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A linear graphical method to predict the effect of compaction on the hydraulic conductivity of clay liners and covers

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Abstract It is proposed to present compaction relationships by plotting the inverse of the dry density versus the molding water content. In the proposed graph, the curves for equal degree of saturation become straight lines. The proposed new graph is shown to be very convenient to assess the saturated hydraulic conductivity, k_{sat} , of non-swelling compacted clay, using a dual porosity model. The value of k_{sat} depends on the secondary porosity between clay clods. The equation developed for equal k_{sat} value appears also as a straight line in the proposed graph. It facilitates the prediction of k_{sat} from field compaction data and thus the prediction of field performance of clay liners and covers.

Keywords Compaction · Clay liner · Permeability · Performance

Résumé Pour présenter les relations de compactage, on propose de por-

ter l'inverse de la masse volumique sèche versus la teneur en eau. Dans le graphe proposé, les courbes d'égal degré de saturation deviennent des droites. Le nouveau graphe proposé s'avère très utile pour évaluer la conductivité hydraulique saturée, k_{sat} , d'une argile compactée non gonflante, à partir d'un modèle de double porosité. La valeur de k_{sat} dépend de la porosité secondaire entre les mottes d'argile. L'équation d'iso valeurs de k_{sat} développée apparaît aussi comme une droite dans le graphique proposé. Ceci facilite la prédiction de k_{sat} à partir des données de compactage de chantier, et donc la prédiction de la performance en place des tapis et couvertures en argile.

Mots clés Compactage · Tapis d'argile · Perméabilité · Performance

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Introduction

For non-swelling clay, the effect of compaction on the saturated hydraulic conductivity, k_{sat} , has been thoroughly investigated. Terzaghi (1922) found that k_{sat} depends on porosity n , and also on the preparation and compaction modes. Mitchell et al. (1965) have shown that specimens compacted wet of optimum may have k_{sat} values 100–1,000 times lower than specimens compacted dry of optimum. These authors defined two

porosities. The porosity of the clay matrix (primary porosity) corresponds to the fine structure at the micron scale of solid particles. The porosity between artificially formed clay clods (secondary porosity) corresponds to a macrostructure resulting from remolding (excavation, transport, handling) or weathering processes (wetting-drying, freeze-thaw). These two porosities can be quantified using techniques such as the mercury intrusion test or scanning electron microscopy (e.g., Delage et al. 1982). The k_{sat} value of compacted non-swelling

clay was found to depend mainly on the secondary porosity. Swelling clays (e.g., bentonite) behave differently and can achieve fairly low k_{sat} values even when compacted dry of optimum (e.g., Chapuis 1981, 2002; Chapuis et al. 1992; Haug and Wong 1992).

In practice, compacted clay layers are controlled using indirect methods (e.g., dry density and water content) and direct methods (e.g., field permeability tests). According to experience, many field tests are done to assess the compaction condition whereas only a few permeability tests are performed. Being able to predict the k_{sat} value at each location at which a compaction test was performed would provide a large data bank of predicted values to be used to assess the overall performance of the liner or cover. This paper proposes a predictive model for k_{sat} and a simple graphical method to predict k_{sat} from the local field values of dry density and water content just after compaction.

Known parameters influencing k_{sat}

Call-for-tender documents for clay liners and covers specify clay compaction conditions. They usually include a minimum dry density (e.g., 95% of the standard Proctor or 90% of the modified Proctor), a minimum water content (e.g., the optimum value) and sometimes a minimum degree of saturation (e.g., 90%) which is known to be important to achieve a low k_{sat} . In a standard or modified Proctor test, the wet side of the compaction curve corresponds to a degree of saturation, S_r , of about 90% for clay (Fig. 1). Discontinuous tiny air bubbles, representing typically about 10% of the void space, are trapped in the compacted clay. They cannot be evacuated during compaction because the clay

becomes impervious to air (e.g., Fredlund and Morgenstern 1977). In turn, this indicates an excellent interlocking of the clods and a low k_{sat} . This near-zero air-permeability of well-compacted clay was used in some projects as a means to control compaction conditions in the field (e.g., Langfelder et al. 1968; Leflaive and Schaeffner 1980).

