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Full Length Research Paper

Effect of soil moisture in the analysis of undrained shear strength of compacted clayey soil

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An experimental study was undertaken to study the principles of soil compaction and establish a relation between the undrained shear strength of compacted clay and its moisture content. Compaction of soil is an important prerequisite for the construction of man-made structures like bridges, roads, dams, embankments etc. In the present study fine grained saturated clay finer than 2 × 10^{-6} m were used for all purposes. An important property of cohesive soils is that compaction increases their shear strength and compressibility. The shear strength of clay is the maximum shear stress it can sustain. It is helpful as the common soil failures are due to shear failures (Iannacchione et al., 1994). Undrained condition of clayey soil occurs when pore water pressure of soil changes due to external loading. If the soil is sheared without changing the water content its strength remains the same. During the study the optimum moisture content was analyzed from the compaction curve. Finally, the shear strength curve was drawn for different compaction efforts which clearly showed an exponential decrease in the shear strength of clayey soil with gradual increase in the water content. Factors other than the change in water content and compaction energy were not considered.

Key words: Undrained shear strength, optimum moisture content, dry density, compaction curve.

INTRODUCTION

Soil compaction is a process of mechanical densification of soil by pressing the soil particles close to each other and removing the air between them. It is of utmost importance in the broad science of Geotechnical engineering playing a significant role in all types of Geotechnical investigations. Compacted soils are widely used in the construction of geotechnical and geo-environmental structures and the durability and stability of these structures are directly related to the achievement of proper soil compaction. Compaction is not appropriate for granular soils. The principal soil properties affected by compaction include settlement, shearing resistance, water movement and volume change. The constitutive equations for volume change, shear strength and flow for unsaturated soil have been generally accepted in Geotechnical engineering (Freedlund and Rahardjo, 1993a). Hence, undrained shear strength analysis of compacted soils is of relevance in dealing with these structures. The shear strength of an unsaturated clayey soil and soil-water characteristic curve depend on the soil structure or the aggregation which in turn depends on the initial water content and the method of compaction. Cohesion appears to be largely due to the intermolecular bond between the adsorbed water surrounding each grain, especially in fine grained soils. Therefore, the value of the cohesion will thus vary with the soil water content, grain size of soils and its compaction. As moisture content increases cohesion decreases because of greater separation of clay particles. The bearing capacity of all types of soils and clayey soils in particular, by and large, depend on their shear strength. The drained and undrained shear strengths of clayey soil are different due to varying soil structures. Shear strength of clayey soil is its tendency of resisting shear movement along the soil surface. Most geotechnical failures involve shear failures of the soil. The shear strength parameters of soil are known as cohesion, c and angle of friction, Ø and are defined by the Mohr-Coulomb failure envelope:

