and 24 %, respectively, measured herein. **Fig. 3b** shows the ring shear FSS values reported by the Castellanos (2014) plot below the residual strength correlation, which confirms problems with his ring shear testing because the FSS always should be greater than the residual strength. **Fig. 3b** also shows the Castellanos (2014) direct shear FSS envelope is in agreement with the FSS correlation, which corresponds to the triaxial mode of shear discussed below. Therefore, the direct shear FSS envelope is too high because it should yield similar FSSs strength as ring shear (Stark et al., 2017). Even using the blenderized LL and CF of 79 % and 35 %, respectively, measured by Castellanos (2014), the ring shear FSS values reported by Castellanos (2014) still plot below the Stark and Eid (1997) residual strength correlation and are in error.

Finally, **Fig. 3c** shows the ring shear FSS values measured herein are in agreement with the Stark and Eid (1997) FSS correlation after the conversion to the triaxial mode of shear discussed below and plot above the residual strength, which is in good agreement with the FSS being greater than the residual strength because there is limited particle re-orientation at the FSS condition. One of the primary uses of an empirical correlation is to verify laboratory data so testing errors can be identified before releasing the data, which was not done by Castellanos (2014).

From these observations, it is concluded that the FSS data reported by Castellanos (2014) and Castellanos et al. (2016) are too low rather than the data in the Stark and Eid (1997) correlation and subsequent updates are too high. The authors should explain why their FSS ring shear envelope for the NOVA clay (see **Fig. 3b**), and other soils tested by Castellanos (2014), plot below the Stark and Eid (1997) residual strength correlation.

FIG. 3 FSS strength envelopes for NOVA clay: (a) measured using direct shear and ring shear by Castellanos (2014) and ring shear by UIUC using ASTM D7608-10 (2010), (b) measured using direct shear and ring shear by Castellanos (2014) and empirical correlation by Stark and Eid (1997) using LL and CF of 65 % and 24 %, and (c) measured using direct shear and ring shear by Castellanos (2014), ring shear by UIUC using ASTM D7608-10 (2010), and empirical correlation by Stark and Eid (1997) using LL and CF of 65 % and 24 %.



The authors also should explain why the torsional ring shear device "results in very conservative fully softened shear strength envelopes" when **Fig. 3a** shows the FSS measured on the NOVA clay using ASTM D7608-10 (2010) and the upper porous disc shown in **Fig. 2b** is significantly higher than the Castellanos (2014) ring shear data and in agreement with the Stark and Eid (1997) correlation.

Triaxial Mode of Shear for FSS Correlations

Based on review of a number of first-time slides (Skempton 1970) in fine-grained cut slopes and compacted embankments, Stark and Eid (1997) determined that the relevant mode of shear for first-time slides is closer to triaxial shear than ring shear. Using the results of consolidated-drained (CD) triaxial compression tests on five different soils at effective confining pressures of 70 and 275 kPa (1463 and 5744 psf), Stark and Eid (1997) introduced a factor of 2.5° to convert the ring shear FSS to the CD triaxial compression mode of shear. This resulted in FSS values that better correspond to the mode of shear observed in "first-time slides" in cut slopes and compacted embankments. Therefore, the fully softened friction angles (ϕ' FSS) presented in Stark and Eid (1997) and subsequent updates (Stark et al. 2005; Stark and Hussain 2013; Gamez and Stark 2014) are ring shear data increased by 2.5° to represent the peak strength of normally consolidated soils with randomly oriented particles in first-time slides in cut slopes and embankments.