Other criteria are related to the liner total thickness, thickness of each layer (usually between 15 and 30 cm), compaction method (e.g., a sheep foot roller with a minimum length of 20 cm for the steel feet) and sometimes a maximum clod size. Either the standard or the modified Proctor test may be used as reference since the two optimum dry densities and the two optimum water contents are well correlated according to Chapuis (2002) who gathered data published by Sherwood (1975), Blotz et al. (1998) and Benson et al. (1999).

A good interlocking, minimizing the secondary porosity, is more easily achieved when the clay deforms without fissuring. This means that the molding water content should be higher than the clay plastic limit. Arquíe (1964) and others (e.g., Leroueil et al. 1992) noted that the clay plastic limit is often close to the optimum water content of the standard Proctor. However, Chapuis (2002) found that the correspondence is very approximate, using data from Daniel (1984, 1985), Boynton and Daniel (1985), Day and Daniel (1985), Mundell and Bailey (1985), Stewart and Nolan (1987), Daniel and Benson (1990), Elsbury et al. (1990), Leroueil et al. (1992), Blotz et al. (1998), Benson et al. (1999) and personal data. The correlation between the optimum water content of the standard Proctor and the liquid limit is equally poor, as shown by Granger (1969), Popovic and Sarac (1980), Benson et al. (1999) and Chapuis (2002). Since these relationships are approximate, it is preferable, in call-for-tender documents, to specify the minimum water content in the field as the plastic limit, instead of the optimum of the standard Proctor, when the soil to be compacted has no swelling properties.

Other considerations for compacted clay relate to the ability of field equipment to achieve the desired compaction in order to obtain a low k_{sat} value. First, the clay plastic limit may be used as a reference for its undrained shear strength, c_u , that is close to 140 kPa (Biares 1972). According to plasticity theory for isotropic materials, its surface bearing capacity is equal to $(\pi + 2)c_u = 700$ kPa. Thus, it is difficult to knead and compact the clay at this water content. This is why a sheep foot roller is frequently used. For a dam core, the water content must be low enough to minimize settlements during construction and after reservoir filling. For liners, mechanical properties are usually less critical but the clay must be able to deform without fissuring. The water content can be fairly high as long as it allows the circulation of compaction equipment. This may be

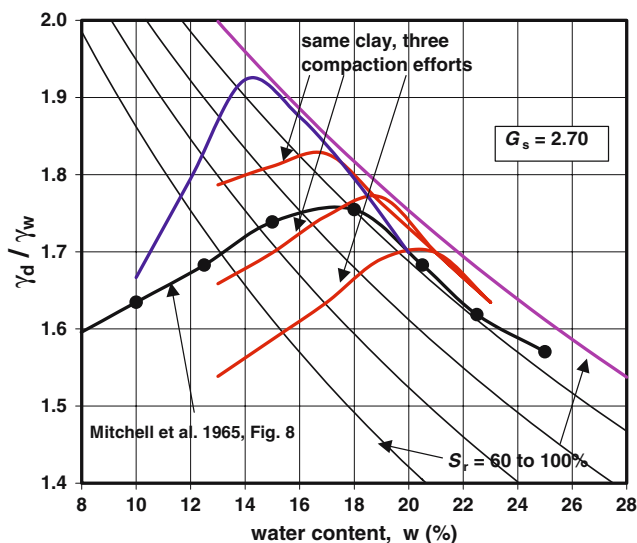


Fig. 1 Examples of typical compaction curves for clay

viewed as either a penetration resistance (e.g., Faure and Da Mata 1994) or a bearing capacity problem that is usually solved when the clay’s undrained shear strength, c_u , is higher than 30 kPa. According to Leroueil et al. (1992), this is achieved when the ratio $(w - w_{opt})/I_P$ is lower than 0.3, where w_{opt} is the standard Proctor optimum water content and I_P is the plasticity index.

Finally, a non-swelling compacted clay must not dry or freeze before being in use, otherwise its k_{sat} value could increase by a factor of 100–1,000 and other properties may be affected (Chamberlain and Gow 1979; Zimmie 1992; Benson and Othman 1993; Othman et al. 1995; Eigenbrod 1996).

Relationship for k_{sat} of compacted clay

Considering the large number of parameters influencing k_{sat} , several approaches can be taken to try to predict it. For predicting the performance of liners, it is important to use k_{sat} which is the maximum value of k (all voids are filled with water) that can be reached for a specimen. Among several predictive methods, Kodikara and Rahman (2002) tried to correlate the moisture contents for the minimum re-saturated k value and the maximum wet unit weight. Benson et al. (1994) defined several trends after having performed a multivariate regression analysis of laboratory determinations of k conducted on a wide variety of clayey soils from the liners of 67 landfills.

