inclined layered systems and have had success in numerical modeling and field measurements. Their results underscore the need to carefully consider moisture redistribution near cover slopes to avoid desaturation.

Another important point made by the discussers is the issue of steady-state analysis versus actual field behavior. It should be noted that our paper examined transient flow in great detail, both experimentally and mathematically. The one example on steady-state analysis was only introduced to emphasize the ability of the numerical model to simulate both steady-state and transient state layered flows. We agree with the discussers that transient modeling is required in most cover applications and we did exactly that in our paper. There are, however, some situations in saturated-unsaturated flow modeling [see, for example, Kisch (1959) and Fredlund and Rahardjo (1993)] where steady-state analysis may be adequate.

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MUNICIPAL SOLID WASTE SLOPE FAILURE. I: WASTE AND FOUNDATION SOIL PROPERTIES[a]

Discussion by Edward Kavazanjian Jr.,[5] J. F. Beech,[6] and Neven Matasović,[7] Members, ASCE

Because of our extensive involvement in municipal solid waste (MSW) landfill engineering and our direct involvement in generation of some of the data employed by the authors, we read with interest the authors' interpretation of the data on MSW and colluvial soil shear strength. While the interpretation presented in this paper is thought provoking, we have some serious concerns about the MSW strength envelope proposed by the authors, particularly at higher confining pressure, and about one of the case histories presented as an example of colluvial foundation soil failure.

One of our primary concerns is the "average" straight-line MSW failure envelope presented in Fig. 5, established by linear regression analysis. Use of a straight-line failure envelope automatically precludes consideration of any nonlinear, confining pressure dependence in waste shear strength. We note that, above a confining pressure of 150 kPa, corresponding to approximately 10–15 meters of waste, nine out of the ten data points in Fig. 5 are below the authors' best-fit straight line. This strongly suggests that a single straight line should not be fit to the data and that the authors' average strength envelope may overpredict shear strength at higher confining pressures.

We also question the usefulness of an "average" strength envelope for MSW. Use of an "average" envelope suggests that all MSW should have similar strength characteristics. When compiling data on MSW of various ages from a variety of geographic locations and climate regimes, the discussers believe it is prudent to use a lower bound strength envelope. To account for the variability of MSW, two of the discussers helped develop a generic lower bound MSW strength envelope consisting of a cohesion of 24 kPa at low confining pressures and a friction angle of 33° at high confining pressures (Kavazanjian et al. 1995). This generic bilinear lower bound envelope, widely used in practice today, accounts for both the confining pressure dependence and the variability of MSW shear strength. If site-specific data is available, a shear strength higher than the generic lower bound value may be used. For instance, site-specific testing and analysis for closure of the Operating Industries, Inc. (OII), landfill indicated that the lower bound MSW shear strength at OII could be characterized by a cohesion of 38 kPa and a friction angle of 31°. This site-specific lower bound strength envelope superseded the generic lower bound strength envelope and was used in stability analyses for the OII project.

We have several other concerns about the MSW shear strength envelope proposed by the authors. Evaluating the author's strength interpretation was complicated by the fact that not all of the references cited in Fig. 5 are provided in the reference list. We could not identify the references cited as "GeoSyntec (1996b)" and "Earth Sciences (1997)." The authors initially question the value of back analyses of waste slopes that have not failed in establishing a representative shear strength envelope for solid waste. The discussers believe that analysis of steep waste slopes that have not failed is a valid and useful tool, particularly if the intent is to establish a lower bound strength envelope. We find it ironic that, subsequent to questioning the value of this type of data, the authors rely upon back analysis of a stable vertical scarp in establishing the waste shear strength properties at the Cincinnati site. Furthermore, despite having previously noted the dependence of this type of analysis on the factor of safety, the authors fail to state what factor of safety was used in their back analysis. The authors also fail to provide any data to substantiate the unit weight of 10.2 kN/m^3 used in the back analysis. Our experience with in situ measurement of unit weight at MSW landfills indicates this value is at the lower bound of representative values for MSW under relatively low confining pressure. Underestimating the unit weight can result in significant overestimating of the cohesive component of the shear strength.

We also question the authors' argument that strain incompatibility can explain why near vertical slopes of MSW remain standing for long periods of time and result in mobilizing an MSW shear strength lower than the peak strength for the Cincinnati failure. As failure of a near vertical MSW slope would likely be a toe failure and thus would involve only MSW, it is difficult to understand how strain compatibility is an issue. With respect to the special case of the Cincinnati failure, the brittle behavior of the foundation material, the ductile behavior of MSW, and the large strains mobilized prior to failure indicate to us that at the time of failure the foundation material mobilized its residual strength while the MSW mobilized its peak strength.

