A Unified Two Independent Stress Variable Approach to Moisture-Change-Induced Unsaturated Soil Volume Change

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Abstract. In 1968, Matyas and Radhakrishna introduced the concept of the state surface, demonstrating that unsaturated soil volume change is dependent on two independent stress state variables, net total stress and suction. For decades the basic theory of unsaturated soils has been known, and a holistic view of the elastoplastic response of unsaturated soils, based on a modified state surface approach (MSSA), makes it clear that a method accounting for independent roles of net total stress and suction is required to quantify volume change of unsaturated soils. Still, reliance on pre-unsaturated-soil-mechanics-era methods persists, particularly within the geotechnical practice community. Unsaturated soil theory forms the basis for compelling arguments for discarding long-held efforts to classify unsaturated soils as exclusively expansive or exclusively collapsible with respect to volume change response. A more fundamental and unified approach to thinking about volume change of unsaturated soils supports the use of a consistent Stress Path Method to practice-based volume change analyses. Implications of geotechnical engineers' continued reliance on expansive and collapsible soil classifications, often based on index-based correlations and non-stress-path appropriate laboratory testing, are explored. Recommendations for laboratory testing and modeling for moisture-change induced unsaturated soil volume change are made.

1 Introduction

1.1 Historical Overview

From discovery in early to mid-1900's of expansion and collapse responses these phenomena have been viewed as uniquely separate geohazards. A 1910 publication cautioned of the hazard of soil collapse, recommending prewetting of ground prior to final grading and irrigation of orchards [1]. One of the earliest reports of a geotechnical engineering hazard of wetting-induced soil expansion was in 1938, relating to a U. S. government project in Oregon [2]. Not only are expansion and collapse volume change responses viewed separately for naturally occurring soil deposits, but the late 1980's saw geohazard terms of hydrocompression and hydroexpansion introduced for compacted soils [3-6]. Although descriptive of actual volume change processes, such added terms again present a picture of a phenomena that is somewhat unusual or unique, perhaps even requiring separate methods of analyses.

It is well-known and accepted that any soil with clay content can expand or collapse or exhibit essentially no volume change in response to wetting, depending on its density and the net total stress [3-10]. Yet researchers and practitioners alike continue the long-held tradition of separation of soils as expansive or collapsible. There are certainly circumstances wherein a deposit can be viewed as strictly expansive or strictly collapsible for engineering purposes, but such heavy emphasis on separation of these two volume change responses to wetting can and has resulted in failures or unexpected infrastructure performance.

In 1968, Matyas and Radhakrishna [10] introduced the concept of the state surface (Fig. 1) and demonstrated that unsaturated soil volume change is dependent on the two independent stress state variables of net total stress and suction. Using net total stress and suction as stress variables, Fredlund and Morgenstern [11] developed a State Surface Approach (SSA) to unsaturated soil volume change problems [12]. For decades now the basic theory of unsaturated soil mechanics, established in terms of two independent stress variables, has been understood [11-14]. Still, reliance on pre-unsaturated-soil-mechanics-era methods persists, particularly within the geotechnical practice community. Nowhere are these criticisms more valid than for unsaturated soil volume change problems. Although having a long way to go for full unsaturated theory implementation, in contrast, unsaturated flow and unsaturated shear strength have received considerable attention in geotechnical practice.

1.2 Compacted and Natural In-Situ Clays Exhibiting Expansion and Collapse Response

In the 1980's and 1990's considerable attention was given to wetting-induced collapse (hydro-

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compression) of deep clay fills. As depicted in Fig. 2, deep compacted clay fills have been demonstrated to be potentially expansive in upper regions, yet collapsible in lower regions [5, 6, 17]. Deep fills comprised of compacted clay, when wetted, may be expansive in upper (shallow) regions yet exhibit overall (net) collapse response. Traditionally thought of as expansive, fat (CH) clays tend to contain clods and clumps that are not easily broken down during the compaction process, rendering these soils some of the most susceptible to collapse response under high confining stress [18]. Lower PI clays (CL and SC) also exhibit both expansion and collapse response under typical field confining stresses.

