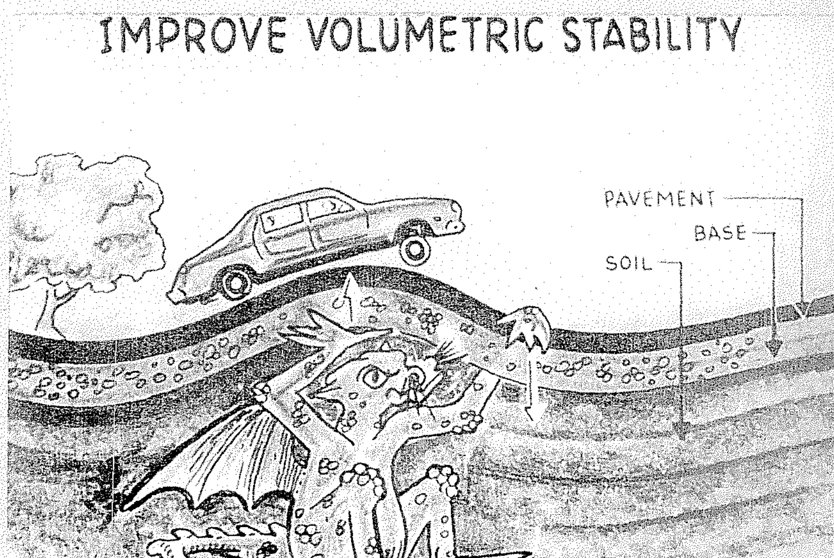
Report No. FHWA-RD-77-94

AN EVALUATION OF EXPEDIENT METHODOLOGY FOR IDENTIFICATION OF POTENTIALLY EXPANSIVE SOILS



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16. Abstract

This report concludes an evaluation of expedient methodology for identifying and qualitatively classifying potentially expansive soils. Seventeen published techniques used for identification/classification purposes were reviewed and evaluated using data collected from an extensive laboratory testing program. A definition of potential swell that is more consistent with field simulation requirements and more representative of in situ volume change behavior is presented. The results of the evaluation of published techniques reveal that the best techniques and thus the best indicators of potential swell are the liquid limit and plasticity index. Other significant indicator properties ranked in descending order are: liquid limit and natural water content combined; shrinkage limit and plasticity index; and shrinkage limit and linear shrinkage. The results of the statistical analysis of the laboratory data confirm the findings of the evaluation of the published techniques. A classification system more consistent with the definition of potential swell and using the liquid limit, plasticity index, and natural soil suction was developed and is presented. Guidelines for the recommended usage of the classification system are given.

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PREFACE

The study of the methodology for prediction and minimization of detrimental volume change of expansive soils in highway subgrades is a 4-year investigation funded by the U. S. Department of Transportation, Federal Highway Administration, under Intra-Government Purchase Order No. 4-1-0195, Work Unit No. FCP 34D1-132.

The work was initiated during June 1974 by the Soils and Pavements Laboratory (S&PL) of the U. S. Army Engineer Waterways Experiment Station (WES). Dr. Donald R. Snethen, Research Group, Soil Mechanics Division (SMD), S&PL, was the principal investigator during the period of this report. The work reported herein was performed by Dr. Snethen and Dr. Lawrence D. Johnson, Research Group, SMD, and Dr. David M. Patrick, Engineering Geology Research Facility, Engineering Geology and Rock Mechanics Division, S&PL. The report was prepared by Drs. Snethen, Johnson, and Patrick. The investigation was accomplished under the general supervision of Mr. Clifford L. McAnear, Chief, SMD, and Mr. James P. Sale, Chief, S&PL.

Directors of WES during the conduct of this portion of the study and preparation of the report were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (force) per square inch	6894.757	pascals
pounds (force) per square foot	47.88026	pascals
tons (force) per square foot	95.76052	kilopascals

AN EVALUATION OF EXPEDIENT METHODOLOGY FOR IDENTIFICATION OF POTENTIALLY EXPANSIVE SOILS

INTRODUCTION

1. The purpose of this research task was to evaluate expedient methodology for identifying and qualitatively classifying potentially expansive soils. The obvious need for qualitative characterization of potential swell is (a) to forewarn the engineer during early planning stages of potential problems with expansive soil and (b) to provide the necessary criteria so that a logical decision process can be applied to the problems associated with expansive soils in highway subgrades. The research effort involved a literature review of the techniques used for identification/classification purposes, a laboratory testing program to provide data to evaluate the published techniques, and an analysis of the laboratory data to determine if additional properties are available which provide a more sensitive indicator of potential swell. The report concludes this phase of the overall study and provides a somewhat different criterion or classification system for identification and classification of potential swell. The techniques reviewed, evaluated, and recommended were developed for the sole purpose of identifying and qualitatively classifying potential swell and should not under any circumstances be confused with or used in place of testing/prediction techniques for estimating potential volume change. The testing/preciction techniques will be reviewed and evaluated in a subsequent interim report.

REVIEW OF IDENTIFICATION TECHNIQUES

Purpose of Identification Techniques

2. The purpose of an identification and/or classification technique for expansive soils is to qualitatively characterize the potential volume change behavior of suspected problem soils. The obvious need for qualitative characterization of potential volume change is two-fold. First, it should serve the purpose of forewarning the engineer during early planning stages of potential problems with expansive soils. Second, it should provide a basis to aid in the decision-making process for dealing with expansive soils in highway subgrades. In other words, the identification/classification technique should provide the necessary information to answer the questions:

- a. Do problems with potential expansion exist and, if so, what relative magnitude is expected?
- b. Is further testing necessary to use the quantitative prediction techniques? If so, what samples should be tested?

Actual quantitative estimation of expected volume change is the next sequence in the decision-making process and is the subject of a specific research task and interim report.

3. In Reference 1 a three-fold categorization of identification and testing techniques is described:

- a. Indirect techniques in which one or more of the related intrinsic properties are measured and complemented with experience to provide indicators of potential volume change. These may be grouped according to soil composition; physicochemical, physical, and index properties; and currently used soil classification systems.
- b. Direct techniques which involve actual measurement of volume change in an odometer-type testing apparatus. These are generally grouped into swell or swell pressure tests depending on the need for deformation or stress-related data.
- c. Combination techniques in which data from the indirect and direct techniques are correlated either directly or by statistical reduction to develop general classifications with regard to probable severity.

Since the purpose of this report is to evaluate identification techniques, two of the three categories, i.e. indirect and combination, will provide the methodology for evaluation.

Definition of Potential Swell

4. Few, if any, of the published indirect or combination techniques appear to provide a universally applicable technique for several reasons. One of the most obvious inconsistencies in the various methods involves the definition of potential swell. As an example, in one procedure[2] the potential swell is defined as the swell (deformation) of an undisturbed specimen from air dried to saturation under 1-psi* surcharge, while in another procedure[3] it is defined as the swell (deformation) of a remolded specimen (optimum moisture content and maximum dry density) under 650 psf (≈4.5 psi) surcharge. Surcharge pressures generally vary from zero (actually a small seating load) to 1000 psf (≈7 psi). Initial specimen conditions are either undisturbed or remolded with the remolded specimens having different initial moisture contents and/or dry densities specified. In two of the published procedures[3,4] the specimens tested were molded of artificially prepared soils using mixtures of commercial clay minerals and sand. In addition, certain published techniques[5-7] require time limits or more precisely, the potential swell is defined as the deformation after a set time period of inundation. Add to all these factors the variations in the ambient environmental conditions (soil profile, climate, etc.) which influence the initial condition of the sampled materials as well as the rate of volume change development, and the task of evaluating identification/classification techniques becomes somewhat difficult.

5. The basic definition of potential swell, whether it is for the purpose of identifying and/or classifying the expansive material or for estimating the amount of anticipated volume change, should provide

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page v.

the best simulation of in situ conditions practical. At a minimum, the definition should specify the initial conditions of the specimen, such as water content, dry density, fabric, and structure, as well as the stress conditions relative to the specimen, such as vertical stress and lateral confinement conditions. Ideally, the amount and rate of water applied to the specimen should simulate actual conditions such as groundwater influences and surface infiltration. The current state of the art allows for simulation of most of these conditions, except compromise is required for the lateral confinement and water application conditions. With this in mind, the definition of potential swell which satisfies the largest portion of the field simulation requirements is:

> Potential swell is the equilibrium vertical volume change or deformation from an odometer-type test (i.e. total lateral confinement), expressed as a percent of original height, of an undisturbed specimen from its natural water content and density to a state of saturation under an applied load equivalent to the in situ overburden pressure.

For estimating anticipated volume change, the above definition should be amended to reflect the final stress conditions such as applied load from the pavement or structure. However, for the purpose of this report, namely the evaluation of identification/classification techniques, the definition will be used as stated; that is, the volume change from natural conditions to saturation under actual overburden stresses.

