SOILS AND FOUNDATIONS Vol. 48, No. 1, 115–125, Feb. 2008
Japanese Geotechnical Society

# AN APPROACH FOR ASSESSMENT OF COMPACTION CURVES OF FINE GRAINED SOILS AT VARIOUS ENERGIES USING A ONE POINT TEST

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## ABSTRACT

Compaction curves of soils are essential for establishing practical and reliable criteria for an effective control of field compaction. This paper deals with the development of a practical method of assessing laboratory compaction curves of fine-grained soils. It is found that for a given fine-grained soil compacted at a particular compaction energy, the relationships between water content ($w$) and degree of saturation ($S$) are represented by power function, which are $w=A_dS^{B_d}$ and $w=A_wS^{B_w}$ for the dry and the wet sides of optimum, respectively (where $A_d$, $A_w$, $B_d$ and $B_w$ are constant). The $B_d$ and $B_w$ values and optimum degree of saturation (ODS) are mainly dependent upon soil type irrespective of compaction energy. The $A_d$ and $A_w$ values decrease with the logarithm of compaction energy and the decrease rates are practically the same for any compacted fine-grained soil. This leads to a simple and rational method to assess the compaction curve wherein the compaction energy varies over a wide range using a one point test (a single test). Assuming that fine-grained soils compacted under standard Proctor energy behave in agreement with Ohio's curves, the modified Ohio's curves for the other three compaction energy levels (296.3, 1346.6 and 2693.3 kJ/m$^3$) are developed based on the proposed method. These curves can be used to assess the entire compaction curves at the required compaction energy based on a single set data of dry unit weight and water content.

**Key words:** compaction curve, compaction energy, fine-grained soils, modified Ohio's curves, one point test (**IGC**: D3/D9)

## 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 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, $\gamma_{dmax}$) of soil in terms of soil index properties and grain size distribution (Davidson and Gardiner, 1949). Ramiah et al. (1970) correlated both OWC and $\gamma_{dmax}$ solely with liquid limit. Jeng and Strohm (1976) correlated the standard energy Proctor OWC and $\gamma_{dmax}$ with index properties of 85 soils. Blotz et al. (1998) used Proctor compaction data from 22 fine-grained soils to correlate OWC and $\gamma_{dmax}$ with liquid limit and compaction energy. Gurtug and Sridharan (2002, 2004) correlated OWC and $\gamma_{dmax}$ of fine-grained soils compacted by various compaction energy Proctor with plastic limit.

Most of the previous research has focused on the prediction of the compaction characteristics (OWC and $\gamma_{dmax}$) 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

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The manuscript for this paper was received for review on April 9, 2007; approved on October 7, 2007.
Written discussions on this paper should be submitted before September 1, 2008 to the Japanese Geotechnical Society, 4-38-2, Sengoku, Bunkyo-ku, Tokyo 112-0011, Japan. Upon request the closing date may be extended one month.

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 a single 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. The 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 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 (Bishop and Edlin, 1950) 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:

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

for the dry side of optimum (1)

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

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 these equations, the liquid limits are used to reflect the differences in the type of clay. 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 $\gamma_{\mathrm{dmax}}$) 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 clay types. There should be more attempts to examine the compaction characteristics and the state parameters for better understanding the compaction behavior of different fine-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 has indicated that all 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, 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 425 $\mu$m sieve in distilled water ($V_d$) to that in carbon tetrachloride 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 (close 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

**Table 1. Basic properties of the tested soils**

| Soil type | Soil composition | | | | LL | PL | $G_s$ | UCSC | Sediment volume (mL/10 gm) | | | Swelling type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Gravel (%) | Sand (%) | Silt (%) | Clay (%) | (%) | (%) | | | In distilled water (a) | In $CCl_4$ (b) | FSR Ratio (a/b) | |
| Silty clay 1 | — | 30.8 | 35.3 | 33.9 | 39.7 | 7.7 | 2.70 | CL | 17.2 | 10.1 | 1.7 | Moderate |
| Silty clay 2 | — | 24.2 | 35.3 | 40.5 | 42.3 | 6.1 | 2.69 | CL | 15.7 | 10.1 | 1.6 | Moderate |
| Silty clay 3 | 13.3 | 15.7 | 38.7 | 32.3 | 47.5 | 15.8 | 2.64 | CL | 13.1 | 12.2 | 1.1 | Low |
| Silty clay 4 | — | 19.3 | 40.1 | 40.6 | 49.3 | 7.4 | 2.65 | CL | 15.0 | 10.0 | 1.5 | Moderate |
| Kaolinite | — | — | 35.4 | 64.6 | 52.0 | 34.8 | 2.62 | CH | 13.1 | 55.2 | 0.2 | Non |
| Weathered clay | — | 44.3 | 28.8 | 26.9 | 63.5 | 32.6 | 2.63 | CH | 20.0 | 15.8 | 1.3 | Low |
| Bentonite + Kaolinite | — | — | 40.6 | 59.4 | 150.5 | 39.2 | 2.58 | CH | 40.1 | 26.0 | 1.5 | Moderate |
| Bentonite + Weathered clay | — | 11.3 | 32.1 | 56.6 | 152.8 | 48.2 | 2.60 | CH | 81.0 | 47.9 | 1.7 | Moderate |
| Bentonite | — | — | 41.9 | 58.1 | 256.3 | 39.2 | 2.66 | CH | 93.3 | 45.2 | 2.1 | High |