Compared with compacted soils, less attention has been given to natural soil deposits exhibiting both expansion and collapse response. Natural clay deposits, particularly those comprised of SC or CL clay, may exhibit low expansion potential when tested at token load confining stress, yet exhibit collapse response to wetting in the field at depth where confining stress is substantial. At confining stress levels associated with routine geotechnical applications, it is the relatively lower PI clays (CL and SC), often in arid regions, that are most likely to exhibit both expansion and collapse under common post-development field wetting conditions.

Houston and Houston [19] reported on soil and foundation movements for a natural silt/clay deposit that

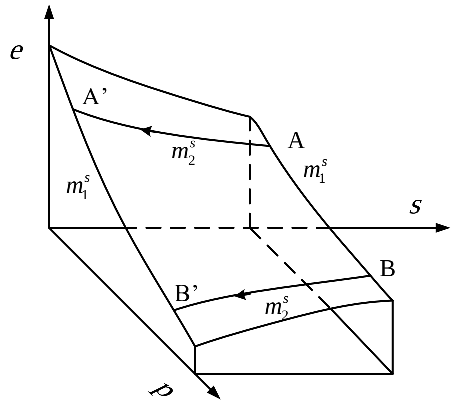

Fig. 1. Warped state surfaces for void ratio of Matyas and Radhakrishna [10], showing instantaneous state surface slopes of Fredlund and Rahardjo [15], from [16]

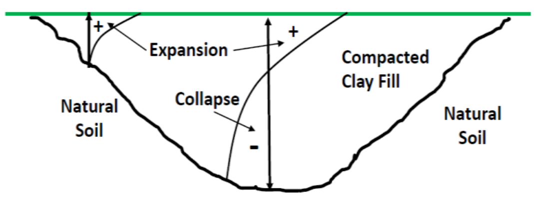

Fig. 2 Schematic of deep compacted clay fill showing shallow zones of expansion (swell) and deeper zones of collapse (compression), modified from [17]

occurred in response to accidental deep wetting. Differential foundation movements resulted in damage leading to litigation. Property damage was extensive, and continued even after partial, and ultimately complete, underpinning of the structure. Periodically, level surveys were performed on the structure during on-going damage, and considerable debate arose among experts regarding the cause (soil expansion or soil collapse) of observed differential movements and associated distress. The site is located within an arid to semi-arid region, with less than 40 mm of rainfall per year, and the deposits are predominantly of alluvial/colluvial origin. The soil profile consisted of silty soils SM/ML (recompacted to 2 m depth and extending in natural form to approximately 4 m depth), underlain by natural CL/SC soils (approximately 4 to 18 m). A relatively intact mudstone exists below 18 m. The accidental wetting (fire hydrant leak, excessive irrigation, and poor drainage) led to more than 18 m deep wetting of soils.

Site investigations performed at early stages of structural distress included oedometer response-to-wetting tests on undisturbed soil specimens. Under typically non-representative low confining stress, the CL/SC soil specimens from the site exhibited low response to wetting strains (zero to 1% expansion) at 3 to 6m depth, and moderate expansion (2 % to 3%) at depths of 9 to 14 m. Fig. 3 shows an example oedometer response-to-wetting test performed at 28 kPa vertical total stress on a specimen collected from 14 m depth. The specimen exhibited about 3% swell upon wetting to zero suction. The applied vertical stress of 28 kPa is considerably less than the estimated 250 kPa in-situ overburden for this specimen.

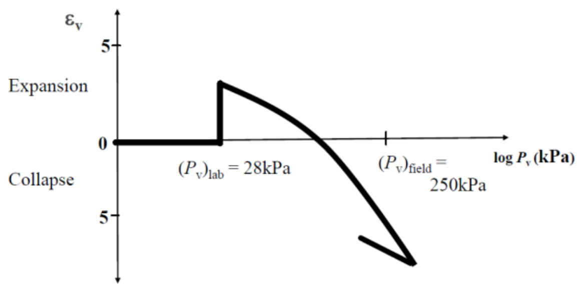

Fig. 3. Schematic of expansion response-to-wetting of undisturbed CL (PI=18) specimen collected from 14 m depth and tested at applied vertical stress of 28 kPa (1.5 m depth-equivalent).

