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AN APPROACH FOR ASSESSEMENT OF COMPACTION CURVES OF SOILS AT VARIOUS ENERGIES USING A ONE POINT TEST

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Abstract

Compaction curves from nine fine-grained and sixteen coarse-grained soils, which cover all soil types classified by the Unified Soil Classification System (USCS) are analyzed to develop the Ohio's compaction curves. For all tested soils, at a particular compaction energy, the relationships between water content (w) and degree of saturation (S) are represented by power function, which are $w = A_d S^{B_d}$ and $w = A_w S^{B_w}$ for the dry and the wet sides of optimum, respectively (where A_d, A_w, B_d and B_w are constant). It is found that the compaction curves of all tested soils follow the Ohio's compaction curves. Based on this findings, Modified Ohio's curves are introduced for both fine and coarse-grained soils under compaction energy levels of 296.3, 1346.6 and 2693.3 kJ/m^3 which are equal to the energy of half standard, half modified and modified Proctor energies. The modified Ohio's curves are useful in rapid estimation of laboratory compaction curves from a single set data of dry unit weight and water content.

Keywords: Compaction curve, compaction energy, fine-grained soils, coarse-grained soil, modified Ohio's curves

Introduction

Soils are materials that are not "made to order" and thus do not always exhibit the properties desired for constructing earth systems. Therefore, modification of soils at the site to improve their engineering properties becomes necessary. Soil compaction is one of the most extensively used techniques to achieve this due to its cost-effectiveness. The aim of compacting earth fills is to reduce settlement and permeability and to increase shear strength. Compaction is essential in

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many applications such as railway subgrades, airfield pavements, and earth retaining structures.

Attempts to model soil compaction have been made since the early 1940s. Most of these modeling attempts included correlation equations for estimating the compaction characteristics (optimum water content, OWC, and maximum dry unit weight, γdmax) of soil in terms of soil index properties and grain size distribution (Davidson and Gardiner, 1949). Ramiah et al. (1970) correlated both OWC and γdmax solely to liquid limit. Jeng and Strohm (1976) correlated the standard energy Proctor OWC and γdmax to index properties of 85 soils. Blotz et al (1998) used Proctor compaction data from 22 fine-grained soils to correlate OWC and γdmax with liquid limit and compaction energy. Gurtug and Sridharan (2002 and 2004) correlated OWC and γdmax of fine-grained soils compacted by various compaction energy Proctor to plastic limit.

Most of the previous research has focused on the prediction of the compaction characteristics (OWC and γdmax) while very few models have been generated to predict the entire compaction curve. The entire laboratory curve is very important since it provides a means for quality control of compaction on site by offering a good understanding of the sensitivity of soil to water. Additionally, such curves are useful for understanding the effect of water content and compaction energy on compaction. A model which can accurately predict compaction curves of any borrow soil is thus a beneficial tool for facilitating engineering decisions. It is vital in projects such as a roadway where the soil types are so variable.

An early study by Joslin (1959) on a large number of compaction curves yielded 26 typical standard Proctor curves (named the Ohio's curves) that are presumed to approximately resemble most of the soil encountered in earth construction. These curves provide a quick method for identifying an approximate compaction curve of a given soil using one water content – bulk density data point determined from the standard Proctor penetration needle. Pandian et al. (1997) have developed a phenomenological model that enables the determination of the density and water content relationship of fine-grained soils separately for the dry and the wet sides of optimum based on liquid limit and specific gravity. However, this model can be applied only to the standard Proctor test. The model yields two portions of the compaction curve,

which intersect to form a sharp angle at the optimum compaction point. Thus, the curve is an inverted V shape, not the well-known bell-shape. This study gave a set of curves, which closely approximated the results of Joslin (1959).

Recently, Nagaraj et al. (2006) have introduced an ideal pore model for rapid estimation of compaction curves of fine-grained soils under different compaction energies separately for the dry and the wet sides of optimum. On the dry side, compacted clays have continuity both in the water and air phases. The air-water interface is formed by the menisci that bridge the space between two clay clusters around the air pore. As the degree of saturation increases, the continuity in the air phase is lost and air would tend to be in the form of occluded air bubbles, leaving behind only continuity of the water phase. Based on their ideal model, two state parameters $w/S^{0.5}$ and w/S^2 were proposed for the dry and the wet sides of the optimum, respectively. The parameter $w/S^{0.5}$ was derived from the assumption that the air-water pores are cylindrical with constant length and uniformly distributed in the air-clay-water system. Whereas the parameter w/S^2 was derived from the assumption that the theoretical equation of determining an increase in the pore air pressure needed to achieve 100% saturation is linear. The relationships between water content (w) and degree of saturation (S) for predicting the entire compaction curve were presented in terms of liquid limit (LL) and compaction energy (E) as follows:

$$\frac{w}{(LL)S^{0.5}} = 1.24 - 0.18 \log E$$

for the dry side of optimum   (1)

$$\frac{w}{(LL)S^2} = 1.70 - 0.28 \log E$$

for the wet side of optimum   (2)

The w and LL are expressed as percentage, and S and E as decimal and kJ/m^3, respectively. In the equations, the liquid limits are used to reflect difference in clay type. For any fine-grained soil, the optimum water content and optimum degree of saturation (degree of saturation at optimum water content, ODS) can be computed by solving these two equations. The solution yields the same ODS value for different clays (having different liquid limits) compacted under the same energy. The ODS increases with compaction energy

($ODS $ = 81.0, 81.6, 82.4 and 83.3% for compaction energies of 296.3, 592.5, 1346.6 and 2693.3 kJ/m^3, respectively). Since the model was developed based on few clays having a specific range of Atterberg's limits, all clays might not necessarily follow the proposed air-water interface. Hence, the proposed state parameters might be valid only for some clays and ODS might be dependent upon clay types.

Even though there are many available empirical equations and methods for predicting compaction characteristics (OWC, and γdmax) and compaction curve, they were developed from a particular range of index properties and swelling potential. As such, they might not be able to apply to all soil types. There should be more attempts to examine the compaction characteristics and the state parameters for better understanding the compaction behavior of different fine and coarse grained soils (having a wide variation in clay mineral, index properties, and grain size distribution) under various compaction energy levels. This understanding would lead to a simple and rational method of assessing the compaction curves. In this paper, an attempt has been made to meet this goal. A step-wise procedure for assessing the compaction curves using a one point test is also proposed.

Laboratory Investigation
Soil samples

The study of the physicochemical behavior involved nine and sixteen types of fine and coarse grained soils respectively. The fine-grained soils could be classified into either non-expanding lattice type soils (kaolinitic soils) or expanding lattice type soils (montmorillonitic soils) (Sridharan and Prakash, 1999a and 1999b). The nine clays which cover these two soil types were used for this investigation. They are Silty clay 1, Silty clay 2, Silty clay 3, Silty clay 4, weathered clay, kaolinite, bentonite, and two mixed clays, which are bentonite + kaolinte (2:1 by dry weight), and bentonite + weathered clay (4:1 by dry weight). The purpose of mixing is to reduce liquid limit and swelling potential of the bentonite. The soil expansivity and probably dominant clay mineral of the tested clays were investigated by the free swell test proposed by Prakash and Sridharan (2004) since it is a simple methodology giving fairly satisfactory prediction of dominant clay mineralogy of soil (Horpibulsuk et al., 2007). The

free swell ratio, FSR, is defined as the ratio of equilibrium sediment volume of 10-g oven-dried soil passing a 425μm sieve in distilled water (V_d) to that in carbon tetra chloride or kerosene (V_k). The silty clays were collected from different locations in Muang district, Nakhon Ratchasima province, Thailand. They are classified as low to moderately swelling type. The weathered clay was sampled at a depth of 1-2 m from Rangsit district (closed to Asian Institute of Technology), Pathumthani, Thailand. It is classified as a low swelling type. The kaolinite and bentonite were obtained from a soil testing company. They are classified as non- and high swelling types, respectively. The bentonite + weathered clay and the bentonite + kaolinite are classified as moderately swelling type. Due to low swelling potential and high amount of larger than 2μm particles of the four silty clays, their liquid and plastic limits are lowest compared to the other clays. The tested clays are non- to high swelling type with low to high plasticity, which cover a wide variation in swelling potential and plasticity.