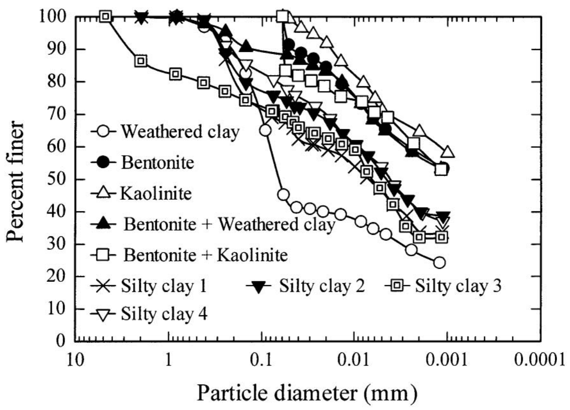


**Fig. 1. Grain size distribution of the tested soils**

bentonite + weathered clay and the bentonite + kaolinite are classified as moderately swelling type. Basic properties, soil classification according to the Unified Soil Classification (USCS) and grain size distribution of the tested clays are presented in Table 1 and Fig. 1. Due to low swelling potential and high amount of $>2\,\mu$m 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.

*Methodology*

All the tested clays were passed through a 19-mm sieve to remove coarser particles. The clays were air-dried for at least three days and then the water content was measured. A 3-kg sample of the air-dried clay was needed for one compaction point (at least five compaction points for each clay). For each point, the air-dried clay was 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 under four energy levels i.e., 296.3, 592.5, 1346.6 and 2693.3 kJ/m$^3$, 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-grained soils at various compaction energies.

Finally, test results of five compacted fine-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 and 3 show typical compaction curves of Silty clay 1 and the bentonite, respectively, under the four levels of compaction energy. The compaction characteristics ($\gamma_{dmax}$, OWC, and ODS) of the tested clays at the four compaction energy levels are summarized in Table 2. It is of interest to mention that for standard Proctor test, all the clays follow Ohio's typical water content–density curves (Joslin, 1958) as shown in Fig. 4. From Table 2, it is noted that even though ODS values are different for different clays, they are within a narrow range (from 81.3 to 90.6%). This range is consistent with the finding of Holtz and Kovacs (1981) that the optimum water content of most fine-grained soils corresponds to a degree of saturation of about 80%. The ODS is dependent upon the clay type. For a given clay, 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; Nagaraj et al., 2006). The other conclusion is that plastic limit, PL, influences the change in OWC (Gurtug and Sridharan, 2002, 2004). The higher the PL, the greater is the OWC. However, it is found from this investiga-

