A SIMPLE TECHNIQUE FOR ESTIMATING THE COEFFICIENT OF PERMEABILITY OF UNSATURATED SOILS

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ABSTRACT
A simple technique is proposed in this paper to estimate the coefficient of permeability of unsaturated soils based solely on conventional soil properties; namely, the saturated coefficient of permeability, degree of saturation (or water content), and the plasticity index, I_p of the soil. The technique is developed based on a relationship derived between the relative coefficient of permeability, k_{rel} (defined as the ratio between unsaturated and saturated coefficient of permeability, k_{unsat} / k_{sat}) and the (*degree of saturation*)$^{\gamma}$. The data from the literature for different soils ranging from sand (I_p = 0%) to clay (I_p = 50%) were used in the development of the presented technique. The results of the study suggest that the fitting parameter γ is strongly dependent on the type of soil, particularly for soils with I_p range of 0 to 20%. A relationship between the fitting parameter, γ and the plasticity index, I_p of the soil is also proposed. The influence of various parameters that influence the coefficient of permeability of unsaturated soils such as the compaction water content, stress state, compaction energy and the wetting-drying cycles were also studied. The results of the research study suggest that the proposed simple technique is a useful tool to estimate the coefficient of permeability of unsaturated soils as a function of degree of saturation or water content.

RÉSUMÉ
Cet article décrit une méthode simple pour estimer le coefficient de perméabilité de sols non-saturés. Cette méthode est basée uniquement sur les propriétés conventionnelles des sols : coefficient de perméabilité saturée, degré de saturation (ou contenu en eau) et indice de plasticité I_p du sol. La méthode repose sur la relation entre le coefficient de perméabilité relative k_{rel} (qui par définition est égal au quotient des perméabilités non-saturées et saturées k_{unsat}/k_{sat}) et le degré de saturation élevé à la puissance γ. Des données issues de la littérature pour différents sols allant du sable (I_p = 0%) à l'argile (I_p = 50%) ont été employées lors du développement de la méthode. Les résultats de cette étude indiquent que le paramètre γ est fortement dépendant du type de sol, particulièrement pour des sols ayant des valeurs de I_p comprises entre 0 et 20%. Une relation entre le paramètre γ et l'indice de plasticité I_p du sol est également proposée. L'influence de divers paramètres influençant le coefficient de perméabilité de sols non-saturés tels que le contenu en eau au moment de la compaction, l'état de contrainte, l'énergie de compaction et les cycles humidité/sechage a aussi été étudiée. Les résultats de la recherche montrent que la méthode proposée est utile pour estimer le coefficient de perméabilité de sols non-saturés en fonction du degré de saturation ou du contenu en eau.

1. INTRODUCTION

The coefficient of permeability is a key engineering property required in the design of geotechnical structures such as the earth dams, pavements, retaining walls and geo-environmental structures used for the management of agricultural, municipal, mine and nuclear wastes through the use of soil covers and liners. The present day engineer is aware that the flow behaviour in soils both in saturated and unsaturated conditions are to be well understood to design soil structures based on rational procedures.

The coefficient of permeability can vary widely in comparison to other engineering properties of soils such as shear strength and volume change. The saturated coefficient of permeability varies about eight to ten orders of magnitude when considering soils that range from a coarse-grained gravel to a fine-grained soil such as clay (Lambe and Whitman, 1979). Typically, the coefficient of permeability of a compacted fine-grained soil can vary about three to six orders of magnitude for the suction range of practical interest to engineers (i.e., 0 to 500 kPa). The flow behaviour is primarily in liquid phase for this suction range in compacted fine-grained soils.

It is a common engineering practice to determine the saturated coefficient of permeability either in the laboratory or in the field. The procedures for determining the saturated coefficient of permeability are relatively simple and are not expensive. Experimental procedures are also available to directly measure the coefficient of permeability of unsaturated soils; but they are time consuming and difficult, and hence costly. As a result, much of research focus has been towards developing semi-empirical procedures to predict the unsaturated coefficient of permeability using the saturated coefficient of permeability and the soil-water characteristic curve. (Gardner 1958, Brooks & Corey 1964, van Genuchten 1980, Fredlund et al, 1994, Leong & Rahardjo 1997).

The soil-water characteristic curve is defined as the relationship between the soil suction and the water content (either gravimetric, w, volumetric, θ, or degree of saturation, S). Several parameters such as compaction water content, stress state, soil structure (or aggregation), compaction energy, mineralogy, texture, organic content and hysterisis influence the soil-water characteristic curve behaviour (Vanapalli et al, 1999, Ng & Pang, 2000). All the parameters that influence the soil-water characteristic curve behaviour also influence the coefficient of permeability of unsaturated soils.