$$\tau = \sigma \ \tan(\phi) + c$$

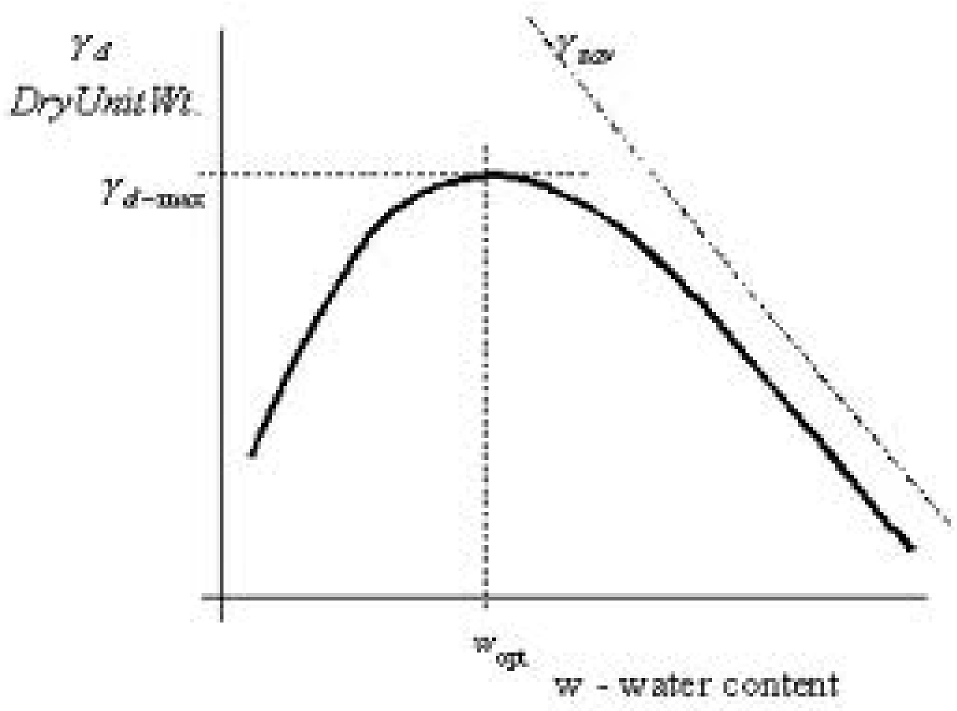


Figure 1. Relation between moisture content and dry unit weight of soil.

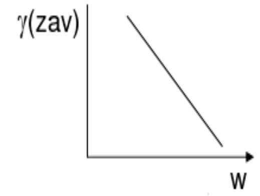
Where, **σ** is the normal stress.

BACKGROUND INFORMATION

The moisture content of a soil has a major impact on how well the soil will compact. When a soil is completely dry it will not compact to it greatest possible density because of friction between the soil particles. As the moisture content increases, the water lubricates the soil, allowing it to move more easily into a compact state and the density increases. Eventually the soil is compacted to its greatest possible dry density (the maximum dry density) and the moisture content at which this happens is referred to as the ‘Optimum Moisture Content’. If the soil is wetted further, the extra water replaces some of the solid soil particles and the dry density reduces as there is less material present. Soil compacted at moisture content greater than the optimum moisture content has exactly the opposite characteristics to the one compacted below it. For a particular compaction effort, the dry density of soil increases with the moisture content of the soil up to the optimum moisture content beyond which it decreases. When the compaction effort increases, the optimum moisture content decreases. The relationship between dry density and water content is usually represented by a graph (Figure 1).

The zero-air-void unit weight is represented by the following equation and the zero-air-void line is shown beside.

$$\gamma(z.a.v) = \frac{G_s\gamma_w}{1+wG_s}$$



It is clear from the given equation that the zero-air-void density is inversely proportional to the moisture content w of the soil. For a given soil and moisture content the best possible compaction is represented by the zero-air-voids curve. The actual compaction curve will always be below. As more water is added and the moisture content exceeds the optimum value the void spaces get filled with water and further compaction is not possible. The specific gravity of water and dry density of soil are assumed constant for a particular moisture content.

CLASSIFICATION OF CLAYEY SOILS

According to their moisture content, clayey soils can be classified into 4 categories namely solid, semisolid, plastic and liquid. As the soil moves from being solid to liquid, the cohesion value (c) decreases. Clay particles are less than 0.00015 inch (0.004 mm) in diameter and are much smaller than ordinary sand. Clayey soils are virtually cohesive soils with high cohesive strength and are fine grained in nature.

PROCEDURE OF COMPACTION

For compacting the clayey soil, STANDARD PROCTOR COMPACTION TESTS were used. These tests are prescribed in ASTM D698. Designed by Proctor (1933), this laboratory test is performed to determine a relationship between the dry density and the moisture content of a soil sample for a particular compactive effort. The compactive effort is the amount of mechanical energy that is applied to the soil mass. In this test the soil is compacted using a 5.5 lb hammer falling a distance of one foot into a solid filled mould in three layers. For every value of moisture content the soil is compacted with 25 blows. Compaction effort designed in this laboratory test is comparable with that obtained in the field. Dry density achieved by mixing soil with different water contents were obtained to determine the maximum dry density and the corresponding optimum moisture content. For a particular compactive effort the dry density depends on the moisture content of the soil. The following apparatus are used during the compaction process:

(i) Moulds – They should be cylindrical with a diameter of 101.6 mm and height of 116.4 mm and therefore a volume of 944 cc. They are fitted with a detachable base plate and a removable collar.
(ii) A metal Rammer – It should have a circular face of 50 mm and weighing 2.49 kg.
(iii) Balances – They should be accurate to .01 g.
(Iv) Sieves – 75 mm, 19 mm and 4.75 mm sieves are required.
(v) Mixing Tools –Mixing pan, spoon,spatula etc.
(vi) Metal tray – It should have dimensions 600 × 800 × 80 mm.
(vii) Cans
(viii) Oven
(ix) Sample Extruder

After compaction the collar and base plate are detached carefully and the weight of the compacted soil in the mould is measured. The soil sample is extruded and cut at the middle from where a chunk is broken and put into the oven in a can for determining the water content in the soil.

