Although McKeen's empirical relationship fits the data for the samples in mid-range, it is less dependable at the extremes. A qualitative assessment of the practical limits of C_h can be made by hypothetically assuming that soil suction changes by approximately -2.15 pF between field moisture and oven-dried conditions (i.e. 4.1 pF - 6.25 pF) for all types of soils. For example, the field moisture content of silty sands might be 10 percent, so $\Delta h/\Delta w$ would be on the order of -21.5. Cleaner sands should have even lower moisture contents, and consequently, lower (more negative or absolute) values of $\Delta h/\Delta w$. One would expect materials in this extreme to exhibit very small volume change due to suction, therefore C_h should approach zero for very negative values of $\Delta h/\Delta w$. On the other hand, the field moisture content of highly plastic clays might be 30 percent, so $\Delta h/\Delta w$ would be on the order of -7.2. These materials are expected to exhibit large changes in volume due to changes in soil suction, thus C_h should continue to become lower (more negative) as $\Delta h/\Delta w$ approaches zero. Given the new data and the foregoing discussion on limits, a relationship shown by the solid curve in Fig. 4 is suggested. Derivation of this logarithmic statistical fit is described in the next section.

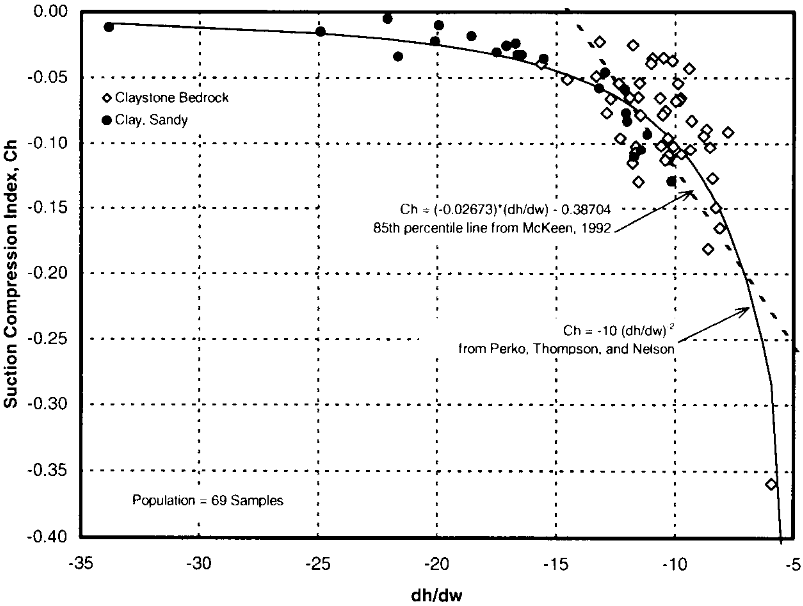

Fig. 4 Suction to Water Content Ratio and Suction Compression Index Data

Heave values predicted using McKeen's method, Eq. (1), and measured suction compression index data are compared with measured one-dimensional swell in Fig. 5. Some uncertainty exists as to the value of soil suction to be used in Eq. (1) that appropriately describes the final conditions in a conventional swell test. Since the sample is completely submerged during this test, there has been some speculation that the specimens approach their field capacity at a suction value of 2.5 pF. At this value, model predictions severely overestimate actual sample swell. By trial and error, the best possible statistical fit between swell based on suction and swell measured conventionally was obtained by setting the final suction value equal to 3.5 pF. It is believed that the difference between field capacity and the final suction value suggested by the best fit is the result of a high osmotic suction component for soils in Denver, Colorado. CTL/Thompson, Inc. is currently conducting a subsequent investigation into the osmotic component of soil and bedrock. Initial evidence indicates that the difference between total and matric suction is almost always on the order of 1.0 pF in the Denver area.