In this paper, the authors use a physically based model relating k_{sat} to the secondary porosity of re-saturated compacted clay (Chapuis 2002). At the end of compaction, all water is assumed to be held within the clods and none between the clods, the secondary porosity being filled with air only. Thus, the air volumetric fraction, or secondary porosity of the compacted clay equals $n_c(1 - S_{rc})$ where n_c is the total porosity after compaction, and S_{rc} is the degree of saturation after compaction (Fig. 2). When the compacted clay specimen is prepared for permeability testing, its degree of saturation increases from S_{rc} to S_r (usually close to 100% when back-pressuring is used). According to several authors, the size of laboratory compacted specimens (about 100 or 150 mm in diameter) is usually large enough to avoid the problem of scale effect that can appear with smaller specimens (e.g., Cazaux and Didier 2002).

The fluid movement in an ideal single fracture yields the Poiseuille flow frequently quoted as the “cubic law.” In real saturated fractured materials, a continuum formulation can be used in which the k_{sat} value may be correlated to the cube of the water filled secondary porosity. The latter is equal to the void volume fraction after compaction, n_c , minus the volume of bound water, $n_c S_{rc}$. Thus,

$$k_{sat} = \text{function of } n_c^3(1 - S_{rc})^3. \tag{1}$$

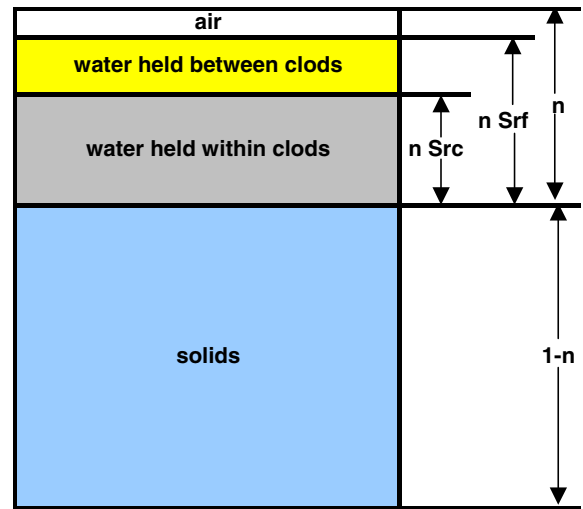


Fig. 2 Schematic illustration of secondary porosity in compacted non-swelling clay

Laboratory data for several compacted clays in Quebec projects (Fig. 3) confirm Eq. 1. Results for other compacted clays (Lambe 1958; Mitchell et al. 1965) provided similar results (Chapuis 2002), the k_{sat} value being more generally represented by

$$k_{sat} = an_c^b(1 - S_{rc})^b \tag{2}$$

where a and b are factors derived by curve-fitting. Equation 2 predicts $k_{sat} = 0$ for a specimen that is fully saturated after compaction, which is unrealistic. This is why a minimum value of 10^{-8} cm/s can be considered when using Eq. 2.

In Fig. 3, the bisecting line represents the case of Eq. 2 where $a = 10^{-2}$ cm/s and $b = 3$. For other

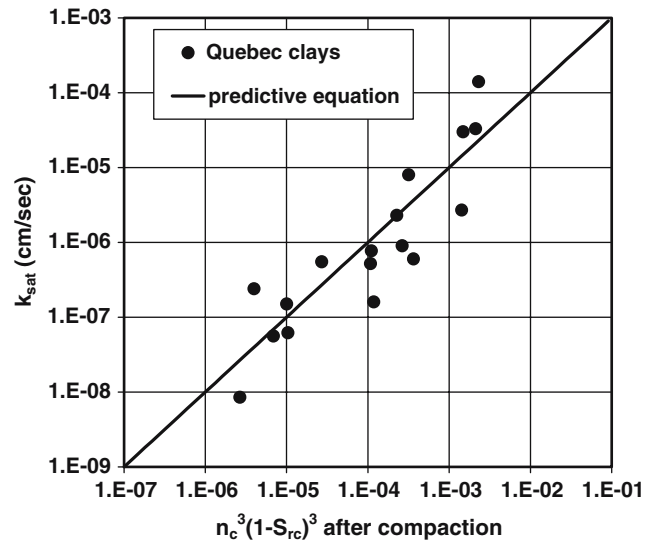


Fig. 3 Permeability test results for re-saturated compacted non-swelling clay

non-swelling clays, the specific values of a and b can be determined experimentally.