The sixteen coarse grained soils cover non-plasticity and plasticity soil types, but limit the plasticity index less than 50 percent. They are well-graded gravel, poorly graded gravel, clayey gravel, silty gravel, well-graded gravel with clay, well-graded gravel with silt, poorly graded gravel with clay, poorly graded gravel with silt, well-graded sand, poorly graded sand, clayey sand, silty sand, well-graded sand with clay, well-graded sand with silt, poorly graded sand with clay, and poorly graded sand with silt. These coarse grained soils were collected from different locations in Muang district, Nakhon Ratchasima province, Thailand. Basic properties, soil classification according to the Unified Soil Classification (USC) and grain size distribution of the tested soils are presented in Table 1 and Figure 1.

Methodology

All the tested soils were air-dried for at least three days and then the water content was measured. A 3-kg sample of the air-dried soils were needed for one compaction point (at least five compaction points for each soil). For each point, the air-dried soils were thoroughly mixed with water by hand and kept in a plastic bag for 24 hours to achieve uniform water content and the water content was measured before compaction. Compaction was carried out in a standard 100-mm diameter mold according to the American Society

Table 1: Basic properties of all tested soils

Soils	Soil composition			LL (%)	PL (%)	G_s	USCS	Sediment volume			Swelling
	Gravel (%)	Sand (%)	Silt and Clay (%)					In distilled water (a)	In CCl_4 (b)	FSRR atio (a/b)	
Silty clay 1	-	30.8	69.2	39.7	7.7	2.70	C L	17.2	10.1	1.7	Moderately
Silty clay 2	-	24.2	75.8	42.3	6.1	2.69	C L	15.9	10.1	1.6	Moderately
Silty clay 3	13.3	15.7	71	47.5	15.8	2.64	C L	13.1	12.2	1.1	Low
Silty clay 4	-	19.3	80.7	49.3	7.4	2.65	C L	15.0	10.0	1.5	Moderately
Kaolinite	-	-	100	52.0	34.8	2.62	C H	13.1	55.2	0.2	Non
Bangkok clay	-	44.3	55.7	63.5	32.7	2.63	C H	20.0	15.8	1.3	Low
Bentonite+ Kaolinite	-	-	100	150.6	39.2	2.58	C H	40.1	26.0	1.5	Moderately
Bentonite+Bangkok clay	-	11.3	88.7	152.9	48.3	2.60	C H	81.0	47.9	1.7	Moderately
Bentonite	-	-	100	256.3	39.2	2.66	C H	93.3	45.2	2.1	Highly
Well-graded gravel	52.34	43.95	3.71	-	-	2.71	G W	-	-	-	-
Poorly-graded gravel	50.83	45.51	3.67	-	-	2.75	G P	-	-	-	-
Well-graded gravel with clay	47.13	44.28	8.59	29.47	14.13	2.73	G W - G C	-	-	-	-
Well-graded gravel with silt	46.68	44.64	8.69	-	-	2.75	G W - G M	-	-	-	-
Poorly-graded gravel with clay	48.69	41.89	9.43	37.83	14.73	2.75	G P - G C	-	-	-	-
Poorly-graded gravel with silt	52.60	38.20	9.21	-	-	2.70	G P - G M	-	-	-	-
Clayey gravel	46.75	31.87	21.38	63.21	13.37	2.66	G C	-	-	-	-
Silty gravel	62.07	25.67	12.27	-	-	2.65	G M	-	-	-	-
Well-graded sand	25.65	69.83	4.52	-	-	2.68	S W	-	-	-	-
Poorly-graded sand	17.35	79.20	3.45	-	-	2.69	S P	-	-	-	-
Well-graded sand with clay	13.09	77.27	9.64	30.37	18.78	2.67	S W - S C	-	-	-	-
Well-graded sand with silt	9.93	80.40	9.67	-	-	2.64	S W - S M	-	-	-	-
Poorly-graded sand with clay	7.59	83.59	8.82	31.24	19.34	2.65	S P - S C	-	-	-	-
Poorly-graded sand with silt	-	91.35	8.66	-	-	2.60	S P - S M	-	-	-	-
Clayey sand	26.41	45.80	27.80	61.10	14.75	2.66	S C	-	-	-	-
Silty sand	24.53	49.12	26.35	-	-	2.69	S M	-	-	-	-
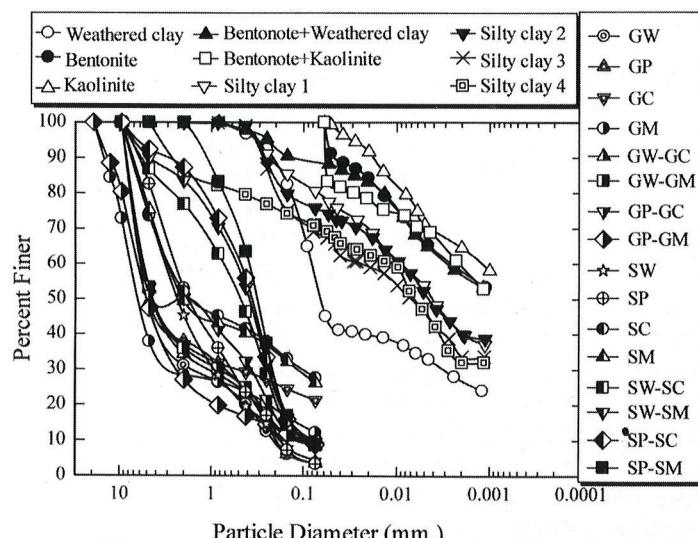
Figure 1: Grain size distribution of the tested soils.

for Testing and Materials (ASTM) standard. According ASTM standard, the standard 100-mm diameter mold is used with Methods A and B. For Method A, 20% or less by mass of the soils is retained on the 4.75 mm sieve. For Method B, more than 20% by mass of the soils is retained on the 4.75 mm sieve and 20% of less by mass of the soils is retained on the 9.5 mm sieve. All tested soils are specified by either the Methods A or B. The soils were compacted under four energy levels of 296.3, 592.5, 1346.6 and 2693.3 kJ/m³, which are equal to the energy of half standard, standard, half modified and modified Proctor, respectively. For each tested point, at least three samples were tested under the same condition for the consistency of the test. In most cases, the results under the same testing condition were repeatable. All test results were analyzed to generate a simple and rational method of assessing compaction curves of different fine and coarse grained soils at various compaction energies.

Finally, test results of five compacted fine and coarse grained soils compiled from the literature have been taken to verify the proposed method. The results were from Proctor (1948); US Army Crops of Engineers (1970); Turnbull and Foster (1956); and Bell (1956).

Test Results

Figures 2 to 3 show typical compaction curves of Silty clay 1, and the well- graded gravel under the four levels of compaction energy. The compaction characteristics (γdmax, OWC, and ODS) of the tested soils at the four compaction energy levels are summarized in Table 2. It is of interest to mention that for standard Proctor test, all the soils follow Ohio's typical water content – density curves (Joslin, 1958) as shown in Figure 4. From Table 2, it is noted that even though ODS values are different for different soils, they are within a narrow range (from 80 to 90.6%). This range is consistent with the finding of Holtz and Kovacs (1981) that the optimum water content of most soils corresponds to a degree of saturation of about 80%. The ODS is dependent upon the soil type. For a given soil, the ODS is practically constant for all the compaction energy levels. This finding contradicts the prediction method proposed by Nagaraj et al. (2006).

From the literature, there are two conclusions on the effect of Atterberg's limits on the compaction characteristics. One is that optimum water content (OWC) of clays increases with liquid limit, LL (Ramiah et al., 1970; Jeng and Strohm, 1976; Pandian et al., 1997; Blotz et al., 1998; and Nagaraj et al., 2006 and etc.). The other is that plastic limit, PL, influences the change in OWC (Gurtug and Sridharan, 2002 and 2004). The higher the PL, the greater the OWC. However, it is found from this investigation (Tables 1 and 2) that besides liquid and plastic limits, other soil characteristics (such as soil composition, FSR, and etc.) affect the compaction characteristics. Test results show that OWC of most tested clays increases with liquid limit. OWC of Silty clay 3 is higher than that of Silty clay 4, even though Silty clay 3 possesses lower LL. This is possibly due to the effect of plastic limit as explained by Gurtug and Sridharan (2002) and (2004). Comparing the kaolinite and the weathered clay, OWC of the kaolinite is higher than that of the weathered clay even though the kaolinite possesses lower LL and their PLs are about the same. This might be due to the kaolinite having a lower amount of coarse particles (sand) and a higher amount of fine particles (silt and clay).