Because the failure surface in first-time slides involve low effective normal stresses and the difference between the triaxial and ring shear fully softened secant friction angles (ϕ' tri and ϕ' ring, respectively) at high effective normal stress is smaller than low effective normal stresses, a constant value of 2.5° was selected to convert ring shear FSSs to CD triaxial compression FSSs. Stark et al. (2017) use CD triaxial test results on over 25 soils to show the average mode of shear conversion factor varies from 3.0° at effective normal stresses less than about 100 kPa to about 2.0° at 400 kPa, depending on the clay-size fraction. This 0.5° difference from 2.5° at low and high effective normal stresses is not significant because the effective normal stresses on shallow failure surfaces are below 100 kPa due to the generally high values of pore-water-pressure ratio (r_u) generated primarily by precipitation. This was the main impetus for Gamez and Stark (2014) extending the Stark and Eid (1997) FSS correlation to an effective normal stress of 12 kPa from the previously lowest effective normal stress of 50 kPa. For example, first-time slides in compacted fine-grained soils are typically shallow slides with semicircular to planar failure surfaces. These slides usually occur at depths of less than 2.5 m (Fleming et al. 1992) or about 20 % to 30 % of the initial slope height (Saleh and Wright 1997). Assuming a value of r_u of 0.4 to 0.6 (Day and Axten 1989; Lade 2010; Kayyal and Wright 1991), the effective normal stresses on the failure surface ranges from 5 to 50 kPa, so 12 kPa is near the middle of this range.

Castellanos et al. (2016) use the CD triaxial compression data for Panoche and Oahe shales in Stark and Eid (1997) to conclude that "the difference in secant friction angle decreases with increasing normal stress and that at high stresses, the conversion factor of 2.5° is unconservative." **Table 1** shows that the Panoche and Oahe shales exhibit the greatest deviation from

TABLE 1 Difference in secant FSS friction angles from ring shear and CD triaxial compression (Eid 1996) and the bold text indicates the two soils used in Castellanos et al. (2016).

Soil Name	Liquid Limit	Clay Size Fraction	FSS Friction Angle Difference at 70 kPa	FSS Friction Angle Difference at 275 kPa
Urbana till	24	18	2.6°	2.8°
Panoche shale	**53**	**50**	**1.9°**	**1.6°**
Pepper shale	94	77	2.1°	3.3°
Oahe shale #1	138	78	3.0°	2.7°
Oahe shale #2	**192**	**65**	**2.9°**	**1.7°**

the 2.5° mode of shear conversion factor of the five soils tested by Eid (1996) at effective confining pressures of 70 and 275 kPa. The difference between ring shear and CD triaxial secant friction angles in **Table 1** range from 1.6° to 3.3°, so Stark and Eid (1997) selected an average conversion factor of 2.5°, which subsequent CD triaxial compression testing (Stark et al. 2017) has shown to be a reasonable value. In summary, a 0.5° difference in the FSS conversion factor at effective normal stresses less than and greater than 100 kPa does not have a significant impact on calculated factors of safety for observed shallow first-time failure surfaces.

Sample Processing

The authors next criticize the use of ball-milling in the UIUC sample processing for FSS testing. All of the soils used by Stark and his co-workers are processed using ASTM procedures for LL (ASTM D4318-10e1 2010) and CF (ASTM D6913-04 2004), which involves passing the soil through the No. 40 sieve, as stated in ASTM D7608-10 (2010). The only soils that are ball-milled are highly indurated claystones and shales that reflect the disaggregation that occurs at the "fully softened" and residual conditions in these indurated materials. If the engineer does not believe highly indurated claystones and shales will be highly disaggregated at the FSS, they can select a lower degree of disaggregation, such as mortar and pestle, milk shake mixer, or blender, to measure the LL and CF for use in the FSS correlation. In general, the level of disaggregation and liquid limit increase as follows:

$$\text{Soaking (ASTM D4318} - \text{10e1)} < \text{Mortar and Pestle} < \text{Shake Mixer} < \text{Blender} < \text{Ball Milling}$$
$$LL_{Soaking} < LL_{Mortar} < LL_{Mixer} < LL_{Blender} < LL_{Ball\ Milling}$$

This is contrary to the authors' conclusion that "blenderizing procedure does not cause a significant effect, less than 10 % decrease, on the fully softened shear strength measured, even though it changes the index properties." Changing the index properties should also change the FSS, otherwise the resulting correlation is not representative of the soil behavior. This further illustrates the need to properly simulate the level of field disaggregation for shear strength and index property testing.