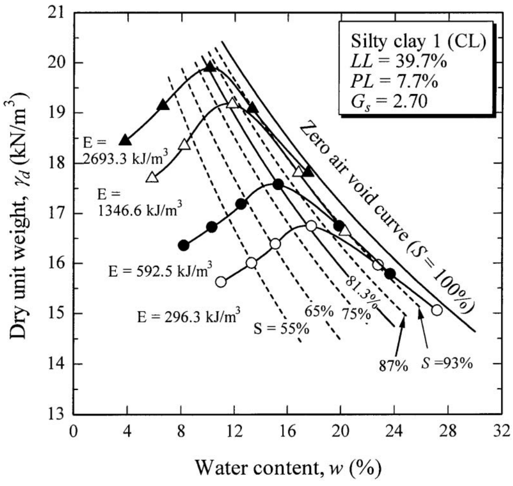


**Fig. 2. Compaction curves of Silty clay 1**

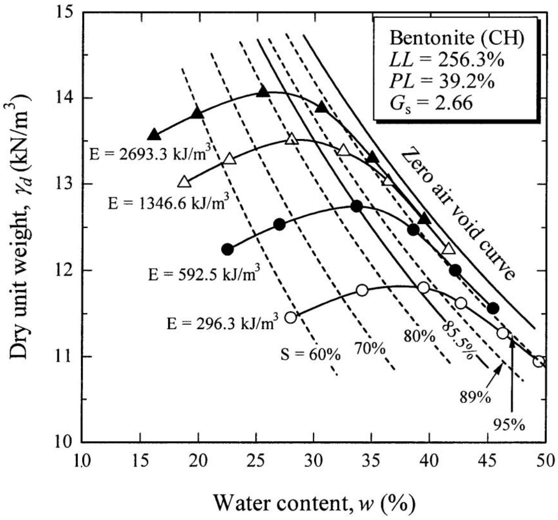


**Fig. 3. Compaction curves of bentonite**

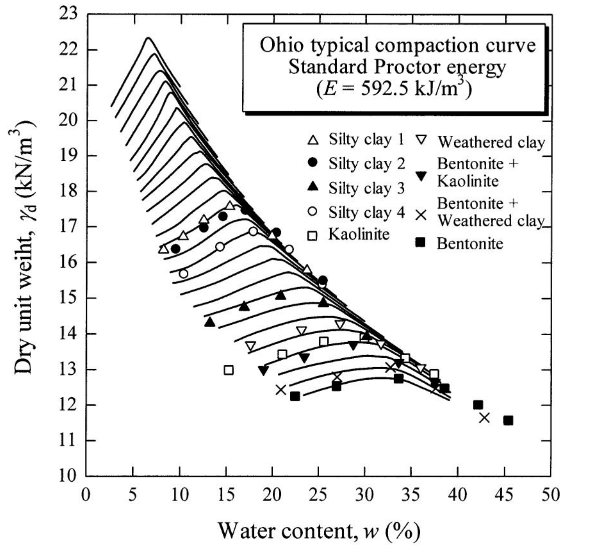


**Fig. 4. Ohio's chart and compaction test results of the studied clays**

tion (Tables 1 and 2) that besides liquid and plastic limits, other soil characteristics (such as soil composition, FSR, and others) 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 lower amount of coarse particles (sand) and higher amount of fine particles (silt and clay).

Gurtug and Sridharan (2004) and Nagaraj et al. (2006)'s 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/m$^3$, the measured OWC is 38.7% while the predicted OWC is 169.6%. This noticeable error might be because the equation was developed based on 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 significant roles 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, $\gamma_{dmax}$ and OWC show a linear relationship with logarithm of compaction energy (Boutwell, 1961, Blotz et al., 1998, and Gurtug and Sridharan, 2004). 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 Fig. 5.

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/m$^3$ can be presented in the following form:

$$\frac{\mathrm{OWC}}{\mathrm{OWC_{st}}} = 2.09 - 0.39 \log E \tag{3}$$

with a high degree of correlation of 0.970. This relationship takes all the combined effects into account. Equation (3) can be used to assess the compaction characteristics of