At field overburden plus structural load stress-level (about 250 kPa), the 14 m depth undisturbed CL specimens collapsed when wetted. Ultimately, through analyses of subsurface wetting and level survey data, the wetting-induce volume change at the site was determined to be collapse. Houston and Houston [19] demonstrated consistency between level surveys and a net collapse response of soils by showing that areas of deepest soil wetting had moved relatively downward compared to areas of more shallow wetting. Having classified the site soils are expansive based on soil type and tests performed at relatively low confinement, engineers had erroneously concluded that differential building and street movements resulted from soil expansion from deep wetting of clays.

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Whether considering compacted or natural soils, engineers must take into consideration the role of both net normal stress and suction when evaluating moisture-change induced volume change of unsaturated soils. Failure to use field-appropriate stress levels in laboratory testing can lead to erroneous conclusions, even to the point of being misleading regarding the direction of soil movements (heave or collapse).

2 Unified Framework for Unsaturated Soil Volume Change

2.1 Unsaturated Soil Volume Change is Complex

The complexity of unsaturated soil volume change response is clearly depicted in the warped virgin loading state surface of Fig. 4. For a given soil with clay content, under low confining stress reduction in soil suction (wetting) results in expansion, but reduction in soil suction results in collapse for high confining stress conditions. Such complex volume change response strongly suggests the adoption of stress-path based testing and modeling methods for practice applications. The Stress Path Method for framing our thinking on solutions to geotechnical engineering problems was introduced by Lambe in 1968 and Lambe and Marr in 1979 [21, 22]. Stress path approaches hold considerable relevance for unsaturated soils given the high degree of complexity and path-dependence of response. As discussed by Lambe and Marr, the Stress Path Method is not actually a constitutive model, but rather a guide for dealing with complex geotechnical engineering problems. The Stress Path Method provides a way of thinking about geotechnical problems and serves as an aid in the planning of site investigation, laboratory testing methods, and model selection. Lambe and Marr [22] suggest the following for complex problems: " (1) Use the stress path method to examine a problem and to obtain an approximate solution; (2) use the stress path method to select an analytical procedure and to determine parameters for a more refined solution…; and (3) having the results from the more refined solution, we select an 'average' element and portray the solution in terms of stress paths for this average element."

For unsaturated soils, the Modified State Surface Approach (MSSA) [23-25] can serve analogously and as a supplement to the Stress Path Method. A simple macro-level elastoplastic framework, the Modified State Surface Approach (MSSA) represents a unifying roadmap for understanding complex volume change response of unsaturated soil, whether the soil exhibits collapse, expansion, or both. Constitutive models for unsaturated soils volume change, whether elastic, elastoplastic or empirical, are often exclusively or primarily relegated to either expansive (shrink-swell) or collapse response to wetting. The MSSA framework provides a holistic view of the elastoplastic response of unsaturated soil that clearly demonstrates the need to look beyond such artificial separations of soil types in the quantification of moisture induced volume change [16]. The MSSA framework embraces volume-change complexities and provides a useful tool for deeper understanding and evaluation of laboratory testing methods and constitutive models for moisture-change induced unsaturated soil volume change. The usefulness of this tool will be demonstrated in the pages which follow.

The deeper our understanding of unsaturated soils becomes, the more compelling the arguments for discarding these long-held efforts to pigeonhole soils into one classification or another, collapsible or expansive. Separation of unsaturated soils as either expansive or collapsible retards progress towards development of a unified approach to unsaturated soil volume change, and encourages use of empirical methods, often applicable only regionally.