Graphical presentation of compaction data

Compaction formulae relate the dry density ρ_d and the degree of saturation S_r to the densities of solids, ρ_s , and water ρ_w , and the void ratio, e , by

$$\rho_d/\rho_w = G_s/(1+e) \quad (3)$$

$$S_r = w(\rho_d/\rho_w)G_s/(G_s - (\rho_d/\rho_w)) \quad (4)$$

where $G_s = \rho_s/\rho_w$ is the specific gravity of solid.

The compaction test results are conventionally plotted in a graph ($x = w$; $y = \rho_d/\rho_w = \gamma_d/\gamma_w$). Then, Eq. 4 becomes

$$S_r = xyG_s/(G_s - y) \quad (5)$$

that can be rearranged as

$$y = \frac{S_r G_s}{x G_s + S_r} \quad (6)$$

indicating that the curves of constant S_r values are hyperbolas in the frame (x, y). Instead of using the conventional graph, this paper proposes to plot the data as $X = w$ and $Y = \rho_w/\rho_d = y^{-1}$. Thus Eq. 4 becomes

$$Y = \frac{XG_s + S_r}{S_r G_s} = \frac{X}{S_r} + \frac{1}{G_s} = \frac{1+e}{G_s} \quad (7)$$

which means that the curves of constant S_r values become straight lines in the frame (X, Y). All constant S_r straight lines intersect at ($X=w=0, Y = \rho_w/\rho_d = 1/G_s$).

Curves of equal k_{sat} value

The equation of equal k_{sat} curve for the proposed model of Eq. 2 can be established as follows. In the usual compaction graph with the coordinates (x, y), as previously defined, S_r is defined by Eq. 4 whereas the porosity n is

$$n = (G_s - y)/G_s \quad (8)$$

Substituting Eqs. 5 and 8 into Eq. 2 yields

$$k_{sat}(\text{cm/s}) = a[(G_s - y - xyG_s)/G_s]^b \quad (9)$$

which gives the equation of equal k_{sat} curve as

$$y = G_s(1 - \alpha)/(1 + xG_s) \quad (10)$$

in which the constant α is defined as

$$\alpha = (k_{sat}/a)^{1/b} \quad (11)$$

where k_{sat} and a have the same unit, e.g., cm/s.

Thus in the usual graph, the curves of constant k_{sat} value are hyperbolas according to Eq. 10, and the curves of constant S_r value are also hyperbolas. In the proposed reference plane (X, Y), it has already been shown that the curves of constant S_r values are straight lines. Similarly, the curves of equal k_{sat} value become straight lines defined from Eq. 10 as

$$Y = (1 + XG_s)/G_s(1 - \alpha) \quad (12)$$

that appear in Fig. 4, in which the linear properties facilitate any reading or interpolation. Note that the mean values $a = 10^{-2}$ cm/s and $b = 3$ of Fig. 3 have been used to draw Fig. 4.

Assessing freeze-thaw effects

Damage induced by freeze-thaw cycles can be assessed using the previous dual porosity model, considering that the damage is mainly an increased secondary porosity. The total porosity and degree of saturation after compaction are noted n_c and S_{rc} , whereas they are noted n_f and S_{rf} after freeze-thaw cycles. If the compacted clay was never frozen and is tested at $S_r \leq 100\%$, its water filled secondary porosity is $n_c(S_r - S_{rc})$ and thus, according to the model, its hydraulic conductivity, k , not necessarily saturated, is

$$k_c(\text{cm/s}) = an_c^b(S_r - S_{rc})^b \quad (13)$$

The compacted clay, after freeze-thaw cycles, is tested for permeability at $S_r \leq 100\%$. The water filled secondary porosity is now the difference between the