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

| Soils | $E$ (kJ/m$^3$) | Test Results | | | Prediction (Nagaraj et al., 2006) | | | Prediction (Gurtug and Sridharan, 2004) | | | Prediction (Eq. (3)) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | OWC (%) | $\gamma_{dmax}$ (kN/m$^3$) | ODS (%) | OWC (%) | $\gamma_{dmax}$ (kN/m$^3$) | ODS (%) | OWC (%) | $\gamma_{dmax}$ (kN/m$^3$) | ODS (%) | OWC (%) | $\gamma_{dmax}$ (kN/m$^3$) | ODS (%) |
| Silty Clay 1 | 296.3 | 17.8 | 16.8 | 83.5 | 26.3 | 14.1 | 81.0 | 7.8 | 20.3 | 100 | 17.4 | 16.9 | 83.1 |
| | 592.5 | 15.6 | 17.6 | 83.1 | 24.4 | 14.7 | 81.6 | 6.9 | 21.5 | 100 | Ref. | Ref. | Ref. |
| | 1346.6 | 11.7 | 19.2 | 83.5 | 22.2 | 15.3 | 82.4 | 5.9 | 22.8 | 100 | 13.4 | 18.5 | 83.1 |
| | 2693.3 | 10.8 | 20.0 | 84.2 | 20.4 | 16.0 | 83.3 | 5.0 | 24.0 | 100 | 11.6 | 19.2 | 83.1 |
| Silty Clay 2 | 296.3 | 19.1 | 16.6 | 86.8 | 28.0 | 13.7 | 81.0 | 6.2 | 21.0 | 100 | 18.6 | 16.8 | 87.0 |
| | 592.5 | 16.5 | 17.5 | 87.0 | 26.0 | 14.2 | 81.6 | 5.5 | 22.2 | 100 | Ref. | Ref. | Ref. |
| | 1346.6 | 13.6 | 18.6 | 86.9 | 23.7 | 14.9 | 82.4 | 4.6 | 23.6 | 100 | 14.3 | 18.3 | 87.0 |
| | 2693.3 | 11.9 | 19.3 | 86.3 | 21.7 | 15.5 | 83.3 | 3.9 | 24.8 | 100 | 12.4 | 19.1 | 87.0 |
| Silty Clay 3 | 296.3 | 24.0 | 14.6 | 81.7 | 31.4 | 12.8 | 81.0 | 16.0 | 17.0 | 100 | 24.8 | 14.4 | 81.7 |
| | 592.5 | 22.0 | 15.1 | 81.7 | 29.2 | 13.3 | 81.6 | 14.2 | 17.9 | 100 | Ref. | Ref. | Ref. |
| | 1346.6 | 20.0 | 15.8 | 82.2 | 26.6 | 14.0 | 82.4 | 12.0 | 19.0 | 100 | 19.1 | 16.0 | 81.7 |
| | 2693.3 | 18.1 | 16.4 | 82.4 | 24.4 | 14.6 | 83.3 | 10.2 | 20.0 | 100 | 16.5 | 16.9 | 81.7 |
| Silty Clay 4 | 296.3 | 20.5 | 16.1 | 88.5 | 32.6 | 12.6 | 81.0 | 7.5 | 20.2 | 100 | 19.9 | 16.2 | 87.4 |
| | 592.5 | 17.7 | 16.9 | 87.4 | 30.3 | 13.1 | 81.6 | 6.6 | 21.3 | 100 | Ref. | Ref. | Ref. |
| | 1346.6 | 15.0 | 17.7 | 85.7 | 27.6 | 13.8 | 82.4 | 5.6 | 22.6 | 100 | 15.4 | 17.7 | 87.4 |
| | 2693.3 | 12.4 | 18.9 | 87.2 | 25.3 | 14.4 | 83.3 | 4.8 | 23.8 | 100 | 13.3 | 18.5 | 87.4 |
| Kaolinite | 296.3 | 33.1 | 13.2 | 91.5 | 34.4 | 12.2 | 81.0 | 35.2 | 12.5 | 100 | 33.0 | 13.2 | 91.2 |
| | 592.5 | 29.3 | 14.0 | 91.2 | 32.0 | 12.7 | 81.6 | 31.2 | 13.2 | 100 | Ref. | Ref. | Ref. |
| | 1346.6 | 26.3 | 14.6 | 91.1 | 29.1 | 13.3 | 82.4 | 26.5 | 14.0 | 100 | 25.5 | 14.8 | 91.2 |
| | 2693.3 | 23.3 | 15.4 | 90.8 | 26.7 | 14.0 | 83.3 | 22.5 | 14.7 | 100 | 22.0 | 15.7 | 91.2 |
| Weathered clay | 296.3 | 30.7 | 13.6 | 89.6 | 42.0 | 10.9 | 81.0 | 33.0 | 12.9 | 100 | 30.6 | 13.6 | 89.7 |
| | 592.5 | 27.2 | 14.4 | 89.7 | 39.1 | 11.4 | 81.6 | 29.2 | 13.6 | 100 | Ref. | Ref. | Ref. |
| | 1346.6 | 23.9 | 15.2 | 89.8 | 35.6 | 12.1 | 82.4 | 24.8 | 14.5 | 100 | 23.7 | 15.2 | 89.7 |
| | 2693.3 | 20.3 | 16.2 | 89.8 | 32.6 | 12.7 | 83.3 | 21.1 | 15.2 | 100 | 20.5 | 16.1 | 89.7 |
| Bentonite + Kaolinite | 296.3 | 32.2 | 13.0 | 87.2 | 99.6 | 6.1 | 81.0 | 39.6 | 11.7 | 101 | 32.1 | 13.0 | 87.7 |
| | 592.5 | 28.5 | 13.8 | 87.7 | 92.6 | 6.4 | 81.6 | 35.1 | 12.3 | 100 | Ref. | Ref. | Ref. |
| | 1346.6 | 24.8 | 14.7 | 88.0 | 84.3 | 7.0 | 82.4 | 29.8 | 13.1 | 100 | 24.8 | 14.6 | 87.7 |
| | 2693.3 | 20.8 | 15.7 | 87.7 | 77.3 | 7.5 | 83.3 | 25.3 | 13.8 | 100 | 21.5 | 15.5 | 87.7 |
| Bentonite + Weathered clay | 296.3 | 36.8 | 12.3 | 89.1 | 101.1 | 6.0 | 81.0 | 48.7 | 10.5 | 100 | 36.7 | 12.3 | 89.5 |
| | 592.5 | 32.6 | 13.1 | 89.5 | 94.0 | 6.4 | 81.6 | 43.2 | 11.1 | 100 | Ref. | Ref. | Ref. |
| | 1346.6 | 28.0 | 14.1 | 89.7 | 85.6 | 6.9 | 82.4 | 36.7 | 11.8 | 100 | 28.4 | 14.0 | 89.5 |
| | 2693.3 | 23.9 | 15.0 | 89.0 | 78.5 | 7.4 | 83.3 | 31.2 | 12.4 | 100 | 24.5 | 14.9 | 89.5 |
| Bentonite | 296.3 | 38.7 | 11.9 | 85.6 | 169.6 | 4.0 | 81.0 | 39.6 | 11.8 | 100 | 38.1 | 12.0 | 86.4 |
| | 592.5 | 33.8 | 12.8 | 86.4 | 157.7 | 4.3 | 81.6 | 35.1 | 12.5 | 100 | Ref. | Ref. | Ref. |
| | 1346.6 | 29.8 | 13.6 | 85.7 | 143.5 | 4.6 | 82.4 | 29.8 | 13.3 | 100 | 29.4 | 13.7 | 86.4 |
| | 2693.3 | 27.4 | 14.1 | 85.8 | 131.6 | 5.0 | 83.3 | 25.3 | 14.0 | 100 | 25.5 | 14.6 | 86.4 |

Note: Gurtug and Sridharan's equations are as follows.
$OWC = k_1(PL)$ and
$\gamma_{dmax} = k_2 \gamma_{d(PL)}$
where $k_1 = -0.344 \log E + 1.88$
$k_2 = -0.145 \log E + 0.57$ ($E$ is expressed as kJ/m$^3$)

$$\gamma_{d(PL)} = \frac{G_s \gamma_w}{1 + (PL) G_s}$$ (Assuming that soils are saturated at plastic limit)

any compacted fine-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 $\gamma_{dmax}$) and compared with the two methods in Table 2. In the prediction, the ODS is assumed as same for all compaction energies and the ODS at standard Proctor energy is taken for determining the maximum dry density, $\gamma_{dmax}$. 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; 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, dependent upon degree of saturation ($S$). Such a relationship exists for the tested clays as well, as shown in Figs. 6 and 7 for Silty clay 1 and the