Computations: The bulk density ρ in kg/m^3 of each compacted specimen is calculated as

$$\rho = (M_2 - M_1)/V,$$

Where M_1 is the mass of the mould and base in kg, M_2 is the mass of the mould, base and soil in kg and V is the volume of the mould. The dry density of the soil sample is given as:

$$\rho_d = \rho/(1 + w)$$

The amount of water to be added with air-dried soil at the commencement of the test is about 8% to 10% below the plastic limit of the soil. The water should be mixed thoroughly and adequately with the soil. The moisture content is calculated as:

$$\mathbf{w = (w_4 - w_3) / (w_4 - w_2)}$$

Where w_4 is the weight of the can + wet soil, w_3 is the weight of the can + dry soil and w_2 is the weight of the empty can.

Effect of compaction energy: As the compaction energy increases the maximum dry unit weight of compaction increases and the optimum moisture content decreases to some extent and maximum dry density increases.

Preparing the sample: The clay was mixed with sufficient amount of water to reach saturation point. The degree of saturation of compacted soil was found to be 100% through back calculation from the measured value of bulk unit weight, water content and specific gravity as given below:

$$S_r = (w.G/e) \times 100\%$$

It may kindly be noted that Khing et al. (1994) following the procedure similar to that achieved 100% saturation in the clay bed (Figure 2).

Determination of undrained shear strength

The undrained shear strength of clayey soil is determined by the Laboratory and Field Vane Shear Tests as per IS: 2720. This test is prescribed in ASTM D4648/ D4648 M-10. It provides a rapid determination of shear strength on undisturbed or remolded or reconstituted soils. This test method covers the miniature vane test in very soft to stiff saturated fine-grained clayey soils ($\phi = 0$). Knowledge of the nature of the soil in which each vane test is to be made is necessary for assessment of the applicability and interpretation of the test results. It is suitable for the determination of undrained shear strength of cohesive soils. It consists of a torque head adjustable in height by means of a lead screw rotated by a drive wheel to enable the vane to be lowered into the specimen. The vane diameter, vane size, rod diameter and vane height are in accordance with the IS codes. The test apparatus consists of a four-blade stainless steel vane which is lowered into the mould containing the compacted soil. Generally, the height of the vane is two times its diameter. It is driven by an external torque supplied by an electric motor. The vane should be inserted into the soil to a depth at least two times the height of the vane. The vane rotates at a slow speed of 0.1º per second. It determines the torsional force required to cause a cylindrical surface to be sheared by the vane; this force is then converted to a unit shearing resistance of the cylindrical surface. It is of basic importance that the friction of the vane rod and instrument be accounted for; otherwise, the friction would be improperly recorded as soil strength. The torque measured at the failure gives the undrained shear strength of the soil at that moisture level. This test is performed on clay compacted with 5, 10 and 15 blows in three layers .The torque is measured using a spring which controls the degree of rotation of the metallic dial. Essentially, the torque is dependent on the degree of rotation of the spring and varies with it. The shear strength of the soil is a function of the torque generated at failure. It is given by:

$$\mathbf{T = \tau \times K}$$

Here, T is the torque in N-m (Lambe and Whitman, 1979), τ is the undrained shear strength at failure in Pa and K is the vane blade constant in m^3.

From experiments, it is found that $K = \{11\ D^2H(1+D/3H)\} / (2 \times 10^6)\}$ in SI system, where D and H are the diameter and height of the vane respectively.