With respect to the authors' discussion of the behavior of colluvial slopes, the second discusser served as the Engineer-

[a]May 2000, Vol. 126, No. 5, by Hisham T. Eid, Timothy D. Stark, W. Douglas Evans, and Paul E. Sherry (Paper 16481).

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of-Record for remedial design for the project identified as a site in southeast Ohio that is depicted in Plate 2. The second discusser was also active in the project during construction. The failure surface shown in Plate 2 is described by the authors as an example of a failure surface in a "weak, highly plastic layer in colluvial soil" involved in a recent slope failure. However, this surface was created by the contractor with an excavator as a safety measure following observation of tension cracks on the bench just above the depicted surface. The discussers therefore do not consider this case to be a good example of a failure surface from a slope failure in a highly plastic layer in colluvium.

In discussing the project in southeast Ohio, the authors also write that "excavation into the colluvium during remediation resulted in many failures along well defined and continuous highly plastic layers [Plate 2(a)]." Failures of the nature depicted in Plate 2(a) were rare during construction. The majority of the failures that occurred during construction occurred along an interface either between a burnt waste residue and the colluvium or between the colluvium and underlying weathered bedrock. These interfaces were approximately parallel to the ground surface. Available evidence indicated that there had been prior failures along these surfaces, predating the remedial design. The evidence indicated that the failures prior to and during construction were typically triggered by a buildup of hydraulic head on the burnt waste residue–colluvium interface or the colluvium–weathered bedrock interface following precipitation. The importance of precipitation on stability was demonstrated during the design process by back analyses of slip surfaces identified through monitoring of slope inclinometers installed as part of a predesign field investigation. These back analyses indicate that the strength along the preexisting failure surfaces was roughly equal to the average residual strength of the colluvium, rather than the residual strength associated with the more plastic material at the site.

Closure by Hisham T. Eid,[8] Timothy D. Stark,[9] W. Douglas Evans,[10] and Paul E. Sherry[11]

The writers welcome the discussers' comments. The failure envelopes proposed for municipal solid waste (MSW) in Fig. 5 are intended to be used for effective normal stresses less than 400 kPa, as indicated in Fig. 5. Reevaluating the shear strength data for effective normal stresses greater than 250 kPa suggests that the trend lines may be stress dependent or nonlinear, as shown in Fig. 8. However, the amount of data at effective normal stresses greater than 250 kPa is sparse. The revised failure envelopes shown in Fig. 8 do not alter the analysis of the slope failure in the companion paper (Stark et al. 2000), because the effective normal stress acting on the steeply inclined portion of the shear surface passing through the MSW is less than approximately 270 kPa.

One of the main conclusions of the writers' study of a number of slope failures involving waste containment facilities,

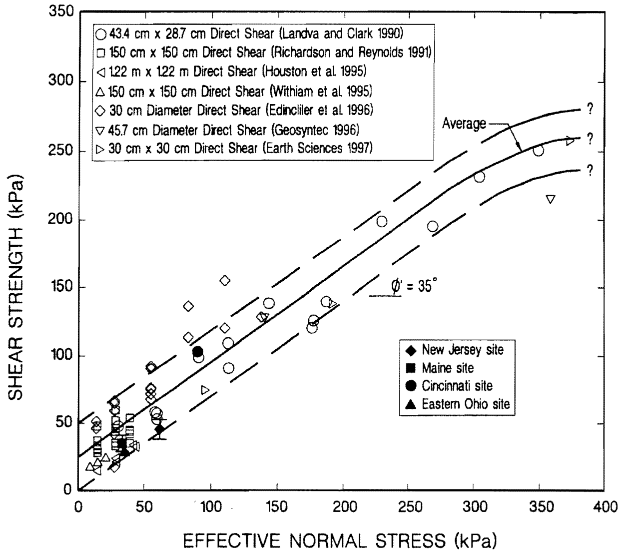

FIG. 8. Stress Dependent Shear Strength of MSW

e.g., Stark (1999), Stark et al. (1998), and Wilson et al. (2000), is that MSW exhibits high shear strength under static conditions; thus, a landfill slope failure usually occurs along a weaker material underlying the MSW and the MSW simply follows along. The interconnection of plastics and other materials probably plays a significant role in developing the high shear strength of MSW, which has allowed vertical slopes to remain stable for months to years. As mentioned in the subject paper, the 60 m high, nearly vertical scarp that resulted from the slope failure remained stable until it was remediated approximately nine months after the slide. This is also in agreement with a 21 m high vertical excavation in MSW in Illinois that has remained stable for over six years. The real design challenge is locating any weaker layers underlying the MSW, e.g., soil and/or geosynthetics, that could compromise the stability of the stronger MSW situated above.