In this research paper, a technique is proposed to estimate the unsaturated coefficient of permeability of both coarse and fine-grained soils. The developed relationship is a normalized function derived between the relative coefficient of permeability, k_{rel} (defined as the ratio between the unsaturated and saturated coefficient of permeability, k_{unsat}/k_{sat}) and the *adjusted degree of saturation,* S^{γ}. The published experimental data from the literature for different soils ranging from sand (I_p = 0%) to clay (I_p = 50%) were used in the development of the relationship. The results of the study suggest that the fitting parameter, γ is strongly related to the type of soil. This is particularly valid for soils with I_p range of 0 to 20%. A relationship between the fitting parameter, γ and the plasticity index, I_p of the soil is also proposed. The influence of various parameters that influence the unsaturated coefficient of permeability such as the compaction water content, stress state, compaction energy and the wetting-drying cycles (i.e., hysteresis) were also studied. The results of the research study suggest that the proposed technique is a useful tool for estimating the coefficient of permeability of unsaturated soils as a function of degree of saturation. The proposed procedure is a simple technique and is based on the information of conventional soil properties that can be easily measured in both the laboratory and field.

2. BACKGROUND

The water flow behaviour in saturated soils is determined using the Darcy's law:

$$v_w = -k_{sat} \frac{\partial h_w}{\partial y} \quad [1]$$

where v_w = flow rate of water, k_{sat} = the saturated coefficient of permeability and $\partial h_w/\partial y$ = the hydraulic head gradient in the direction of flow.

The saturated coefficient of permeability can be described as a factor relating water flow rate to the hydraulic gradient and is a measure of the ease of water movement in soil. The resistance of water movement in a saturated soil is primarily a function of soil particle size and their arrangement and distribution of pores. All the pores are essentially filled with water in a saturated soil. In other words, water flows through all the pore channels under fully saturated conditions (S=100%). As a result, the coefficient of permeability of a saturated soils is considered to be a function of void ratio, e, and assumed to be constant value (Lambe and Whitman, 1979).

Darcy's law is also valid for unsaturated soils (Freeze, 1971, Lam et al, 1987). The unsaturated coefficient of permeability of a soil is dependent on the pore-size distribution and the amount of pore space available for water. However, in an unsaturated soil, the coefficient of permeability is a function of the combined changes in the void ratio and the degree of saturation (Lloret and Alonso, 1980; Fredlund, 1981). From a practical perspective, the change in void ratio in an unsaturated soil is relatively small and hence its effect on the coefficient of permeability can be considered secondary. The flow of water in an unsaturated soil can only occur through the continuous channels of soil pores that contain water. The amount of pore space available for water to flow through soil decreases as a result of air entry into the soil. The reduction in degree of saturation of soil (S<100%) associated with an in increase in air content results in an increase in the negative pore-water pressure (i.e., soil suction) of the soil. In other words, the coefficient of permeability of an unsaturated soil is related to the variation of the degree of saturation or water content and soil suction (i.e., soil-water characteristic curve) and is not a constant value.

Childs (1940) was one of the first investigators who demonstrated that the soil-water characteristic curve could be used as a tool to obtain the pore-size distribution of a soil. Since then, several procedures have been presented in the literature that use the soil-water characteristic curve and the saturated coefficient of permeability to predict the variation of the coefficient of permeability of an unsaturated soil with respect to suction (Gardner 1958, Brooks & Corey 1964, van Genuchten 1980, Fredlund et al 1994, Leong & Rahardjo 1997).

Three different types of modelling techniques are commonly used to predict the unsaturated coefficient of permeability. These include empirical, macroscopic and statistical models. Empirical models or equations are developed using the results of laboratory tests. Several researchers have summarized and normalized the data into a curve or function (Richards 1952, Gardner 1958). Macroscopic models are analytical expressions that take into account many variables that influence the flow of water through the soil (Brooks & Corey 1964). Statistical models are the most widely used models for predicting the unsaturated coefficient of permeability. These models have been developed by considering the probability of liquid phase continuity between pores of various sizes in formulating the probability function.

Several functions developed using the statistical approach require knowledge of the *residual degree of saturation* for the soil (i.e., where an increase in soil suction does not result in significant reduction in water content). Examples of such functions include the van Genuchten (1980) and the Fredlund & Xing (1994) equations. The equation proposed by van Genuchten (1980) is useful for predicting the unsaturated coefficient of permeability for a suction range between 0 to 1500 kPa. The Fredlund & Xing (1994) method is useful for predicting the unsaturated coefficient of permeability over the entire suction range (0 to 10^6 kPa) for all types of soils.

Leong and Rahardjo (1997) suggested a different formulation for predicting the unsaturated coefficient of permeability. This formulation relates the coefficient of permeability to soil suction and relies on a fitting parameter *p*, which must be established for each specific soil. The idea of using a fitting parameter was further researched by Fredlund et al (2001). Approximately 300 sets of permeability data were used to determine typical values for the fitting parameter. Their research includes a statistical analysis of the fitting parameter based on soil type. The results of the statistical analysis show increased scatter in fitting parameters for fine-grained soils.