Among the basic drawbacks of this method is the assumption of full mobilization of the strength along a cylindrical failure surface as reported by Ladd et al. (1977). However, several studies have shown that mobilization of strength can be:

(i) Triangular: Shear strength mobilization is the maximum at the periphery and it decreases linearly to zero at the center.
(ii) Uniform: Shear strength mobilization is constant from the periphery to the soil center.
(iii) Parabolic: Shear strength mobilization is the maximum at the periphery and decreases parabolically to zero at the center.

Bjerrum (1974) showed that as the plasticity of soils increases, shear strength values obtained from Vane Shear Test may give results that are unsafe for foundation design. For this reason he suggested the correction:

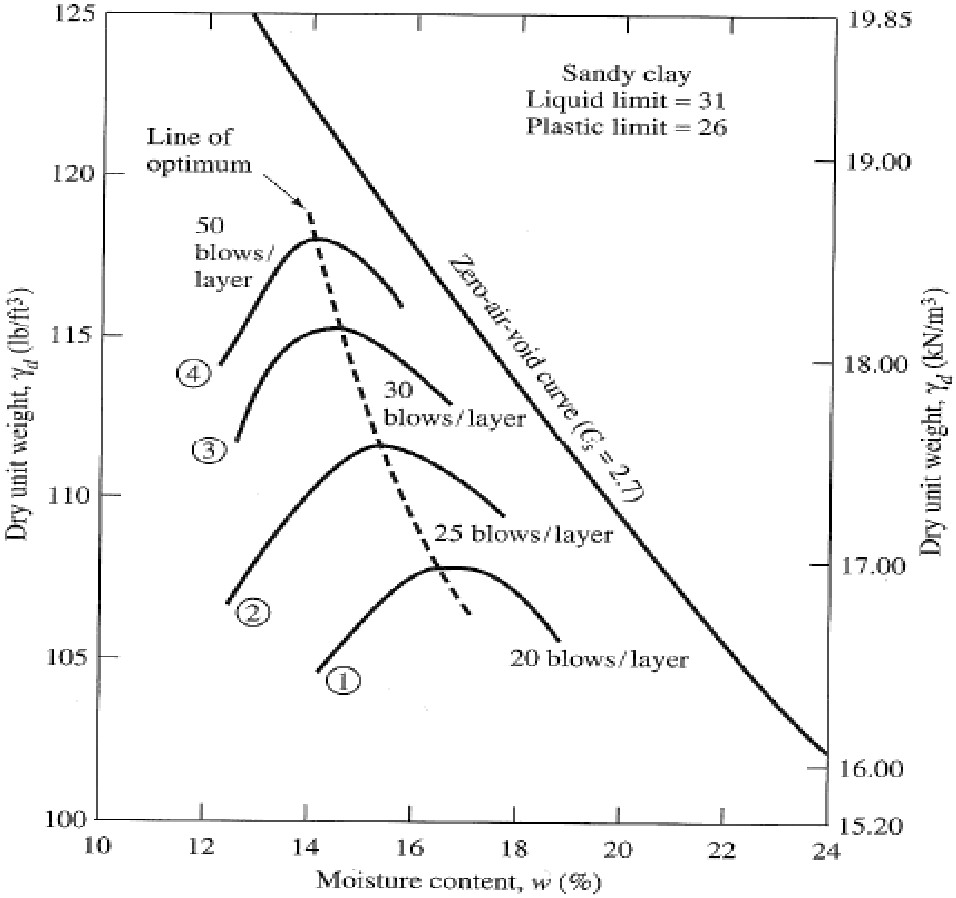


Figure 2. Effect of compaction energy on moisture content and dry unit weight.

$C_{u\,(design)} = \mu .\ C_{u\,(vane\ shear)}$
μ = correction factor = $1.7 - 0.54 \log (PI)$

Recently, Morris and Williams (1994) gave the correlation of μ as:

$\mu = 1.18\, e^{-.08(PI)} + 0.57$
$\mu = 7.01\, e^{-.08(LL)} + 0.57$, LL = Liquid Limit (%)

Empirical relation between the effective overburden pressure and undrained shear strength

The first such relation was proposed by Skempton (1957) and is given as: $(C_{u\,(VST)}) / \sigma_0' = 0.11 + 0.0037(PI)$, where PI is the Plasticity Index of the soil.