Gurtug and Sridharan (2004) and Nagaraj's et al. (2006) equations were employed to predict the compaction characteristics and presented in Table 2 as an example based on Atterberg's limits. It is found that the Nagaraj et al.'s equation overestimates OWC for the clays with $LL > 50\%$, especially for the bentonite. At $E = 296.3$ kJ/m³, the measured OWC is 38.7% while the predicted OWC is 169.6%. This noticeable error might be
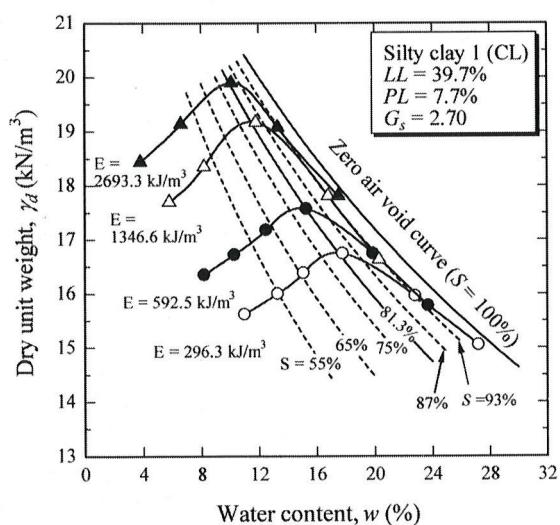

Figure 2: Compaction curves of Silty clay 1.
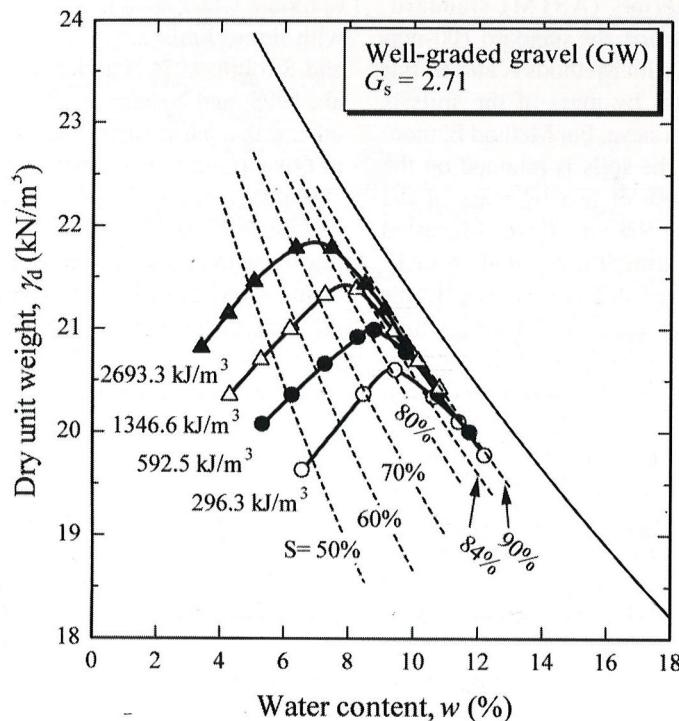
**Figure 3: Compaction curves of well-graded gravel.**
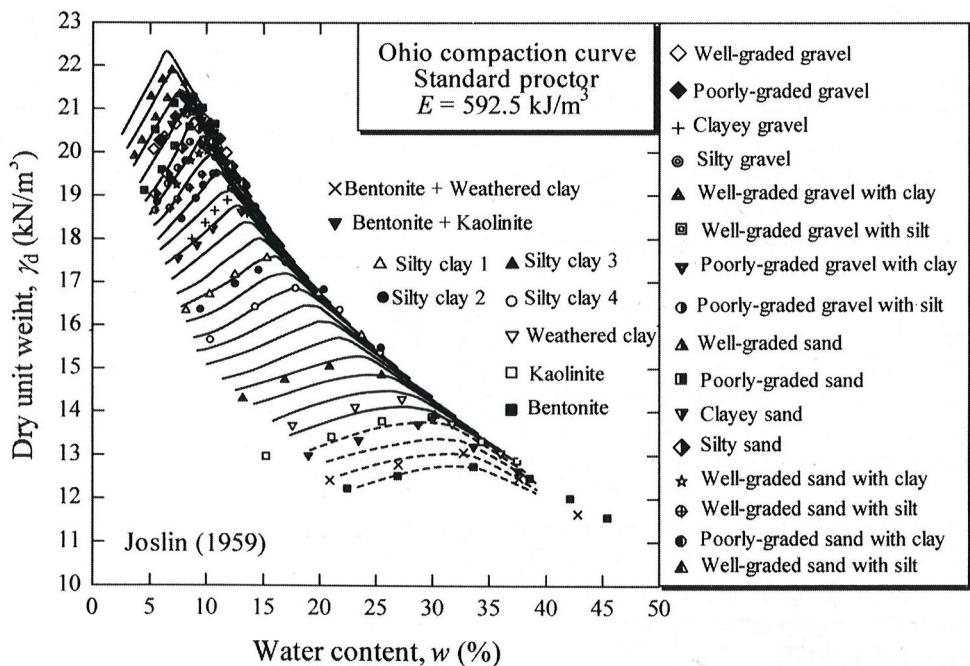
Figure 4: Ohio's chart and compaction curves of all the tested clays.

Table 2: **Comparison of measured and predicted compaction characteristics of all tested soils.**

Soils	E (kJ/m³)	Test Results			Prediction (Eq. 3)		
		OWC (%)	γ_{dmax} (kN/m³)	ODS (%)	OWC (%)	g_{dmax} (kN/m³)	ODS (%)
Silty	296.3	17.8	16.8	83.5	17.4	16.9	83.1
Clay 1	592.5	15.4	17.6	83.1	Ref.	Ref.	Ref.
	1346.6	11.7	19.2	83.5	13.4	18.5	83.1
	2693.3	10.2	20.0	84.2	11.6	19.2	83.1
Silty	296.3	19.1	16.6	86.8	18.6	16.8	87.0
clay 2	592.5	16.5	17.5	87.0	Ref.	Ref.	Ref.
	1346.6	13.6	18.6	86.9	14.3	18.3	87.0
	2693.3	11.7	19.3	86.3	12.4	19.1	87.0
Silty	296.3	24.0	14.6	81.7	24.8	14.4	81.7
clay 3	592.5	22.0	15.1	81.7	Ref.	Ref.	Ref.
	1346.6	20.0	15.8	82.2	19.1	16.0	81.7
	2693.3	18.1	16.4	82.4	16.5	16.9	81.7
Silty	296.3	20.5	16.1	88.5	19.9	16.2	87.4
clay 4	592.5	17.7	16.9	87.4	Ref.	Ref.	Ref.
	1346.6	15.0	17.7	85.7	15.4	17.7	87.4
	2693.3	12.4	18.9	87.2	13.3	18.5	87.4
Kaolinite	296.3	33.1	13.2	91.5	33.0	13.2	91.2
	592.5	29.3	14.0	91.2	Ref.	Ref.	Ref.
	1346.6	26.3	14.6	91.1	25.5	14.8	91.2
	2693.3	23.3	15.4	90.8	22.0	15.7	91.2
Bangkok	296.3	30.7	13.6	89.6	30.6	13.6	89.7
clay	592.5	27.2	14.4	89.7	Ref.	Ref.	Ref.
	1346.6	23.9	15.2	89.8	23.7	15.2	89.7
	2693.3	20.3	16.2	89.8	20.5	16.1	89.7
Bentoinite	296.3	32.2	13.0	87.2	32.1	13.0	87.7
+	592.5	28.5	13.8	87.7	Ref.	Ref.	Ref.
Kaolinite	1346.6	24.8	14.7	88.0	24.8	14.6	87.7
	2693.3	20.8	15.7	87.7	21.5	15.5	87.7
Bentoinite	296.3	36.8	12.3	89.1	36.7	12.3	89.5
+	592.5	32.6	13.1	89.5	Ref.	Ref.	Ref.
Bangkok	1346.6	28.0	14.1	89.7	28.4	14.0	89.5
clay	2693.3	23.9	15.0	89.0	24.5	14.9	89.5
Bentoinite	296.3	38.7	11.9	85.6	38.1	12.0	86.4
	592.5	33.8	12.8	86.4	Ref.	Ref.	Ref.
	1346.6	29.8	13.6	85.7	29.4	13.7	86.4
	2693.3	27.4	14.1	85.8	25.5	14.6	86.4