Several published methods have proven to be valuable tools to predict the unsaturated coefficient of permeability. All the methods use the soil-water characteristic curve as a tool to predict the unsaturated coefficient of permeability. As detailed earlier, research studies have shown that parameters such as compaction water content, stress state, compaction energy and the wetting-drying cycles influence both the soil-water characteristic curve and the unsaturated coefficient of permeability. Laboratory investigations related to the measurement of soil-water characteristic curves taking into account all the parameters that influence their behaviour can be costly and time consuming. This research paper presents a simple technique to estimate the coefficient of permeability of unsaturated soils as function of the degree of saturation. Some investigators have earlier proposed relationships between the coefficient of permeability and the degree of saturation (Burdine, 1952 and Brooks & Corey, 1964). These methods require the information of the soil-water characteristic curve to predict the unsaturated coefficient of permeability. The estimation of the coefficient of permeability in the proposed simple method in this paper relies on conventional soil properties and the information of soil-water characteristic curve is not necessary.

3. NORMALIZATION TECHNIQUE

The experimental data available in the literature for various soils representing both coarse and fine-grained soils has been correlated to show a relationship between the *degree of saturation*, S and the *relative coefficient of permeability*, k_{rel}. The relative coefficient of permeability, k_{rel} is defined as the ratio between the unsaturated and saturated coefficient of permeability, (i.e., k_{unsat}/k_{sat}).

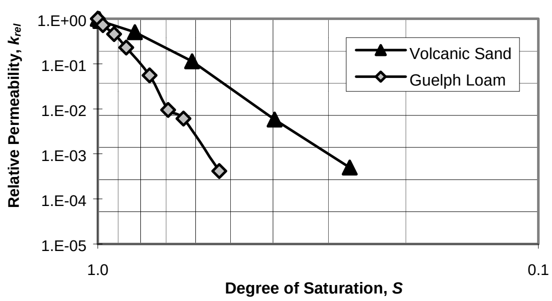

Figure 1. Comparison of k_{rel} and S for two soils.

Figure 1 shows the relationship between k_{rel} and S for two soils, namely, sand and loam for suction ranges of 0 - ~10 kPa and 0 - ~50 kPa respectively. The experimental studies related to these two soils, namely Volcanic sand and Guelph Loam, were published respectively by Brooks & Corey (1964) and Elrick & Bowman (1964).

The results suggest that the relationship between k_{rel} versus S is a relatively straight line when plotted on a logarithmic scale. Furthermore, the relationship between the k_{rel} and S follows a defined trend line for different soils provided the degree of saturation is raised to a numerical value, which is defined as a fitting parameter, γ. This is referred to as the *adjusted degree of saturation,* S^{γ} in the remainder of this paper. The concept is illustrated in Figure 2. Note that different fitting parameter values γ of 0.70 and 1.45 were used for the sand and loam respectively.

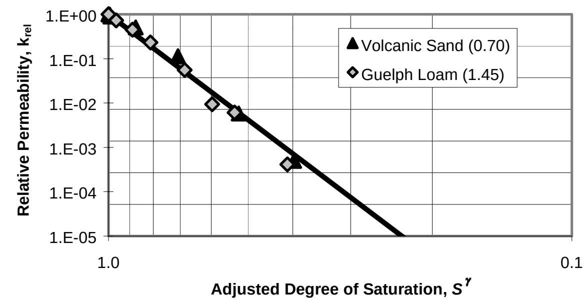

Figure 2. Comparison of k_{rel} and S for soils in Figure 1 using different γ values.

Using the technique illustrated in Figure 2, experimental data for four soils were normalized and plotted in Figure 3. The published experimental results by Brooksand Corey (1964) were used in Figure 3. The experimental suctions ranges for the Brooks and Corey study ranged from 0-~10 kPa for sands and fragmented mixture and 0-50kPa for Touchet silt loam.

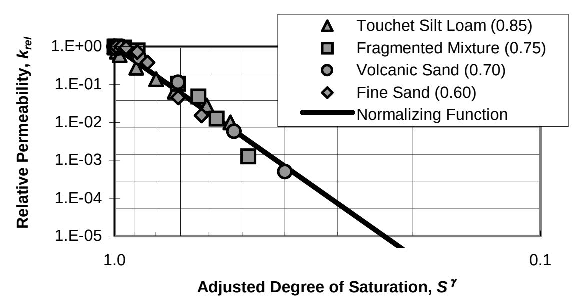

Figure 3. k_{rel} versus S^{γ} for different soils (data from Brooks & Corey (1964)

Research studies have shown that relationship between k_{rel} and S^{γ} is a unique straight line for different soils, both coarse and fine-grained. However, fitting parameter, γ values were varied for different soils such that all soils follow the same trend line. More discussions are presented in later part of the paper about this relationship.