Summary of Indirect Techniques

6. In Reference 1, Table 5 described five indicator groups which comprise the indirect techniques for identification/classification of potentially expansive soils. The indicator groups are soil composition, physicochemical properties, physical properties, index properties, and soil classification. The combination techniques are solely dependent on correlation of index properties with measured volume change. In fact, the combination techniques are simply extensions of the index property indicator group so that more factors could be considered. This point is made to simplify subsequent discussions.

Soil composition indicator group

7. The soil composition indicator group is totally concerned with the determination of the type and, to a lesser extent, amount of clay mineral present in the soil. The identification of the clay mineral is positive indication of potential problem; however, the clay mineralogy does not present an adequate correlation with respect to the amount of volume change that is likely to occur. A point that is of more concern from the practical operational standpoint is that most of the methodology (i.e. equipment and trained personnel) is not readily available on a cost-effective basis for routine use. In summary, the determination of the clay mineralogy is a reasonably accurate indicator that problems could exist; however, very little can be determined about the relative magnitude of the problem. This lack of correlation with potential swell and the logistics problems with routine use have hampered and will continue to hamper the use of the methods included in the soil composition indicator group.

Physicochemical property indicator group

8. The physicochemical property indicator group provides simpler testing procedures than the soil composition group; however, the simplicity is offset by poor correlations with measured volume change. The published relationships show, at best, a general qualitative indication of potential swell. In other words, the magnitude of potential swell generally increases with increasing cation exchange capacity and is influenced by the type and amount of cation present.

Physical property indicator group

9. The physical property indicator group provides several propercies which have significant influence on the volume change characteristic, but individually the properties provide little or no indication of potential swell from a relative magnitude standpoint. The colloidal content has been used in combination with other index properties[2] to categorize potential swell. The other properties--specific surface area, soil fabric, and soil structure--influence the amount and rate of volume change. The influences are explained in more detail elsewhere.[1]

Index property indicator group

10. The most widely used indicator group for identification/classification of expansive soils is the index properties group. The major factors which result in the popularity of this group are (a) the practicality from the standpoint that most of the properties involved are routinely determined by all State Highway Agencies and (b) experience has shown that potential swell correlates reasonably well with several of the simple index properties. In most cases, the index property group variables, i.e. Atterberg limits or shrinkage properties, are correlated with past experiences and used individually to categorize the potential problem from expansive soils. Examples of these simple categorizations are given in Table 5, Reference 1. On occasions where measured potential swell values are available, the index properties are used individually or combined to correlate with potential swell. The result is several multiproperty categorizations of relative magnitude of potential volume change. This constitutes the combination category previously discussed. This property indicator group includes the largest number of published identification/classification techniques which will be considered in the evaluation of methodology.

Soil classification indicator group

11. The soil classification system indicator group is another group which deals in simple properties of the soils, but does not provide more than a general indication that a problem might exist. In the American Association of State Highway and Transportation Officials (AASHTO) classification system, the A-6 and A-7 subgrade groups constitute a majority of the potentially expansive soils. In the Unified Soil Classification System (USCS), the CL and CH categories generally cover the range of potential expansivity with the possibility of some MH soils showing expansive characteristics to a lesser degree. The Soil Conservation Service Classification System or Soil Taxonomy[8-11] as it is now called, is the most detailed classification system in current use. Soil taxonomy uses many of the basic properties as well as temperature and moisture regimes and climate to describe soils. In soil taxonomy, the vertisol order includes all of the expansive soils. Within the vertisol

order, the major suborders are Torrerts, Uderts, Usterts, and Xererts. The system is based on several formative elements which provide individual meaning to the total descriptive term. In the vertisol order, the basic formative element is "ert"; therefore, when these three letters appear in a soil descriptive name, that material is generally considered to be potentially expansive.

EVALUATION OF IDENTIFICATION TECHNIQUES

12. As mentioned earlier, the purpose of this research was to evaluate current methodology for identifying/classifying potentially expansive soils. The information presented in Reference 1 and discussions in the preceding section of this report indicate that the index property indicator group most effectively balances simplicity and practicality with reasonable accuracy for identification/classification purposes. Within the index property group and the combination category, which is merely an extension of the index property group, 17 published techniques or criteria were selected for evaluation using the data collected for this study. Since it was impossible to duplicate the conditions of development of each of the techniques, the evaluation process is based on applying the techniques to data collected during this study and comparing the relative magnitudes with those determined using the previously presented definition of potential swell. Four additional published techniques were omitted from the comparisons because of imposed time limits placed on potential swell measurements.[5-7]

Selection of Identification Techniques

13. The identification/classification techniques represented by the index property indicator were selected generally on the basis of their simplicity and the indicated correlations with measured volume change. With regard to field experience, several of the techniques have been used considerably with reasonable success. The techniques selected for evaluation are described in some detail in Reference 1 and will be presented in brief form here to provide continuity.

Louisiana Department of Transportation[12]

14. The Louisiana Department of Transportation uses the Atterberg limits (liquid limit (LL) and plasticity index (PI)) balanced with field experience to identify potentially expansive soils. The criteria used for identifying and classifying potential swell are:

LL, %	PI, %	Potential Swell Classification
20-49	15-24	Low to medium
50-70	25-46	High
>70	>46	Very high to severe

Kansas Highway Commission[13]

15. The Kansas Highway Commission (KHC) also uses the Atterberg limits (PI) to indicate potentially expansive soils. In addition, KHC generally follows up with an odometer-type volume change test (1-psi surcharge) to better estimate the quantity of anticipated swell. The KHC criteria for potential swell are:

PI, %	Potential Swell Classification
<15	Low or none
15-35	Moderate
>35	High

Raman[14]

16. This method uses the Atterberg limits (LL, PI, and shrinkage limit (SL)), but in a different configuration. Raman defines the shrinkage index (SI) as the difference between the LL and the SL (LL - SL). The criteria recommended by Raman for identification/classification are:

PI, %	SI, %	Degree of Expansion
<12	<15	Low
12-23	15-30	Medium
23-32	30-40	High
>32	>40	Very high

Sowers[15,16]

17. Sowers' early work[15] used only the PI as an indicator of potential swell. In his later work[16] he combines the PI with the SL to provide additional accuracy. The criteria are:

SL, %	PI, %	Potential Volume Change
>12	<15	Probably low
10-12	15-30	Probably moderate
<10	>30	Probably high

One interesting note in Sowers' work is his reference to the water-plasticity ratio or liquidity index (LI). His data indicate that little swell will occur when the soil moisture reaches a value which results in a LI of 0.25.

Dakshanamurthy and Raman[17]

18. This method is based on a modification of Casagrande's plasticity chart, which includes PI and LL, with the addition of the SI (LL - SL). Figure 1 is a graphical representation of the recommended criteria. A simplification of the procedure using the LL is:

LL, %	Potential Swell Classification
0-20	Nonswelling
20-35	Low swelling
35-50	Medium swelling
50-70	High swelling
70-90	Very high swelling
>90	Extra high swelling

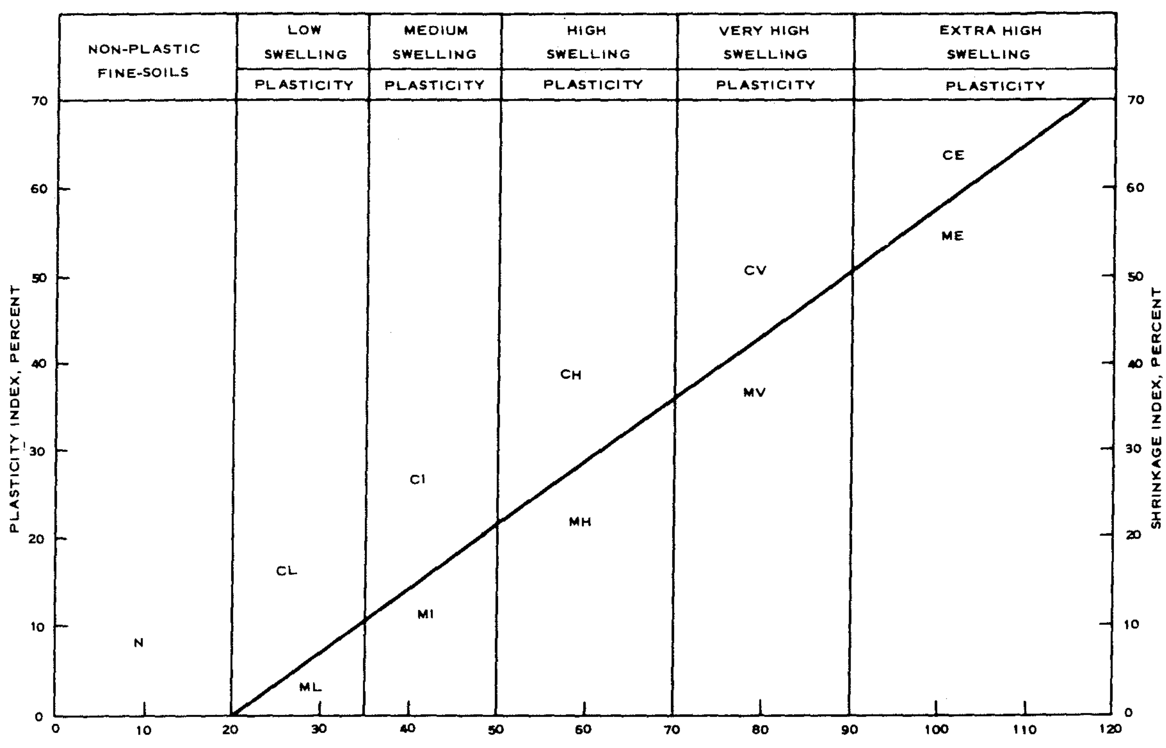

Figure 1. Chart for potential expansiveness of soils (from Reference 17)