Continuous Strength Envelope

This Castellanos et al. (2016) criticism is perplexing because a continuous FSS strength envelope is obtained from the Stark and Eid (1997) FSS correlation by drawing an envelope through effective normal stresses of 12, 50, 100, and 400 kPa and the origin, because uncemented, normally consolidated fine-grained soil does not exhibit a cohesion intercept. The resulting FSS envelope can be used directly in a stability analysis, or a power function can be used to increase the number of data points used to describe the FSS strength envelope using the values of power function coefficients "a" and "b" presented in Gamez and Stark (2014). Equation 1 presents the power function derived by Mesri and Shahien (2003) for FSS and the coefficients "a" and "b":

$$\tau_{FSS} = a^* P_a^* \left[\frac{\sigma'_n}{P_a}\right]^b \quad (1)$$

where:

$\tau_{\,FSS}$ = the fully softened shear strength on a plane with σ' at failure,

σ' = the effective normal stress, and

P_a = the atmospheric pressure.

In addition, Gamez and Stark (2014) present 95 % confidence limits on the values of "a" and "b" to facilitate use of reliability methods in stability analyses as suggested by Duncan (2000).

In summary, Stark and Eid (1997) present the first FSS correlation that yields a continuous, stress-dependent FSS strength envelope for slope stability analyses, which allows practitioners to plot the envelope using five effective normal stresses (including the origin). If additional data points are desired, practitioners can estimate them using the power function in Eq 1, but the additional data points should be guided by the five data points derived from the Stark and Eid (1997) FSS correlation.

Three Clay-Size Fraction Groups

Finally, the authors criticize the "step" between the three CF groups, ($CF \leq 20$, $25 \leq CF \leq 45$, and $CF \geq 50$) in the Stark and Eid (1997) FSS correlation. Stark and Eid (1997) purposefully left these two steps or gaps between the three CF groups to highlight the three different modes of particle shearing from Lupini et al.

FIG. 4

Castellanos (2014) photographs of Vicksburg Buckshot clay non-blenderized at a liquidity index of 1.59 obtained from direct shear specimens after shearing at an effective normal stress of (a) 144.4 kPa (3016 psf), (b) 216.2 kPa (4516 psf), and (c) 288.0 kPa (6016 psf). The photos show minimal soil in the top shear box and a gap between the soil and the shear box wall in the top box (right photograph) indicating progressive failure and change in the specimen area during shear (Castellanos 2014, pp. 512–513).