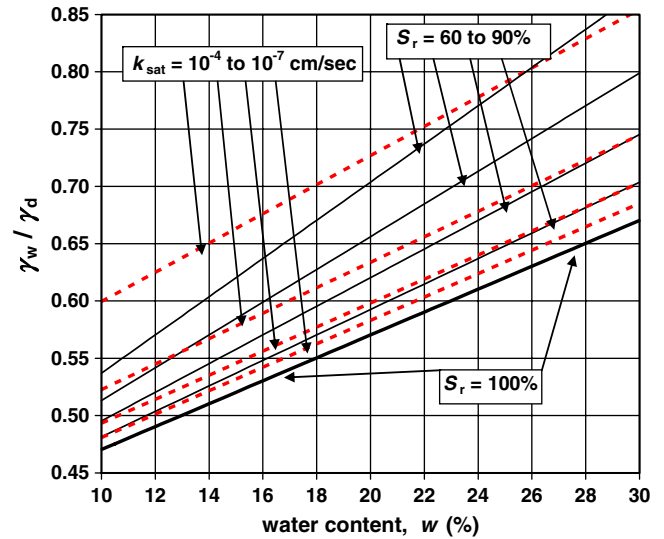


Fig. 4 Proposed plotting for curves of equal degree of saturation (*fine solid lines*) and equal values of saturated hydraulic conductivity after compaction and re-saturation (*bold broken lines*)

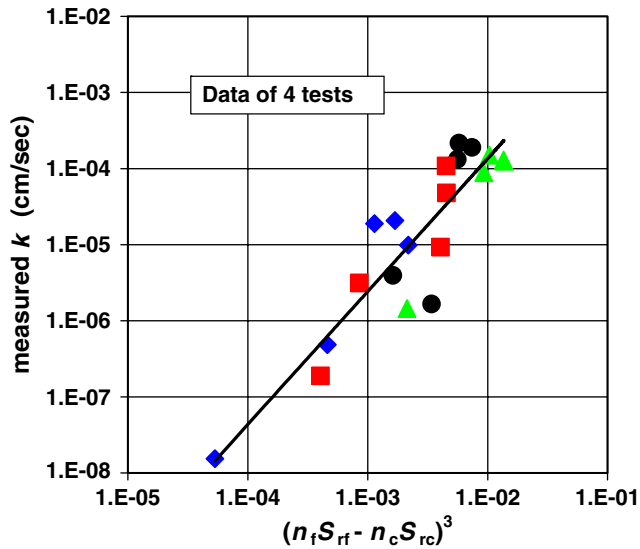


Fig. 5 Assessing the effects of freeze-thaw and drying-wetting cycles

water volume during testing, $n_f S_{rf}$, and the volume of bound water, $n_c S_{rc}$, and thus the hydraulic conductivity k_f is given as

$$k_f(\text{cm/s}) = a(n_f S_{rf} - n_c S_{rc})^b. \quad (14)$$

The adequacy of Eq. 14 to represent the k_f value of frost-damaged compacted clay was assessed with the detailed data provided by Aubertin and Dagenais (2000) for four clay specimens. The specimens were tested in rigid-wall permeameters after compaction and then after 5, 10, 15 and 20 freeze-thaw cycles (no external effective stress was applied during these cycles). The degree of saturation for each permeability test was evaluated using the mass and volume method (Chapuis et al. 1989;

Chapuis 2004). When plotted versus the right member of Eq. 14, the test data (Fig. 5) indicate that the proposed model can correctly assess the impact of frost damage on k_{sat} .

Discussion and conclusion

Laboratory compaction data are usually plotted as $y = \rho_d/\rho_w = \gamma_d/\gamma_w$ versus $x = w$. In the (x, y) frame, the curves of equal degree of saturation S_r are hyperbolas. It is proposed here to plot the data as $Y = (\rho_d/\rho_w)^{-1}$ versus $X = w$. In the new (X, Y) frame, the curves of equal S_r are straight lines passing through the point $X=0, Y = \rho_w/\rho_d = 1/G_s$. This new frame proves useful when assessing the saturated hydraulic conductivity, k_{sat} , of compacted non-swelling clays. Based on laboratory test data, a model is proposed to predict k_{sat} as a function of the compacted clay secondary porosity. The curves of equal predicted values of k_{sat} appear as straight lines in the new (X, Y) frame.

Once laboratory permeability tests have been performed on the compacted clay to determine the values of its a and b parameters in the model, the proposed plotting frame and the linearity of the predictive equations can be used to assess rapidly, in the field, the k_{sat} value at each location where the compaction is assessed. This, in turn, can help to assess the overall performance of a clay liner or cover, which is a statistically complicated problem, highly dependent on extreme k values (e.g., Chapuis 1990, 2002; Benson et al. 1999; Guyonnet et al. 2003), which means that minor defects have a large influence on the overall performance.

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