Evaluation of SWCC Curves and Undrained Shear Parameters at Different Densities and Saturations of Unsaturated Clay

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Abstract. The behaviour of unsaturated soils in terms of physical and mechanical properties is somewhat different than typical saturated soils. Undrained shear parameters of soil having an unsaturated state are analyzed. Moreover, the influences of moisture content, dry density are also observed. The saturation of the specimens ranges from 20%, 40%, 60%, 80% and the dry density ranges as per standard proctor density and modified proctor density of particular soil type. Fredlund's modified Mohr-Coulomb failure envelope is used to evaluate undrained shear parameters of unsaturated soils. The soil matric suction is evaluated using a contact filter paper technique. It is an effort towards how soil compacted fills and slopes have behaved after its construction while they are exposed to the natural environment.

Keywords**:** Unsaturated Soils, Shear Strength, Matric Suction, Moisture Content, Density

1. Introduction

There are numerous soil materials encountered in engineering practice whose behaviour is not consistent with the principles and concepts of classical, saturated soil mechanics. The presence of more than one fluid phase, for example, results in material behaviour that is challenging to engineering practice. Unsaturated soils (i.e., water and air in the voids) form the largest category of soils which do not adhere in behaviour to classical saturated soil mechanics (D. G. Fredlund et al. 2012). Almost 60% land area on earth is arid or semi-arid region so that these soils strata are not in fully saturated state (D. G. Fredlund et al. 2012), moreover conventional soil mechanics considers fully saturated soil condition for shear strength analysis as worst-case condition but there were some landslides happened while soils are in unsaturated state also (T. V. Bharat et al. 2017). As artificial fills or earthen dam after construction does not remain in the same condition in terms of saturation during its life period. So that we need to analyze the soil condition in an unsaturated state as well to figure out the real-time behaviour of the soil strata out there. Here CI and CH soils of south

Gujarat region is used for the tests regarding evaluation in undrained shear parameters of unsaturated soils. Saturation ranges from 20%, 40%, 60% and 80% to simulate unsaturated state in soil specimen. The test was performed by remoulded soil specimens up to the desired saturation percentage. The densities derived from standard proctor and modified proctor test is considered. The physical tests of particular soil type also carried out for the check of the sensitivity of soils.

2. Method

2.1 Material

Two types of soils are collected from two different cities of south Gujarat region in this experiment which is (1) Medium Plastic Clay and (2) High Plastic Clay from Dahej and Surat cities respectively. Table 1 presents the physical properties and both Proctor test results, which mentions grain size analysis, atterberg limits, IS classification, free swell index, specific gravity, standard Proctor test and modified Proctor test results. All of the tests are performed twice.

Table 1. Physical properties

Soil Property	Dahej	Surat
Gravel %	1.5	5.5
Coarse Sand %	1.5	4
Medium Sand %	5	2
Fine Sand %	22	8.5
Silt + Clay (%)	70	79.5
Liquid Limit%	40	60
Plastic Limit %	18	21
Plasticity Index %	22	39
IS Classification	CI	CH
Specific Gravity gm/cm^3	2.794	2.789
Free Swell Index %	15	64
S.OMC[a] (Standard) %	17.50	20.30
S.MDD[b] (Standard) gm/cm^3	1.70	1.60
M.OMC[c] (Modified) %	16.82	16.32
M.MDD[d] (Modified) gm/cm^3	1.84	1.84

[a.] S.OMC = Standard proctor test optimum moisture content
[b.] S.MDD = Standard proctor test maximum dry density
[c.] M.OMC = Modified proctor test optimum moisture content
[d.] M.MDD = Modified proctor test maximum dry density

2.2 Instruments

The instruments used are a mould with a diameter of 100 mm, height 125 mm. There are three sample tubes with a diameter of 28 mm and height 130 mm. Sampler with a diameter of 28 mm and height 74 mm, a plunger with 20 mm thickness and 98 mm the diameter. Hydraulic sample extractor is needed to compress and also extract the sample from the mould (Shah et. al. 2018). Three-layer measurement tools were also used. The instruments used are different than the universal remoulding tool. This old is used to extract three samples from the same old to get more uniformity in the specimens. Among three samples two samples are for triaxial UU tests and one sample is to check for the uniformity of desire density and saturation.