Ladd et al. (1977) proposed : $(C_u / \sigma_0')_{overconsolidated} / (C_u / \sigma_0')_{normally\ consolidated} = (OCR)^{0.8}$, OCR is the Overconsolidation ratio and is given as OCR = σ_c' / σ_0', σ_c' is the preconsolidation pressure.

RESULTS

Proctor compaction test

Estimation of optimum moisture content

The optimum moisture content was found to be around 16% from the compaction curve. The maximum dry density recorded was 17.53 g/cc (Table 1 and Figure 3).

Atterberg's Test

The results of the Atterberg Limit Test are given below:

Liquid Limit: 84%
Plastic Limit: 46%

Procedure of vane shear tests

For the laboratory miniature vane shear test the compaction is done so as to account for the overburden pressure in the field. The following were noted:

For compaction of sample in mould:

(i) Weight of hammer: 17.65 N
(ii) Height of drop: 210 mm
(iii) Number of layers: 3
(iv) Diameter of vane: 1.2 cm

Table 1. Proctor compaction test results.

Weight of mould + soil (kg)	Weight of empty mould (kg)	Weight of wet soil (kg)	Density of soil (g/cc)	Moisture content (%)	Dry density (g/cc)
6.364	4.625	1.739	17.39	9	15.955
6.488	4.625	1.863	18.63	12	16.63393
6.613	4.625	1.988	19.88	14	17.4386
6.659	4.625	2.034	20.34	16	17.53448
6.626	4.625	2.001	20.01	18	16.95763
6.611	4.625	1.986	19.86	20	16.55
6.578	4.625	1.953	19.53	22	16.0082
6.522	4.625	1.897	18.97	24	15.05556

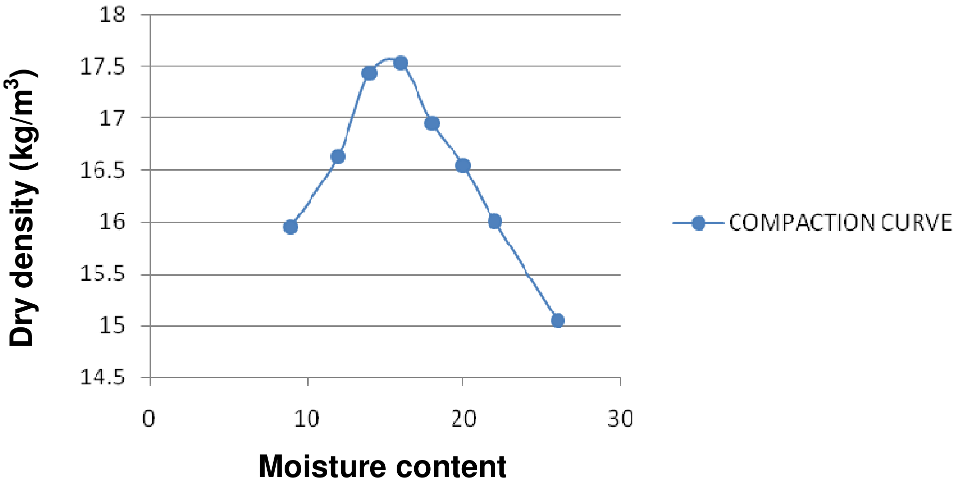


Figure 3. Compaction curve.

Table 2. Atterberg's limits.

Depth (m)	Moisture content (%)	Liquid limit	Plastic limit
1.0	20.44	76	32
2.0	28.18	72	34
3.0	34.52	72	28
4.0	37.86	68	30
5.0	39.12	68	28
6.0	42.52	70	27
7.0	45.40	68	30
8.0	49.22	68	29

(v) Height of vane- 2.4 cm
(vi) Mould diameter- 3.8 cm
(vii) Mould height – 10 cm
(viii) Volume of mould – 113.46 cc

Calculation of compaction energy:

(a) For 5 blows: E = (5 * 3 * 0.01765 * 0.210) / 113.46 * 10^{-6} = 490 kN-m / m^3
(b) For 10 blows: E = (10 * 3 * 0.01765 * 0.210) / 113.46 * 10^{-6} = 980 kN-m / m^3
(c) For 15 blows: E = (15 * 3 * 0.01765 * 0.210) / 113.46 * 10^{-6} = 1470 kN-m / m^3

For the field test the undrained shear strength is calculated for both the undisturbed and remolded state. First, the vane is pushed into the soil. The torque is applied at the top of the torque rod to rotate the vane at a uniform speed. The soil is classified as A-7-6 according to the AASHTO system. The Atterberg's Limits are recorded as shown in Tables 2 to 4.