Table 2: **Comparison of measured and predicted compaction characteristics of all tested soils. (Continued)**

Soils	E (kJ/m³)	Test Results			Prediction (Eq. 3)		
		OWC (%)	γ_{dmax} (kN/m³)	*ODS* (%)	*OWC* (%)	γ_{dmax} (kN/m³)	*ODS* (%)
GW	296.3	9.52	20.13	80.4	9.3	20.2	79.8
	592.5	8.52	20.62	79.8	Ref.	Ref.	Ref.
	1346.6	7.78	21.05	80.2	7.3	21.3	79.8
	2693.3	6.60	21.68	79.1	6.3	21.9	79.8
GP	296.3	9.59	20.27	79.7	9.4	20.4	79.8
	592.5	8.58	20.82	79.8	Ref.	Ref.	Ref.
	1346.6	7.68	21.35	80.1	7.3	21.5	79.8
	2693.3	6.91	21.77	79.4	6.4	22.1	79.8
GW-GC	296.3	7.48	21.21	77.7	7.7	21.1	77.7
	592.5	7.00	21.50	77.7	Ref.	Ref.	Ref.
	1346.6	6.19	22.01	78.0	6.0	22.1	77.7
	2693.3	5.25	22.60	77.5	5.2	22.7	77.7
GW-GM	296.3	8.92	20.63	79.7	9.1	20.5	80.0
	592.5	8.35	20.96	80.0	Ref.	Ref.	Ref.
	1346.6	7.57	21.37	79.4	7.1	21.7	80.0
	2693.3	6.62	21.91	78.7	6.2	22.2	80.0
GP-GC	296.3	9.17	20.16	74.5	9.2	20.1	74.3
	592.5	8.39	20.59	74.3	Ref.	Ref.	Ref.
	1346.6	7.86	20.94	74.9	7.1	21.3	74.3
	2693.3	6.76	21.56	74.0	6.2	21.9	74.3
GP-GM	296.3	10.82	19.39	79.9	10.3	19.6	79.5
	592.5	9.42	20.07	79.5	Ref.	Ref.	Ref.
	1346.6	8.38	20.61	79.4	8.0	20.8	79.5
	2693.3	7.22	21.26	79.3	7.0	21.4	79.5
GC	296.3	12.32	18.18	75.3	12.4	18.1	74.9
	592.5	11.35	18.60	74.9	Ref.	Ref.	Ref.
	1346.6	10.25	19.14	75.1	9.7	19.4	74.9
	2693.3	9.10	19.68	74.2	8.4	20.1	74.9
GM	296.3	9.67	19.68	79.8	9.8	19.6	79.6
	592.5	8.93	20.04	79.6	Ref.	Ref.	Ref.
	1346.6	8.10	20.44	79.0	7.6	20.7	79.6
	2693.3	7.29	20.95	80.2	6.6	21.3	79.6
SW	296.3	8.32	20.25	74.8	7.8	20.5	74.8
	592.5	7.13	20.94	74.9	Ref.	Ref.	Ref.
	1346.6	6.21	21.50	74.7	6.1	21.6	74.8
	2693.3	5.18	22.15	74.2	5.3	22.1	74.8

Table 2: Comparison of measured and predicted compaction characteristics of all tested soils. (Continued)

Soils	E (kJ/m³)	Test Results			Prediction (Eq. 3)		
		OWC (%)	γ_{dmax} (kN/m³)	ODS (%)	OWC (%)	γ_{dmax} (kN/m³)	ODS (%)
SP	296.3	9.72	19.57	75.1	9.3	19.8	75.3
	592.5	8.52	20.23	75.3	Ref.	Ref.	Ref.
	1346.6	7.65	20.71	75.0	7.3	21.0	75.3
	2693.3	6.69	21.29	75.2	6.3	21.5	75.3
SW-SC	296.3	11.37	18.97	79.7	10.8	19.3	79.6
	592.5	9.82	19.71	79.6	Ref.	Ref.	Ref.
	1346.6	8.43	20.36	78.6	8.4	20.5	79.6
	2693.3	7.32	21.01	79.3	7.3	21.1	79.6
SW-SM	296.3	11.41	18.81	79.9	11.4	18.8	79.5
	592.5	10.44	19.23	79.5	Ref.	Ref.	Ref.
	1346.6	9.87	19.57	80.6	8.9	20.0	79.5
	2693.3	9.00	20.01	80.7	7.7	20.6	79.5
SP-SC	296.3	12.25	18.49	80.0	11.9	18.6	79.9
	592.5	10.84	19.12	79.9	Ref.	Ref.	Ref.
	1346.6	9.78	19.63	79.9	9.2	19.9	79.9
	2693.3	8.75	20.20	80.7	8.0	20.5	79.9
SP-SM	296.3	14.06	17.54	80.6	14.5	17.4	80.9
	592.5	13.20	17.91	80.9	Ref.	Ref.	Ref.
	1346.6	11.96	18.32	79.2	11.2	18.7	80.9
	2693.3	10.80	18.81	78.8	9.8	19.4	80.9
SC	296.3	14.13	17.75	80.0	14.1	17.8	80.4
	592.5	12.83	18.32	80.4	Ref.	Ref.	Ref.
	1346.6	11.42	17.40	80.7	10.9	19.2	80.4
	2693.3	10.07	19.54	80.0	9.5	19.9	80.4
SM	296.3	10.15	19.64	79.5	10.1	19.7	80.1
	592.5	9.18	20.17	80.1	Ref.	Ref.	Ref.
	1346.6	8.15	20.74	80.4	7.8	20.9	80.1
	2693.3	7.35	21.21	80.9	6.8	21.5	80.1

because the equation was developed based from low to medium plasticity clays. The Gurtug and Sridharan's equation provides reasonable prediction for the high PL clays ($PL > 32.6\%$) while underestimates OWC for the low PL clays (Silty clays 1 to 4). It can thus be concluded that equations using LL or PL solely cannot describe the compaction characteristics. The combined effects of LL, PL, and other soil characteristics all play a significant role on the compaction characteristics. To obtain more precise assessment of compaction characteristics, the combined effects must be taken into consideration.

It is long known that maximum dry unit weight and optimum water content are affected by increasing compaction energy up to a specific level. Beyond this level, the effect tends to be less pronounced and finally levels off. As such, γdmax and OWC show a linear relationship with logarithm of compaction energy (Boutwell, 1961, Blotz et al., 1998, and Gurtug and Sridharan, 2004, etc.). A relationship between OWC and log E of different clays (data from Blotz et al., 1998, Gurtug and Sridharan, 2004 and the authors) is shown in Figure 5.
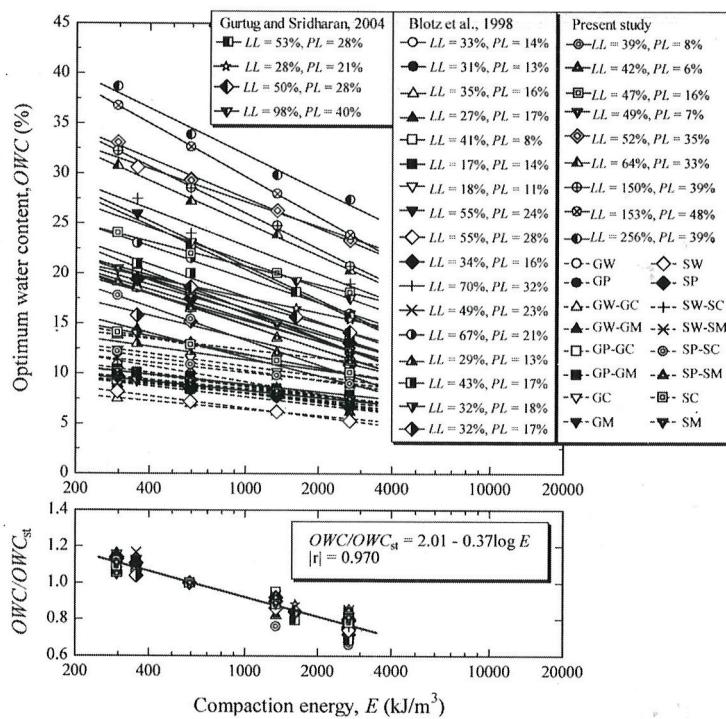
Figure 5: Relationship between OWC and compaction energy and its normalization.