2.3 Experimental Calculations

All the tests are done regarding the Indian Standards. Now for calculation of saturation moisture content, specific gravity is an important factor thus we determined specific gravity until we get the accuracy to 0.03gm/cm^3. The equations used in determining the saturation and bulk density are mentioned below as equation 1 & 2,

$$M/C = \frac{S\gamma \times ((\frac{G}{\rho d}) - 1)}{G} \quad (1)$$

$$\rho = \rho d \times (1 + \frac{S\gamma}{100}) \quad (2)$$

Where, M/C = moisture content, S_γ = saturation percentage, G = specific gravity, ρ_d=dry density, ρ=bulk density.

2.4 Sample Preparation

Now to determine compaction test, we add 10% of moisture in the soil and put it into a desiccator and put the desiccator partly submerged in 27ºC water to let the soil distribute moisture evenly. By doing this we encountered more accurate results of compaction test and repetitions also gave the same accurate results. From this experiment, we followed these steps for remoulding the sample also. The remoulding is done in three equal layers and compressed it in the mould hydraulically. After the remoulding, the sample is extracted in three tubes with the help of sample extractor. From the tubes, extracted sample used to prepare unconfined compressive strength test specimens. The size of the specimen is 38 mm in the diameter and 76 mm in height.

3. Results and discussion

3.1 Evaluation of SWCC Curves for CI & CH Soils

Soil matric suction is measured having variation in dry density and degree of saturation using contact filter paper technique confirming ASTM 5298 - 10. For the achievement of the appropriate density, a sample is cast with three plungers made up of aluminium metal again that does not affect while in contact with soil and water mixture. The plungers are shaped in the manner that can compact soil sample in two layers in PVC moulds. The PVC moulds having 50 mm dia. And 60 cm of height with 10 mm of the freeboard is used. The dimensions of the moulds are so designed that it can accommodate enough soil samples that confirm ASTM 5298 – 10. Soil SWCC curves for both the soils then derived to understand unsaturated soil behaviour. All SWCC curves are validated by RETC software for soil water retention developed by Van Genuchten (1994). The relation between dry density, moisture content & Soil matric suction can be understood by the following figure.

