A simplified approach to estimating the evolution of residual shear strength of unsaturated soils with suction

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Abstract. Several researchers have investigated the effect of suction and partial saturation on the angle of residual shear strength. Most of these investigations involve the adoption and application of a method of controlling suction on the ring shear apparatus and performing ring shear tests on the same soil for various values of suction. Methods adopted include both the axis translation technique for control of suction over the range 50-1500 kPa and the saturated salt solutions method for control of suction in the range of several MPa. The general picture from these investigations is that the residual shear strength failure envelope remains linear but corresponding to higher values of the angle of residual shearing resistance for constant suction; this value increasing with increasing suction. The paper presents an attempt to normalise values of measured angle of residual shearing resistance for various suction values with the angle of residual shear strength of the corresponding fully saturated soil. This normalisation verified the linear increase of the ratio $\tan\varphi_{res(s)}/\tan\varphi_{res(s=0)}$ with suction. This linear increase allows for estimation of the evolution of $\tan\varphi_{res(s)}$ with suction if $\varphi_{res(s)}$ for one specific suction can be measured. This observation led to the measurement of $\tan\varphi_{res(s)}$ of clayey soils in conventional ring shear apparatus without suction control, simply by removing water from the shear box while shearing continues and measuring shear strength until its stabilisation, taking place after the specimen in the shear box came to equilibrium with prevailing laboratory atmospheric conditions. Using the chilled mirror hygrometer to measure equilibrium suction after ring shear completion indicated that equilibrium suction due to laboratory atmospheric conditions is practically constant over the time needed for a single test on one soil. This observation along with the previous observation on the linear increase of the ratio $\tan\varphi_{res(s)}/\tan\varphi_{res(s=0)}$ with suction, makes valid the estimation of evolution of residual shear strength of unsaturated soils with suction using only a conventional ring shear apparatus and a chilled mirror hygrometer. The paper concludes by outlining the approach, presenting measurements and a relation obtained between $\tan\varphi_{res(s)}/\tan\varphi_{res(s=0)}$, suction and liquid limit.

1 Introduction

Residual shear strength and its significance have been well recognised especially in relation to the reactivation of landslides along pre-existing slip surfaces as in palaeolandslides [1, 2]. The shear strength of a fully saturated clayey soil is described by the Mohr-Coulomb failure envelope corresponding to a cohesion intercept c´ and a maximum angle of shearing resistance φ'_{peak} at rupture, a post-rupture failure envelope corresponding to practically negligible cohesion intercept and a post-rupture angle of shearing resistance φ'_{pr} generally smaller or equal to φ'_{peak} and, after very large shear strain, by a failure envelope corresponding to zero cohesion intercept and the minimum angle of shearing resistance, termed the angle of residual shear strength, φ'_{res}, which is the failure envelope corresponding to the minimum possible shear strength due to the realignment of clay particles along the shear plane [1]. The angle of residual shear strength depends on the range of the vertical stress applied during shear [2, 3, 4, 5], the grain-size distribution of the soil tested [1, 2, 6, 7, 8], plasticity [8, 9], the mineral composition of soils [6, 8, 10, 11], the rate of shear strain applied [12] and the chemical composition of the pore water of soils [13, 14, 15, 16].

Palaeolandslides are often reactivated after shorter or longer intervals of minimum or even zero movements. Reactivation is most often associated with heavy, prolonged rainfall, and can be the result of a rise in the ground water table (or more generally an increase in the pore water pressures acting on the slip surface) or the loss of shear strength gained due to partial saturation upon inundation. The latter has been the subject of extensive research, both in the field [17] and in the laboratory [18, 19, 20, 21, 22, 23]. Fig. 1 shows an example from Greece, on the island of Skiros in North Aegean. An east-facing slope consisting of various clayey and silty formations, failed initially in 2004 after very heavy rainfall, with spectacularly large deformations as shown by the house that moved and even rotated without failure. The landslide remained at its place practically with minimum interventions after 2004, simply remediating a local road crossing the landslide, but was reactivated in 2019, again after heavy, prolonged rainfall which led to the design of heavy stabilization measures currently being constructed.

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Fig. 1. Bassales landslide in Skiros island, North Aegean Sea, Greece. A landslide activated by heavy, prolonged rainfall, leading to large deformation causing the characteristic translation and rotation of the house in the ellipse.

As part of the geotechnical investigation following the 2019 reactivation, a field station measuring suction and volumetric water content was installed. Measurements were made at three different depths, down to 1.70m, and showed for a period of measurements extending over more than three years values of suction as high as 200 kPa decreasing during wet periods to as low as 20 kPa, but not to zero over the particular monitoring period [17]. This particular example of a landslide shows the effect that loss or gain of shear strength due to partial saturation can have not only for the shear strength of soils before rupture or shear to very large strains [24, 25] but also for the residual shear strength.