4. THE INFLUENCE OF VARIOUS PARAMETERS ON THE UNSATURATED COEFFICIENT OF PERMEABILITY

Several parameters influence the soil-water characteristic curve behaviour. Some of the key parameters include wetting-drying cycles (i.e., hysteresis), compaction water content, stress state, and compaction energy. The parameters that influence the soil-water characteristic curve also influence the coefficient of permeability of unsaturated soils and hence the above technique. This section examines the influence of these parameters on the proposed k_{rel} versus S^{γ} relationship.

4.1 Wetting and Drying Cycles

The water flow behaviour in a soil in the drying (i.e., desorption) and wetting (i.e., absorption) phases is different. As a result, the soil-water characteristic curve behaviour and the variation of the water coefficient of permeability with respect to soil suction exhibit hysterisis. Studies by Nielsen et al (1972) show that the coefficient of permeability of an unsaturated coarse grained soil is uniquely related to the degree of saturation, S or the volumetric water content, θ, both in the wetting and drying cycles. Fredlund and Rahardjo (1993) reported similar observations analysing Liakaopoulos (1965) experimental results on a sandy soil. In other words, there is no hysterisis in the relationship between the unsaturated coefficient of permeability and the degree of saturation or volumetric water content. This is mainly due to reason that the volume of water flow is a direct function of the volume of the water in soil.

The influence of wetting and drying cycles on the proposed k_{rel} versus S^{γ} is studied for two different soils, namely Guelph Loam and London Clay. k_{rel} versus S^{γ} relationships were plotted using Elrick & Bowman (1964) experimental results of Guelph Loam for a suction range of 0 - ~50 kPa (Figure 4). The results suggest that the k_{rel} versus S^{γ} relationship follows the same trend line as observed for other soils (see Figures 2 and 3). Guelph Loam is a medium-grained soil and a unique behaviour is observed with respect to k_{rel} versus S^{γ} for both the wetting and drying phases. These observations are consistent with that of Nielsen et al. (1972) and Fredlund and Rahardjo (1993) studies for coarse-grained soils. The fitting parameter γ value for is 1.45 for both the wetting and drying cycles for the Guelph loam.

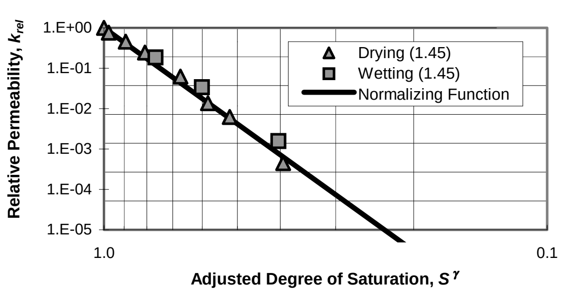

Figure 4: k_{rel} versus S^{γ} for wetting and drying, Guelph Loam (data from Elrick & Bowman, 1964)

Figure 5 shows the relationship between k_{rel} *versus* S^{γ} wetting & drying for London Clay (Croney & Coleman, 1954). London Clay is fine-grained soil (clay content equal to 57%) with a plasticity index I_p equal to 43%. Experimental data for London Clay related to the variation of unsaturated coefficient of permeability with respect to soil suction are not available. This information is however predicted using the saturated coefficient of permeability and the soil-water characteristic curve. SoilVision™ 2.04 was used to predict the coefficient of permeability using the Brooks and Corey (1964) equation. The results suggest that k_{rel} versus S^{γ} for the fine-grained London Clay follows the same trend line as other soils. However, the fitting parameter, γ for the drying and wetting paths is 1.55 and 1.90, respectively. In the following Figure 5, the drying and *wetting* lines are plotted within the wider *normalizing function* line.

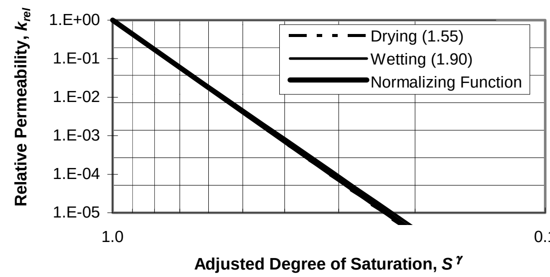

Figure 5. k_{rel} versus S^{γ} wetting & drying, London Clay (data from Croney & Coleman, 1954)

4.2 Compaction Water Content

The effects of soil structure that arise due to the influence of compaction water content on the relative coefficient of permeability were studied as part of this research paper. The compaction water content has a significant influence on the resulting soil structure in a fine-grained soil (Lambe, 1958). The term 'soil structure' used in this paper may be defined as the arrangement of soil particles in a compacted fine-grained soil. Several researchers have shown that flow behaviour in fine-grained compacted soils is significantly influenced by the soil structure (Lambe, 1958, Mitchell, ____). Furthermore, Vanapalli et al (1999) has shown that the behaviour of the soil water characteristic curve for fine-grained soils is also significantly influenced by variations in soil structure.