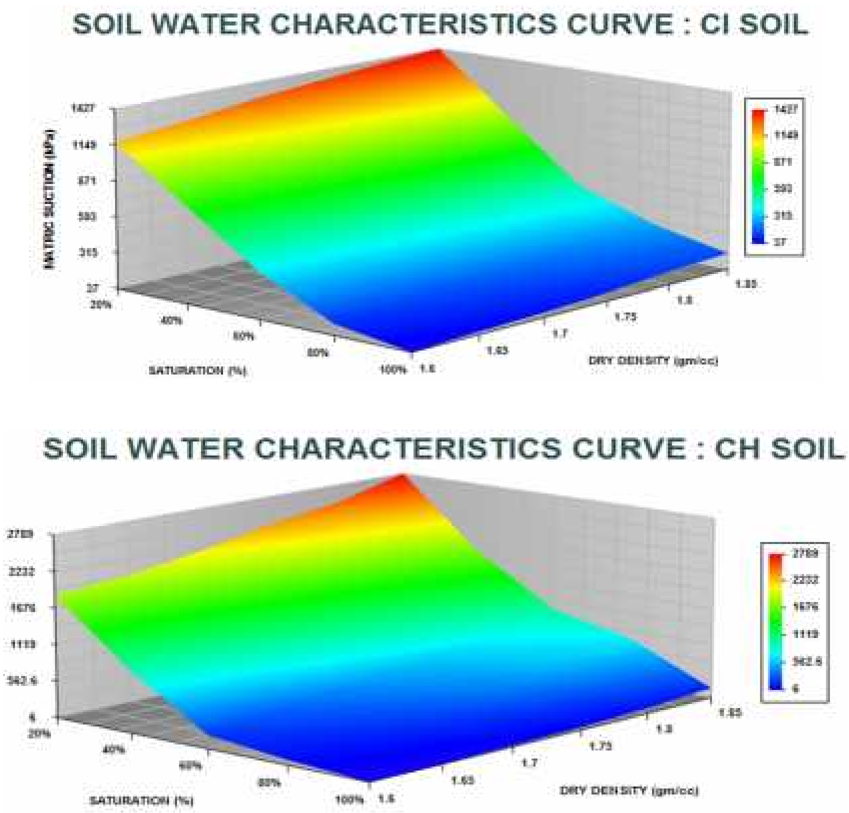


Fig. 1 SWCC Curves for CI and CH Soils

3.2 Triaxial UU Test Results of CI and CH Soils

The results of such shear parameters are evaluated as per unsaturated soil mechanics which is somewhat different from conventional saturated soil mechanics. This particular way of shear parameter evaluation from shear testing involves soil matric suction parameter that can impact remarkably in shear strength of soil especially when the soil sample is unsaturated. In this method, two identical specimens are tested at each dry density having the same moisture content at different confining pressure. Furthermore, for the true shear parameter evaluation, the soil cohesion and angle of internal friction of two consecutive moisture variation of same dry density are taken into account for the determination of true cohesion and the angle which reflects the shear strength due to soil matric suction or negative pore water pressure. So that the results of the shear parameters can be considered as saturation group in particular like 20% - 40%, 40% - 60%, 60% - 80%. It can be evaluated by following the formula of Fredlund's extended Mohr-Coulomb failure envelope,

$$(\sigma_1 - u_a) = (\sigma_3 - u_a) \cdot \tan^2 (45 + \phi'/2) + 2C_1 \cdot \tan (45 + \phi'/2) \quad (3)$$

$$C_1' = C' + (u_a - u_w) \cdot \tan \phi^b \quad (4)$$

Where,

$\sigma_1 - u_a$ = net normal stress state on the failure plane at failure,

$(\sigma_3 - u_a)$ = Confining Pressure at failure

C_1' = Cohesion obtained from the test

ϕ' = Angle of internal friction obtained from the test

$(u_a - u_w)$ = Soil matric suction

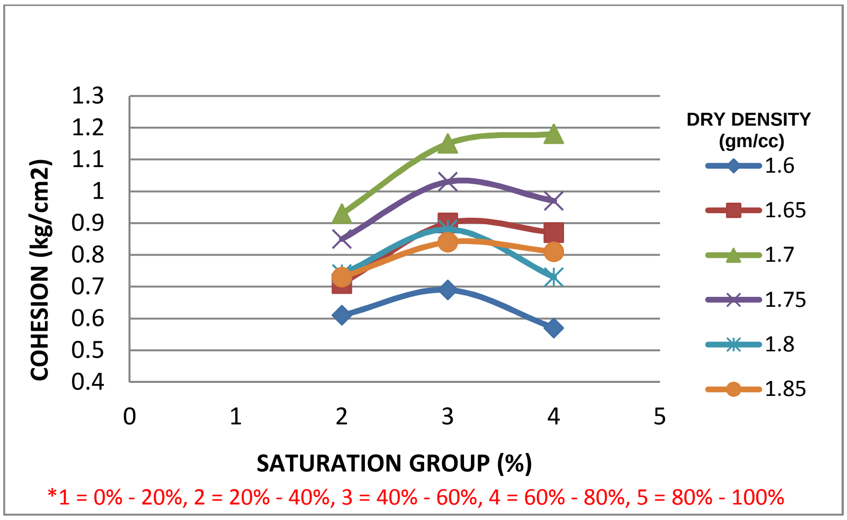
ϕ^b = angle indicating the rate of increase in shear strength concerning a change in matric suction

The considered densities in CI and CH soils are 1.60, 1.65, 1.70, 1.75, 1.80 and 1.85 gm/cm^3 out of which 1.70 gm/cm^3 is standard Proctor test density and 1.85 gm/cm^3 is modified Proctor test density for CI Soil and 1.60 gm/cm^3 is standard Proctor test density and 1.85 gm/cm^3 is modified Proctor test density for CH Soil. Now, for each density, the saturation moisture content is introduced from 20 to 80% with an interval of 20%. The test results are mentioned in table 2 below.