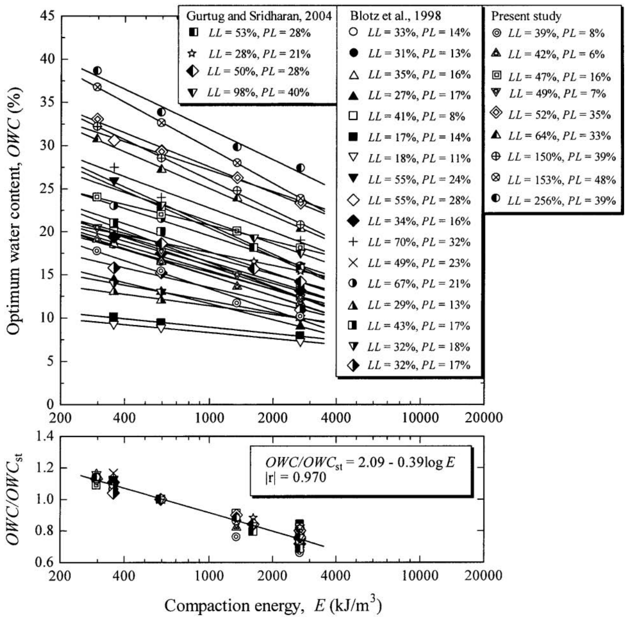


**Fig. 5. Relationship between OWC and compaction energy and its normalization**

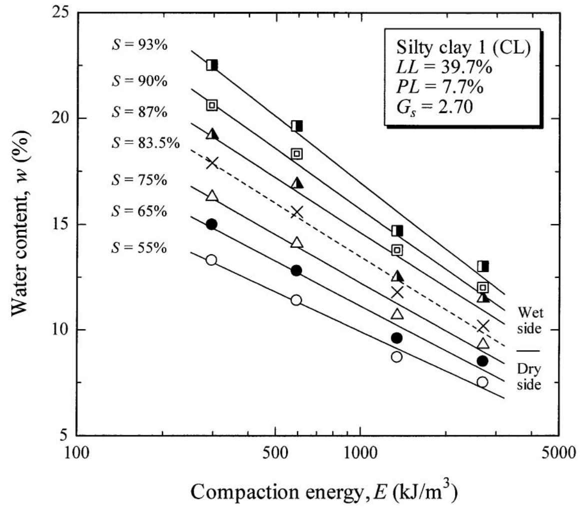


**Fig. 6. Relationship between water content and compaction energy of Silty clay 1**

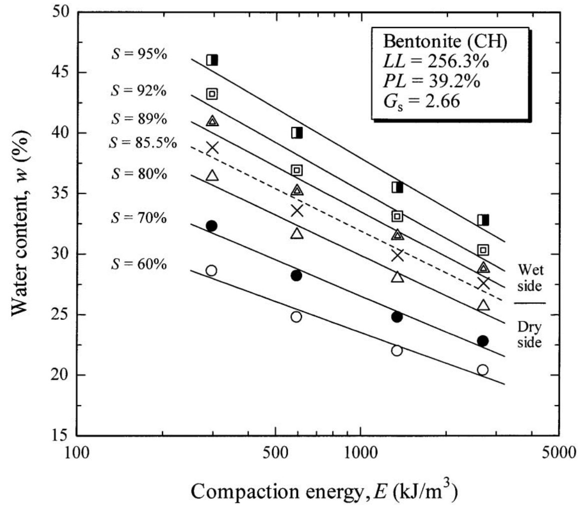


**Fig. 7. Relationship between water content and compaction energy of bentonite**

bentonite, respectively. The existence of the linear relations shows that the air in the compacted clay samples having the same water content is easier to expel from the clay mass with the increase in the compaction energy, resulting in an increase in the degree of saturation.

Recent work on the micro structural 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 (*see* Figs. 6 and 7), 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 clays which have widely varying soil characteristics. In other words, the parameters $w/S^{0.5}$ and $w/S^2$ are not constant for all clay types. A more general relationship between the water content and the degree of saturation at a specific compaction energy is now proposed as a power function of the form:

$$w = A_d S^{B_d} \quad \text{for the dry side of optimum} \tag{4}$$

$$w = A_w S^{B_w} \quad \text{for the wet side of optimum} \tag{5}$$

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 Figs. 8 and 9 for Silty clay 1 and the bentonite, 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 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 clays). It is noted that even though the parameters $A_d$, $B_d$, $A_w$, and $B_w$ are different for different clays, the ratios $A_d/A_{dst}$ 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 clays and are very close 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 con-

**Table 3. Values of $A_d$, $A_w$, $B_d$ and $B_w$ for all the tested soils**

| Soils | $E$ (kJ/m$^3$) | $A_d$ | $B_d$ | $A_w$ | $B_w$ | $A_d/A_{dst}$ | $A_w/A_{wst}$ | 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 | 11.56 | 0.72 | 15.20 | 2.16 | 0.65 | 0.66 | 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 | 0.86 | 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 |
| Weathered 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 |
| | 2693.3 | 22.18 | 0.81 | 26.43 | 2.44 | 0.75 | 0.75 | 0.75 |
| Bentonite + Kaolinite | 296.3 | 35.70 | 0.75 | 40.78 | 1.72 | 1.13 | 1.13 | 1.13 |
| | 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 |
| | 2693.3 | 22.94 | 0.75 | 26.05 | 1.72 | 0.77 | 0.73 | 0.73 |
| Bentonite + Weathered clay | 296.3 | 40.33 | 0.80 | 45.92 | 1.92 | 1.13 | 1.13 | 1.13 |
| | 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 |
| | 2693.3 | 26.24 | 0.81 | 29.88 | 1.92 | 0.74 | 0.74 | 0.73 |
| Bentonite | 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 |