The effects of variation in compaction water content on the relationship between the k_{rel} and S^{γ} were studied for a clay till from Indian Head, Saskatchewan, using the results of Vanapalli et al (1997). Indian Head till is a fine-grained soil (clay content of 30%) with a plasticity index I_p of 17%. Experimental data for the measured values of unsaturated permeability are not available. However, the analyses are based on predicted values of the unsaturated coefficient of permeability using similar procedures as discussed earlier.

Figure 6 shows the closest possible relationship between the k_{rel} and S^{γ} with the trend line using a single best fitting parameter γ equal to 1.90. The relationship shown in the figure demonstrates that the relative coefficient of permeability, k_{rel} is dependent on the soil structure (i.e., compaction water content) for fine-grained soils.

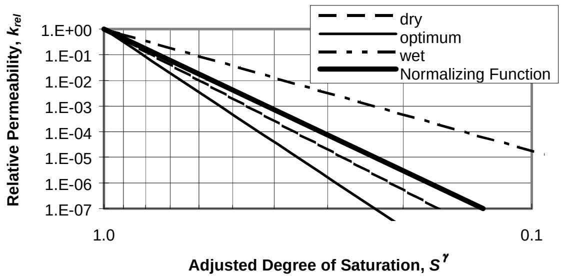

Figure 6. k_{rel} versus S^{γ} for Indian Head Till using a single fitting parameter, γ (data from Vanapalli et al, 1997)

Figure 7 shows a better fit for the three different compaction water contents. To achieve this, different fitting parameter γ values were used (as shown) for the different initial compaction water content conditions.

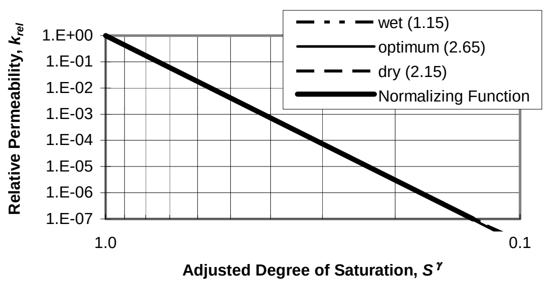

Figure 7. k_{rel} versus S^{γ} for Indian Head Till using different fitting parameters, γ (data from Vanapalli et al, 1997)

The fitting parameter γ values range from 1.15 to 2.65. The results show significant variations in the relationship between the k_{rel} and S^{γ} for the Indian Head till compacted with different initial water content conditions.

4.3 Compaction Energy

Compaction energy has a significant effect on the flow behaviour of soils, particularly fine-grained soils (Lambe, 1958). The effect of a variation of compaction energy on the soil water characteristic curve was studied using published data for Mudstone by Leong & Rahardjo (2002). The data available for this soil included the saturated coefficient of permeability and the soil water characteristic curve for various compaction energies and initial moisture contents. The unsaturated coefficient of permeability for the various conditions were predicted using similar procedures as discussed earlier.

The following Figure 8 presents the relationship between the k_{rel} and S^{γ} for three compactive efforts, *standard* proctor, *enhanced* proctor and *modified* proctor. The soil specimens presented in Figure 8 were each initially compacted at a degree of saturation equal to 83%. Fitting parameter, γ values ranging from 1.05 to 1.70 have been used to adjust the predicted data to the proposed trend line.

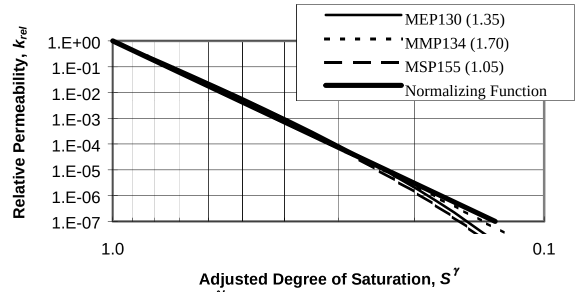

Figure 8. k_{rel} versus S^{γ} for mudstone, compacted at 83% saturation using various compaction energies (data from Leong & Rahardjo, 2002)

4.4 Stress State

The effect of stress state on the proposed relationship between the k_{rel} and S^{γ} were studied for different soils representing fine and coarse-grained soils (i.e., a sand, silt and clay till).

