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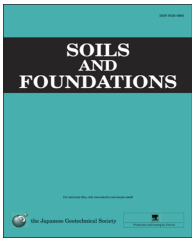

Modelling the compaction curve of fine-grained soils ☆

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Abstract

A theoretical model for the compaction curve of fine-grained soils at various compaction efforts for the entire range of water content is presented in this study. The prediction method is based on the assumption that the compaction curve represents the state surface at the yield state in an unsaturated condition. Thus, for each applied compaction effort, the compaction curve relates to one yielding point on the saturated normal consolidation line (NCL). For a given soil, the model requires the NCL, S_{rc}, and one point from any compaction curve to predict the compaction curves for different compaction efforts. Moreover, the lines of equal suctions on the compaction curves can be determined if the SWCC, the wetting path, is known. The model introduced here provides additional theoretical understanding of the soil's volume change behavior of the compaction curve. The model was verified in two ways: first it was verified quantitatively, by experimental results, and second it was verified qualitatively, by examining the relationships from other models in the literature. The model was further applied to experimental data reported in the literature on previous static and dynamic compaction tests. The results show that the model fits the experimental data very well. Finally, a simple chart, based on this model and using only liquid limits, is presented to estimate γ_{dmax} and OMC quickly.

Keywords: Modelling; Compaction curve; Compacted soils; Volume change; Yield state; Fine-grained soils; Unsaturated soil; Suction

1. Introduction

The aim of this study is to model the compaction curves at various compaction efforts for the entire range of water content for fine-grained soils. It is assumed that the compaction curves reproduce the volumetric yielding surface or the state surface at the yield state in an unsaturated condition (Al-Badran and Schanz, 2009a; Al-Badran, 2011). The state surface at the yield state in an unsaturated condition is a unique surface which includes all points from different initial conditions. The position of the yielding surface is defined by the NCL's constant degree of saturation, S_r-lines (Al-Badran, 2001, 2011). The concept of the S_r-lines is modified according to the microstructural consideration of Nagaraj et al. (2006a, 2006b). Consequently, each point of the compaction curve represents a normal consolidated or yield state and results in an increase in the applied net stress or the compaction effort until a specific value under a constant water content condition can be reached for soil in an initially loose state. Thus, for each

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compaction effort applied, the compaction curve relates to one yielding point of the saturated NCL. The parameters involved in this model are functions of the void ratio of the saturated NCL (e_{NCL}) of the effective stress equivalent to the compaction effort, the degree of saturation S_r, the critical degree of saturation S_{rc} (the degree of saturation at the optimum moisture content, OMC), the parameter that controls the influence of the degree of saturation to increase the void ratio under a constant compaction effort (R), and the parameter that controls the position of the maximum value for the void ratio under each net stress or compaction effort (M). However, for a given soil, the model requires the NCL, S_{rc}, and one point from any compaction curve to predict the compaction curves for different compaction efforts. The prediction of any further compaction curve for a specific compaction effort requires only the e_{NCL} of the equivalent effective stress. In addition, a simple chart, based on this model and using only liquid limits, will present a quick estimation of γ_{dmax} and optimum moisture content OMC. Moreover, the lines of equal suctions on the compaction curves can be determined if the soil–water characteristic curve, SWCC (wetting path) is known.

2. Literature review of compaction modelling

Previous studies on soil compaction models can be divided into two main groups:

(1) Models that use empirical correlations for both cohesive and cohesionless soils, which relate optimum water content, OMC, and maximum dry density or unit weight γ_{dmax}, to soil properties, such as the Atterberg index (liquid limit, *LL*, and plastic limit, *PL*), the specific gravity of solids (G_s), and the grain-size distribution (Davidson and Gardiner, 1949; Turnbull, 1948; Ring et al., 1962; Ramiah et al., 1970; Jeng and Strohm, 1976; Livneh and Ishai, 1978; Wang and Huang, 1984; Korfiatis and Manikopoulos, 1982; Al-Kafaji, 1993; Basheer and Najjar, 1995; Najjar and Basheer, 1996; Blotz et al., 1998; Sridharan and Nagaraj, 2005; Gurtug and Sridharan, 2002; Jesmani et al., 2008).