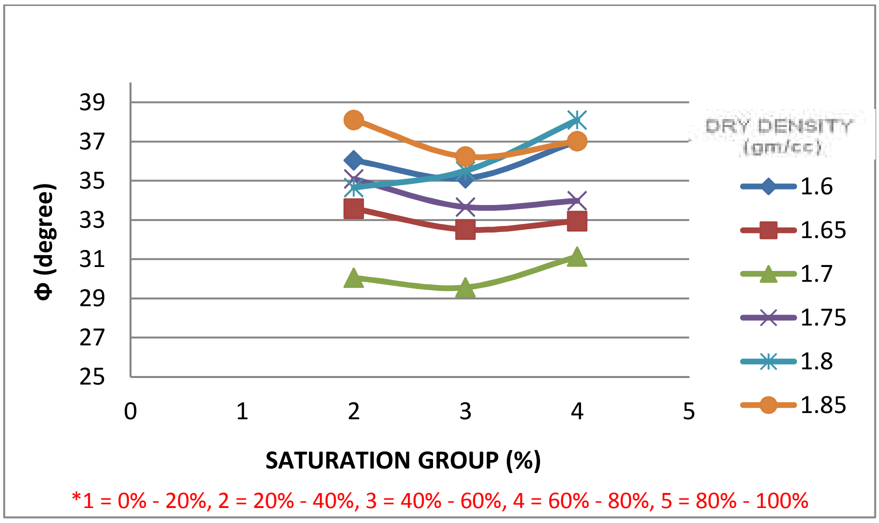
The Confining pressure range for two identical specimens for triaxial UU test is 1.0 kg/cm^2 and 2.0 kg/cm^2 respectively. Two identical Specimens having the same density and moisture content are tested and the results in terms of cohesion, friction angle and the angle contributing soil matric suction are evaluated as per unsaturated soil mechanics using extended Mohr-Coulomb criterion proposed by D. G. Fredlund.

Table 2. Evaluated Shear Parameters of CI and CH Soils

γ_d (g/cc)	Sat. Group (%)	C (kg/cm^2)		ϕ (˚)		ϕ^b (˚)	
		CI	CH	CI	CH	CI	CH
1.6	20 - 40	0.61	0.75	36.04	39.09	6.14	0.12
	40 - 60	0.69	0.84	35.13	38.82	11.6	0.3
	60 - 80	0.57	0.87	37.02	38.45	15.6	2.7
1.65	20 - 40	0.71	0.84	33.58	38.44	2.48	0.18
	40 - 60	0.9	0.93	32.51	38.07	4.65	0.78
	60 - 80	0.87	0.98	32.94	37.29	6.26	1.18
1.70	20 - 40	0.93	0.93	30.04	37.41	0.87	0.47
	40 - 60	1.15	1.05	29.56	36.43	1.07	0.47
	60 - 80	1.18	1.08	31.12	35.99	3.95	1.21
1.75	20 - 40	0.85	1.05	35.09	36.27	0.97	0.11
	40 - 60	1.03	1.10	33.66	35.85	3.16	0.67
	60 - 80	0.97	1.03	33.98	35.02	11.13	3.56
1.80	20 - 40	0.74	1.32	33.64	30.52	4.81	0.39
	40 - 60	0.88	1.44	35.51	28.13	8.56	0.93
	60 - 80	0.73	1.27	38.1	27.38	13.02	3.84
1.85	20 - 40	0.73	1.45	38.1	29.32	2.91	0.21
	40 - 60	0.84	1.46	36.23	27.78	5.29	1.05
	60 - 80	0.81	1.33	37.02	23.23	9.63	3.92



a)