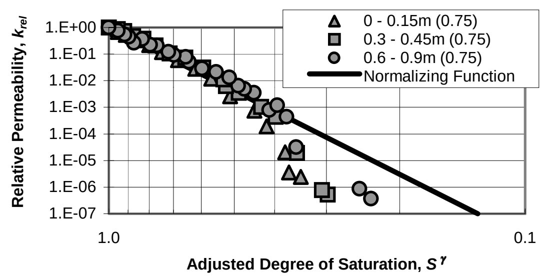

Figure 9. k_{rel} versus S^{γ} for Lakeland Sand (data from Elzeftawy & Cartwright, 1981)

Figure 9 shows the relationship using experimental data published by Elzeftawy and Cartwright (1981). In this study, the unsaturated hydraulic conductivity was measured in soils derived from various depths including 0-0.15m, 0.3-0.45m and 0.6-0.9m for a suction of about 0 – 25 kPa. The data reflects the effect of stress history on the unsaturated permeability behaviour. A fitting parameter, γ of 0.75 has been used for the three stress states of the sand. The data presented in Figure 9 remains consistent to suction values of about 15 kPa.

The influence of applied loading on the relationship between the k_{rel} and S^{γ} was analysed for a silty soil using the experimental results of Huang (1994) for a suction range of 0 – ~90 kPa. The data is presented in the following Figure 10. Fitting parameter γ values ranging from 0.78 to 1.00 have been used in order to adjust the experimental data to the proposed trend line.

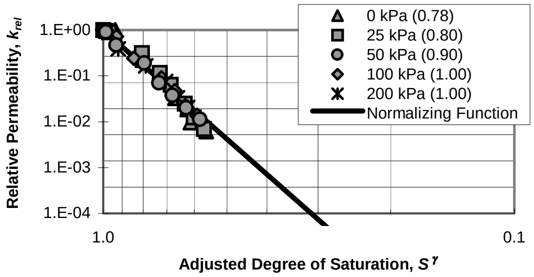

Figure 10. k_{rel} versus S^{γ} for silt (data from Huang, 1994)

The results suggest that the fitting parameter, γ increases slightly with an increase in applied load, however the fitting parameter only ranges from about 0.78 to 1.0. This suggests that applied loading does not significantly influence the relationship between the relative coefficient of permeability, k_{rel}, and the adjusted degree of saturation S^{γ} for estimating the unsaturated coefficient of permeability for either the sand or the silt.

The effect of stress state (i.e., loading) was also analysed for a clay till using the results of Vanapalli et al (1997). Figure 11 presents the relationship between the k_{rel} and S^{γ} for clay till specimens compacted at an initial water content representing *dry of optimum* conditions and subjected to different stress states.

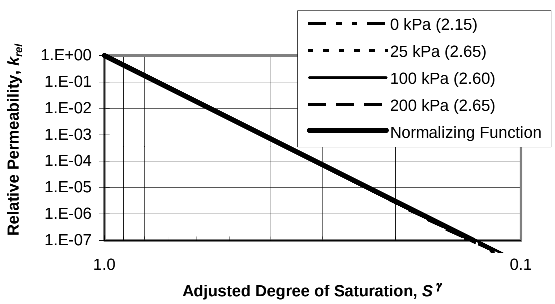

Figure 11. k_{rel} versus S^{γ} for Indian Head Till compacted 'dry of optimum' (data from Vanapalli et al, 1997)

As shown in Figure 11, the fitting parameter γ values range from about 2.15 to 2.65 for the till initially compacted 'dry of optimum'. Similar studies for specimens compacted at 'optimum' show fitting parameter γ values ranging from 1.30 to 2.65. For 'wet of optimum', fitting parameter γ values ranged from 1.15 to 1.25. Although the range of fitting parameters is slightly increased for the fine-grained soil, the results show that the applied loading generally do not have a significant effect on the relationship between the k_{rel} and S^{γ} for Indian Head till.

5. SIMPLIFIED COEFFICIENT OF PERMEABILITY FUNCTION

The proposed simplified function takes into account various parameters such as hysteresis, soil texture, stress state and the soil structure that influence the coefficient of permeability of an unsaturated soil. The development of this function is presented in the following paragraphs.

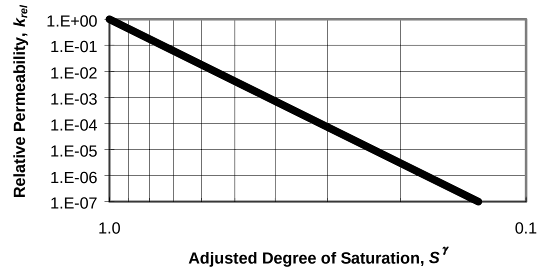

Figure 12 Proposed permeability function

The mathematical relationship shown in Figure 12 between the k_{rel} and S^{γ} is given below:

$$k_{rel} \sim S^{7.9\gamma} \quad [2]$$

where S is the *degree of saturation* and $k_{rel} = k_{unsat}/k_{sat}$.

Relationships between the k_{rel} and S^{γ} were developed for various soils. Table 1 summarizes the results of various soils including the fitting parameter γ values and the plasticity index, I_p values.