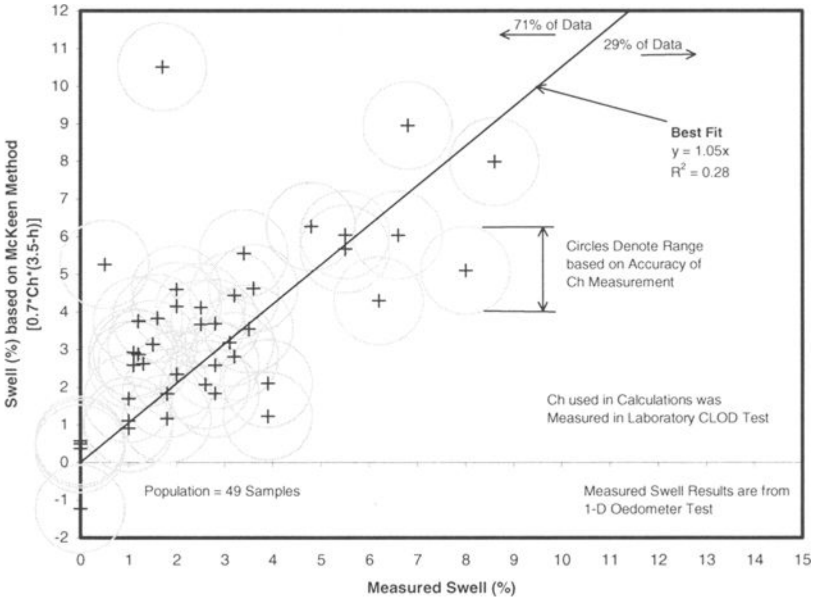

Fig. 5. Comparison Between McKeen Model and Measured Swell

Due to geologic uplifting and subsequent weathering of bedrock along the toe of the Rocky Mountains, a number of different geologic units appear from east to west across the Colorado Front Range. Geologic information was available for a number of the sites where samples were obtained. Suction compression indices were averaged for each major geologic unit. Results are shown in Fig. 6 along with a local bedrock stratigraphic column. It is observed that the suction compression index is strongly related to geology. In fact, the volume change responses of older, Cretaceous system formations are significantly greater than that of the younger, Tertiary system formations. This conclusion is consistent with local philosophy.

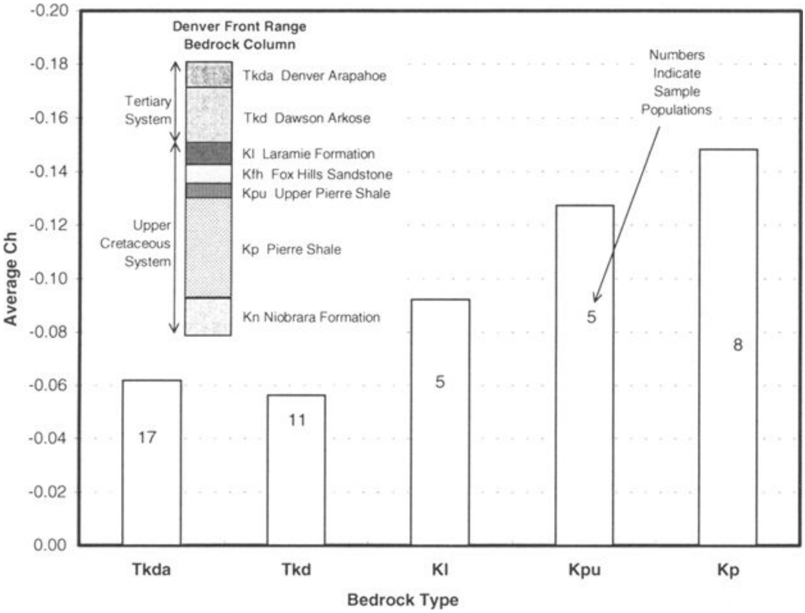

Fig. 6 Suction Compression Indices for Various Colorado Bedrock Types

Analysis

Through iterations of empirical data analysis, the relationship shown in Fig. 7 was eventually found between C_h and the $\Delta h/\Delta w$ ratio. In this figure, the logarithm of the absolute values of $1/C_h$ and $\Delta h/\Delta w$ are plotted with respect to one another. A statistical linear regression was performed on the data and the resulting slope and intercept were astonishingly close to integers.

