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Discussion

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Discussion: Analysis of a full-scale slope failure test on a sludge embankment

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Verreydt *et al.* (2019) presented an embankment slope stability study of a very complicated man-made and heterogeneously deposited material in Belgium. This material is an industrial sludge, composed mostly of calcium fluoride, which is a result of chemically produced phosphate fertilisers deposited after been compressed (to release water and consolidate) under a pressure of 1.5 MPa. To give more space for the deposition of more sludge, embankments are built to contain this material. An experimental programme of load-controlled full-scale field trials of sludge deposited by gravity (without pressure applied) was undertaken to estimate the shear strength at failure. This was intended to evaluate a new sludge deposit. Although there are geotechnical studies about sludge from other sources such as sewage, landfills and other industrial residuals (e.g. Chu *et al.*, 2012; O'Kelly, 2004; Zhan *et al.*, 2014), the study by Verreydt *et al.* (2019) is probably one of a few dedicated to fertiliser sludge.

Verreydt *et al.* (2019) decided to carry out in situ shear vane tests to evaluate the undrained shear strength (s_u) and its scatter due to the simplicity of the test. This discussion will comment on this site investigation test and the s_u results. It will suggest the need for supplementary information in order to make a more comprehensive analysis of the highly variable undrained shear strength results.

Since s_u is usually calculated using the torque (T) applied to rotate the vane and the vane geometry, a brief description of the vane used in the in situ tests is needed, such as the vane dimensions (namely height H , diameter D and blade thickness t of the vanes) as well as the geometry (rectangular or with angles on top or below or both) and material (e.g. steel or alloy steel). For example, if $H/D = 2$, $s_u = 6 T/(7\pi D^3)$ (ASTM, 2018). It is not clear if the field vane tests (FVTs) were carried out using or not using a casing or protection to avoid disturbing the soil while driving the vane, or if the vane was put down into a pre-bored hole and then FVTs were performed.

Apart from the instrument and testing procedure description, it is not clear what undrained shear strength was measured and adopted in the analyses. This is very important because the authors mention that there was a mixture of over-consolidated and normally consolidated sludge. A maximum or peak undrained shear strength ($s_{u,max}$) can be mobilised in over-consolidated materials during the beginning of the vane rotation, as shown in Figure 20(a). Then, a residual or remoulded value of undrained shear strength ($s_{u,res}$) can be reached after a much larger value of rotation. However, in normally consolidated materials the response is different since a maximum value of s_u occurs for large rotations, as shown in Figure 20(b). Consequently, scatter can increase when peak and residual strength values are mixed up. It would be useful to provide s_u - θ curves to observe the response of the sludge in terms of peak and residual strength as well as identifying whether the sludge is normally consolidated or over-consolidated. Perhaps an over-consolidation ratio (OCR) analysis may be useful to correlate s_u with the OCR.

Following the previous comment on the s_u - θ response, a question arises about the vane rotation velocity $\dot{\theta}$ during the FVTs. Usually, a value around to 6°/min (0.1°/s) is adopted for an undrained response, which is fast compared with that used in laboratory tests and even faster than that in slope failures, although not fast enough for tailings, for example (Olguín and Ortúzar, 2015). This information is relevant to confirm whether the FVTs were performed under undrained, partially drained or drained conditions. Rate effects can be considered using a power expression such as (Biscontin and Pestana, 2001; Schnaid, 2009):

$$6. \quad s_u/s_{u,ref} = (\dot{\theta}/\dot{\theta}_{ref})^\beta$$

where $s_{u,ref}$ is a reference undrained shear strength determined at a vane rotation velocity $\dot{\theta} = \dot{\theta}_{ref}$ when $s_u = s_{u,ref}$ and β is a material-dependent constant to be determined, although it may be around 0.05 (Biscontin and Pestana, 2001; Schnaid, 2009).

Figure 20. Undrained shear strength, s_u , against vane rotation, θ , showing maximum and residual strengths for (a) over-consolidated and (b) normally consolidated materials

Instead, the authors used a method that relies on the plasticity index (PI) of clays to account for rate effects by means of the time to slope failure (6 h) and the sludge PI = 34%, resulting in a correction factor $\mu_R = 0.851$ (Chandler, 1988). In other words, without using the vane rotation velocity $\dot{\theta}$ and not considering whether the material was normally consolidated or over-consolidated. From laboratory direct shear test results in clay, it has been shown that rate effects can lead to a decrease in the peak stress ratio τ_p/σ_n (shear stress/normal stress) for normally consolidated clays and to an increase in τ_p/σ_n with shear velocity in over-consolidated clays (Martinez and Stutz, 2019). Although this has not yet been verified for shear vane tests, it may explain the high variability of s_u from the FVTs. As a final comment, continuous measurements with depth, such as in cone penetration tests (CPTs), may offer a better option to evaluate the variability of s_u .