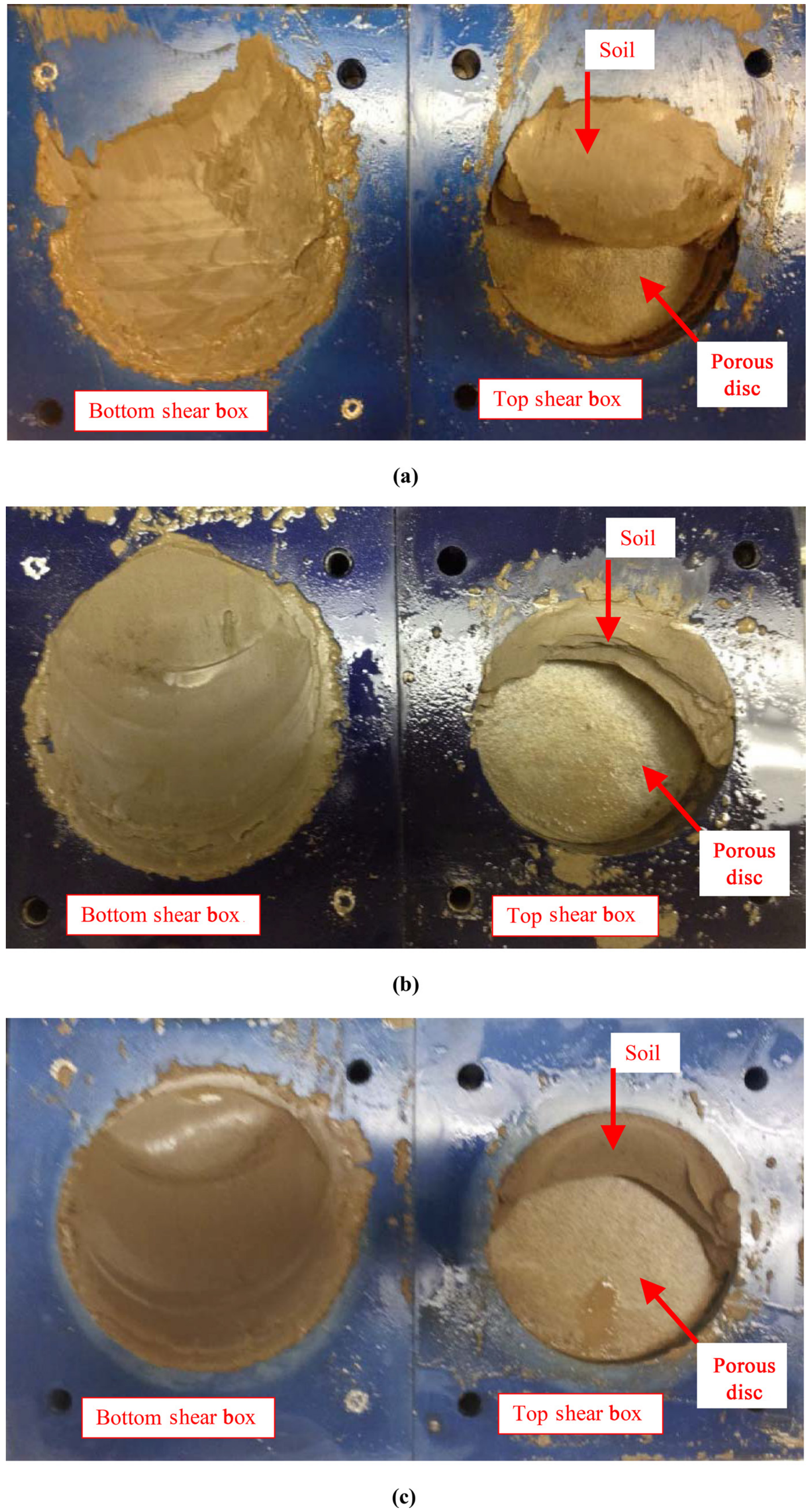


TABLE 2 Measured vertical displacement during direct shear testing of Vicksburg Buckshot clay non-blenderized at a liquidity index of 1.59 (Castellanos 2014, pp. 514–520).

			Vertical Displacement (mm)		
Effective Normal Stress (kPa)	Initial Specimen Thickness (mm)	One-Half Initial Specimen Thickness (mm)	Consolidation Stage (mm)	Shearing Stage (mm)	Consolidation and Shearing (mm)
24.7	36.83	18.42	9.14	1.52	10.66
48.6	35.53	17.77	11.68	1.02	12.70
96.5	35.81	17.91	13.84	0.76	14.60
144.4	35.31	17.66	13.72	1.52	15.24
216.2	34.80	17.40	14.99	0.76	15.75
288.0	36.58	18.29	17.27	0.76	18.03

(1981), i.e., rolling, transitional, and sliding, that occur in fine-grained soils. These two CF gaps were created because there is no rigid boundary when a range of natural soils change from rolling to transitional particle shearing and from transitional to sliding particle shearing. The writer understands the authors would like rigid boundaries for their FSS curve fitting and correlation, but soils vary and a gap between CF groups forces the users to understand the underlying soil behavior and discourages the "blind use" of FSS correlations. Instead, engineering judgment should be used especially between the transitional ($25 \leq CF \leq 45$) and sliding ($CF \geq 50$) modes of particle shearing, because there is a much larger decrease in the fully softened and residual strengths at this boundary than the rolling ($CF \leq 20$) and transitional ($25 \leq CF \leq 45$) particle shear boundary.