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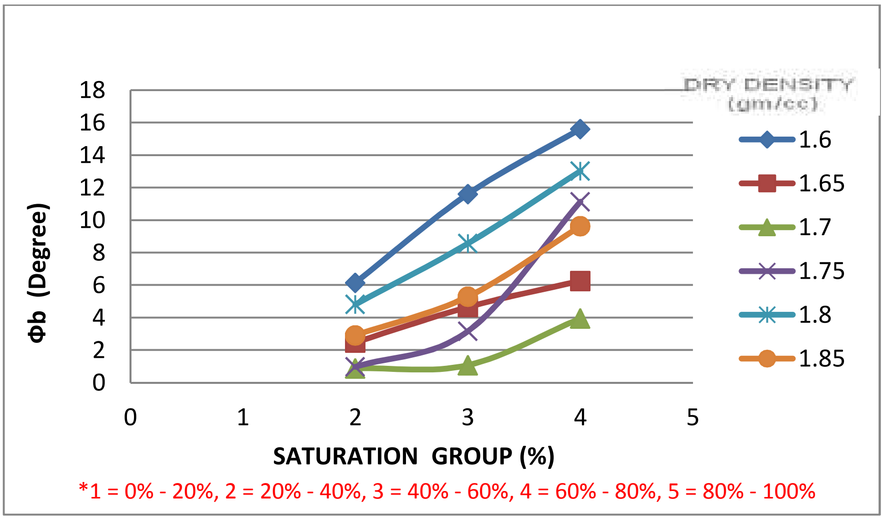
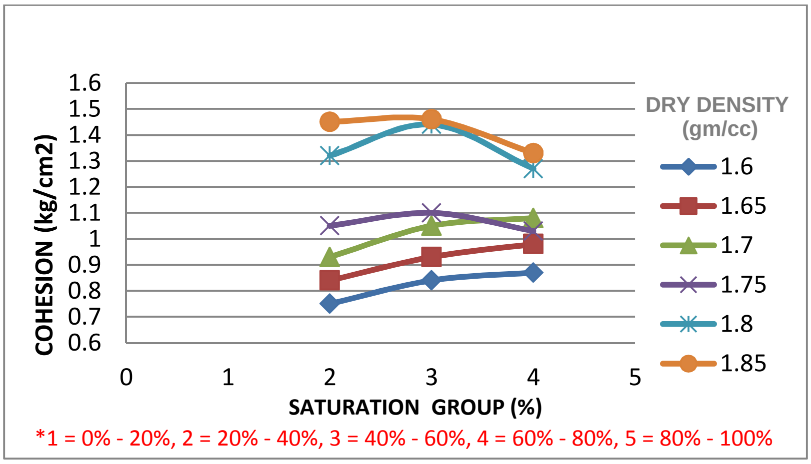


c)

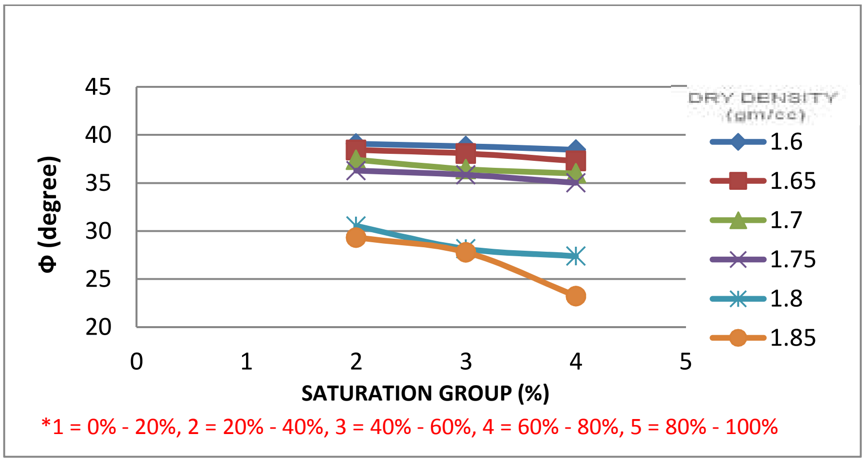
Fig. 2 a) saturation group VS cohesion, **b)** saturation Group VS friction angle, **c)** saturation group VS Friction angle w.r.t soil matric suction of CI soil

Now, at standard proctor density CI soil showed the highest cohesion and that is also got rise as we go the lowest saturation group to the highest saturation group is taken for the evaluation. After standard proctor density cohesion goes down in all saturation groups having some variation within the saturation group in particular. It looks like at modified proctor density the cohesion goes down regarding lesser moisture content due to rise in dry density. When the angle of internal friction is a concern it shows appropriate results as per the variation of cohesion at each density and saturation group variations. As per fig. we can say conventionally that if the soil cohesion is more the angle of friction is less.