The equation for the straight line in Fig. 7 is

$$Log(\frac{-1}{C_h}) = 2.0\ Log(\frac{-\Delta h}{\Delta w}) - 1.0 \tag{8}$$

which, by algebraic manipulation, simplifies to

$$C_h = -10\ (\frac{\Delta h}{\Delta w})^2 \tag{9}$$

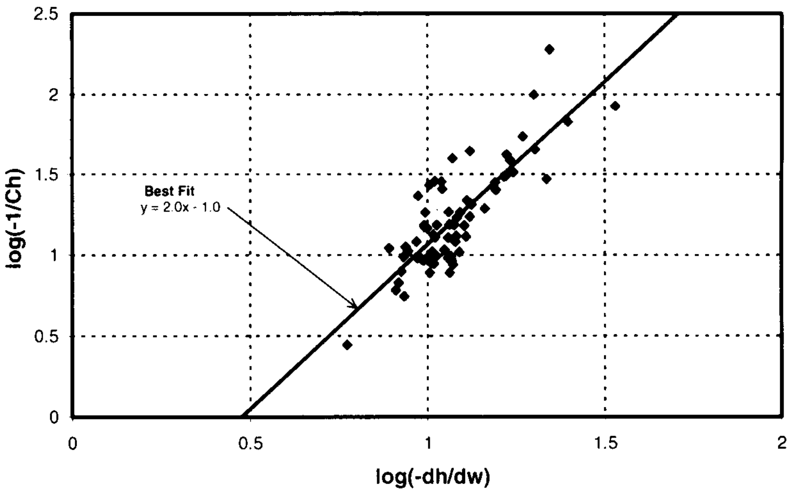

Fig. 7 Logarithmic Fit Analysis

This is the equation for the solid curve plotted in Fig. 4, as described previously. For purposes of discussion, Eq. (9) will be referred to as the PTN relationship.

The PTN relationship (Eq. (9)) is compared with the presently used McKeen linear empirical relatonship (Eq. (2)), in Fig. 8. Expansive soil classifications of low, moderate and high heave potential based on McKeen (1992) are shown at the top of the graph. The differences between the suction compression indices determined by the two methods are plotted along the y-axis. Above the zero baseline (i.e. the line depicting where the two methods are equal), the shaded area indicates that the PTN relationship yields more negative values than does the McKeen relationship, indicating that it is more conservative. Conversely, the shaded area below the baseline indicates that the McKeen relationship is more conservative than the PTN relationship.

A significant observation is that, for moderate expansive soils, both methods are essentially the same, within the expected accuracy of the CLOD test. For low expansive soils, the McKeen relationship predicts positive values of C_h indicating compression, whereas the PTN relationship tends toward zero. For these low expansive soils, the differences between McKeen and PTN are not particularly relevant except that the PTN relationship prevents misleading predictions of soil compression. At the other extreme, the PTN relationship again tends toward more negative values of C_h than those of the McKeen relationship. Consequently, the PTN relationship tends toward higher estimates of soil heave.