It has been possible to generalize the OWC and E relationship by considering a particular energy, E_k, and the corresponding optimum water content, OWC_k, as reference values (Blotz et al., 1998). Such an attempt has been done herein using the OWC value at standard Proctor energy (OWC_{st}) as a reference value. The normalized OWC and compaction energy relationship for compaction energy ranging from 296.3 to 2693.3 kJ/m³ can be presented in the following form:

$$\frac{OWC}{OWC_{st}} = 2.01 - 0.37 \log E \qquad (3)$$

with a high degree of correlation of 0.962. This relationship takes all the combined effects into account. Equation (3) can be used to assess the compaction characteristics of any compacted fine and coarse grained soil at any compaction energy when the OWC at standard Proctor energy is known. With known optimum degree of saturation (practically the same value for different compaction energy levels), the maximum dry unit weight is hence calculated. This equation is used to predict the compaction characteristics (OWC and γdmax) and compared with the two methods in Table 2. It is noted that Eq.(3) gives the best agreement with the laboratory results.

Analysis of Compaction Curve

The data analysis on the dry and the wet sides of optimum (Pandian et al., 1997; and Nagaraj et al., 2006) reveals that for a particular compaction energy, the relationship between water content (w) and the logarithm of compaction energy (E) is linear and dependent upon degree of saturation (S). Such a relationship exists for the tested soils as
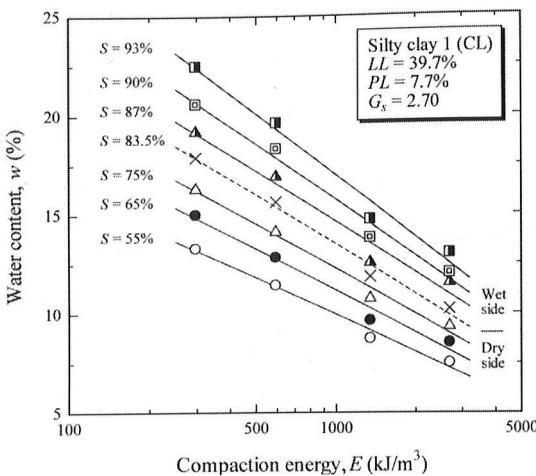

**Figure 6: Relationship between water content and compaction energy of silty clay 1.**
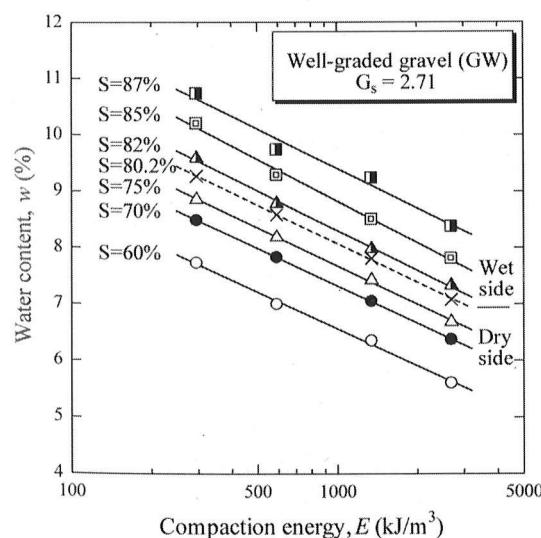
Figure 7: Relationship between water content and compaction energy of well-graded gravel.

well, as shown in Figures 6 and 7 for silty clay 1 and the well-graded gravel, respectively. The existence of the linear relationships shows that the air in the compacted soil samples having the same water content is easier to expel from the soil mass with the increase in the compaction energy, resulting in an increase in the degree of saturation.

Recent work on the microstructural model for compacted fine-grained soils (Nagaraj et al., 2006) reveals that for a particular compaction energy, even though the water content changes with degree of saturation (*vide* Figures 6), the state parameters $w/S^{0.5}$ and w/S^2 are constant for the compaction paths on the dry and the wet sides of optimum, respectively. In the present study, it is however found that the proposed state parameters cannot be applied to the tested soils which have widely varying soil characteristics. In other words, the parameters $w/S^{0.5}$ and w/S^2 are not constant for all soil types. A more general relationship between the water content and the degree of saturation at a particular compaction energy is now proposed as a power function of the form:

$$w = A_d S^{B_d}$$

for the dry side of optimum   (4)

$$w = A_w S^{B_w}$$

for the wet side of optimum 7   (5)

where A_d, B_d, A_w and B_w are constants. The w and S are expressed as percentage and decimal fraction, respectively.

The proposed equations fit well the laboratory test results as shown in Figures 8 and 9 for Silty clay 1 and the well-graded gravel, respectively. Based on these two proposed relationships, a new method of determining the optimum degree of saturation (*ODS*) is introduced. The *ODS* is the point of intersection of the two proposed relationships. This method was used for determining the compaction characteristics are shown in Table 2.

The values of A_d, B_d, A_w and B_w for all tested soils are summarized in Table 3. These parameters are mainly dependent upon the soil type. For a given soil, the A_d and A_w values decrease with increasing compaction energy. Whereas the B_d and B_w values are practically constant for all compaction energy levels. In other words, they are

irrespective of compaction energy. The B_d value varies from 0.70 to 0.86 and the B_w value from 1.50 to 2.72. This contradicts the assumption of Nagaraj et al. (2006) (assuming $B_d = 0.5$ and $B_w = 2.0$ for all soils). It is noted that even though the parameters A_d, B_d, A_w and B_w are different for different soil, the ratios A_d / Ad_{st} and A_w/A_{wst} (where A_{dst} and A_{wst} are A_d and A_w values at standard Proctor energy, respectively) are almost the same for all the tested soils and are very closed to the ratio OWC/OWC_{st} (*see* Table 3). This is to be expected because B_d and B_w values are practically constant for different compaction energy levels, hence, the change in OWC (w at $S = ODS$) with compaction energy is mainly controlled by A_d and A_w (*see* Equations (4) and (5)).

From this study, it can be concluded that the compaction curves are dependent upon soil types. Generally, silts are water sensitive i.e., a small increase in water content can cause a major change in dry unit weight for a given compaction energy. Clays are energy sensitive, wherein a small change in compaction energy can produce large changes in dry unit weight (Johnson and Sallberg, 1960; and Bergado et al., 1996). The parameters A_d, B_d, A_w, and B_w can describe the difference in compaction curves of various fine and coarse grained soils as illustrated by Figures 10 and 11. For given values of B_d and B_w, the maximum dry unit weight increases (optimum water content decreases) with decreasing the values of A_d and A_w (*vide* Figure 10). The parameters B_d and B_w control the degree of water sensitivity (slope of the compaction paths) on the dry and the wet sides of optimum, respectively. The lower the values of B_d and B_w, the greater the degree of water sensitivity (*see* Figure 11). The slope of the curves becomes zero (no change in dry unit weight with water content) when the B_d and B_w values are 1.0.

Suggested Approach for Assesment of Compaction Curves

The characteristic of compaction curves of fine and coarse grained soils has been analyzed using the two power relationships between water content and degree of saturation (Eqs. 4 and 5). The compaction paths on both the dry and the wet sides of optimum can now be drawn using these two relationships. Given a known compaction curve of any fine and coarse grained soil under a particular compaction energy, the following procedure is suggested for assessing the compaction curves under any compaction energy.