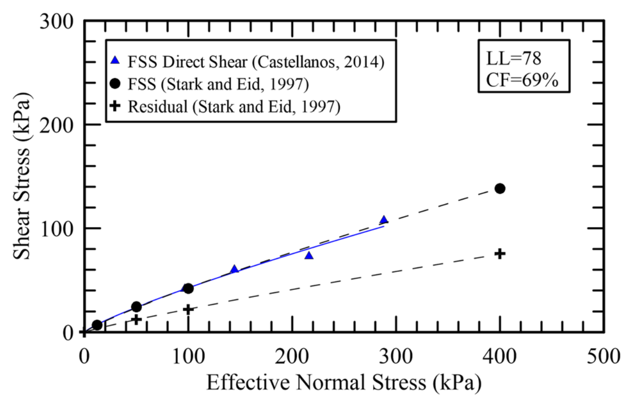
Castellanos et al. (2016) Direct Shear Testing

The authors state that 46 different soils were tested but 34 of the 46 soils are from Texas, e.g., the Dallas Floodway Project that is discussed in Gamez and Stark (2014) and Stephens et al. (2011). Consequently, the Castellanos et al. (2016) correlation has limited application to other geologic formations and sites. More importantly, the direct shear data ASTM D3080/D3080M-11 appears to be derived from Castellanos (2014), which also involved questionable test procedures as described below.

Fig. 4 shows photographs of Vicksburg Buckshot clay (VBC) direct shear specimens after testing by Castellanos (2014) at effective normal stresses of 144.4 kPa (3016 psf), 216.2 kPa (4516 psf), and 288.0 kPa (6016 psf). These photographs show at least two major issues with the testing procedure and FSS direct shear testing: (1) lack of sufficient soil in the top shear box and along the shear surface between the top and bottom halves of the shear box; and (2) a gap between the soil and the shear box wall in the top shear box, which indicates progressive failure and change in specimen area during shear even if there was sufficient normally consolidated soil in the top shear box. In this test on VBC, the direct shear specimen was initially about 36 mm thick with each shear box being about 18 mm thick (see **Table 2**). Because a FSS specimen is reconstituted and has a high initial moisture content, care must always be taken during consolidation and shearing so sufficient soil is still present along the shear surface to measure a reliable value of FSS. In other words, there must be sufficient specimen thickness above the opening between the top and bottom halves of the shear box after consolidation for proper shearing. Because the reconstituted specimen is near the liquid limit and the top half of the shear box is usually only about 18 mm thick, consolidation can reduce the thickness significantly. For example, **Table 2** shows the total vertical displacement (15.24, 15.75, and 18.03 mm) that occurred during consolidation and shear of the VBC at the three highest effective normal stresses (114.4, 216.2, and 288.0 kPa) is just slightly less than one-half the initial specimen thickness (17.66, 17.40, and 18.29 mm), which resulted in minimal soil remaining in the top shear box, as shown in **Fig. 4**.

More surprising than the photographs in **Fig. 4** is the values of FSS obtained from the corresponding shear stress–shear displacement relationships for VBC are in excellent agreement with the Stark and Eid (1997) correlation even though there is

FIG. 5 Strength envelope for Vicksburg Buckshot clay non-blenderized at a liquidity index of 1.59 using direct shear data from (Castellanos 2014, p. 510) and FSS and residual strength envelopes derived from empirical correlations in Stark and Eid (1997) using LL and CF measured by Castellanos (2014).



insufficient soil in the top shear box and the correlation is for the triaxial mode of shear, i.e., increased 2.5 degrees above direct shear. **Fig. 5** presents the FSS strength envelope for VBC non-blenderized at a liquidity index of 1.59 using data from Castellanos (2014) and the FSS and residual strength envelopes estimated from the Stark and Eid (1997) correlation using the LL of 78 and CF of 69 measured by Castellanos (2014). Even though there is insufficient soil in the upper shear box, the values of FSS obtained from the shear stress–shear displacement relationships for the direct shear tests shown in **Fig. 4** are in excellent agreement with the Stark and Eid (1997) correlation, which includes the 2.5° triaxial compression mode of shear conversion. Thus, given the problems with the testing performed by Castellanos (2014), the authors should explain how FSSs can be measured with insufficient soil in the top shear box and/or remove this data from their proposed correlation. If there is another source of direct shear data it should be cited and the reasons for replacing the Castellanos (2014) data presented. Stark et al. (2017) shows the ring shear and direct shear devices yield similar values of FSS, which are lower than CD triaxial values.