The discussers suggest that the lower bound failure envelope proposed by Kavazanjian et al. (1995) should be used to account for MSW variability. The proposed average failure envelope in Fig. 5 is slightly higher than the lower bound failure envelope presented by Kavazanjian et al. (1995), and this difference did not significantly change the calculated factors of safety for this case history. This is attributed to the failure surface being steeply inclined through the MSW, which minimizes the effective normal stress acting on this portion of the failure surface and thus the contribution of the MSW friction angle to the factor of safety. In addition, the values of cohesion are similar. For example, the change in the factor of safety for the two-dimensional analysis described in the companion paper (Stark et al. 2000) decreased less than 0.05 when the lower bound envelope proposed by Kavazanjian et al. (1995) was used instead of the average MSW failure envelope proposed in Fig. 5. In fact, Schmucker and Hendron (1998) show no practical change in the factor of safety (0.999 versus 1.000) for this case history when using the lower bound MSW failure envelope proposed by Kavazanjian et al. (1995) with a friction angle of 28° and a cohesion of zero, respectively, in their analysis of cross section B-B′.

In summary, experience with a number of recent waste slope failures suggests that MSW exhibits a high shear strength under static conditions that can be characterized by the average failure envelope (effective stress cohesion = 25 kPa and friction angle = 35°) in Fig. 5 for effective normal stresses less than or equal to 250 kPa. At effective normal stresses greater than 250 kPa, the failure envelopes may be stress dependent, as suggested by the discussers, but the current data is limited

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and thus question marks are shown in Fig. 8 near an effective normal stress of 400 kPa. Thus, it is recommended that testing and stability evaluations focus on the materials underlying the MSW, e.g., soils and/or geosynthetics.

The reference GeoSyntec (1996b) corresponds to the GeoSyntec reference cited in the subject paper, with the letter "b" being a typographical error. The moist unit weight of 10.2 kN/m^3 was used by GeoSyntec in their stability analyses of this case history, e.g., Schmucker and Hendron (1998). The Earth Sciences (1997) reference was inadvertently omitted during the publication process and is presented herein. The writers did not "question the value of back analysis of waste slopes that have not failed," as the discussers suggest, but only stated that "back-calculated shear strength parameters from landfill slopes that had not failed also were not included because the actual factor of safety is not known and the back-calculated shear strength is sensitive to the assumed factor of safety." In summary, the writers simply decided not to include back analyses of unfailed slopes in the development of the MSW failure envelopes in Fig. 5, which does not preclude the discussers from doing so. The writers used a factor of safety of unity in the back-analysis of the scarp because in the days immediately following the failure a few small slides occurred in the scarp/graben area. The parametric study referred to in the paper was designed to model these smaller failures and thus bracket a site-specific value of the MSW effective stress cohesion.

The discussers' final concern about the Cincinnati failure involves the concept of strain incompatibility between the MSW and foundation material. The concept of strain incompatibility was investigated because the writers believe that the brown native soil underlying the MSW mobilized a shear strength near the residual value. Strain incompatibility is one of the reasons presented for mobilization of a postpeak shear strength in a soil that had not undergone previous sliding. The other reasons for mobilizing a postpeak strength in the native soil include the colluvial nature of the foundation material indicating prior down slope movement and thus shear displacement, waste placement activities that usually involved pushing waste from the top to the bottom of the slope, soil creep along the inclined bedrock surface, lateral displacement of the MSW causing shear displacement in the underlying foundation material, as evidenced by slope inclinometer data, and blasting in the adjacent excavation. Therefore, the strain incompatibility concept refers to the prefailure condition and mobilization of a postpeak shear strength in the foundation soil prior to failure, not the condition of the vertical scarp after the slope failure as suggested by the discussers. If the vertical scarp condition was being considered, the failure would likely be a toe failure and thus there would be little impact on the foundation material. The reference to MSW remaining nearly vertical for long periods of time was made to suggest that MSW may be mobilizing only a percentage of the peak strength, i.e., effective stress cohesion = 25 kPa and friction angle = 35°, in a slope failure because of strain incompatibility. The peak shear strength of MSW is probably greater than $c' = 25$ kPa and $\phi' = 35°$ to enable MSW slopes to remain at or near vertical for extended periods of time. For example, the peak shear stress measured in the direct shear test on MSW in Fig. 6 is approximately 88 kPa, whereas the peak shear stress corresponding to $c' = 25$ kPa and $\phi' = 35°$ at an effective normal stress of 55 kPa is only 64 kPa.