Anderson and Thomson[18]

19. The authors of this method use the PI alone, but rather than qualitatively describe the degree of expansion alone, they add a categorization of measured potential swell. The recommended criteria are:

PI, %	Potential Swell, %	Degree of Expansion
<20	<1.5	Low
20-31	1.5-4.0	Medium
31-39	4.0-6.0	High
>39	>6.0	Very high

Ranganatham and Satyanarayana[19]

20. This method uses the Atterberg limits (LL and SL) in combination to define the SI (LL - SL). These authors were the first to use the SI for identification of expansive soils. The criteria are:

SI, %	Potential Swell Classification
<20	Low
20-30	Medium
30-60	High
>60	Very high

Saito and Miki[20]

21. This method defines the plasticity ratio (PR) as the PI divided by the PL and uses this ratio to correlate with measured swell. The corresponding criteria for potential swell are:

PR	Potential Volume Change, %	Potential Swell Classification
<0.6	<3	Low
0.6-1.0	3-10	Medium
1.0-2.0	10-50	High
>3.0	>50	Very high

U. S. Bureau of Reclamation[2] (USBR)

22. This method involves direct correlation of observed volume change with colloidal content, PI, and SL. The degree of expansion and limits of correlated properties are shown in the following tabulation:

Data from Index Tests			Probable	
Colloid Content %-1 μm	PI, %	SL, %	Expansion %	Expansion
<15	<18	>15	<10	Low
13-23	15-28	10-16	10-20	Medium
20-31	25-41	7-12	20-30	High
>28	>35	<11	>30	Very high

Experience has shown that this method correlates reasonably well with expected behavior and provides a good indicator of potential volume change. The major criticisms of the method are that the colloidal content indicates amount but not the type of clay constituents and that the hydrometer test is not a routine test in many agency laboratories.

Altmeyer[21]

23. In a discussion to Holtz's paper presenting the USBR method, Altmeyer brought out the major criticisms of the method and suggested a method based on correlations between percent swell and the SL and linear shrinkage. The results of his recommendations are as follows:

Linear Shrinkage %	SL, %	Probable Swell, %	Degree of Expansion
<5	>12	<0.5	Noncritical
5-8	10-12	0.5-1.5	Marginal
>8	<10	>1.5	Critical

One minor criticism of Altmeyer's method is its lack of application to in situ behavior since the data were collected on remolded samples.

Seed, Woodward, and Lundgren[3,4]

24. The potential swell of an expansive soil is defined from correlations of percent swell from odometer tests using laboratory prepared and compacted samples with percent clay size (-2 μm) and soil activity. A statistical relationship is defined for potential swell in terms of clay content and activity and compared with measured volume change. The potential swell may be categorized as follows:

Potential Swell, %	Degree of Expansion
0-1.5	Low
1.5-5	Medium
5-25	High
>25	Very high

Chen[22]

25. In an effort to simplify the USBR method (i.e. eliminate the need for hydrometer analysis) and to provide some relative measure of soil density, a correlation was made between odometer swell data and percent passing the No. 200 sieve, LL, and standard penetration resistance. The resulting classification of the degree of expansion is as follows:

Laboratory and Field Data				
% < No. 200	LL, %	Standard Penetration Blows per Foot	Probable Expansion %	Degree of Expansion
<30	<30	<10	<1	Low
30-60	30-40	10-20	1-5	Medium
60-95	40-60	20-30	3-10	High
>95	>60	>30	>10	Very high

Vijayvergiya and Ghazzaly[23]

26. The method defines a swell index for an expansive soil as the ratio of the natural water content w_i to the LL and correlates it with odometer swell and swell pressure data. Rather than a specific degree of expansion, limits of probable swell and swelling pressure are defined as shown in the following tabulation:

w_i/LL	Probable Swell Pressure, tsf	Probable Swell, %
>0.5	<0.3	<1
0.37-0.5	0.3-1.25	1-4
0.25-0.37	1.25-3.0	4-10
<0.25	>3.0	>10

Vijayvergiya and Sullivan[24]

27. The method is correlation of odometer swell data with LL and dry density. Here again, degree of expansion is not defined; instead, a family of curves relates the parameters with quantitative volume change (Figure 2). The basic material data for the correlation are good; however, experience with application of the system is somewhat limited.

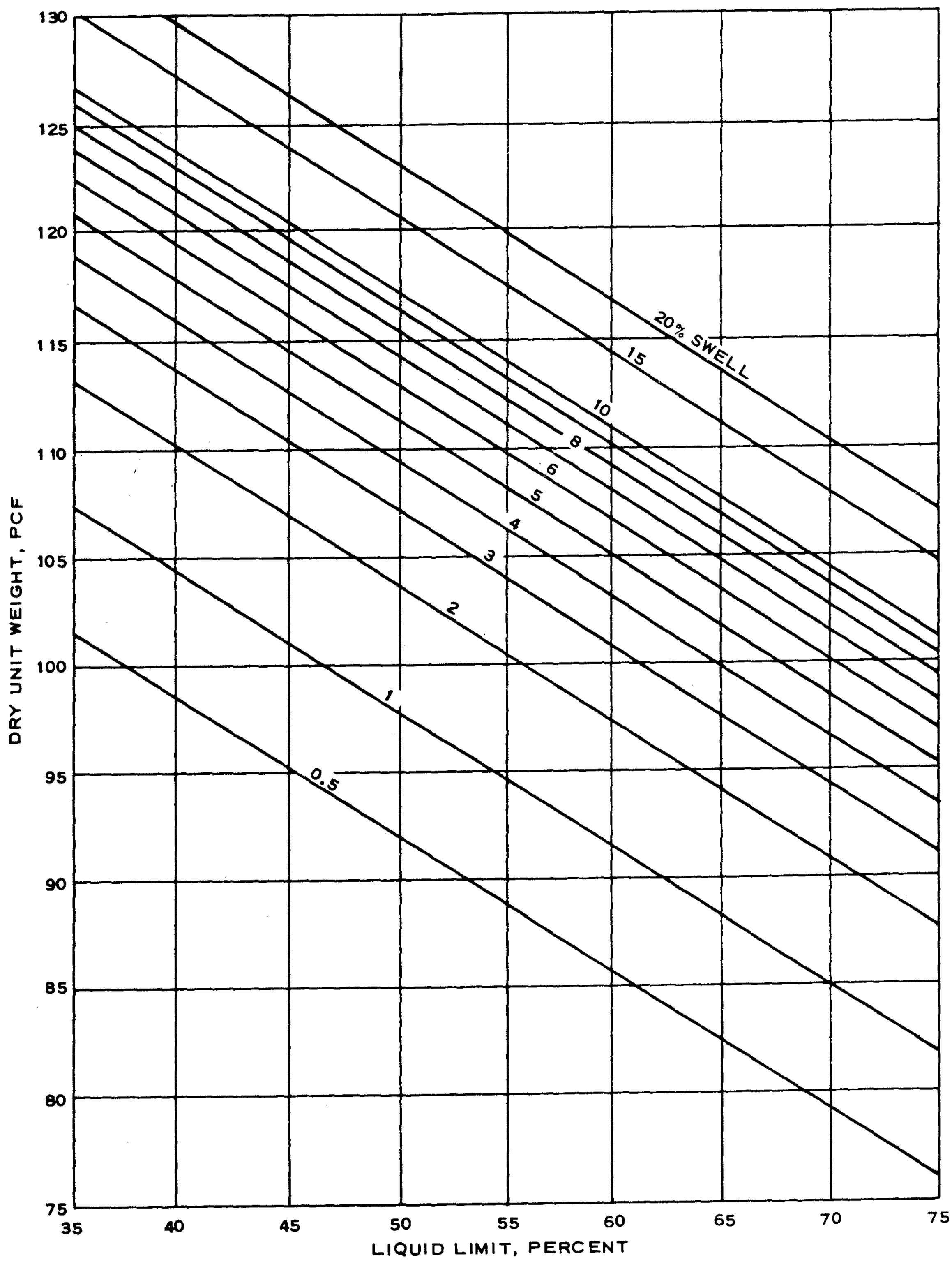

Figure 2. Correlation of percent swell, LL, and dry unit weight (from Reference 24)

Sorochan[25]

28. The correlation involves relating the swelling index (void ratio, e, after free expansion divided by the initial sample void ratio, e_o) to the PI. The resulting degrees of expansion with regard to correlated parameters are as follows:

Swelling Index, e/e_o					
15 < PI <20	20 < PI <25	25 < PI <30	30 < PI <35	35 < PI <40	Degree of Expansion
<1.12	<1.11	<1.09	<1.08	<1.07	Nonswelling
1.12-1.23	1.11-1.21	1.09-1.19	1.08-1.17	1.07-1.15	Slight
1.23-1.39	1.21-1.30	1.19-1.28	1.17-1.25	1.15-1.22	Medium
>1.39	>1.30	>1.28	>1.25	>1.22	High

The methcd considers two of the properties important to volume change; however, an expansion test must be conducted to use the method. In addition, the upper limits of the PI are less than PI values encountered in many naturally occurring expansive soils.