The sensitivity of the clay is the ratio of the undrained shear strength in the undisturbed state to the remolded state and is found to be 3.04. The plot is drawn with the undrained shear strength (kN/m^2) along Y-axis and moisture content along X-axis (Figure 4).

The shear strength curve is plotted with the moisture content (%) along X-axis and the undrained shear

Table 3. Undisturbed field shear strength.

Depth (m)	Moisture content (%)	Undrained shear strength (kN/m^2)
1.0	20.44	48.914
2.0	28.18	44.784
3.0	34.52	57.932
4.0	37.86	32.119
5.0	39.12	21.659
6.0	42.52	24.406
7.0	45.40	18.847
8.0	49.22	18.754

Table 4. Remolded field shear strength.

Depth (m)	Moisture content (%)	Undrained shear strength (kN/m^2)
1.0	20.44	26.876
2.0	28.18	21.225
3.0	34.52	22.542
4.0	37.86	14.870
5.0	39.12	5.114
6.0	42.52	5.790
7.0	45.40	5.215
8.0	49.22	5.208

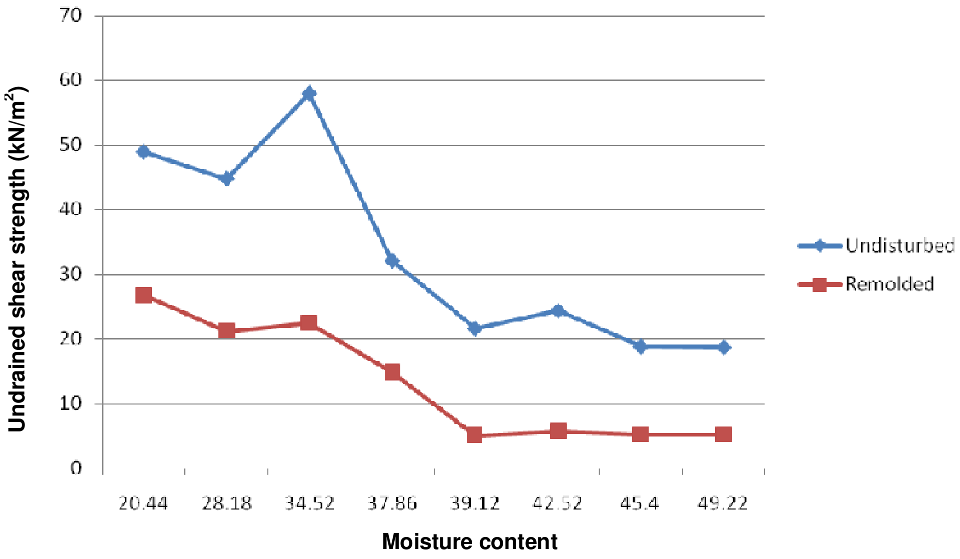


Figure 4. Relation between undrained shear strength and moisture content.

strength (kN/m^2) along Y-axis.

The blue line of the Figure 5 is for 5 blows, red line for 10 blows and green line for 15 blows. The three curves clearly indicate an exponential decrease in the shear strength of compacted clayey soil with gradual increase in moisture content (Tables 5 to 7).

DISCUSSION

The undrained shear strength of soil is a function of its moisture content and mineralogical properties. It is seen that the Laboratory Vane Shear Test shows steeper decrease in the undrained shear strength than the Field