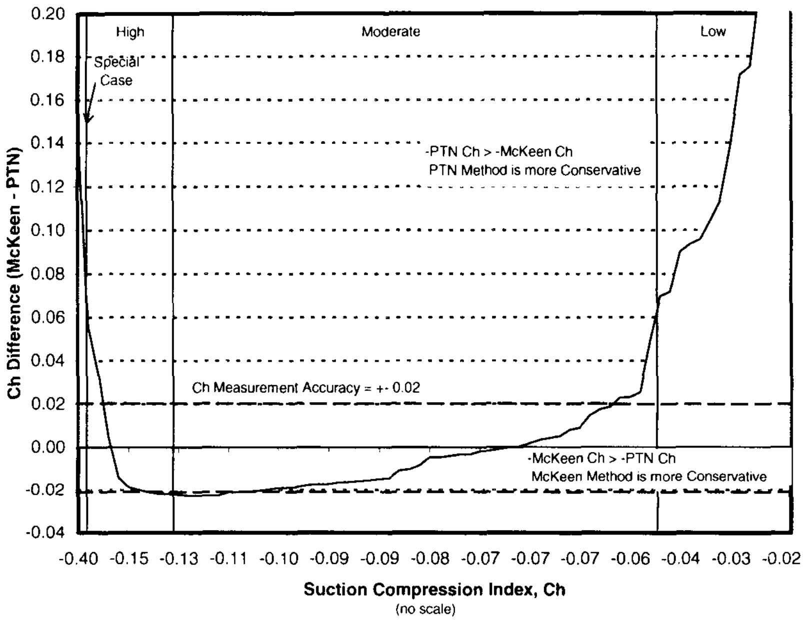

Fig. 8 Comparison between McKeen and PTN Empirical Relationships

Further analysis of laboratory CLOD test data qualitatively indicated that C_h values are exponentially related to soil plasticity. There also appears to be some dependence on silt and clay content, as should be expected. It is desirable to better relate suction compression index to the Atterberg limits and gradation of a soil specimen. Statistical regressions were performed on the data, but a convenient representation was not found. Instead a semi-empirical approach was taken. The method is called semi-empirical because it is theoretically derived based on the empirical PTN relationship.

It is believed that the plastic limit of a soil generally corresponds to a soil suction value of between 3.0 and 3.5 pF (McKeen, 1992). As mentioned previously, the suction of oven-dried soil has been found experimentally to be 6.25 pF. The change in water content between the plastic limit and oven-dried conditions is simply the plastic limit. Therefore, the suction compression index according to the PTN relationship should be approximately equal to

$$C_h \approx -10\left(\frac{3.25-6.25}{PL}\right)^{-2} \approx -\frac{10}{3}PL^2 \qquad \mathbf{(10)}$$

where PL is the plastic limit (%). However, this equation does not account for the sand fraction of the soil, which has a C_h of nearly zero. The expression in Eq. (10) can be adjusted to account for the coarse fraction by performing a simple correction similar to a "rock correction" in soil density testing. Subtracting the coarse volume, C, from the total volume in the definition of C_h given by Eq. (5) yields

$$-\frac{10}{3}PL^2 = \frac{\Delta V}{(V_t - C)\Delta h} = \frac{\Delta V}{V_t\Delta h - C\Delta h} \tag{11}$$

Taking the inverse of Eq. (11) results in

$$-\frac{3}{10PL^2} = \frac{V_t\Delta h}{\Delta V} - \frac{C\Delta h}{\Delta V} \tag{12}$$

The volume of coarse material in a soil is

$$C = \frac{W_c}{\gamma_w G_s} \tag{13}$$

where G_s is soil mineral specific gravity, and W_c, the weight of coarse grained solids, is simply

$$W_c = V_t\gamma_d(1-F) \tag{14}$$

where γ_d is the dry unit weight of soil and F is the weight percent passing the No. 200 sieve. Substituting Eq. (14) into Eq. (13) and then the result into Eq. (12) produces

$$-\frac{3}{10PL^2} = \frac{V_t\Delta h}{\Delta V} - \frac{\gamma_d(1-F)}{\gamma_w G_s}\frac{V_t\Delta h}{\Delta V} \tag{15}$$

Recognizing that $\gamma_d/(\gamma_w G_s) = 1/(e+1)$ where e is void ratio, and that $V_t\Delta h/\Delta V$ is the inverse of C_h, the semi-empirical relationship between suction compression index, plastic limit and percent passing the No. 200 sieve is found by solving Eq. (15) for C_h

$$C_h \approx -\frac{10}{3}PL^2\left(\frac{e+F}{e+1}\right) \tag{16}$$

The validity of Eq. (16), hereafter termed the PL-200 relationship, was evaluated by comparing C_h values with those determined using the McKeen and PTN relationships, as shown in Fig. 9. Ratios of predicted to measured C_h are shown in the larger graph. In the smaller graph, C_h values were used to categorize samples according to the expansive soil classification provided by McKeen (1992). Soil sample classifications based on the measured swell from one-dimensional, oedometer type tests are also shown.

Inspection of Fig. 9 reveals that the McKeen relationship poorly matches measured C_h for low swelling soils at the larger (least negative) values of C_h, but otherwise exhibits good correlation. The PL-200 relationship tends to underestimate C_h in the midrange, but appears to be a worthwhile method especially considering that the plastic limit and percent passing the No. 200 sieve information was obtained from representative samples and not from the actual samples tested. Predictions based on the PTN relationship most closely fall within the boundaries of accuracy anticipated for the laboratory CLOD test method. All three C_h relationships are valid for classification of samples according to low, moderate or high swell potential.