Nayak and Christensen[26]

29. The method involves the development of two statistical relationships, one for swell and the other for swelling pressure, in terms of PI, clay content, and initial moisture content. The developed relationships are:

$$S_p = (2.29 \times 10^{-2})(PI)^{1.45} \frac{C}{w_i} + 6.38$$

where

S_p = predicted swell percentage

C = clay content, percent

w_i = initial moisture content

and

$$P_p = (3.5817 \times 10^{-2})(PI)^{1.12} \frac{C^2}{w_i^2} + 3.7912$$

where P_p = predicted swelling pressure, psi

Komornik and David[27]

30. This is another statistical comparison of measured data which provides a relationship for predicting swelling pressure using LL, natural dry density γ_d, and w_i. The relationship for predicted swelling pressure is:

$$\log P = -2.132 + 0.0208(LL) + 0.000665(\gamma_d) - 0.0269(w_i)$$

The dry density and swelling pressure are in kg/m^3 and kg/cm^2, respectively.

31. The last two procedures[26,27] are actually empirical prediction techniques, but were included in the evaluation of identification/classification since they represent correlations between Atterberg limits, physical properties, and measured volume change. Since no categories of volume change are presented with the techniques, comparisons will be made between the predicted and measured swell or swell pressure.

Field Sampling and Laboratory Testing

32. The field sampling program was initiated through contacts with 11 State Highway Agencies in which agency representatives were requested to recommend appropriate geologic formations and site locations based on the simple criterion that the material be representative of an areally extensive deposit of expansive soil which poses problems as defined by the State Highway Agency. It was also requested that the sites be located along the alignment of a recently constructed highway or in the graded alignment of a proposed highway. As a result of the State Highway Agency recommendations, 20 field sampling sites were selected. Table 1 provides a summary of the 20 site locations, geologic formations sampled, samples tested, natural moisture contents and densities, and soil classifications. The site numbers assigned in Table 1 will be used throughout the remainder of the report. More details regarding the sampling sites, including site locations, site descriptions, site geology,

Table 1

Summary of General Site Information and Soil Classifications

Site No.	Site Location	Geologic Formation	Boring/ Sample No./ Depth, ft	Natural Moisture Content %	Natural Dry Density pcf	Soil Classification	
						USCS	AASHTO
1	Jackson, Miss.	Yazoo	U-2/1/1.0-3.2	40.3	80.3	CH	A-7-5 (81)
2	Hattiesburg, Miss.	Hattiesburg	U-2/1/1.0-2.9	25.6	93.8	CH	A-7-6 (36)
3	Monroe, La.	Alluvial material	U-2/2/3.5-4.9	39.5	81.8	CH	A-7-5 (68)
4	Lake Charles, La.	Prairie terrace material	U-2/1/1.0-3.1	20.6	105.6	CH	A-7-6 (33)
5	San Antonio, Tex.	Taylor	U-2/4/3.5-5.1	24.0	95.4	CH	A-7-5 (35)
6	Vernon, Tex.	Vale	U-1/4/4.8-7.2	13.8	119.7	CL	A-6 (11)
7	Durant, Okla.	Washita	U-2/2/3.5-4.7	15.4	117.9	CL	A-7-6 (30)
8	Hennessey, Okla.	Hennessey	U-1/2/3.5-5.6	12.5	124.9	CL	A-7-6 (25)
9	Holbrook, Ariz., No. 1, I-40	Chinle	U-2/1/2.5-4.2	9.4	111.5	CL	A-6 (10)
10	Holbrook, Ariz., No. 2, SH 180	Chinle	U-2/1/2.0-4.3	19.3	101.5	CH	A-7-6 (24)
11	Price, Utah	Mancos	U-1/1/1.2-3.2	9.4	107.8	CL	A-7-6 (27)
12	Hays, Kans.	Blue Hill	U-2/1/1.4-3.4	26.1	97.2	CH	A-7-6 (58)
13	Ellsworth, Kans.	Graneros	U-2/1/2.0-4.3	16.7	112.8	CL	A-7-6 (22)
14	Limon, Colo., No. 1, I-70	Pierre	U-1/5/4.2-6.3	26.4	98.2	CH	A-7-6 (35)
15	Limon, Colo., No. 2, I-70	Laramie	U-1/1/3.4-5.0	38.2	78.8	CH	A-7-6 (44)
16	Denver, Colo.	Denver	U-3/4/5.7-7.8	16.0	103.9	CL	A-6 (10)
17	Newcastle, Wyo., No. 1, SH 16	Mowry	U-2/1/3.0-5.2	26.4	97.5	CH	A-7-6 (31)
18	Newcastle, Wyo., No. 2, US 85	Pierre	U-1/2/3.0-3.9	15.7	97.5	CH	A-7-6 (25)
19	Billings, Mont.	Bearpaw	U-2/1/3.1-4.6	17.6	110.8	CH	A-7-6 (50)
20	Reliance, S. Dak.	Pierre	U-2/1/1.7-3.9	34.5	83.4	CH	A-7-5 (42)

sample description, description of climate, and other pertinent information, are given in Reference 28.

33. The laboratory testing program encompassed the determination of a majority of the physical, mechanical, physicochemical, and mineralogic properties currently used by engineers to characterize soils in general and expansive soils in particular. Reference 28 gives a detailed description of the entire laboratory testing program as well as a summary of the data in tabulated form (Tables 6-13, Reference 28). Tables 7, 8, and 11 from Reference 28 are repeated here as Tables 2, 3, and 4, respectively, to provide the data required to use the published techniques. The data in Table 4 are somewhat different than Table 11 because the data have been replotted using an expanded scale and a slightly different and more consistent criterion for interpreting the τ-w plots to obtain the soil moisture suction parameters.

34. During the overburden swell testing program, overburden pressure was supposed to reflect in situ conditions of wet density and depth to test specimen, thus yielding a measured deformation corresponding to the potential swell as defined earlier. However, because of an error in testing assignment, a constant overburden pressure of 0.28 tsf was used for all specimens. For test specimens whose actual and tested overburden pressures did not agree, a second specimen was tested. The results of the reruns and those tests not requiring additional testing are given in Table 5. With the reruns completed, all of the overburden swell test data conform with the definition of potential swell. Briefly, the overburden swell test procedure begins by applying a very small seating load followed by application of the overburden pressure and inundation of the specimen. The specimen is allowed to swell to equilibrium (end of swell condition), then the specimen is consolidated in increments to the void ratio corresponding to overburden conditions and rebounded in decrements to the seating load (end of test condition).