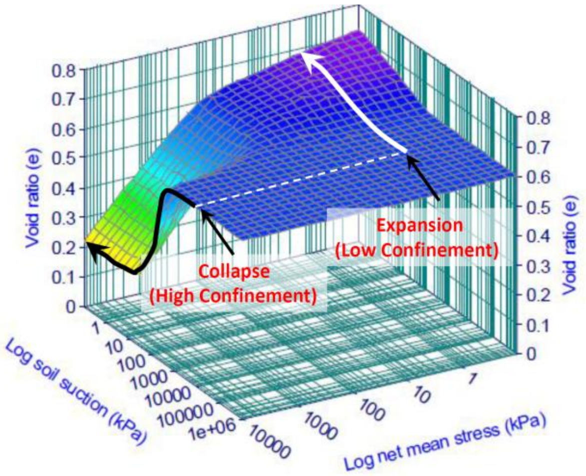


Fig. 4. Warped void ratio surface (modified from [20])

2.2 Stress Path Method Overview for Unsaturated Soil

In brief, the Stress Path Method for unsaturated soils is as follows:

- Field-representative specimens closely matching initial state of stress (in terms of confining stress, suction, density, structure, and stress history) are used in laboratory or field testing.
- Soil response and parameters are obtained from laboratory (or field) tests that follow, as closely as possible, the stress path expected to occur in the field (in terms of p and s).
- Response (e.g., strain, shear strength, flow) in the laboratory test is assumed to be the same as for the corresponding point in the field.

Complexities of soil response (nonlinearity, elastoplasticity, hydro-mechanical coupling, hysteresis, two stress state dependence) are addressed through a laboratory- field matching processes. For unsaturated soil behavior, a stress path approach can be particularly useful. Stress-path methods for soil testing and modeling are needed in the absence of not-currently-available robust and experimentally validated elastoplastic constitutive model across the full range of stress state variables of interest – one that includes hydraulic and mechanical hysteresis and hydromechanical coupling.

The Stress Path Method requires consideration of the entire past history and likely future changes to the soil. As such, a stress path approach takes into account soil structure, density, moisture content, and all past and future loading and unloading. The need for stress path-based methods in unsaturated soil mechanics has been known for decades. As stated by Brackley [7, 26], "it is vital to follow at the laboratory the expected stress-path to which the sample will be subjected in the field." Justo, et al. [7] further note that expansive-collapsing soils are "neither elastic nor linear and so stress path must be borne in mind."

Nonetheless, non-stress-path appropriate laboratory tests and index property-based methods continue to be used in identification of moisture-sensitive soils (expansive and collapsible soil). Largely due to path-dependency, differences of opinion on best-practices for unsaturated soil volume-change testing and analyses, and with the continued categorization of unsaturated soil as either expansive or collapsible. Confusion arising from our failure to carefully consider stress-path effects likely also contributes to the proliferation of correlations and regionally-focused methods of analyses for moisture-change-induced unsaturated soil volume change.

2.3 Overview of the MSSA

The conventional approach is for elastoplastic models to be developed in an incremental form using simple stress-strain relationships. Because unsaturated soil behavior is highly nonlinear and dependent on multiple stress state variables, major challenges arise for model development when the incremental form for elastoplastic behavior is used, and difficulties in selection of laboratory tests and for model calibration ensue.

The most-used unsaturated soil elastoplastic models are based on the Barcelona Basic Model (BBM) [12], which was developed primarily for collapse response to wetting (reduction in suction), and the Barcelona Expansive Soil Model (BExM) [13] which was developed for expansion response to wetting. Both the BBM and the BExM can simulate wetting–induced swelling and wetting-induced collapse through the suction increase (SI) and suction decrease (SD) yield curves at low stress levels and the loading collapse (LC) yield curve at high stress level. However, Zhang and Lytton [24] and Houston and Zhang [16] show that the evolutions of the SI and SD yield curves do not align with experimentally verified shapes of unsaturated soil virgin state surfaces. The discrepancy in the shape of the virgin loading surface between multi-yield surface models and experimental data can give the erroneous impression that elastoplastic models are dealing with unsaturated soil behavior that is significantly different from that observed by early researchers using SSA methods.