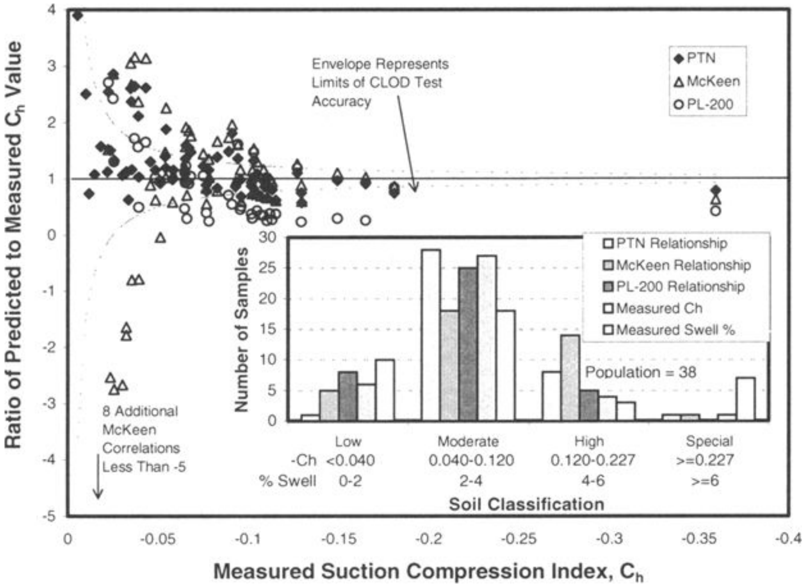

Fig. 9 Summary Comparison Between Various C_h Prediction Models

Conclusions

A laboratory investigation was conducted into the determination of the suction compression index, C_h (McKeen, 1992), using the CLOD test method (McKeen, 1985, Nelson and Miller, 1992, Hamberg, 1985). A new empirical correlation (termed the PTN relationship) was developed to relate C_h to the ratio of change in suction to change in water content. The PTN relationship agrees closely with an empirical correlation previously presented by McKeen, but is more realistic and accurate at very low or very high ratios of suction to water content change. A semi-empirical relationship was also developed that relates C_h to the Plastic Limit. This method appears to correlate fairly well with the other methods for the soils tested. Heave prediction based on suction also correlated well with conventional one-dimensional swell measurements. A procedure for expediting the CLOD test is presented.

Acknowledgments

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Nomenclature

γ_w	unit weight of water (g/cm^3)
γ_r	unit weight of resin (g/cm^3)
γ_h	compressibility coefficient (Pa^{-1})
γ_d	unit weight of soil (g/cm^3)
ΔH	soil heave (m)
Δh	change in soil suction (pF)
Δt	soil layer thickness (m)
Δw	change in specimen water content (%)
σ	total stress (Pa)
D_s	suction-volume change constitutive parameter
D_t	effective stress-volume change constitutive parameter
f	lateral restraint factor
F	weight fraction passing the No. 200 sieve (%)
PL	plastic limit (%)
s	load effect coefficient
u_a	pore air pressure (Pa)
V_i	initial volume of CLOD specimen (cm^3)
V_f	oven dried volume of specimen (cm^3)
w_i	initial specimen water content (%)
W_s	weight of solids (g)
W1	initial weight of CLOD specimen (g)
W2	weight of tagged specimen (g)
W3	weight of resin coated, tagged specimen (g)
W5	initial specimen buoyant force (g)
W7	weight of oven dried specimen (g)
W8	oven dried specimen buoyant force (g)

References

Fredlund, D.G. and Rahardjo, H. (1993). Soil Mechanics for Unsaturated Soils, John Wiley & Sons, Inc., New York.

Hamberg, D.J. and Nelson, J.D. (1984). "Prediction of Floor Slab Heave", Proceedings of the 5th International Conference on Expansive Soils, Adelaide, South Australia, pp. 137-140.