Given the importance of unsaturated soils' shear strength, test methods allowing its measurement that have been established for saturated soils, have also been extended for unsaturated soils, including the ring-shear test [18, 19, 20, 21, 22, 23]. Yet this usually ends in methods that are quite expensive, time-consuming and presently quite limited in very few research centres and even fewer industry partners. On top of that, something often overlooked, is the need for very experienced and specialised personnel not necessarily available as easily and frequently as one may think. Attempts to use low-cost alternatives to estimate unsaturated soil shear strength parameters corresponding to peak shear strength have already been presented [25]. The paper presents work attempting to simplify the effort to estimate the evolution of residual shear strength with suction on the basis of tests performed in a conventional Bromhead-type ring shear apparatus [26] during which water was removed from the cell while shear continued until stabilisation of the shear strength under temperature and humidity in the laboratory. These are discussed in Section 3 after presenting some observations on published test results in Section 2.

2 Observations on published test results

Ring shear tests on a silty clay of low plasticity (w_L=30%, I_p= 14%, G_s=2.71) were performed [18] using a Bromhead-type ring shear apparatus [26] modified for the application of total suction by means of relative humidity control in the cell of the apparatus. The angle of residual shear strength of the soil increased from 19.6° for the fully saturated soil to 22.0° for suction 32 MPa, 22.8° for suction75 MPa, and 24.5° for suction 277 MPa. Given that the maximum vertical stress applied was 300 kPa, φ'_{res} was constant over the range of vertical stress applied. The same apparatus was used also [19] to measure φ'_{res} of 28° in Boom Clay from Belgium (w_L=55%, I_p=28%) for suction 70 MPa, when φ'_{res} of the same soil fully saturated is only 13°, and again [20] to measure φ'_{res} of 28.2° on FEBEX bentonite (w_L=102%, I_p=49%, G_s=2.70) for suction of 75 MPa and 22.3° for suction of 18 MPa, when φ'_{res} of the same soil fully saturated is only 7.5°. These results are summarized in Fig. 2. The angle of residual shear strength measured in [18, 19, 20] is plotted against suction in Fig. 2a and the same results are normalized by dividing the tangent of the angle of residual shear strength at suction s, $\varphi_{res(s)}$, with the tangent of the angle of residual shear strength of the fully saturated soil, $\varphi_{res(s=0)}$, and plotting the ratio $\tan \varphi_{res(s)} / \tan \varphi_{res(s=0)}$ against suction in Fig. 2b. These results show that the angle of residual shear strength increases with suction, with the rate of increase also increasing with increasing plasticity and the ratio $\tan \varphi_{res(s)} / \tan \varphi_{res(s=0)}$ increasing linearly with suction as observed elsewhere as well for similarly large [23] and also much smaller values of suction [21]. This change in the angle of residual shear strength is attributed to the creation of very strong conglomerates of clayey platelets because of drying as suction increases, an explanation verified by scanning electron microscopy [20].

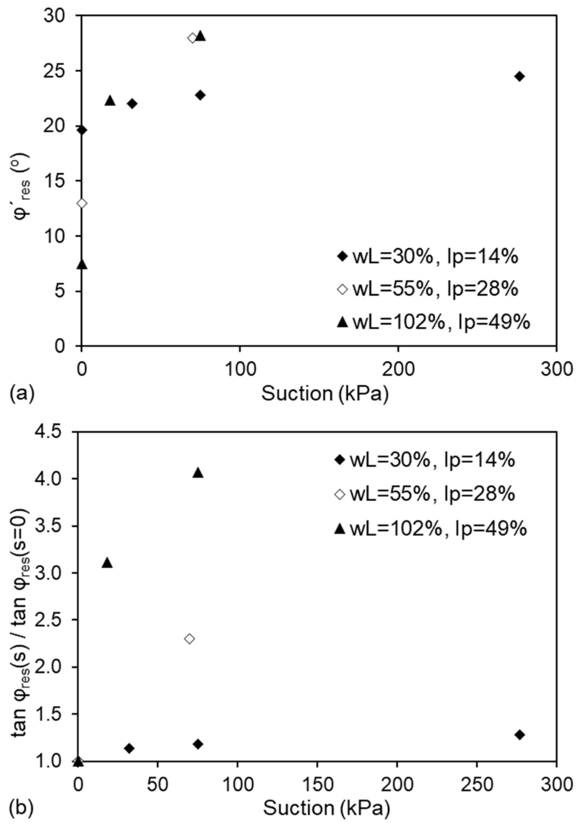

Fig. 2. Effect of suction on the angle of residual shear strength from published results: a) angle of residual shear strength with suction, and b) ratio $\tan \varphi_{res(s)} / \tan \varphi_{res(s=0)}$ with suction.