Analysis of Data

35. The evaluation of expedient methodology for identification/classification of expansive soils involved a two-fold effort. First, the

Table 2

Summary of Specific Gravity, Grain-Size Distribution, and Atterberg Limits and Indices

Site No.	Specific Gravity	Grain Size, % No. 200	Grain Size, % 2 μm	Liquid Limit %	Plastic Limit %	Plasticity Index	Activity	Liquidity Index
1	2.69	98	82	104	36	68	0.83	0.06
2	2.68	84	38	61	20	41	1.08	0.14
3	2.72	96	57	96	38	58	1.02	0.03
4	2.72	82	37	56	17	39	1.05	0.09
5	2.73	97	36	58	27	31	0.86	-0.10
6	2.83	89	38	34	21	13	0.34	-0.55
7	2.75	98	43	48	21	27	0.63	-0.21
8	2.82	98	57	47	23	24	0.42	-0.44
9	2.75	69	23	34	18	16	0.70	-0.54
10	2.81	84	13	54	29	25	1.92	-0.39
11	2.74	97	42	46	20	26	0.62	-0.41
12	2.75	98	61	75	24	51	0.84	0.04
13	2.63	91	32	49	28	21	0.66	-0.54
14	2.80	98	44	56	25	31	0.70	0.05
15	2.76	98	64	63	24	39	0.61	0.36
16	2.72	63	33	38	19	19	0.58	-0.16
17	2.71	91	24	55	25	30	1.25	0.05
18	2.78	97	45	50	28	22	0.49	-0.56
19	2.76	97	44	69	24	45	1.02	-0.14
20	2.72	94	61	80	34	46	0.75	0.01

Table 3

Summary of Measured Shrinkage Properties

Site No.	Shrinkage Limit %	Shrinkage Ratio	Shrinkage* Index	Bar Linear Shrinkage %
1	9.8	1.83	94.2	23.2
2	14.5	1.86	46.5	19.2
3	20.5	1.70	75.5	19.5
4	12.4	1.93	43.6	17.7
5	16.2	1.73	41.8	18.8
6	14.8	1.89	19.2	20.0
7	20.3	1.61	27.7	12.1
8	18.9	1.76	28.1	14.4
9	14.5	1.85	19.5	13.4
10	16.8	1.77	37.2	12.8
11	19.8	1.72	26.2	26.2
12	17.6	1.75	57.4	20.2
13	23.6	1.58	25.4	13.6
14	20.2	1.68	35.8	14.4
15	18.3	1.72	44.7	15.6
16	15.5	1.83	22.5	11.0
17	19.1	1.75	35.9	12.0
18	19.0	1.72	31.0	12.6
19	12.8	1.92	56.2	19.6
20	27.3	1.49	52.7	16.0

* Shrinkage index = liquid limit - shrinkage limit.
** Percent free swell measured in graduated cylinder.

Table 4

Summary of Soil Moisture Suction Data

Site No.	w Moisture Content %	τ* Soil Suction tsf	τ-w Equation Coefficients** A	B
1	42.8	4.79	5.093	0.1031
2	26.7	1.92	3.537	0.1219
3	49.7	0.31	3.911	0.0889
4	24.6	0.75	3.278	0.1325
5	22.7	1.74	3.903	0.1613
6	13.5	3.16	15.500	1.111
7	15.8	0.66	9.455	0.6061
8	19.5	1.49	2.456	0.1170
9	10.9	17.44	4.931	0.3448
10	17.4	34.88	5.167	0.2083
11	9.1	23.43	2.591	0.1342
12	26.6	1.77	5.107	0.1786
13	17.2	3.16	10.056	0.5556
14	25.7	7.75	3.270	0.0930
15	38.0	1.64	7.667	0.1961
16	14.5	19.50	5.968	0.3226
17	26.9	2.65	6.333	0.2222
18	15.5	25.81	6.333	0.3175
19	18.4	1.64	5.471	0.2857
20	33.8	2.05	5.869	0.1639

* Total soil suction at natural moisture content.

** $\text{Log}\ \tau = A - Bw$.

Table 5

Summary of Data from Overburden Swell Tests

Site No.	Initial Conditions*				End of Swell Conditions				End of Test Conditions				Δe**	Swell† %
	e_o	w_o	S_o	γ_o	e_f	w_f	S_f	γ_f	e	w	S	γ		
1	1.138	40.3	97.4	80.3	1.409	51.3	100	71.2	1.485	54.9	100+	69.1	0.271	12.7
2	0.7826	25.6	87.7	93.8	0.8061	30.1		92.6	0.8147	28.2	92.9	92.2	0.0235	1.32
3	1.105	39.5	98.6	81.8	1.125	40.8		81.0	1.179	42.6	99.8	79.0	0.020	0.96
4	0.6079	20.6	92.2	105.6	0.6210	22.8		104.7	0.6280	22.2	96.2	104.3	0.0131	0.82
5	0.7851	24.0	83.5	95.4	0.7966	29.2		94.8	0.823	31.6	100+	93.5	0.0115	0.64
6	0.4750	13.8	82.2	119.7	0.4753	16.8		119.7	0.485	22.7	100+	118.9	0.0003	0.02
7	0.4546	15.4	93.2	117.9	0.4608	16.8		117.5	0.472	16.6	96.7	116.6	0.0062	0.43
8	0.4082	12.5	86.4	124.9	0.4084	14.5		124.9	0.409	13.3	91.6	124.9	0.0002	0.01
9	0.5387	9.4	48.0	111.5	0.5588	20.3		110.1	0.590	19.0	88.7	108.0	0.0201	1.31
10	0.728	19.3	74.5	101.5	0.791	28.1		97.9	0.794	27.5	97.2	97.8	0.063	3.65
11	0.5858	9.4	44.0	107.8	0.5910	21.6		107.5	0.5980	24.0	100+	107.1	0.0052	0.33
12	0.765	26.1	93.8	97.2	0.783	28.5		96.2	0.810	27.7	94.1	94.8	0.018	1.02
13	0.4554	16.7	96.4	112.8	0.4605	17.5		112.4	0.463	16.6	94.5	112.2	0.0051	0.35
14	0.7791	26.4	94.9	98.2	0.7944	28.4		97.4	0.826	28.7	97.1	95.7	0.0153	0.86
15	1.185	38.2	89.0	78.8	1.188	43.0		78.7	1.203	41.8	95.9	78.2	0.003	0.14
16	0.633	16.0	68.8	103.9	0.685	25.2		100.7	0.729	25.2	93.9	98.2	0.052	3.18
17	0.734	26.4	97.5	97.5	0.748	27.6		96.7	0.776	28.3	98.6	95.2	0.014	0.81
18	0.779	15.7	56.0	97.5	0.827	29.7		94.9	0.824	25.0	84.2	95.1	0.048	2.70
19	0.5542	17.6	87.7	110.8	0.5598	20.3		110.4	0.569	22.4	92.2	110.3	0.0056	0.36
20	1.035	34.5	90.7	83.4	1.073	39.5	100	81.9	1.108	38.7	95.2	80.6	0.038	1.87

Note: e = void ratio, w = moisture content (%), S = degree of saturation (%), γ = dry density (pcf).

* Corresponds to overburden conditions on e-log p plot.

** $\Delta e = e_f - e_o$.

† % swell = $\Delta e/(1 + e_o)$.

data collected during the laboratory testing program were used in conjunction with the published identification/classification techniques to compare the indicated qualitative magnitude of swell with the measured potential swell as previously defined and measured in the overburden swell test. Second, the measured potential swell and laboratory data were analyzed using the statistical analysis program to obtain the best correlations between the two groups of data.

Establishment of
potential swell categories

36. It was stated earlier that the evaluation of the published techniques is basically an evaluation of the techniques as they are applied rather than how they were developed since there was a large variation in the definition of potential swell used. Evaluation of the accuracy of the published techniques requires a basis or standard for comparison, or, more precisely, a categorization of the potential swell as previously defined and measured in the laboratory testing program. Table 5 summarizes the measured swell from the odometer swell tests on undisturbed samples under loads equivalent to the in situ overburden pressure. The swell varies from 0.01 to 12.7 percent, with the majority of the measured values between 0.14 and 3.65 percent. During previous discussions with representatives of the State Highway Agencies it was indicated that a two- or three-category classification of potential swell would be preferable to the four- to six-category classifications published in the literature. With this in mind, the measured potential swell was divided into three categories. The three categories and their corresponding potential swell limits are:

Potential Swell, %	Potential Swell Classification
<0.5	Low
0.5-1.5	Marginal
>1.5	High

For discussion purposes, this classification will be denoted as the WES classification throughout the remainder of this report. These ranges of potential swell seem low as compared with some of the published techniques; however, they are consistent with identification/classification techniques which used comparable magnitudes of applied load in the potential swell testing program. In addition, this range of categories divides the 20 samples tested into three groups of approximately the same number. The high category indicates that the material has the maximum potential for volume change and that the characteristic properties (i.e. moisture content, density, fabric, structure, etc.) are conducive to the occurrence of volume change when moisture is made available. The low category indicates that the material has minimal potential for volume change and that the characteristic properties inhibit volume change. The marginal category indicates the presence of moderate to maximum potential for volume change, but the characteristic properties are not consistent with the high category, and the resulting volume change is generally less than anticipated depending on the sensitivity of the material with respect to variations in the characteristic properties.

Application of published techniques

37. In the interest of simplicity for the following data presentations and discussions, the previously described published techniques will be assigned the following alphabetic characters which will be used throughout the remainder of the analysis portion of the report.