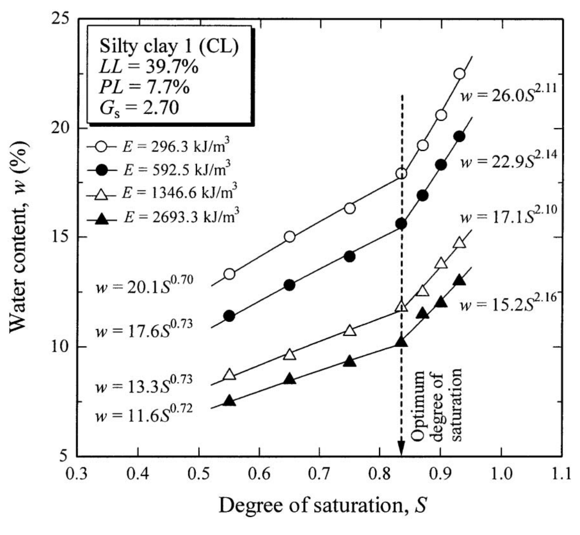


**Fig. 8. Relationship between water content and degree of saturation at four energy levels of Silty clay 1**

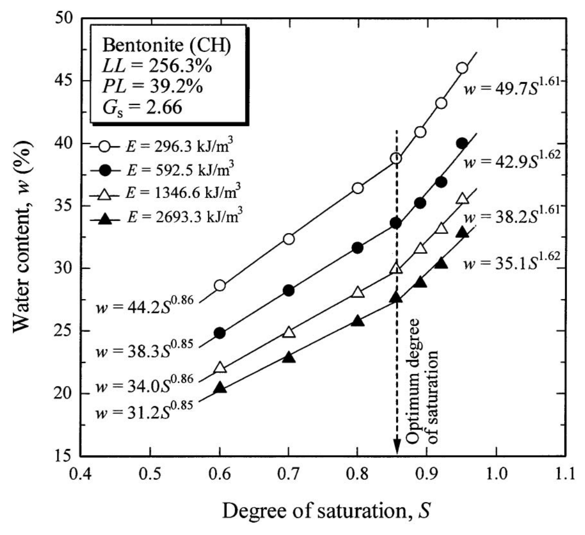


**Fig. 9. Relationship between water content and degree of saturation at four energy levels of bentonite**

trolled by $A_d$ and $A_w$ (*see* Eqs. (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; 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-grained soils as illustrated by Figs. 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 $A_w$ (*see* Fig. 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 value of $B_d$ and the higher the value of $B_w$, the greater is the degree of water sensitivity (*see* Fig. 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.

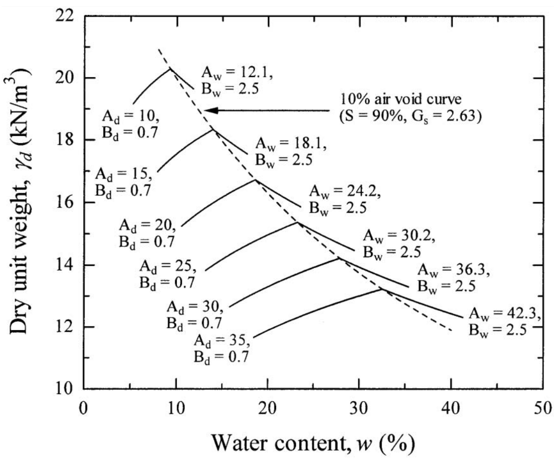


**Fig. 10. Effect of $A_d$ and $A_w$ on compaction curves**

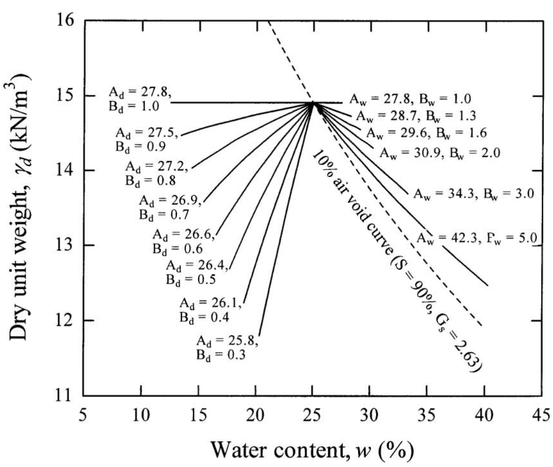


**Fig. 11. Effect of $B_d$ and $B_w$ on compaction curves**

## SUGGESTED APPROACH FOR ASSESSMENT OF COMPACTION CURVES

The characteristic of compaction curves of fine-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-grained soil under a specific 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 ($\gamma_{dmax}$, 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 $(\gamma_{dmax})_{st}$ by assuming that the ODS value is the same for all compaction energy levels.
3. Determine the optimum compaction point ($\gamma_{dmax}$, 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 $\gamma_d$.
6. Draw a curve connecting ($\gamma_d$, $w$) points obtained from step (5).