1.   From the known compaction curve for a particular compaction energy, determine A_d, B_d, A_w, and B_w values and the compaction characteristics (γdmax, OWC and ODS) using Eqs. (4) and (5).
2.   From the calculated OWC and ODS values, determine the OWC_{st} value using Eq. (3), and hence $(\gamma d$max$)$st by assuming that the ODS value is the same for all compaction energy levels.
3.   Determine the optimum compaction point $(\gamma d$max, $OWC)$ for the required compaction energy by substituting the OWC_{st} value into Eq. (3).
4.   Determine A_d and A_w values for the required compaction energy from the OWC value using the following equations

$$A_d = \frac{OWC}{ODS^{B_d}} \tag{6}$$

$$A_w = \frac{OWC}{ODS^{B_w}} \tag{7}$$

5.   Determine w for both the dry and the wet sides of optimum at different values of degree of saturation using Eqs. (4) and (5), respectively, and hence γ_d.
6.   Draw a curve connecting (γ_d, w) points obtained from step (5).

Figures 12 through 17 show the predicted and the measured compaction curves of the soils compiled from the literature. It is found that the predicted and the measured curves are in very good agreement with errors acceptable for engineering purpose. This reinforces the application of the proposed method in assessing the compaction curves.

Assuming that fine and coarse grained soils compacted under standard compaction energy (592.5 kJ/m³) follow Ohio's curves, the modified Ohio's curves for different compaction energy levels (296.3, 1346.6 and 2693.3 kJ/m³) are developed using the proposed method as shown in Figures 17 to 19. These curves are useful in assessment of compaction curve at the required compaction energy using a set of data of water content and dry unit weight.

Table 3: Values of A_d, A_w, B_d and B_w for all tested soils.

Soils	E (kJ/m³)	A_d	B_d	A_w	B_w	A_d/A_{dst}	A_w/A_{wst}	OWC/OWC_{st}
Silty clay 1	296.3	20.14	0.70	25.96	2.11	1.14	1.13	1.15
	592.5	17.65	0.73	22.90	2.14	1.00	1.00	1.00
	1346.6	13.30	0.72	17.07	2.10	0.75	0.75	0.76
	2693.3	11.50	0.72	14.87	2.21	0.65	0.65	0.66
Silty clay 2	296.3	21.26	0.75	24.40	1.72	1.16	1.16	1.16
	592.5	18.29	0.75	20.96	1.73	1.00	1.00	1.00
	1346.6	15.10	0.75	17.33	1.73	0.82	0.82	0.82
	2693.3	13.13	0.76	15.17	1.74	0.72	0.72	0.71
Silty clay 3	296.3	28.25	0.80	33.26	1.61	1.10	1.10	1.09
	592.5	25.84	0.80	30.37	1.60	1.00	1.00	1.00
	1346.6	23.44	0.80	27.47	1.61	0.90	0.90	0.91
	2693.3	21.07	0.79	24.64	1.60	0.81	0.81	0.82
Silty clay 4	296.3	22.36	0.70	24.69	1.51	1.15	1.14	1.16
	592.5	19.49	0.71	21.68	1.50	1.00	1.00	1.00
	1346.6	16.79	0.72	18.94	1.50	0.8	0.87	0.85
	2693.3	13.63	0.71	15.21	1.51	0.70	0.70	0.70
Kaolinite	296.3	35.48	0.79	42.05	2.71	1.12	1.12	1.13
	592.5	31.54	0.80	37.54	2.70	1.00	1.00	1.00
	1346.6	28.34	0.81	33.80	2.71	0.90	0.90	0.90
	2693.3	25.21	0.80	30.35	2.72	0.80	0.80	0.80
Bangkok clay	296.3	33.60	0.81	40.21	2.45	1.13	1.13	1.13
	592.5	29.68	0.80	35.44	2.43	1.00	1.00	1.00
	1346.6	26.05	0.81	31.06	2.45	0.87	0.87	0.88
Bentonite	2693.3	22.18	0.81	26.43	2.44	0.75	0.75	0.75
+	296.3	35.70	0.75	40.78	1.72	1.13	1.13	1.13
Kaolinite	592.5	31.53	0.76	35.78	1.72	1.00	1.00	1.00
	1346.6	27.30	0.76	30.86	1.72	0.86	0.86	0.87
Bentonite	2693.3	22.94	0.75	26.05	1.72	0.77	0.73	0.73
+	296.3	40.33	0.80	45.92	1.92	1.13	1.13	1.13
Bangkok clay	592.5	35.70	0.81	40.43	1.93	1.00	1.00	1.00
	1346.6	30.57	0.81	34.49	1.92	0.85	0.85	0.86
Bentonite	2693.3	26.24	0.81	29.88	1.92	0.74	0.74	0.73
	296.3	44.19	0.86	49.66	1.61	1.15	1.16	1.14
	592.5	38.31	0.85	42.87	1.62	1.00	1.00	1.00
	1346.6	34.04	0.86	38.21	1.61	0.89	0.89	0.88
	2693.3	31.22	0.85	35.14	1.62	0.81	0.82	0.81

Table 3: Values of A_d, A_w, B_d and B_w for all tested soils. (Continued)

Soils	E (kJ/m3)	A_d	B_d	A_w	B_w	A_d/A_{dst}	A_w/A_{wst}	OWC/OWC_{st}
GW	296.3	11.13	0.70	13.39	1.53	1.11	1.11	1.12
	592.5	9.98	0.70	12.06	1.53	1.00	1.00	1.00
	1346.6	9.08	0.70	10.89	1.53	0.91	0.90	0.91
	2693.3	7.78	0.70	9.48	1.54	0.78	0.79	0.77
GP	296.3	11.24	0.70	16.22	2.32	1.12	1.12	1.12
	592.5	10.05	0.70	14.46	2.31	1.00	1.00	1.00
	1346.6	8.97	0.70	12.84	2.32	0.89	0.89	0.90
	2693.3	8.13	0.70	11.81	2.32	0.81	0.82	0.81
GW-GC	296.3	8.96	0.72	11.71	1.77	1.07	1.07	1.07
	592.5	8.37	0.72	10.91	1.76	1.00	1.00	1.00
	1346.6	7.38	0.72	9.57	1.76	0.88	0.88	0.88
	2693.3	6.29	0.72	8.24	1.77	0.75	0.75	0.75
GW-GM	296.3	10.48	0.71	13.77	1.91	1.07	1.08	1.07
	592.5	9.78	0.71	12.81	1.92	1.00	1.00	1.00
	1346.6	8.92	0.71	11.79	1.91	0.91	0.92	0.91
	2693.3	7.85	0.72	10.47	1.92	0.80	0.82	0.79
GP-GC	296.3	11.41	0.74	14.43	1.54	1.09	1.09	1.09
	592.5	10.46	0.74	13.25	1.54	1.00	1.00	1.00
	1346.6	9.74	0.74	12.25	1.54	0.93	0.92	0.94
	2693.3	8.46	0.74	10.76	1.54	0.81	0.81	0.81
GP-GM	296.3	12.47	0.63	18.34	2.35	1.14	1.14	1.15
	592.5	10.89	0.64	16.15	2.35	1.00	1.00	1.00
	1346.6	9.71	0.64	14.43	2.35	0.89	0.89	0.89
	2693.3	8.37	0.64	12.46	2.35	0.77	0.77	0.77
GC	296.3	14.67	0.62	19.08	1.54	1.08	1.08	1.09
	592.5	13.58	0.62	17.72	1.54	1.00	1.00	1.00
	1346.6	12.23	0.62	15.93	1.54	0.90	0.90	0.90
	2693.3	10.93	0.62	14.39	1.54	0.81	0.81	0.80
GM	296.3	14.67	0.62	19.08	1.54	1.08	1.08	1.09
	592.5	13.58	0.62	17.72	1.54	1.00	1.00	1.00
	1346.6	12.23	0.62	15.93	1.54	0.90	0.90	0.90
	2693.3	10.93	0.62	14.39	1.54	0.81	0.81	0.80
SW	296.3	10.16	0.69	13.88	1.76	1.17	1.17	1.17
	592.5	8.70	0.69	11.90	1.76	1.00	1.00	1.00
	1346.6	7.60	0.69	10.40	1.76	0.87	0.87	0.87
	2693.3	6.36	0.69	8.76	1.76	0.73	0.74	0.73
SP	296.3	11.63	0.63	19.06	2.35	1.14	1.15	1.14
	592.5	10.18	0.63	16.56	2.34	1.00	1.00	1.00
	1346.6	9.16	0.63	15.03	2.35	0.90	0.91	0.90
	2693.3	8.01	0.63	13.07	2.35	0.79	0.79	0.79