Louisiana Department of Transportation	LDOT
Kansas Highway Commission	KHC
Raman	Raman
Sowers	Sowers
Dakshanamurthy and Raman	D&R
Anderson and Thomson	A&T
Ranganatham and Satyanarayana	R&S
Saito and Miki	S&M
U. S. Bureau of Reclamation	USBR
Altmeyer	Altmeyer
Seed, Woodward, and Lundgren	SWL
Chen	Chen
Vijayvergiya and Ghazzaly	V&G
Vijayvergiya and Sullivan	V&S
Sorochan	Sorochan
Nayak and Christensen	N&C
Komornik and David	K&D

Table 6 summarizes the classification of potential swell of the 20 sampling sites as indicated by each of the published techniques. The N&C and K&D techniques are more directly related to prediction of volume change rather than identification/classification; however, they are included here since they are combination techniques based on Atterberg limits and physical properties. Classifications of potential swell were not given for either of these techniques, therefore, actual values were calculated for comparison with measured values. The K&D technique uses swell pressure as a measure of potential swell rather than percent swell. For each value calculated using the K&D technique, the number directly below it in parentheses in Table 6 is the measured swell pressure from the laboratory testing program.

Discussion of results

38. Careful examination of Table 6 shows that no published identification/classification technique provides a generally applicable methodology for identifying and qualitatively classifying potential swell. However, some of the techniques provide reasonably accurate and consistent indication of problem conditions. For example, the LDOT procedure agrees with the U. S. Army Engineer Waterways Experiment Station (WES) categorization for classification of potential swell of 10 of the 20 sampling sites and is conservative in its classification for nine of the remaining 10 samples. Using this rationale, the relative accuracy of the published techniques may be compared as shown in Table 7. Ideally, the best technique should result in a majority of responses in the "agreement" and "conservative" columns and as few as possible in the "nonconservative" column when compared with the WES categorization. The higher the percentage of "agreements" versus the percentage of "conservative" responses, the better the technique.

39. Of the 17 techniques evaluated, four balance accuracy and conservatism best, namely: LDOT, Sowers, Altmeyer, and V&G. All four of these techniques involve Atterberg limits in some form, either individually or in combination. Within this group of techniques, the relative accuracy and conservatism is best for the LDOT procedure and decreases in the order of V&G, Sowers, and Altmeyer. In other words, the

Table 6

Summary of Indicated Potential Swell Using Published Identification Techniques

Site Number	Potential Swell %	LDOT	KHC	Raman	Sowers	D&R	A&T	R&S	S&M	USBR	Alt-meyer	SWL	Chen*	V&G**	V&S**	Soro-chan	N&C %	K&D tsf
1	12.7	Sev	High	V. High	High	E. High	V. High	V. High	High	V. High	Crit	V. High	V. High	Med	Low	High	25.94	0.49 (3.82)
2	1.32	High	High	V. High	High	High	V. High	High	High	High	Mar	High	High	Med	Low	Non	13.51	0.28 (0.96)
3	0.96	Sev	High	V. High	High	E. High	V. High	V. High	High	High	Mar	V. High	V. High	Med	Low	Non	16.61	0.25 (0.43)
4	0.82	High	High	V. High	Mod	High	V. High	High	High	High	Mar	High	High	Med	Low	Non	12.67	0.22 (0.35)
5	0.64	High	Mod	High	Mod	High	High	High	High	High	Mar	High	High	Med	Low	Non	11.37	0.28 (0.90)
6	0.02	Low	Low	Med	Low	Low	Low	Low	Med	Med	Mar	Low	Med	Med	Low	Non	8.98	0.31 (0.66)
7	0.43	Low	Mod	Med	Mod	Med	Med	Med	High	High	Mar	Med	High	High	Med	Non	13.99	0.52 (0.65)
8	0.01	Low	Mod	Med	Low	Med	Med	Med	High	High	Mar	Med	High	High	High	Non	16.85	0.71 (0.06)
9	1.31	Low	Low	Med	Low	Low	Low	Low	Med	Med	Mar	Low	Med	High	Low	Non	9.50	0.33 (1.17)
10	3.65	High	Mod	High	Mod	High	Med	High	Med	Low	Mar	Med	High	High	Low	Non	8.30	0.46 (0.93)
11	0.33	Low	Mod	Med	Mod	Med	Med	Med	High	Med	Mar	Med	High	V. High	Med	Non	22.80	0.89 (0.17)
12	1.02	Sev	High	V. High	High	V. High	V. High	High	High	High	Mar	V. High	V. High	High	Low	Non	22.33	0.61 (0.95)
13	0.35	Low	Mod	Med	Low	Med	Med	Med	Med	Med	Mar	Med	High	High	Low	Non	10.00	0.45 (1.16)
14	0.86	High	Mod	High	Mod	High	High	High	High	High	Mar	High	High	Med	Low	Non	11.93	0.24 (0.80)
15	0.14	High	High	V. High	Mod	High	V. High	High	High	High	Mar	High	V. High	Low	Low	Non	14.16	0.10 (0.38)
16	3.18	Low	Mod	Med	Low	Med	Low	Med	Med	Med	Mar	Med	Med	Med	Low	Non	10.03	0.22 (1.00)
17	0.81	High	Mod	High	Mod	High	Med	High	High	Med	Mar	High	High	Med	Low	Non	9.27	0.22 (1.07)
18	2.70	High	Mod	Med	Low	High	Med	High	Med	Med	Mar	Med	High	High	Low	Non	12.15	0.44 (2.37)
19	0.36	High	High	V. High	High	High	V. High	High	High	High	Mar	High	V. High	High	Med	Non	20.67	1.05 (0.59)
20	1.87	Sev	High	V. High	High	V. High	V. High	High	High	High	Mar	High	V. High	Med	Low	Sli	17.84	0.39 (2.54)

Note: Sev = Severe, Mod = Moderate, V. High = Very High, Med = Medium, E. High = Extra High, Crit = Critical, Mar = Marginal, Non = Nonswelling, Sli = Slight.

* No Standard Penetration data available.

** Categories of potential swell were not given in reference. Values used were assigned by author.

Table 7

Comparison of WES Categories and Classification by Published Identification Techniques for 20 Sampling Sites

Published Technique	Number of Sites for which Classification in Agreement With WES Categories	Number of Sites on Conservative Side	Number of Sites on Nonconservative Side
LDOT	10	9	1
KHC	6	10	4
Raman	4	14	2
Sowers	9	7	4
D&R	5	13	2
A&T	4	12	4
R&S	5	13	2
S&M	3	14	3
USBR	4	13	3
Altmeyer	9	7	4
SWL	3	13	4
Chen	5	14	1
V&G	9	8	3
V&S	3	4	13
Sorochan	1	0	19
N&C	0	20	0
K&D	2	3	15

most consistent indicator of potential swell is first, the LL and PI; second, the LL and natural w_i combined; third, SL and PI; and finally, the SL and linear shrinkage. As will be discussed later, this is consistent with the analysis of the WES categorization and laboratory data.

Analysis of WES categorization and laboratory data

40. The second portion of the evaluation of expedient identification/classification methodology involved a comparison by statistical analysis of the WES categorization of potential swell with the laboratory data, the purpose being to verify the evaluation of published techniques and determine if more sensitive indicators of potential swell are available. This portion of the evaluation involved the analysis by stepwise linear regression of the measured potential swell (dependent variable) with the 31 independent variables listed in Table 8. Higher order (greater than linear) comparisons were not attempted since the purpose of the statistical analysis was not to develop equations but simply to point out the better comparisons using the correlation coefficient, r . The r is a measure of the mutual relationship between two variables (dependent and independent). More precisely, r is a measure of the degree of closeness of the linear relationship between two variables. The r always lies between -1 and +1, with positive r values indicating that both variables are increasing. Negative r values indicate that one variable is increasing while the other is decreasing. To even be considered as a useful r value for r^2 comparison purposes, the r should be greater (or less) than +0.7 (-0.7) with the better values being closer to ± 1.

41. The laboratory data were analyzed as one group, i.e. all 20 sampling sites combined. In addition, three additional groups, one based on physiography and two based on climate, were analyzed. The physiographic group[29] consisted of three subgroups:

Atlantic and Gulf Coastal Plains Subgroup--Sites 1-5

Colorado Plateau Subgroup--Sites 9-11

Great Plains Subgroup--Sites 6-8, 12-20

The first climatic group was based on a 6-year average (1970-1975) of

Table 8

Summary of Independent Variables Used in Statistical Comparisons

Variable	Description
w_i(OST)	Initial moisture content from overburden swell test, percent
γ_i(OST)	Initial dry density from overburden swell test, pcf
%-200	Percent minus No. 200 sieve
%-2μm	Percent minus 2 micrometres (percent clay)
LL	Liquid limit, percent
PL	Plastic limit, percent
PI	Plasticity index, percent
Activity	Ratio of PI to percent minus 2μm
LI	Liquidity index $(w_{nat} - PL)/PI$
PR	Plasticity ratio, PI/PL
SL	Shrinkage limit, percent
SR	Shrinkage ratio
SI	Shrinkage index, LL - SL
BLS	Bar linear shrinkage, percent
τ_{nat}	Soil suction (tsf) at natural moisture content
A	Y-intercept of soil suction versus water content plot
B	Slope of soil suction versus water content plot
$C_{\tau\alpha}$	Soil suction index, $\Delta e/\Delta\tau$, based on volumetric compressibility factor, α
$C_{\tau\bar{\alpha}}$	Soil suction index, $\Delta e/\Delta\tau$, based on vertical compressibility factor, $\bar{\alpha}$
pH	pH of the natural material
CEC	Cation exchange capacity, milliequivalents/100 g
ΣEC	Summation of exchangeable cations, milliequivalents/100 g
ESP	Exchangeable sodium percentage, percent
ΣPFC	Summation of pore fluid cation, milliequivalents/litre
SAR	Sodium absorption ratio
% Mont	Percent montmorillonite