3 Tests in the ring-shear apparatus with water removed from the cell

Following the observation from published results mentioned in Section 2, a test was performed in a conventional Bromhead-type ring shear apparatus [26] on a silty clay with w_L of 45% and I_p of 23%. The angle of residual shear strength of the fully saturated soil was 26.5°. Another test was repeated on the same soil but this time water was removed from the cell while shear strain was still applied until stabilization of the shear resistance measured. Then water was added again to observe strength loss until new stabilization of the shear strength to practically the same value as before water removal. This was repeated for another value of vertical stress and a third where water was not added again so as to measure total suction on the sample in a chilled-mirror hygrometer. Common observations on the stress-strain diagrams of Fig. 3 are:

- Shear strength increases slowly after water removal at the beginning but after approximately 15% of additional shear strain, corresponding to approximately 12 hrs (0.05°/min rate of torsional shear), it increases rapidly. This time corresponds probably to the time needed of the soil in the sample to start desaturating.
- After this rapid increase, shear strength exhibits a maximum value and more shear strain after this peak causes gradual decrease of shear strength to constant values with increasing shear strain observed as characteristic 'plateaus' on the stress-strain curves in Fig. 3. These 'plateaus' are considered to correspond to residual shear strength under the suction attained under the combined action of relative humidity and temperature in the atmospheric conditions of the laboratory.
- When water was added in the cell of the apparatus, shear strength from these 'plateaus' dropped rapidly to a new 'plateau' of constant shear stress with increasing shear strain corresponding practically to the same shear strength as before water removal (although slightly higher).

These observations are summarised in the failure envelopes shown in Fig. 4. The failure envelope corresponding to the fully saturated soil (φ'_{res}=26.5°) before removal of water serves as the lower bound of strength. The failure envelope moves to the position corresponding to the peak values of strength observed after removal of water at each vertical stress (c′=22 kPa, φ′=39.5°), dropping as shear strain increases to the failure envelope corresponding to the suction attained in the laboratory atmospheric conditions ($\varphi'_{res(s)}$=37.0°).