Table 1. Plasticity indices, I_p and Fitting Parameter γ for normalized soils

Soil	γ	I_p (%)	Reference
Lakeland Sand	0.75	0	Elzeftawy & Cartwright, 1981
Superstition Sand	0.75	0	Richards, 1952
Fine Sand	0.60	0	Brooks & Corey, 1964
Volcanic Sand	0.70	0	Brooks & Corey, 1964
Fragmented Mixture	0.75	0	Brooks & Corey, 1964
Lagoa	0.85	0	Gerscovich et al, 2002
Querosene	1.30	0	Gerscovich et al, 2002
Vista Chinesa	1.50	19	Gerscovich et al, 2002
Touchet Silt Loam	0.80	3*	Brooks & Corey, 1964
Silt	0.90	6	Huang, 1994
Yolo Light Clay	1.20	10*	Moore, 1939
Guelph Loam	1.45	10*	Elrick & Bowman, 1964
Mudstone	1.20	14	Leong & Rahardjo, 2002
Indian Head Till	1.87	19	Vanapalli et al, 1997
London Clay	2.20	43	Croney & Coleman, 1954
Regina Clay	3.40	51	Khanzode et al, 2002

* Estimated plasticity index values from clay content

The following Figure 13 presents the fitting parameter, γ variation with the plasticity index, I_p using the summarized results from Table 1.

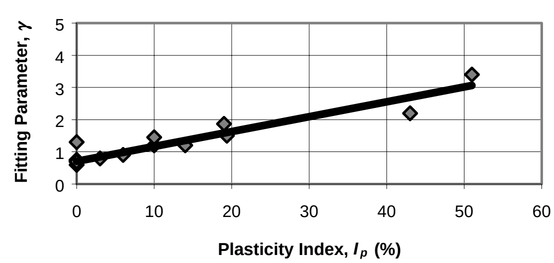

Figure 13 Relationship between fitting parameter γ and plasticity index.

There is a reasonably well-defined relationship between the fitting parameter, γ and the plasticity index, I_p (Figure 13). The relationship given in Figure 13 allows a fitting parameter γ to be selected for any soil based on the plasticity index, I_p value. The mathematical function represented by the trend line given in the figure is provided as follows:

$$\gamma = 4.64 (I_p) + 0.71 \quad [3]$$

where I_p is the plasticity index of the soil.

However, there is scatter in the relationship for plasticity index, I_p values greater than 20%. Such a behaviour could be attributed to the influence of soil structure on the coefficient of permeability of unsaturated soils or due to the limited available data analysed.

6. SUMMARY AND CONCLUSIONS

In this research paper, a simple technique is proposed to estimate the unsaturated coefficient of permeability based on conventional soil properties that include the saturated coefficient of permeability, degree of saturation or water content and the plasticity index.

This normalized function is a relationship between the relative coefficient of permeability, k_{rel} (defined as the ratio of k_{unsat}/k_{sat}) and the *adjusted degree of saturation*, S^{γ}. The results of the present study suggest that the stress state or applied loading does not have significant influence on the proposed relationship between k_{rel} and S^{γ}. The results also suggest that soil hysteresis does not affect the k_{rel} versus S^{γ} relationship for coarse-grained soils; however, an effect due to hysteresis on the relationship was noted for fine-grained soils. Soil structure (initial compaction water content) and compaction energy also have a significant influence on the proposed relationship.

The coefficient of permeability data presented in this study has been normalized using logarithmic scales into a single function with reasonable degree of success. The function relies on a fitting parameter γ. This fitting parameter, γ is related to the plasticity index, I_p of the soil. Figure 13 demonstrates a distinct trend of this relationship. A mathematical function has been extrapolated to estimate the value of γ based on the plasticity index, I_p.

The numerical results show good agreement with experimental data for a plasticity range of 0 to 50%, particularly for soils with a plasticity index ranging from 0 to 20% (sandy and silty soils). For this range, all the discussed parameters have little or no influence on the proposed relationship.

The simple approach presented in this research paper to estimate the unsaturated coefficient of permeability based on water content or degree of saturation, plasticity index, I_p and saturated coefficient of permeability, k_{sat} is valuable for practicing engineers. The proposed method would allow the practicing engineer to estimate the unsaturated coefficient of permeability with data that is typically readily available. A more rigorous design approach can be undertaken using the simple functional relationship proposed in this paper towards the analysis of earth dams, slope, roadbed, foundation or other waste management structures.

7. ACKNOWLEDGMENTS

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8. REFERENCES

Brooks, R.H. and Corey, A.T. 1964. Hydraulic Properties of Porous Media. Colorado State University Hydrology Paper, No. 3, 27p.

Burdine, N.T. 1952. Relative permeability calculations from pore-size distribution data. Trans. AIME.

Childs, E.C. 1940. The use of soil moisture characteristics in soil studies. Soil Science, 50: 239-252.