Table 3: Values of A_d, A_w, B_d and B_w for all tested soils. (Continued)

Soils	E (kJ/m³)	A_d	B_d	A_w	B_w	A_d/A_{dst}	A_w/A_{wst}	OWC/OWC_{st}
SW-SC	296.3	13.22	0.66	16.61	1.67	1.16	1.16	1.16
	592.5	11.43	0.67	14.37	1.66	1.00	1.00	1.00
	1346.6	9.91	0.67	12.59	1.66	0.87	0.88	0.86
	2693.3	8.54	0.67	10.76	1.67	0.75	0.75	0.75
SW-SM	296.3	13.43	0.72	17.55	1.92	1.09	1.08	1.09
	592.5	12.33	0.73	16.25	1.93	1.00	1.00	1.00
	1346.6	11.54	0.73	14.94	1.92	0.94	0.92	0.94
	2693.3	10.52	0.73	13.61	1.93	0.85	0.84	0.86
SP-SC	296.3	14.13	0.64	18.53	1.85	1.13	1.13	1.13
	592.5	12.50	0.63	16.47	1.86	1.00	1.00	1.00
	1346.6	11.27	0.63	14.84	1.86	0.90	0.90	0.90
	2693.3	10.02	0.63	13.02	1.86	0.80	0.79	0.81
SP-SM	296.3	16.56	0.76	19.84	1.59	1.07	1.07	1.07
	592.5	15.50	0.76	18.49	1.59	1.00	1.00	1.00
	1346.6	14.20	0.76	17.17	1.59	0.92	0.93	0.91
	2693.3	12.93	0.76	15.76	1.59	0.83	0.85	0.82
SC	296.3	16.70	0.75	24.43	2.45	1.11	1.11	1.10
	592.5	15.10	0.75	21.92	2.46	1.00	1.00	1.00
	1346.6	13.40	0.75	19.30	2.46	0.89	0.88	0.89
	2693.3	11.91	0.75	17.48	2.46	0.79	0.80	0.78
SM	296.3	11.73	0.63	16.11	2.01	1.11	1.11	1.11
	592.5	10.54	0.62	14.51	2.06	1.00	1.00	1.00
	1346.6	9.33	0.62	12.74	2.05	0.88	0.88	0.89
	2693.3	8.39	0.63	11.29	2.03	0.80	0.78	0.80
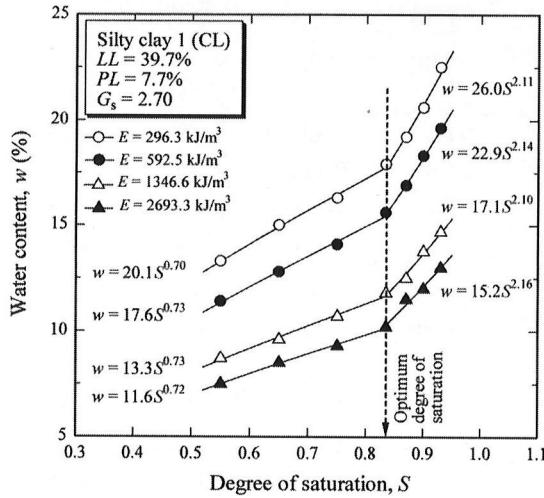
Figure 8: Relationship between water content and degree of saturation at different compaction energies of silty clay 1.
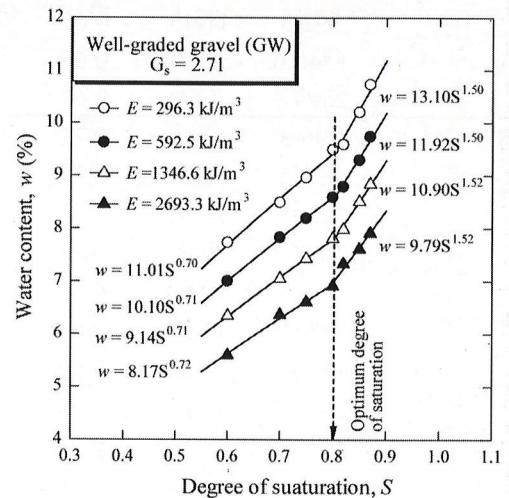
Figure 9: Relationship between water content and degree of saturation at different compaction energies of well-graded gravel.
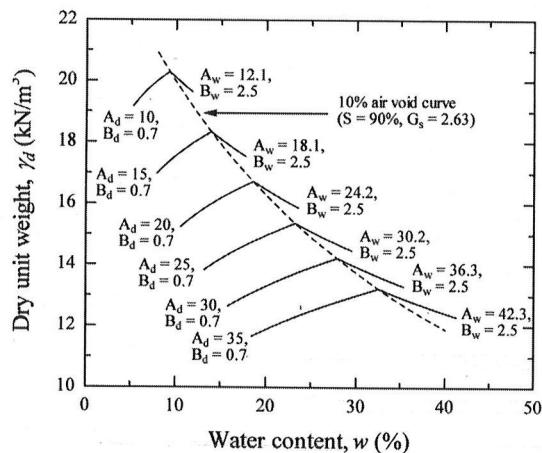
**Figure 10: Effect of A_d and A_w on compaction curves.**
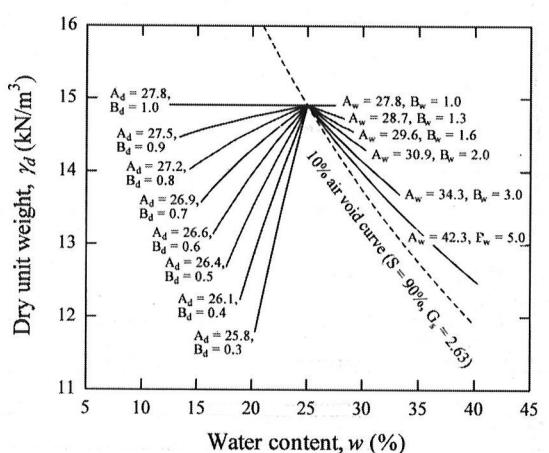
Figure 11: Effect of B_d and B_w on compaction curves.

Conclusions

The present paper deals with the characteristics of compaction curves for fine and coarse grained soils. A method of assessing the compaction curves based on a one point test is presented. The following conclusions can be drawn.

1. Compaction characteristics (OWC and γdmax) of fine and coarse grained soils are dependent upon the combined effects of liquid and plastic limits, and other soil characteristics (such as soil composition, FSR, and etc). As such, equations using LL or PL solely cannot assess the compaction characteristics. The relationship between normalized optimum water content and compaction energy is introduced to take the combined effects into account.

2. On the dry and the wet sides of optimum, the relationships between the water content (w) and the degree of saturation (S) at a particular compaction energy are represented by the power function as follows:

$$w = A_d S^{B_d} \quad \text{for the dry side of optimum}$$

$$w = A_w S^{B_w} \quad \text{for the wet side of optimum}$$

The parameters A_d and A_w control the maximum dry unit weight. The maximum dry unit weight increases (optimum water content decreases) with decreasing values of A_d and A_w. The constants B_d and B_w are dependent upon soil type and regardless of compaction energy. The parameters A_d, B_d, A_w and B_w can capture compaction curves of various fine and coarse grained soils.

3. A simple and rational method for assessing the laboratory compaction curves of fine and coarse grained soils wherein the compaction energy varies over a wide range using a one point test has been proposed. The verification and the applicability of this method are illustrated in this paper.

4. The modified Ohio's curves are useful in assessment of compaction curves under the other three compaction energy levels (296.3, 1346.6 and 2693.3 kJ/m³) using a set of data of dry unit weight and water content.