Figures 12 through 16 show the predicted and the

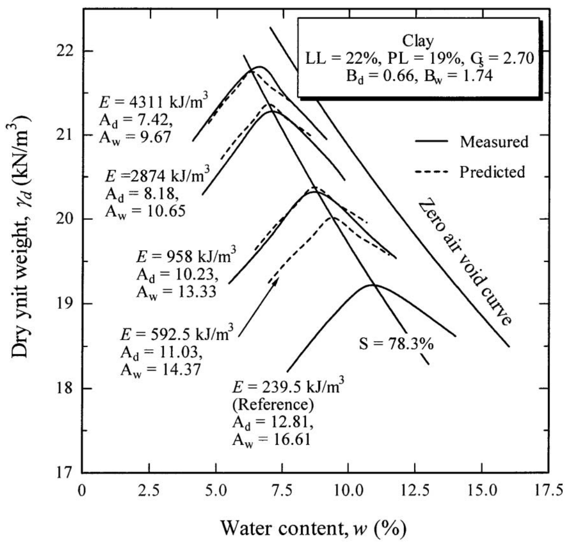


**Fig. 12. Predicted and measured compaction curves of clay (data from Proctor, 1948)**

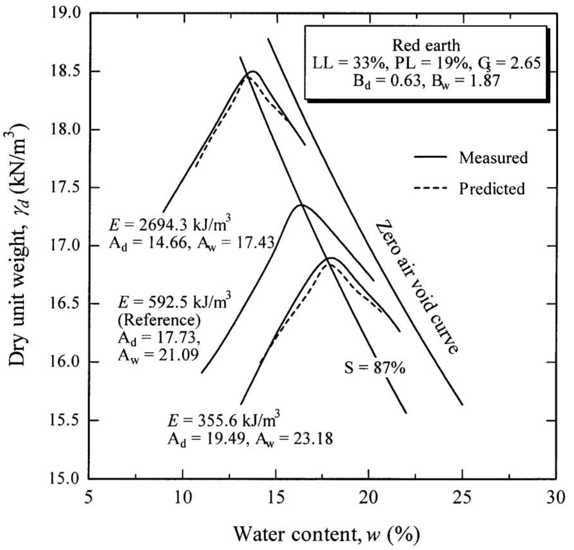


**Fig. 13. Predicted and measured compaction curves of red earth (data from US Army Corps of Engineers, 1970)**

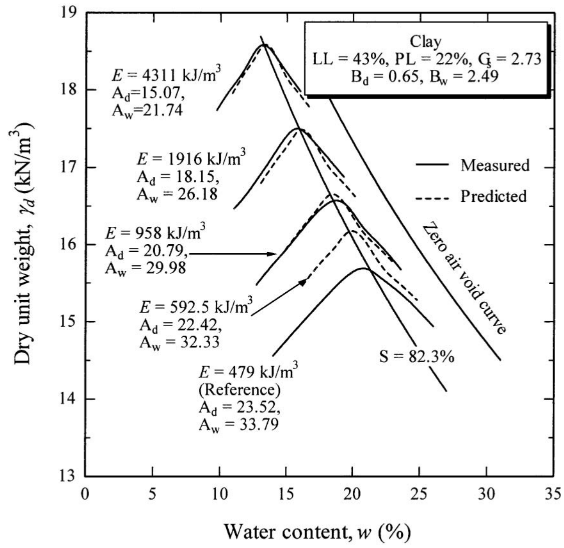


**Fig. 15. Predicted and measured compaction curves of clay (data from Proctor, 1948)**

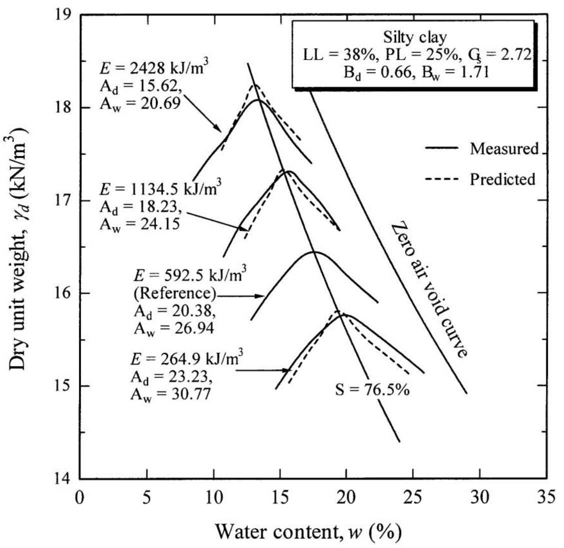


**Fig. 14. Predicted and measured compaction curves of silty clay (data from Turnbull and Foster, 1956)**

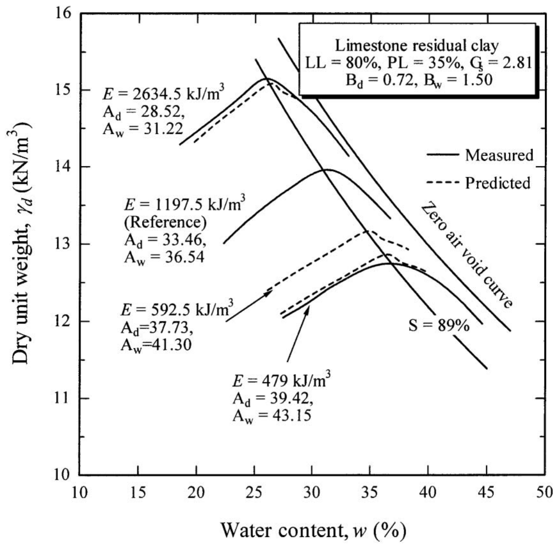


**Fig. 16. Predicted and measured compaction curves of limestone residual clay (data from Bell, 1956)**

measured compaction curves of the clays 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-grained soils compacted under standard compaction energy (592.5 kJ/m$^3$) follow Ohio's curves, the modified Ohio's curves for different compaction energy levels (296.3, 1346.6 and 2693.3 kJ/m$^3$) are developed using the proposed method as shown in Figs. 17 to 19. These curves are useful in the assessment of compaction curve at the required compaction energy using a set of data of water content and dry unit weight.