Authors' reply

The authors appreciate contributor's comments and remarks.

An estimation of the undrained shear strength was made using the Geonor H-70 FVT apparatus, which uses a tapered steel vane measuring 60 mm $\times$ 120 mm. The blades are about 4 mm thick. The vane was pushed or hammered to the required depth. No encasing is present around the vane, but rod friction is measured separately by use of an 180° anti-friction slip coupling system (Geonor, 2020).

The authors are aware that, due to vane insertion, distortion occurs that may lead to an under- or overestimation of the undrained shear resistance (Terzaghi *et al.*, 1996). This can be related to the blade thickness and the waiting period of insertion. Disturbance of the soil by insertion of the vane is more pronounced for sensitive clays (Chandler, 1988; La Rochelle *et al.*, 1973); the calcium fluoride sludge had a sensitivity of about 4, thereby corresponding to a medium to sensitive clay (Skempton and Northey, 1952) (1–2, low sensitivity; 2–4 medium sensitivity; 4–8 sensitive; 8–16 extra sensitive). Hence, the effects of disturbance due to insertion of the vane were

considered to be limited. However, the effects were not quantified.

The peak and remoulded shear strengths were recorded during the FVTs. Residual shear strength after reaching peak strength was not measured. An accurate measurement of the residual shear strength is hard to acquire given the gradual transition from peak shear strength to constant residual shear strength (Figure 21).

The vane shear test apparatus used is a hand-held device. Torque is applied by hand and the apparatus does not have the capability of performing s_u - θ measurements. The rotation speed was kept as low as possible, however, experience shows that a hand-held vane shear test is usually faster than the advised 6°/min. In the FVTs carried out, the time to failure was commonly between 0.5 and 2 min, resulting in a rotation speed of the order of 10–20°/min. Hence, fully undrained shear was still applied.

Figure 21. Relationship between shear strength and vane revolutions in vane shear tests for over-consolidated (OC) and normally consolidated (NC) materials (Chaney and Richardson, 1988)

The authors agree with the use of the following power expression or semi-logarithmic law (Biscontin and Pestana, 1999) for normally consolidated soil; however, the OCR of the sludge in the embankment varied between 1 and 3.

$$7. \quad s_u/s_{u, \text{ref}} = 1 + \alpha \log(\dot{\theta}/\dot{\theta}_{\text{ref}}) \approx 1 + \alpha \log(t_{f0}/t_0)$$

Here, $s_{u, \text{ref}}$ is the reference undrained shear strength determined at a vane rotation velocity $\dot{\theta} = \dot{\theta}_{\text{ref}}$ or corresponding to the reference time to failure (t_{f0}) and α is a characteristic soil parameter. The vane shear velocity was not accounted for. Regarding the estimated rotation speed of 10–20°/min, the undrained shear strength could be overestimated by 2.6–6.2%.

The results of tests conducted by Martinez and Stutz (2019) on the interface shear strength of normally consolidated clays in direct shear tests are contradictory to the research on the effect of time to failure on strength using FVTs by Chandler (1988), Schlue *et al.* (2010) and Biscontin and Pestana (2001). Here, a higher normalised vane shear strength was noticed at higher rotation rate. Soils with high plasticity showed the largest increase of more than 10% per log increase in rotation rate. The rotation speed not only influences the shear results, but also the permeability of the sludge determines the magnitude of the deviation.

To conclude, the above power law or semi-logarithmic law does not take into account over-consolidation or permeability of the material. Nevertheless, to the authors' knowledge it is the best correlation available at the moment. It is a useful model and will be applied in future analyses. The authors agree that additional research on this topic is needed to enable more accurate evaluations of the influencing factors on shear.

No CPT tests were executed on the (small) test embankment. A larger testing zone is being constructed, with a sludge embankment of $260 \times 150 \times 16 \text{ m}^3$, on which a combination of field tests (FVTs and piezocone penetration tests) will be made to support the analysis. Along with piezocone testing, FVTs remain necessary to determine a material-dependent cone factor (N_{kt}) for the calculation of the undrained shear strength from a cone resistance profile.

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