Castellanos et al. (2016) FSS Correlation

Finally, the authors select the product of plasticity index (PI) and clay-size fraction (CF) for their FSS correlation "because it showed a stronger relationship with the parameters "a" and "b" than the liquid limit, which is used in other fully softened shear strength correlations." The authors appear to be selecting correlation parameters based on curve-fitting regression instead of soil behavior.

Stark and Eid (1997) use the LL in the FSS correlation because it is indicative of clay mineralogy, i.e., particle size. As the particle size decreases, the particle surface area increases, the LL increases, and the drained FSS decreases. However, liquid limit does not completely describe the soil behavior. As a result, Stark and Eid (1997) include CF because it indicates the quantity of clay minerals, i.e., soil particles smaller than 0.002 mm, and particle shearing mode. In summary, the LL and CF parameters were selected so users could understand how changes in soil behavior and shearing produce changes in the FSS. To complete the FSS correlation, Stark and Eid (1997) include the effect of effective normal stress in the correlation, which results in a stress-dependent FSS strength envelope that captures the combined influence of effective stress, plasticity, and grain-size dependence on FSS.

The authors use curve fitting techniques, and not soil behavior, to select their correlation parameters. This is obvious by the selection of PI and CF because PI reflects both CF and plasticity so the authors actually include the effect of CF twice in their correlation by multiplying PI by CF. In contrast, Mesri and Shahien (2003) use the FSS data from Stark and Eid (1997) to present an FSS correlation based solely on PI because PI reflects both CF and plasticity. This results in the authors' using a parameter that does not reflect the three modes of particle shearing and soil behavior and most, if not all, users do not have a sense of proportion for values of PI times CF, which ranges from 0 to 4.5.

Summary

This discussion refutes the authors' five main criticisms of the Stark and Eid (1997) FSS correlation and subsequent updates (Stark et al. 2005; Stark and Hussain 2013; Gamez and Stark 2014) and suggests that the authors' proposed testing and correlation should be used with caution. In particular, this discussion shows:

1. When used properly and in accordance with ASTM D7608-10 (2010), the torsional ring shear device provides appropriate values of FSS for the ring shear and direct shear modes of shear.
2. Converting the ring shear results to the triaxial compression mode of shear (ASTM D7181-11) is prudent for "first-time slides" in compacted and overconsolidated fine-grained soils and the constant adjustment factor of 2.5° remains suitable, especially for the low effective normal stresses encountered in "first-time slides."
3. The user should determine the level of particle disaggregation that will occur in the field and select the appropriate sample-processing method, e.g., passing the soil through the No. 40 sieve, mortar and pestle, milk shake mixer, blender, or ball-milling, to simulate "full softening."
4. Stark and Eid (1997) FSS correlation and subsequent updates (Stark et al. 2005; Stark and Hussain 2013; Gamez and Stark 2014) yield continuous and stress-dependent FSS strength envelopes for slope stability analyses, allowing practitioners to plot the stress-dependent strength envelope using five normal stresses, including the origin. These five data points can be augmented using the power function proposed by Mesri and Shahien (2003) in Eq 1 and the "a" and "b" parameters and confidence limits in Gamez and Stark (2014).
5. Use of three distinct clay-size fraction groups in the Stark and Eid (1997) correlation and subsequent updates captures the non-rigid or non-distinct boundaries between rolling, transitional, and sliding particle modes of shear proposed by Lupini et al. (1981) for a wide range of naturally occurring soils.
6. The FSS correlation presented by the authors should be used with caution because it is based on questionable direct shear data from Castellanos (2014), a limited number of geologic formations, and curve fitting using a limited database.

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