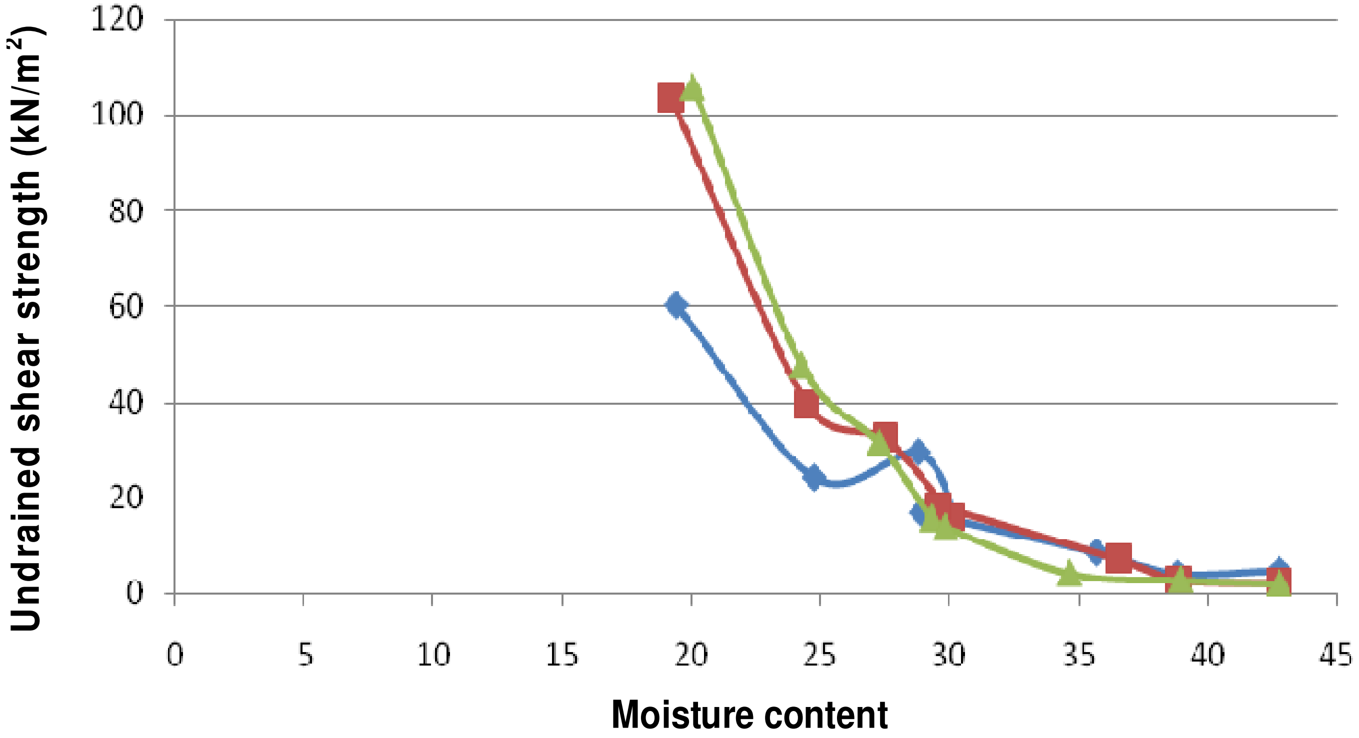


Figure 5. Relation between undrained shear strength and moisture content.

Table 5. Laboratory Vane Shear result for 5 blows.

Weight of empty mould (g)	Empty mould + wet soil (g)	Weight of wet soil	Bulk density (g/cc)	Weight of empty can (g)	Weight of empty can + wet soil (g)	Weight of empty can + dry soil (g)	Dry soil weight (g)	Weight of water (g)	Moisture content (%)	Spring type	Initial angle (°)	Final angle (°)	Rotation (°)	Torque (kg-cm)	Shear strength (kN/m²)
1544	1733	189	1.66583	35.671	56.517	53.131	17.46	3.386	19.3929	F	170	289	119	3.8125	60.1974
1544	1752	208	1.83329	30.537	54.398	49.665	19.128	4.733	24.7438	E	135	227	92	1.53846	24.2915
1544	1764	220	1.93906	30.551	63.079	55.808	25.257	7.271	28.7881	F	160	209	49	1.875	29.6053
1544	1758	214	1.88617	30.474	56.171	50.22	19.746	5.951	30.1377	F	169	182	13	0.96154	15.1822
1544	1763	219	1.93024	30.479	52.841	47.83	17.351	5.011	28.8802	F	345	362	17	1.075	16.9737
1544	1753	209	1.84211	40.113	73.939	65.044	24.931	8.895	35.6785	E	132	147	15	0.55128	8.70445
1544	1747	203	1.78922	40.259	59.398	54.046	13.787	5.352	38.8192	E	138	144	6	0.27273	4.30622
1544	1746	202	1.78041	31.234	57.037	49.308	18.074	7.729	42.7631	E	130	137	7	0.31818	5.02392

Table 6. Laboratory Vane Shear result for 5 blows.