Wheeler and Sivakumar [27] experimentally verified the uniqueness of the virgin loading void ratio surface for unsaturated soils. Taking advantage of the uniqueness of the virgin loading surface and bypassing the incremental approach, the MSSA is a macro-level framework that simplifies the process of constitutive modeling and creates a clear guide for model development [24], model calibration [28], and comparisons across existing constitutive models [16, 24, 29]. Under isotropic stress conditions, the MSSA is illustrated by Fig. 5. Fig. 5a shows the stress paths for three isotropic loading-unloading-reloading tests. Fig. 5b shows a typical unsaturated soil response in the v-ln$p$ plane, neglecting hysteresis. Under a constant suction $s = s_2$, the soil specimen has an initial condition of point D. Assuming the three test specimens have identical stress history, the initial yield curve of the soil would be LY_1 in Fig. 5a with a preconsolidation stress of p_o* at $s = 0$ kPa and the yield stress at $s = s_2$ is p_2 at point E (Fig. 5b). The soil is loaded from D to E to V, unloaded from V to D', and then reloaded to F, as shown in Fig. 5b. The following observations, highlighting the key features of the MSSA, can be most easily described under simplifying assumptions of isotropic loading, expansion response-to-wetting, and constant κ and κ_s:

1) Regardless of stress path and stress history, the shape and position of the virgin loading curve EVF are always the same for the soil in the v-ln$p$ plane, Fig. 5b. Plastic loading only changes the range of the virgin loading curve. For example, the initial virgin loading curve for the soil is EVF. After loading from D to E to V, the virgin curve for the soil is VF. Compression tests can be performed at any arbitrary suction level, as shown in Fig. 5a and 5b. Consequently, the virgin curves at different suction levels as shown in Fig. 5b will form a "plastic (virgin) loading surface" in the v-p-s space such as BEHUXYZWB in Fig. 5c. The location and shape of the plastic surface will always remain the same in the v-p-s space and the plastic surface is unique. Here, the plastic surface BEHUXYZWB in Fig. 5c is the shape of the state boundary surface for isotropic conditions.
2) During an elastic loading or unloading process, for example, from D to E, from V to D', or from D' to V, the shape and position of the unloading-reloading curve remain unchanged in the v-ln$p$ plane. During a plastic loading process, the shape and slope of the unloading-reloading curve remains unchanged in the v-ln$p$ plane, but its position will change. Specifically, for assumed constant κ and κ_s the unloading-reloading (elastic) curve will move downward in parallel with the original unloading-reloading curve. The range of the lower elastic zone also expands due to the increase in the preconsolidation stress from p_o* to p_1^*.
3) The yield point V is the intersection of the unloading-reloading curve and the virgin loading curve for s=s_2.

The MSSA has been extended to triaxial stress states in the v-p-q-s space [30], to hydro-mechanical coupling, including hysteresis [25, 31, 32], and to nonlinear soil properties (i.e., non-constant κ and κ_s) [33]. In this paper, the practice-based nature of this presentation results in an emphasis on wetting paths and oedometer methods. Although not required by the MSSA, to aid in visualization herein, most of the MSSA schematics of oedometer tests are depicted under the common assumptions of K_o=1 and κ and κ_s constant, and for the void ratio constitutive surfaces only. Of course, K_o is known to change during the wetting process, and κ_s is known to decrease as suction approaches zero. Importantly, κ_s is known to decrease with increasing p (confinement) as the unsaturated soil transitions from expansion to collapse response.

3 Two Independent Stress Variables

Early attempts at development of an unsaturated soils theory using a single-valued effective stress were discarded in favor of a two stress state variable approach in the 1970's and 1980's. A primary reason for abandonment of single-valued stress state variable methods was observed wetting-induced collapse of unsaturated soils juxtaposed with wetting-induced expansion. These two very different responses to soil wetting required both positive (consistent with saturated soil response) and negative χ parameters in the following single-valued stress variable expression proposed by Bishop [34]:

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \quad (1)$$

The χ parameter was found not to be degree of saturation, as originally speculated, and was also found to not range from 0 to 1 [8, 35]. Volume change and shear strength response of an unsaturated soil cannot be explained by a single "effective" stress, and Nuth and Laloui [36] discuss that the terminology of single-valued effective stress is "quite misleading" because a second variable (e.g., relationship between soil suction and degree of saturation) is always required. In other words, any "effective" stress for unsaturated soils is constitutive in nature [37], as widely accepted.

Nonetheless, in the 1990's a search for single-valued "effective" stress again emerged among unsaturated soil mechanics researchers, and such search continues today. Some researchers have suggested that a single-valued "effective" stress is possible for unsaturated soils when elastoplastic response is considered [36, 38]. For this reason, a brief discussion is presented here on why two independent stress state variables are required for a unified approach to unsaturated soil volume change problems, whether considering elastic or elastoplastic response.