Concerning the colluvial failure surface shown in Plate 2(a), some of the blocks of material shown near the bottom of the exposed shear plane slid during the second and third writers' visit to the site, even though construction was not occurring at that time. In addition, the shear surface shown in Plate 2(a) extends into the slope [to the right in Plate 2(a)] away from the exposed failure surface almost parallel to the pipe in the foreground. The failure surface appears as a dark inclined line extending from the exposed shear surface slightly downward into the colluvial material. Whether this failure surface developed in the colluvium naturally or as a result of construction activities (as acknowledged by the writers) is inconsequential in the context of the paper. The important factor is that the shear surface propagated through a heterogeneous mixture of soil and rock particles [see Plate 2(b)], forming a large (approximately 60 × 20 m) and thin (approximately 10 mm thick) failure surface. This confirms that a failure surface can develop along a continuous seam of high plasticity clay in a heterogeneous colluvial deposit that contains substantial rock fragments [see Plate 2(b)]. The contributions of the rock fragments to the shear strength mobilized along this failure surface are clearly limited, if there are any at all, because sliding occurred along a thin, rock-free layer of high plasticity clay. Therefore, the contribution of the rock fragments to the mobilized shear strength along this shear surface is significantly less than conventionally believed.

This shear surface is similar to others observed before the second discusser became involved with the project. One example of such a shear surface in the colluvium is shown in Fig. 9 and was observed near the creek, which was outside the area of waste residue. This shear surface was observed at least six months prior to the second discusser's involvement in the project. Observation of this shear surface and several other episodes of sliding at the site led to the second and third writers' involvement in the project and the subsequent remedial measures undertaken at the site.

The third writer photographed and sampled the shear surface in Fig. 9, which was not located at the interface either between the burnt waste residue and the colluvium or between the colluvium and underlying weather bedrock, which is also the case for the shear surface shown in Plate 2(a). The trowel in Fig. 9 is inserted into colluvial material and not waste residue or bedrock. The shear surface was located 1–2 m above the underlying bedrock and no waste residue was present in this area. In addition, the sample shown in Plate 2(b) was taken from the lower side of the exposed shear surface in Plate 2(a). It can be seen that this sample does not correspond with the interface between the colluvium and underlying weathered bedrock or the burnt waste residue/colluvium interface because waste residue is not located above the shear surface in Plate 2(a). In summary, there is ample evidence that shear surfaces corresponding to continuous high plasticity clay seams existed within this heterogeneous colluvium. This is typical of other colluvial deposits investigated by the writers and reported in the literature cited in the subject paper and is one of the main points that the writers tried to illustrate in the paper.

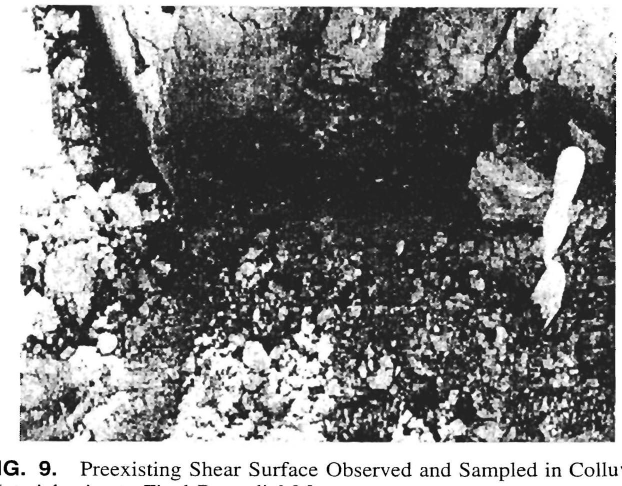

FIG. 9. Preexisting Shear Surface Observed and Sampled in Colluvial Material prior to Final Remedial Measures

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