(Continued)

Table 8 (Concluded)

Variable	Description
w_i/PL	Ratio of $w_i(OST)$ to plastic limit
w_i/LL	Ratio of $w_i(OST)$ to liquid limit
$A - (B \cdot PL)$	Sum of indicated variables
A/B	Ratio of indicated variables
CEC activity	Cation exchange capacity/percent minus No. 200 sieve

the Thornthwaite Moisture Index (TMI).[30,31] This climatic group had three subgroups:

Humid Subgroup (TMI > 20)--Sites 1-4

Moist Subhumid Subgroup (0 < TMI < 20)--Sites 7,8,12,13

Dry Subhumid Subgroup (-20 < TMI < 0)--Sites 5,6,9-11,14-20

The second climatic group was based on the 1975 TMI since the samples were obtained and tested during 1975. This group also had three subgroups:

Humid Subgroup (TMI > 20)--Sites 1-4,7,8

Moist Subhumid Subgroup (0 < TMI < 20)--Sites 5,6,12,13,19

Dry Subhumid Subgroup (-20 < TMI < 0)--Sites 9-11,14-18,20

In both climatic groups, site 11 was actually classified in a semiarid subgroup (TMI < -20); however, since analysis of a subgroup with a single observation was not practical or significant, site 11 was included in the Dry Subhumid Subgroup.

42. Table 9 summarizes the correlation coefficients greater (or less) than +0.7 (-0.7) for the three groups based on physiography and climate. For the combined group the correlation coefficients shown are greater (or less) than +0.5 (-0.5) since no r values meeting the previous criteria were obtained.

43. As expected the individual subgroups resulted in higher correlation coefficients; however, it is difficult to determine whether the variables actually correlate or the small number of observations is an overriding factor. For variables which result in significant r values in four or less of the subgroups, the small number of observations and the relative magnitudes of the data are likely the reasons for the higher r values. For variables resulting in significant r values in five or more of the subgroups, it is likely that the variable actually correlates with potential swell.

44. Based on the previous discussion, six variables (Table 8) yield significant correlation coefficients when considering the nine subgroups, namely: percent - 2 μm, LL, PI, SI, BLS, and τ_{nat}. One, percent - 2 μm, shows a contradiction (i.e. both + and $-r$ values) which raises some doubt about its actual correlation even though experience

Table 9

Summary of Correlation Coefficients Greater (or Less) Than +0.7(-0.7)

From Statistical Comparisons

Analysis Groups		w_1 (OST)	γ_1 (OST)	%-200	%-2μm	LL	PL	PI	Activity	LI	PR	SL	SR	SI	BLS	τ_{nat}	A	B	C_{Ia}	$\bar{C}_{Ia}$	pH	CEC	ΣEC	ESP	ΣPFC	SAR	% Mont	w_1/PL	w_1/LL	A - (B · PL)	A/B	CEC Activity
Combined Group* 20 Sampling Sites						0.52		0.50						0.60						0.51											0.51	
Physiographic Group	Atlantic and Gulf Coastal Plains Subgroup (n = 5)				0.90	0.71		0.77						0.81	0.95	0.93	0.92							0.76								
Physiographic Group	Colorado Plateau Subgroup (n = 3)	0.96	-0.79		-0.92		0.80		0.97		-0.77			0.78	0.75	0.80	0.78					0.99					0.99	0.85	0.83			
Physiographic Group	Great Plains Subgroup (n = 12)															0.83																
Climatic Group I Six-Year Average TMI	Humid Subgroup (n = 4)				0.90	0.70		0.79	-0.97					0.80	0.95	0.95	0.95						0.76	0.86					-0.78			
Climatic Group I Six-Year Average TMI	Moist Subhumid Subgroup (n = 4)	0.97	-0.97			0.92		0.90	0.96	0.85	0.86			0.88	0.77						-0.72			0.92		0.92	0.92	0.97	0.82			
Climatic Group I Six-Year Average TMI	Dry Subhumid Subgroup (n = 12)															0.72																
Climatic Group II 1975 TMI	Humid Subgroup (n = 6)				0.83	0.73		0.76				-0.71		0.80	0.74	0.93								0.86								
Climatic Group II 1975 TMI	Moist Subhumid Subgroup (n = 5)	0.97	-0.91	0.81	0.72	0.82		0.70		0.85	0.73			0.74		0.70	0.78	0.83	0.92	0.92					-0.72	0.79	0.78	0.91				
Climatic Group II 1975 TMI	Dry Subhumid Subgroup (n = 9)										-0.75																					

* Correlation coefficients given are greater (or less) than +0.5 (-0.5).

has shown that percent clay has an influence on volume change behavior. Of the remaining five variables, three resulted in "relatively significant" correlation coefficients when the data were analyzed as a combined group, namely: LL, PI, and SI. ("Relatively significant" does not reflect significance from a statistical point of view, rather it indicates the highest correlation coefficients obtained in the analysis.) Although BLS and τ_{nat} were not "relatively significant" in the combined group analysis, two factors which are related to soil suction were; that is, $C_{\tau\bar{\alpha}}$ and A/B. $C_{\tau\bar{\alpha}}$ is the suction index, or more precisely, the rate of change of soil suction with void ratio based on the vertical compressibility factor, $\bar{\alpha}$. A/B is the ratio of the intercept (A) to the slope (B) of the soil suction versus water content curve.

45. As indicated earlier, the evaluation of the published techniques and analysis of potential swell and laboratory data agree on the properties which are the best indicators of potential swell. They include LL, PI, SI (LL - SL), and BLS. In addition, the analysis of laboratory data shows that soil suction is a very good indicator of potential swell.

Establishment of criteria for identifying potential swell

46. Although four of the published identification/classification techniques were shown to be reasonably accurate in achieving their purpose of identifying problem soils, it was decided to modify the categories and the relative ranges of the properties included in the categories to conform better with the definition of potential swell presented in this report. Two alternatives were available for establishing the criteria; one was to develop a general criterion based on all the data collected and analyzed as a combined group and the other was to develop individual criteria for either the physiographic or climatic groups. The former alternative (i.e. one general criterion) was selected because the latter alternative posed several problems as follows:

- a. The alternative would result in several different categories which would make implementation more difficult and exchange of information virtually impossible.

b. The number of observations within the subgroups was small as compared with the land area represented by the subgroup, thus leaving doubt about the accuracy and applicability of the criteria, as well as the acceptability of the statistical analysis.

c. The TMI is a transient value which varies from year to year and, although it will most likely be useful for prediction of final moisture content, it does not show promise for climatic classification for identification purposes.

d. Physiographic delineation[29] was shown to be a useful tool for discussion of occurrence and distribution of expansive soils, but no direct genetic implication exists.

e. Indications are that identification of expansive soils is not as critical a problem as testing the soil and estimating the anticipated volume change.

In establishing the general criteria, the previously defined classifications of potential swell (low, marginal, high) were combined with the measured potential swell and physical properties to more accurately or at least conservatively identify the problem soils. Various combinations of ranges of the indicator properties were tried in an effort to optimize the accuracy and conservatism of the identification/classification criteria. The following ranges were found to provide the most accurate classification:

LL, %	PI, %	τ_{nat}, tsf	Potential Swell, %	Potential Swell Classification
>60	>35	>4	>1.5	High
50-60	25-35	1.5-4	0.5-1.5	Marginal
<50	<25	<1.5	<0.5	Low

The SI was included in the trial criteria with the same ranges as the PI and did not reduce or increase the accuracy of the classification, therefore, it was not included in the final criteria. The relative merits of using the three properties combined (LL, PI, τ_{nat}) are evident in the following tabulation:

Properties	Accurate	Conservative	Not Conservative
LL	11	5	4
LL + PI	8	8	4
LL + PI + τ_{nat}	12	6	2
LL + PI + SI	8	8	4
LL + PI + SI + τ_{nat}	12	6	2

The LL alone is a good indicator of potential swell with a total of 16 of the 20 samples falling in the accurate and conservative columns. Combining the LL and PI somewhat reduces the accuracy, but the reduction is balanced on the conservative side. Combining LL, PI, and τ_{nat} increases the accuracy as well as decreasing the nonconservative rating. The lack of influence of the SI on the overall system is obvious in the last two comparisons.