Hamberg, D.J. (1985). "A Simplified Method for Predicting Heave in Expansive Soils", Masters Thesis, Colorado State University, Fort Collins, Colorado

Matyas, E.L. and Radhakrishna, H.S. (1968). "Volume Change Characteristics of Partially Saturated Soil", *Geotechnique*, Vol. 18, No. 4, pp. 432-448.

McOmber, R.M., and Thompson, R.W. (2000). "Verification of Depth of Wetting for Potential Heave Calculations", Proceedings of Sessions on Unsaturated Soils at Geo-Denver 2000, The Geo-Institute, ASCE, Denver, Colorado (this conference).

McKeen, R.G., and Nielsen, J.P. (1978). "Characterization of Expansive Soils for Airport Pavement Design", U.S. Department of Transportation, Federal Aviation Administration, Interim Report No. FAA-RD-78-59, Systems Research & Development Service, Washington, D.C. 20590.

McKeen, R.G. (1981). "Design of Airport Pavements for Expansive Soils", U.S. Department of Transportation, Final Report No. DOT/FAA/RD-81/25, Systems Research & Development Service, Washington, D.C. 20590.

McKeen, R.G. (1985). "Validation of Procedures for Pavement Design on Expansive Soils", U.S. Department of Transportation, Federal Aviation Administration, Report No. DOT/FAA/PM-85/15, Program Engineering and Maintenance Service, Washington, D.C. 20591

McKeen, R.G. (1992). "A Model for Predicting Expansive Soil Behavior", Proceedings of the 7th International Conference on Expansive Soils, pp. 1-6

McQueen, I.S., and Miller, R.F. (1968). "Calibration and Evaluation of a Wide-Range Gravimetric method for Measuring Moisture Stress", Soil Science, Vol. 106, No. 3, pp. 225-231.

Miller, D.J. and Nelson, J.D. (1993) "The Role of Osmotic Suction in Stress State", ASCE Annual Meeting Session on Unsaturated Soil, Dallas, TX, ASCE Geotechnical Special Publication No. 39

Nelson, J.D. and Miller, D.J. (1992) Expansive Soils: Problems and Practice in Foundation and Pavement Design, John Wiley and Sons, New York, NY

Thompson, R.W. (1997) "Evaluation Protocol for Repair of Residences Damaged by Expansive Soils", Special Publication No. 68, Proceedings of Sessions on Unsaturated Soils at Geo-Logan '97, The Geo-Institute, ASCE, Logan, Utah.

Thompson, R.W. and McKeen, R.G. (1995) "Heave Prediction using Soil Suction: A Case History", ASCE Soil Suction Applications in Geotechnical Engineering Practice, Geotechnical Special Publication, No. 48, pp. 1-12.

U.S. Department of Agriculture (1972) "SCS, Soil Survey Laboratory Methods and Proceedures for Collecting Soil Samples", Soil Survey Investigations Report No. 1, Soil Conservation Service

Verification of Depth of Wetting for Potential Heave Calculations

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Robert W. Thompson, P.E.[2]

Abstract

A protocol has been developed for calculation of potential future heave of basement floors in residential structures in the Colorado Front Range area. Data from swell/consolidation tests commonly used in the area and soil suction tests are used to predict potential heave. The calculations are very dependent upon the anticipated depth of wetting. Pre-construction soil suction data were compared to post-construction suction data. The results indicate the assumptions of depth of wetting developed for the protocol are appropriate in most instances. Unusually deep wetting may occur in areas where geologic conditions allow water to penetrate more easily into soils and sedimentary bedrock.

Introduction

The widespread presence of expansive soils and bedrock is well known in the Front Range area of Colorado. The existence of the swelling materials creates risk for man-made improvements constructed on these soils and bedrock. The risks can be mitigated through proper engineering design, but not eliminated. The historical geotechnical practice in the Denver area has been to judge potential heave based upon one-dimensional swell/consolidation tests, other laboratory tests, soil profile, ground water conditions and other factors, and to qualitatively assess the likely behavior in terms of low to high swell potential. Swell testing has emerged as the primary tool used in the assessment of likely structural performance (Thompson, 1992). The Colorado

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