Figure 12: Predicted and measured compaction curves of clay (data from Proctor, 1948).
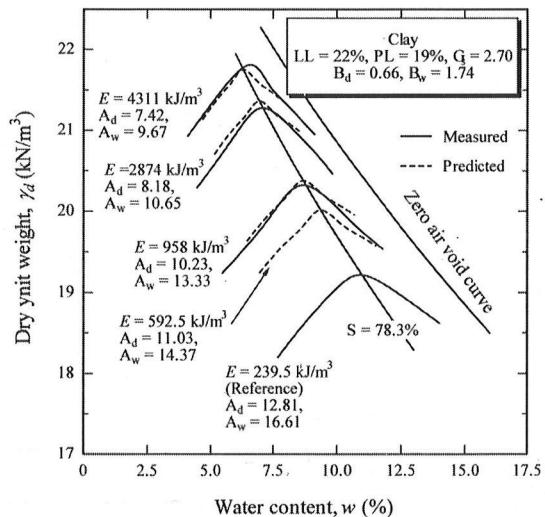
**Figure 13: Predicted and measured compaction curves of red earth (data from US Army of Engineer, 1970).**
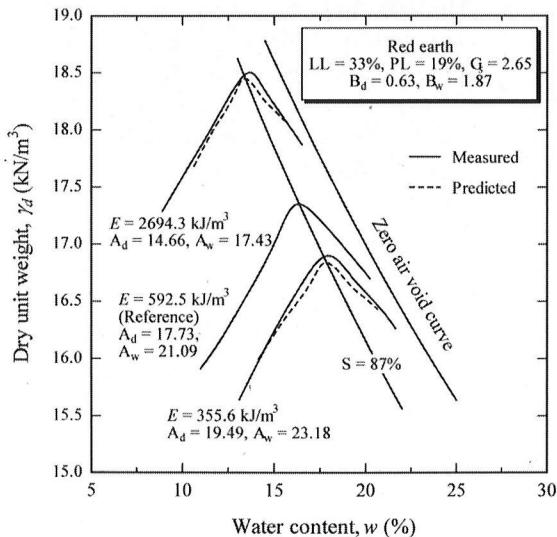
**Figure 14:** **Predicted and measured compaction curves of silty clay (data from Turnbull and Foster, 1956).**
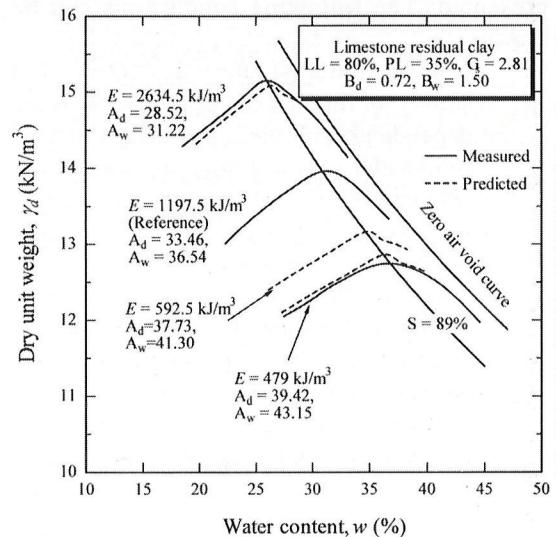
Figure 15: **Predicted and measured compaction curves of limestone residual clay (data from Bell, 1956).**
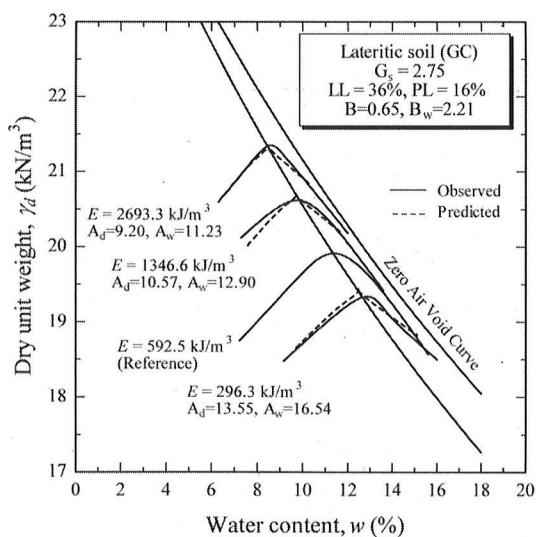

Figure 16: **Predicted and measured compaction curves of clayey gravel (data from Ruenkrairergsa, 1982)**
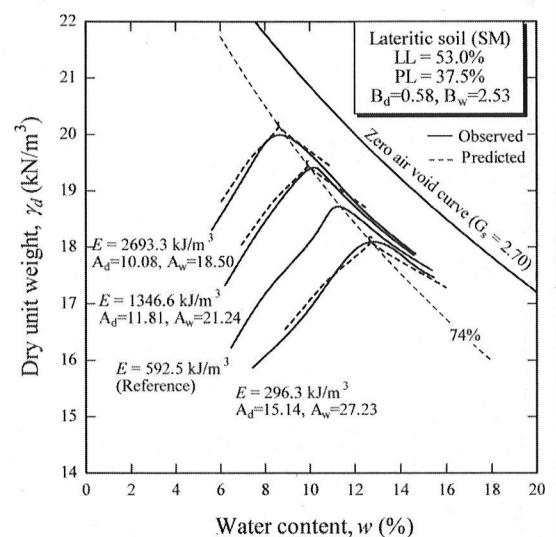
**Figure 17:** **Predicted and measured compaction curves of silty sand (data from Horpibulsuk et al., 2004).**
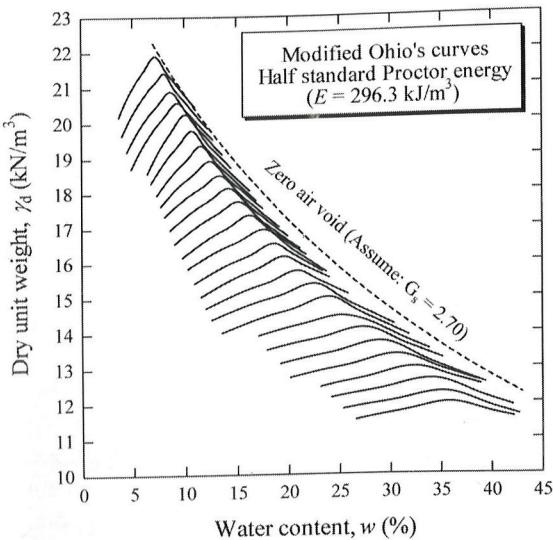
Figure: 18: Modified Ohio's curves for compaction energy of 296.3 kJ/m³.
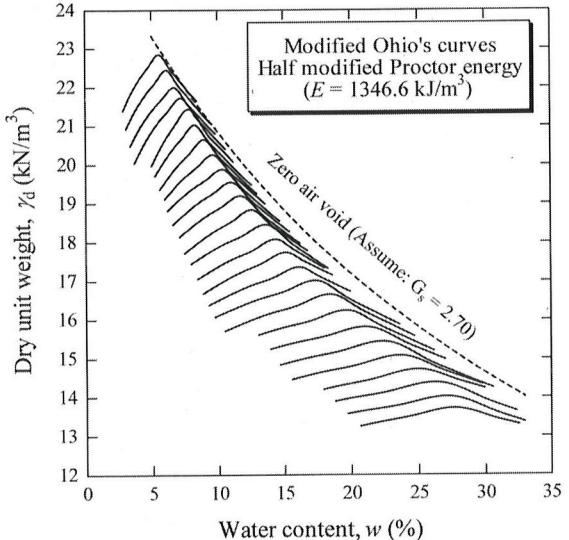
Figure 19: Modified Ohio's curves for compaction energy of 1346.6 kJ/m³.
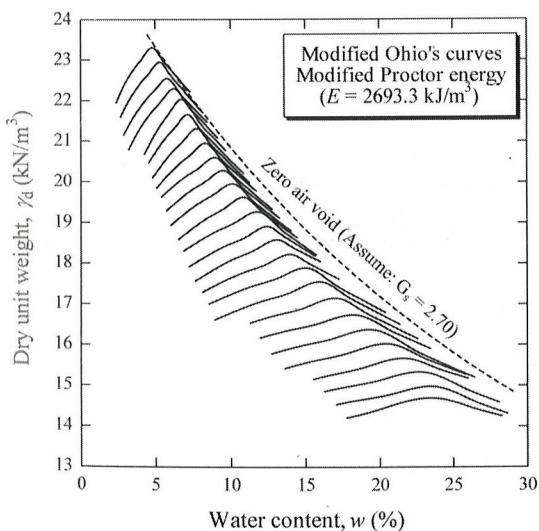
Figure 20: Modified Ohio's curves for compaction energy of 2693.3 kJ/m³.

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