Elrick, D.E. and Bowman, D.H., 1964. Note on improved apparatus for soil moisture flow measurements. *Soil* Science Society of America, Proceedings, 28: 450-453.

Elzeftawy, A. and Cartwright, K., 1981. Evaluating the saturated and unsaturated hydraulic conductivity in soils. In Permeability and Groundwater Contaminant Transport, ASTM STP 746, T.F. Zimmie and C.D. Riggs, Eds. Amer. Soc. Testing and Materials, 1981, 168-181.

Fredlund, D.G., 1981. Panel Discussion: Ground Water and Seepage Problems, Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering (Stockholm, Sweden), Vol. 4: 629-641.

Fredlund, D.G., Xing, A. and Huang, S. 1994. Predicting the permeability for unsaturated soils using the soil-water characteristic curve. Canadian Geotechnical Journal, 31: 533-546.

Fredlund, D.G. and Rahardjo, H. 1993. Soil mechanics for unsaturated soils. New York: John-Wiley & Sons Inc.

Fredlund, D.G. and Xing, A. 1994. Equations for the soil-water characteristic curve. Canadian Geotechnical Journal, 31: 517-532.

Fredlund, D. G., Xing, A. and Huang, S., 1994. Predicting the permeability function for unsaturated soils using the soil-water characteristic curve. Canadian Geotechnical Journal, 31: 533-546.

Fredlund, D.G., Fredlund, M.D., and Zakerzadeh, N., 2000. Predicting the permeability function for unsaturated soils. International Conference on Clays and Clay Minerology, Japan, Shioukoza.

Freeze, R.A., 1971. Influence of the unsaturated flow domain on seepage through earth dams. Water Resources Research, 7:929-940.

Gardner, W.R., 1958. Some steady state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil Science, 85(4): 228-232.

Huang, S., 1994. Evaluation and laboratory measurement of the coefficient of permeability in deformable, unsaturated soils. Doctoral thesis, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.

Huang, S., Barbour, S.L. and Fredlund, D.G. 1998. Measurement of the coefficient of permeability for a deformable unsaturated soil using a triaxial permeameter. Canadian Geotechnical Journal, 35: 426-432.

Khanzode, R.K., Vanapalli, S.K., and Fredlund, D.G., 2002. Measurement of soil-water characteristic curves for fine-grained soils using a small-scale centrifuge. Technical note accepted for publication in the Canadian Geotechnical Journal.

Lambe, T.W., 1958. The engineering behavior of compacted clay, ASCE J. Soil Mech. Found. Div., Paper No. 1655, 84: 1-35.

Lambe, T.W. and Whitman, R.V., 1979. Soil Mechanics. Wiley.

Leong, E.C. and Rahardjo, H., 1997. Permeability functions for unsaturated soils. Journal of Geotechnical and Geoenvironmental Engineering. 123: 1118-1126.

Leong, E.C. and Rahardjo, H., 2002. Soil-water characteristic curves of compacted residual soils. Unsaturated Soils Proceeding of the 3rd International Conference on Unsaturated Soils, UNSAT 2002, Eds Juca et al: 271-276.

Liakopoulous, A.C., 1965. Theoretical solution of the unsteady unsaturated flow problems in soils. Bulletin of the International Association of Science and Hydrology, 10: 5-35.

Lloret, A. and Alonso, E.E., 1980. State surfaces for partially saturated soils. Proceedings of the 11th International Conference on Soil Mechanics and Foundation Engineering (San Francisco, CA), Vol. 2: 557-562.

Moore, R.E., 1939. Water conduction from shallow water tables. Hilgardia, 12:383-426.

Ng, Charles W.W. and Pang, Y.W., 2000. Influence of stress state on soil-water characteristics and slope stability. Journal of Geotechnical and Geoenvironmental Engineering. 126: 157-166.

Nielsen, D.R., Jackson, R.D., Cary, J.W., and Evans, D.D., 1972. American Society Agronomy and Soil Science, America, Madison, WI.

Richards, L.A., 1952. Water conducting and retaining properties of soils in relation to irrigation. In Proceeding of an International Symposium on Desert Research, Jerusalem. 523-546.

SoilVision 2.04. Software Package for Modelling the Engineering Behavior of Unsaturated Soils. Soil Vision Systems Ltd.

Vanapalli S.K., Fredlund, D.G., and Pufahl, D.E. 1997. Saturated-unsaturated shear strength and hydraulic conductivity behavior of a compacted glacial till. *50th Canadian Geotechnical Conference*, Ottawa, Canada.(page nos)

Vanapalli, S. K., Fredlund, D. G., and Pufahl, D. E. 1999. The influence of soil structure and stress history on the soil-water characteristics of a compacted till. Geotechnique, 49: 143-159.

van Genuchten, M.T., 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal, 44: 892-898.