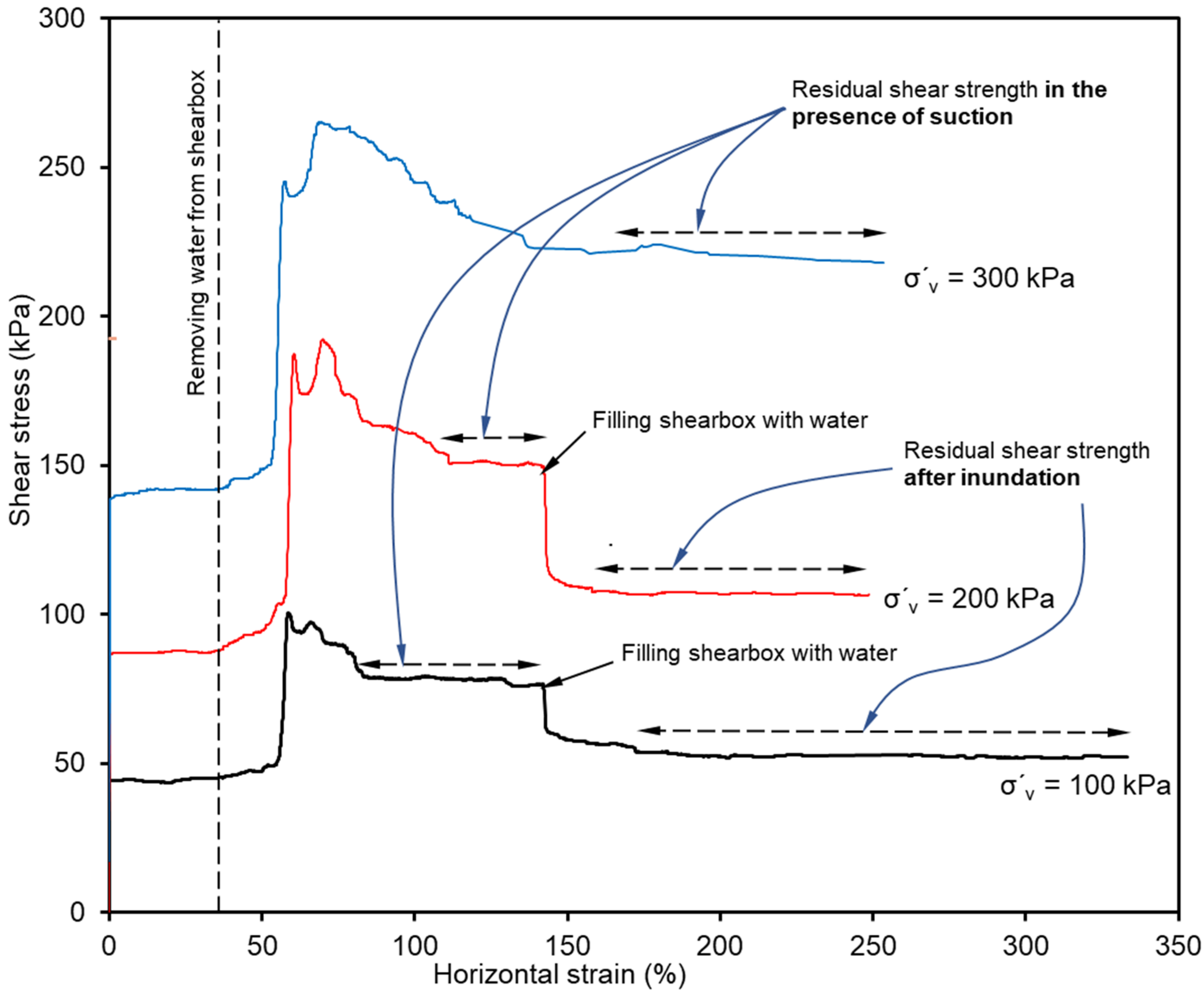

Fig. 3. Shear stress-horizontal strain for the 3 vertical stress values and the characteristic points of water removal and inundation.

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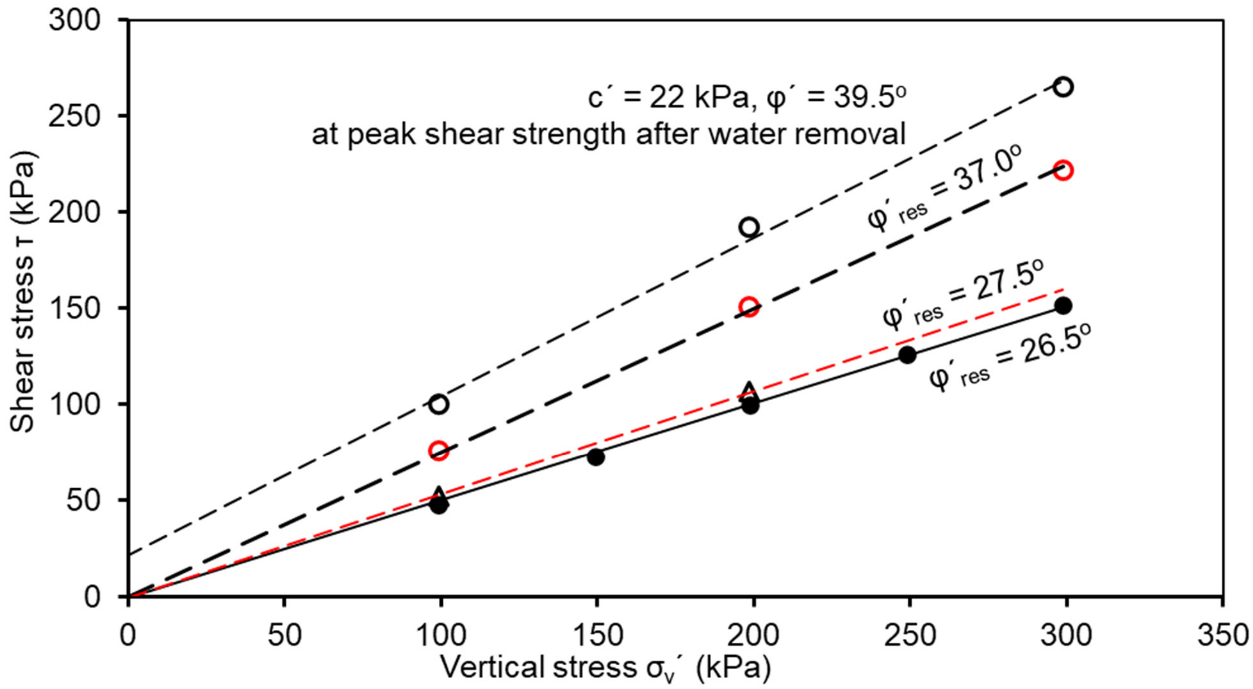

Fig. 4. Failure envelopes for the conditions applied and shown in the stress-strain curves in Fig. 3.