## CONCLUSIONS

The present paper deals with the characteristics of compaction curves for fine-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 $\gamma_{dmax}$) of fine-grained soils are dependent upon the combined effects of liquid and plastic limits, and other soil characteristics (such as soil composition, FSR, 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

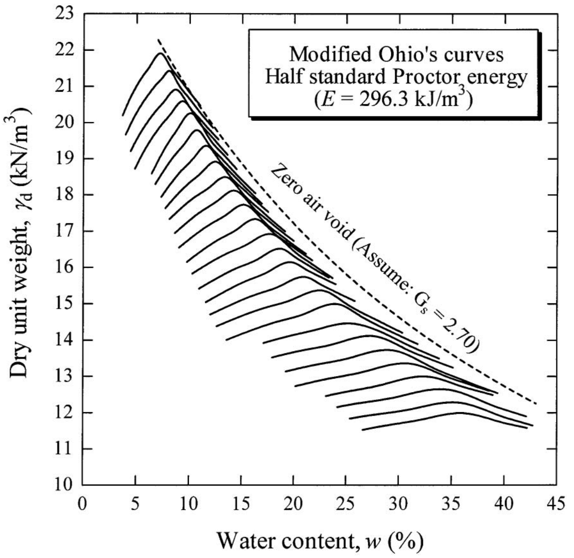


**Fig. 17. Modified Ohio's curves for compaction energy of 296.3 kJ/m$^3$**

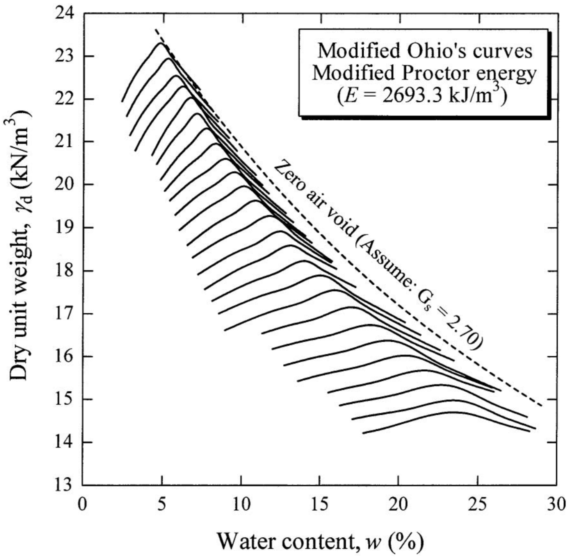


**Fig. 19. Modified Ohio's curves for compaction energy of 2693.3 kJ/m$^3$**

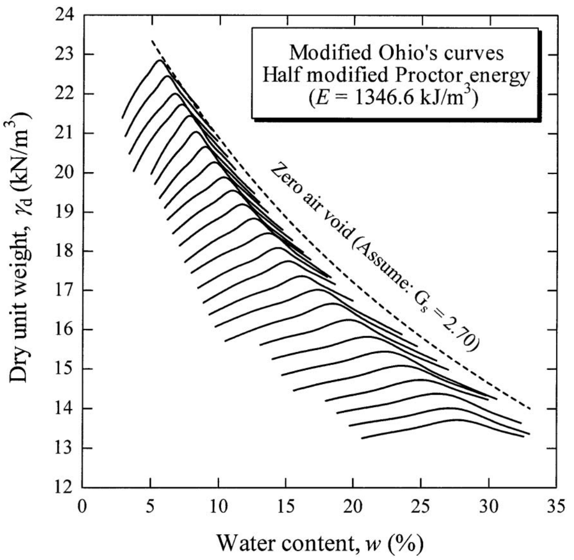


**Fig. 18. Modified Ohio's curves for compaction energy of 1346.6 kJ/m$^3$**

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-grained soils.

3. A simple and rational method for assessing the laboratory compaction curves of fine-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 the assessment of compaction curves under the other three compaction energy levels (296.3, 1346.6 and 2693.3 kJ/m$^3$) using a set of data of dry unit weight and water content.

## ACKNOWLEDGEMENT

The authors wish to acknowledge the financial support provided by the Commission on Higher Education (CHE) and the Thailand Research Fund (TRF) under the contract MRG5080127.

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