(2) Models for the entire range of compaction curves describing the compaction characteristics (Joslin, 1959; Rethati, 1988; Hilf, 1991; Howell et al., 1997; Nagaraj and Bindumadhava, 1992; Nagaraj, 1994; Pandian et al., 1997; Basheer, 1998, 2001; Li and Sego, 2000; Nagaraj et al., 2006a; Honda et al., 2007; Kurucuk et al., 2008; Horpibulsuk et al., 2008a, 2008b).

An early work by Joslin (1959) yielded 26 typical standard Proctor curves (named Ohio's curves). Rethati (1988) presented an empirical approach to modelling the compaction curves based on fitting a simple quadratic equation to the water content, w, and the dry density, γ_d, relationship (w–γ_d). Hilf (1991) and Howell et al. (1997) used second-, third-, and fourth-degree polynomial equations to model the compaction curves. Nagaraj and Bindumadhava (1992) and Nagaraj (1994) developed a semi-empirical phenomenological model to determine the w–γ_d relationship separately for the dry of optimum, *DOP,* and the wet of optimum, *WOP*, based on the *LL* and the *Gs* for each *CE*. Pandian et al. (1997) presented the linear relationships of $w-LL$, $[w/(S_r)^{0.5}]$–LL, $[w\ (S_r)^{2}]$–LL, for the standard Proctor test. Basheer (1998) developed models for both the compaction characteristics and the compaction curves. Li and Sego (2000) derived an equation with both soil and compaction effort parameters to predict the complete compaction curves of fine-grained soils for all $w > 0$. Basheer (2001) suggested empirical models using both statistical regression and ANNs to predict the compaction curves of cohesive soils based on the soil properties and compaction efforts. Nagaraj et al. (2006a) introduced an ideal pore model (linear relationship) to estimate the compaction curves of fine-grained soils quickly for different compaction efforts for *DOP* and *WOP*. Based on their ideal model, state parameters $w/S_r^{\ 0.5}$ and $w/S_r^{\ 2}$ were proposed for *DOP* and *WOP*, respectively. Honda et al. (2007) presented a method to determine the maximum dry density–optimum moisture content (w–γ_d) relationship based on the unsaturated normal consolidation lines (*NCL*) of the constant water content condition behavior. Kurucuk et al. (2008) presented an approach to predict the soil compaction curve during undrained loading. They investigated the effect of soil suction, stiffness, and pore air pressure on the shape of the compaction curve.

Several studies (Joslin, 1959; Nagaraj and Bindumadhava, 1992; Nagaraj, 1994; Nagaraj et al., 2006a) yielded a set of compaction curves that are nearly parallel for all soils for any *LL*. Others (Basheer, 2001; Horpibulsuk et al., 2008a, 2008b) have demonstrated that the compaction curves of natural soils are rarely parallel to each other (some of them have flatter curves and others have sharp peaks).

3. Material used

The materials used in this study are pure bentonite 100B, and a mixture of bentonite and quartz sand, 30% bentonite and 70% sand mixture, 30B (Agus, 2005). The basic properties investigated in this study were performed based on ASTM standards (ASTM, 1997) and DIN standards (DIN, 1987). The

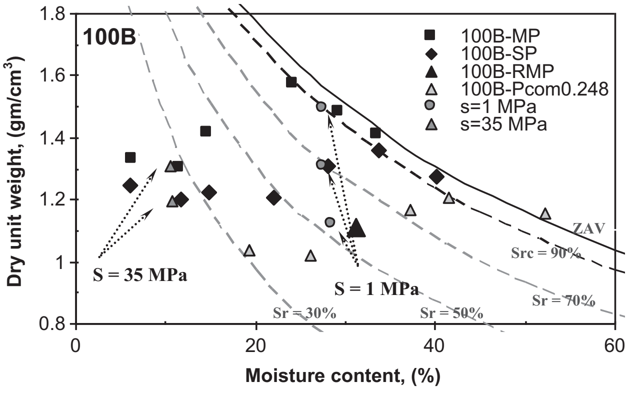

Fig. 1. Dynamic and static experimental compaction curves for different CE, and points of equal suction for 100B mixtures.