Once water is added again, then the failure envelope drops close to the failure envelope before water removal but with a slightly increased angle of residual shear strength (27.5°). The suction measured in the chilled mirror hygrometer after completion of the test at 300 kPa was approximately 20 MPa.

The test described offers hindsight into the changes of shear strength along a part of a sliding surface in a landslide. A reactivation period is followed by a period of smaller movements because of suction increase, followed by reactivation because of the strength loss caused by the suction loss along certain parts of the sliding surface.

To make use of these observations and the results from tests on various soils, the tangent of the angle of residual shear strength after water removal was divided by the tangent of the angle of residual shear strength of the fully saturated soil and the ratios for various soils tested (Table 1) are plotted in Fig. 5 against liquid limit. An exponential best-fit curve passing through tan $\varphi_{res(s)}$ / tan $\varphi_{res(s=0)}$ = 1 is shown. This relation allows for an estimation of the ratio tan $\varphi_{res(s)}$ / tan $\varphi_{res(s=0)}$ at 20 MPa (in the laboratory these data were collected, in the same way, for another laboratory: at the suction attained in its own atmospheric conditions) from w_L. If the angle of residual shear strength of the fully saturated soil is also measured, then the angle of residual shear strength at any suction may be estimated on the basis of the linearity mentioned in Section 2 of the evolution of tan $\varphi_{res(s)}$ / tan $\varphi_{res(s=0)}$ with suction. Obviously more experimental data are needed to support this method more reliably, still the observations of linearity mentioned in Section 2 and the ability to actually estimate one, single tan $\varphi_{res(s)}$ / tan $\varphi_{res(s=0)}$ ratio value using a conventional ring-shear apparatus and a chilled-mirror hygrometer make its potential worth of further research.

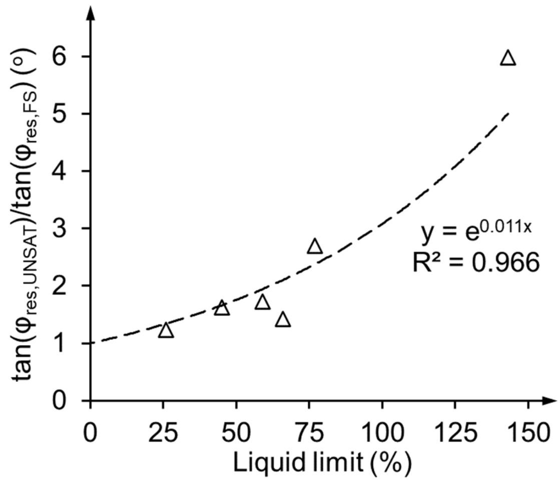

Fig. 5. Evolution of the ratio tan $\varphi_{res(s)}$ / tan $\varphi_{res(s=0)}$ with the liquid limit and an exponential best-fit curve.

Table 1. Data from soils used in Fig. 5.

w_L	w_P	I_p	φ'_{res}	φ'_{res} (s=20 MPa)
(%)	(%)	(%)	(°)	(°)
26	21	5	30.5	35.9
45	22	23	24.8	37
59	23	36	24.1	37.7
66	29	37	15.2	21.2
77	31	46	16.3	38.3
143	35	108	7.32	37.56

4 Conclusions

Ring-shear tests were performed on clayey soils in conventional ring shear apparatus without suction control, simply by removing water from the shear box while shearing continues and measuring shear strength until its stabilisation, taking place after the specimen in the shear box came to equilibrium with prevailing laboratory atmospheric conditions. Using the chilled-mirror hygrometer to measure equilibrium suction after ring shear completion indicated that equilibrium suction due to laboratory atmospheric conditions is practically constant over the time needed for a single test on one soil. This observation along with the observation from published experimental results on the linear increase of the ratio of $\tan\varphi_{res(s)}/\tan\varphi_{res(s=0)}$ with suction, makes valid the estimation of evolution of residual shear strength of unsaturated soils with suction using only a conventional ring shear apparatus and a chilled mirror hygrometer. There seems to be a relation between the ratio of $\tan\varphi_{res(s)}/\tan\varphi_{res(s=0)}$ with liquid limit allowing the possibility to proceed to an estimation of the evolution of the angle of residual shear strength only on the basis of liquid limit and the angle of residual shear strength of the fully saturated soil. Obviously, further validation with more experimental data is needed.

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