Weight of empty mould (g)	Empty mould + wet soil (g)	Weight of wet soil	Bulk density (g/cc)	Weight of empty can (g)	Weight of empty can + wet soil (g)	Weight of empty can + dry soil (g)	Dry soil weight (g)	Weight of water (g)	Moisture content (%)	Spring type	Initial angle (°)	Final angle (°)	Rotation (°)	Torque (kg-cm)	Shear strength (kN/m²)
1544	1751	207	1.82448	35.44	55.907	52.61	17.17	3.297	19.2021	H	161	243	82	6.55556	103.509
1544	1770	226	1.99194	34.293	60.219	55.123	20.83	5.096	24.4647	E	138	304	166	2.5	39.4737
1544	1764	220	1.93906	33.175	59.264	53.64	20.465	5.624	27.4811	H	345	357	12	2.0625	32.5658
1544	1757	213	1.87736	31.941	61.567	54.715	22.774	6.852	30.0869	F	168	182	14	1	15.7895
1544	1761	217	1.91262	40.138	64.404	58.867	18.729	5.537	29.5638	F	343	363	20	1.15	18.1579
1544	1750	206	1.81566	36.169	51.027	47.053	10.884	3.974	36.5123	E	136	146	10	0.45455	7.17703
1544	1737	193	1.70108	30.539	52.725	46.521	15.982	6.204	38.8187	E	139	143	4	0.18182	2.87081
1544	1747	203	1.78922	34.294	56.926	50.15	15.856	6.776	42.7346	E	140	143	3	0.13636	2.15311

Table 7. Laboratory Vane Shear result for 15 blows.

Weight of empty mould (g)	Empty mould + wet soil (g)	Weight of wet soil	Bulk density (g/cc)	Weight of empty can (g)	Weight of empty can + wet soil (g)	Weight of empty can + dry soil (g)	Dry soil weight (g)	Weight of water (g)	Water content (%)	Spring type	Initial angle (°)	Final angle (°)	Rotation (°)	Torque (kg-cm)	Shear strength (kN/m²)
1544	1760	216	1.9038	31.681	57.319	53.044	21.363	4.275	20.0112	H	165	250	85	6.72222	106.14
1544	1773	229	2.01838	31.23	66.81	59.872	28.642	6.938	24.2232	F	168	243	75	3.025	47.7632
1544	1765	221	1.94787	31.682	59.174	53.29	21.608	5.884	27.2307	H	348	359	11	2	31.5789
1544	1760	216	1.9038	33.175	60.953	54.663	21.488	6.29	29.2722	F	169	183	14	1	15.7895
1544	1757	213	1.87736	35.44	67.961	60.496	25.056	7.465	29.7933	F	349	360	11	0.88462	13.9676
1544	1716	172	1.51599	32.293	54.655	48.906	16.613	5.749	34.6054	E	139	145	6	0.27273	4.30622
1544	1744	200	1.76278	32.301	70.849	60.053	27.752	10.796	38.9017	E	138	142	4	0.18182	2.87081
1544	1747	203	1.78922	34.294	56.926	50.15	15.856	6.776	42.7346	E	140	143	3	0.13636	2.15311

Test. This could be partly attributed to the fact that due to the absence of any overburden pressure the sample in the lab exhibits the maximum shear strength at a moisture content which is close to the Optimum Moisture Content. It will be slightly more than the one obtained from the Proctor Compaction Test because of different compaction energy. It is found that the Lab Shear Test values are significantly higher than the Field Shear Test values for the same moisture content and hence correction as suggested by Bjerrum (1973) has to be applied for checking the safety against shear failure during foundation design. It is also noted that the corrected values for the shear strength obtained in lab and field are about 80% lower than the actual values (Mohd et al., 1997).

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