Lastly, a very important observation is noted that at the lower saturation group the Φ^b angle is very less that means that at that particular saturation group the matric suction is highest in other words the negative pore water pressure is more at that particular saturation. On the other hand at higher saturation group the angle Φ^b got sudden rise because at higher saturation ranges the soil matric suction goes down so is a contribution in ultimate cohesion too. We can say that at fully saturation state the angle Φ^b can be reported the same as the angle of internal friction and that onwards it may be analyzed by conventional saturated soil mechanics.



a)



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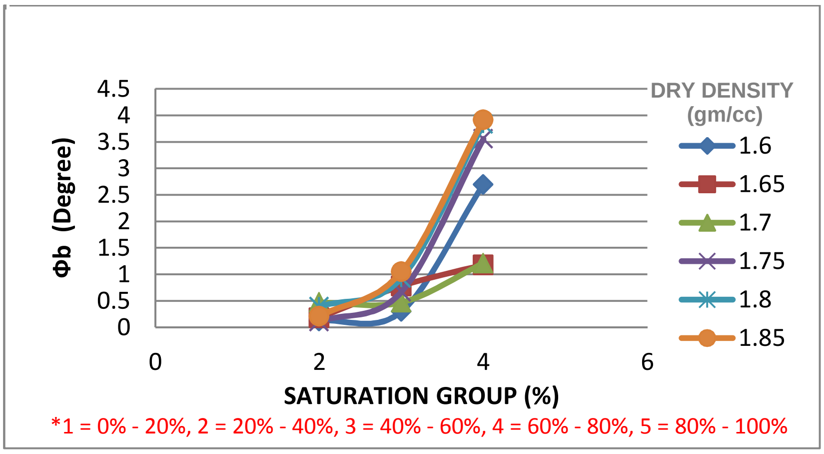

c)

Fig. 3 a) saturation group VS cohesion, **b)** saturation Group VS friction angle, **c)** saturation group VS Friction angle w.r.t soil matric suction of CH soil

Now, at modified proctor density CH soil showed the highest cohesion and at 40% - 60% saturation group and after that, at highest saturation group lower value of cohesion at modified proctor density is reported. After standard proctor density cohesion got a rise in all saturation groups having some variation within the saturation group in particular. It looks like at modified proctor density the cohesion goes highest regarding lesser moisture content due to rise in dry density. When the angle of internal friction is a concern it shows appropriate results as per the variation of cohesion at each density and saturation group variations. As per fig. we can say conventionally that if the soil cohesion is more the angle of friction is less.

Observation is noted again in CH or high plastic soil that at the lower saturation group the Φb angle is very less that means that at that particular saturation group the matric suction is highest in other words the negative pore water pressure is more at that particular saturation. On the other hand at higher saturation group the angle Φb got sudden rise because at higher saturation ranges the soil matric suction goes down so is a contribution in ultimate cohesion too. We can say that at fully saturation state the angle Φb can be reported the same as the angle of internal friction and that onwards it may be analyzed by conventional soil mechanics.

4. Conclusions

- Starting from the initial stage of evaluation of soil specific SWCC curves it is noticed that soil matric suction is depended mainly on chemical property of soil like water retention capacity, cohesion, and temperature conditions etc. It depends on density and saturation conditions as well. It is observed that more the plastic the soil is more pressure we need to extract water from the soil mass.

- Below standard Proctor density, each soil shows almost the same strength behaviour at different saturations for both types of soils. From the Triaxial UU test, it is noticed that CI soil gives maximum cohesion at standard proctor density whereas CH soil gives maximum cohesion at modified proctor density at 40% to 60% saturation group. On the other hand bentonite clay shows maximum cohesion after standard proctor density but before of modified proctor density.
- The most important conclusion is the relation of soil matric suction with soil shear properties. At lower saturation or in negative pore pressure condition the angle of friction due to matric suction is less that means the contribution of matric suction in true cohesion in that condition is maximum.
- On the other hand with an increase in saturation condition or increase in pore pressure conditions the Φb angle range have sudden rise up to 15˚ from almost 1.0 ˚ results lesser contribution in actual shear strength conditions. And ultimately at fully saturation conditions, the angle that represents strength contribution due to matric suction (Φb) is equal to ϕ

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