SUMMARY

47. This report, through its literature review, summarizes the state of the art with respect to expedient methodology for identifying and qualitatively classifying expansive soils. The report presents a more comprehensive definition of potential swell, and through the use of laboratory data and statistical analysis procedures, the techniques which constitute the state of the art are evaluated and slightly modified to provide a more accurate procedure for identification/classification of expansive soils. Some of the more important points concerning the evaluation of published identification/classification techniques and analysis of laboratory data are summarized in the following paragraphs.

48. The definition of potential swell which satisfies the largest portion of the field simulation requirements is:

> Potential swell is the equilibrium vertical volume change or deformation from an odometer-type test (i.e. total lateral confinement), expressed as a percent of original height, of an undisturbed specimen from its natural water content and density to a state of saturation under an applied load equivalent to the in situ overburden pressure.

This definition yields the volume change potential of a material when the initial specimen and stress conditions are identical to the in-situ conditions. For predicting anticipated volume change, as will be discussed in a subsequent report, the aforementioned definition should be amended to reflect the anticipated final stress conditions such as applied load from the pavement or structure.

49. The categorization and classification of potential swell denoted as the WES classification and given in the following tabulation is a better classification of potential swell with regard to in situ conditions.

Potential Swell, %	Potential Swell Classification
<0.5	Low
0.5-1.5	Marginal
>1.5	High

The ranges of potential swell are low as compared with many of the published techniques; however, they are consistent with identification/classification techniques which used comparable magnitudes of applied load in the potential swell testing programs, i.e., Altmeyer.[21]

50. Evaluation of the 17 published techniques selected for consideration using the previously described definition and classification of potential swell indicated that four of the techniques balance both accuracy and conservatism. These techniques, in order of decreasing accuracy and conservatism are: LDOT, V&G, Sowers, and Altmeyer. In other words, the evaluation shows that the most consistent indicators of potential swell are first, the LL and PI; second, the LL and w_i combined; third, SL and PI; and finally, the SL and linear shrinkage.

51. Analysis of the laboratory data using correlation studies of potential swell versus 31 independent variables showed that the most consistent indicators of potential swell are LL, PI, SI, BLS, and soil suction at the w_i , τ_{nat} . This is consistent with the results of the evaluation of published identification/classification techniques.

52. Using the WES classification of potential swell, the categories of indicator properties which maximize the accuracy and conservatism of the criteria for identifying and qualitatively classifying expansive soils are:

LL, %	PI, %	τ_{nat} , tsf	Potential Swell, %	Potential Swell Classification
>60	>35	>4	>1.5	High
50-60	25-35	1.5-4	0.5-1.5	Marginal
<50	<25	<1.5	<0.5	Low

RECOMMENDED USAGE

53. In a previous report[29] the user was provided with a qualitative concept for identifying problem areas involving potentially expansive soils with emphasis on regional or corridor level planning. The information presented in this report is a continuation of the "narrowing" process and extends the decision process from published maps and experience to actual data for specific lengths of roadway. The information is intended as a guide to a more confident identification and qualitative classification of potentially expansive soils. The procedures should not be confused with or used in place of testing and prediction techniques for quantitatively estimating anticipated volume change. The identification/classification techniques are a prerequisite to the testing/prediction techniques and may be used as an aide to determining which soils should be tested for swell predictions. To minimize the hazard of misuse of the information in this report, the second step in the overall decision process for dealing with expansive soils in highway subgrades has been prepared, see Figure 3.

54. Following the field exploration and sampling program, routine testing of the samples will provide a majority of the data necessary to identify and qualitatively classify the potential swell of the soils (i.e., LL, PI). The remaining factor, soil suction, should be determined, and then the WES classification of potential swell, as shown in the following tabulation, may be used:

LL, %	PI, %	τ_{nat}, tsf	Potential Swell, %	Potential Swell Classification
>60	>35	>4	>1.5	High
50-60	25-35	1.5-4	0.5-1.5	Marginal
<50	<25	<1.5	<0.5	Low

The classification system above may be used without the soil suction criteria; however, it should be noted that the accuracy and conservatism of the system are reduced when the LL and PI are used without the soil suction criteria. For soils which exhibit a low classification of potential swell, the pavement design may be completed using basic

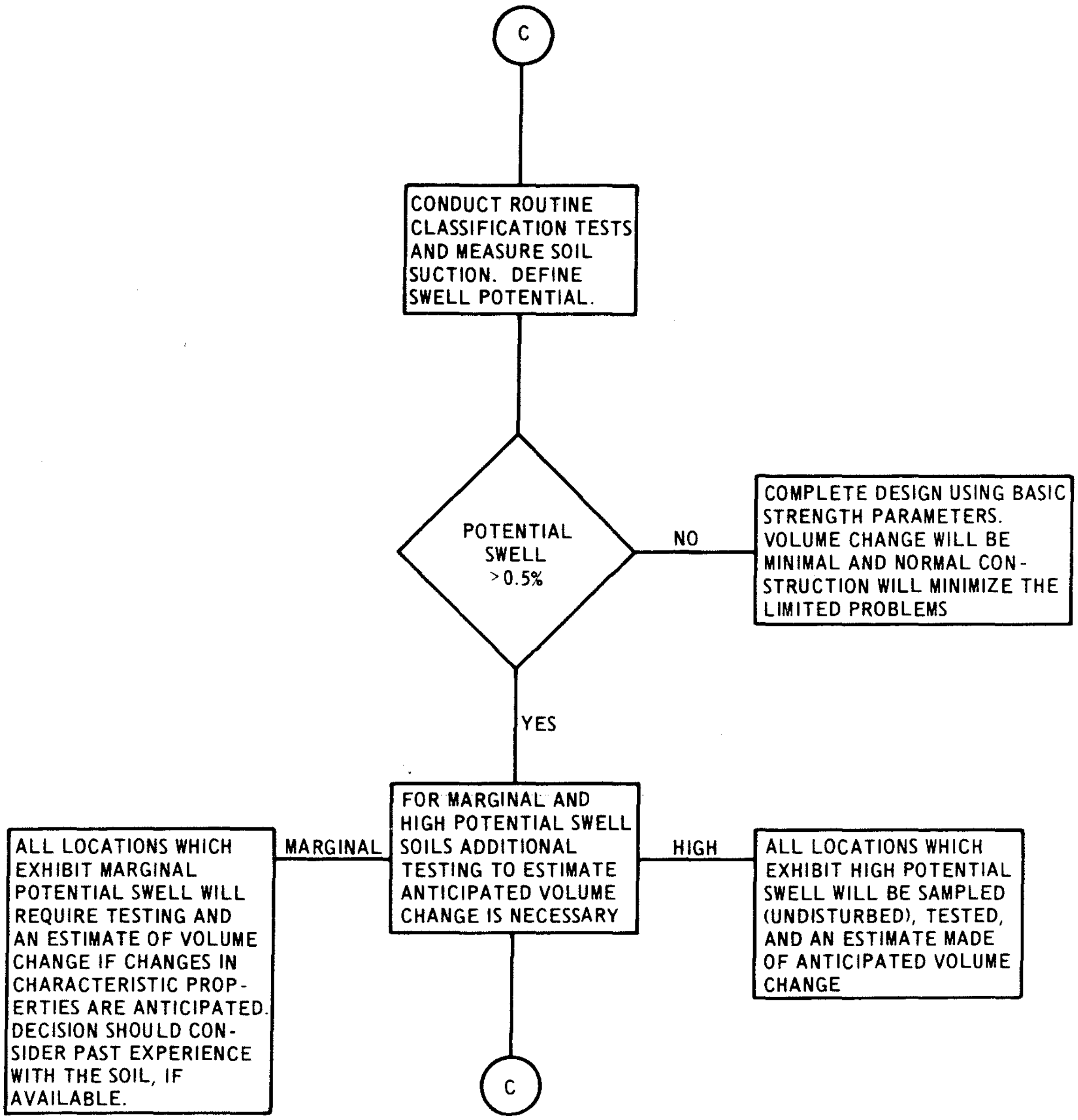

Figure 3. Recommended decision process for identifying and qualitatively classifying potentially expansive soils

strength parameters with the confidence that expansion problems will be minimal and normal construction procedures will further minimize the limited problems. For soils which exhibit a high classification of potential swell, all locations should be tested (undisturbed samples) and an estimate of the anticipated volume change made. Specific testing and prediction techniques are not recommended at this time since they are the subject of a separate research task and will be discussed in detail in a subsequent report and the next step of the decision process. For soils which exhibit a marginal classification of potential swell, additional testing at that location should be judged on the conditions at the specific site. The marginal category is indicative of a moderate to high capacity for volume change, but characteristic properties preclude the development of swell. For example, a marginal classified soil which has a relatively high w_i (i.e., greater than the PL) and a low natural density will most likely not cause serious problems and therefore not require testing. However, if conditions are such that the properties (water content or density or both) are likely to change during and following construction, then additional testing and an estimate of the volume change corresponding to the new conditions are necessary.

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