Effective stress was introduced for saturated soils. Defined as the difference between total stress and pore water pressure, effective stress is considered to be the stress state controlling shear strength and volume change response of saturated soils. For saturated soils, provided the effective stress remains constant, it is asserted that there is no volume change, or change in

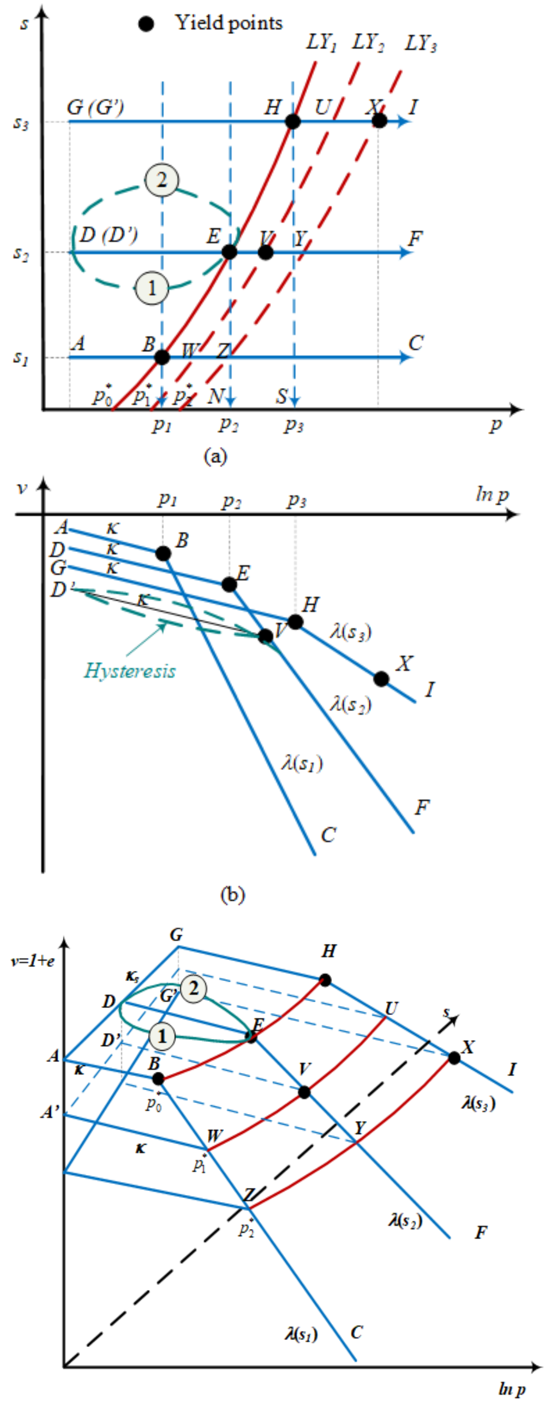


Fig. 5. Illustration of the MSSA principles from [16]. (a) Conventional interpretation of tests to determine parameters for the BBM [12]; (b) Volume change upon loading at different suctions from suction-controlled compression tests; (c) Three-dimensional representation of volume change of the soil.

shear strength. For unsaturated soils, a clear definition for an "effective" single-valued stress state variable is not readily available. Still, the most commonly adopted definition for "effective" stress for unsaturated soils is also constant-volume-based. A soil yield definition of "effective" stress has also been contemplated [39].

Fig. 6 depicts the MSSA view of the transition from saturated to unsaturated soil state. Because yield curves and constant volume curves are identical for saturated soil conditions (effective stress principles apply), soil yield and constant volume definitions are identical. However, for unsaturated soils, constant volume and yield curves diverge, as shown in Fig. 6 and as demonstrated through laboratory testing [24].

Thus, for unsaturated soils the definition of "effective" stress is unclear. A constant volume-based definition produces the uncomfortable results that yield can occur under constant "effective" stress conditions. A soil yield-based definition produces the uncomfortable result that volume change can occur under constant "effective" stress conditions.

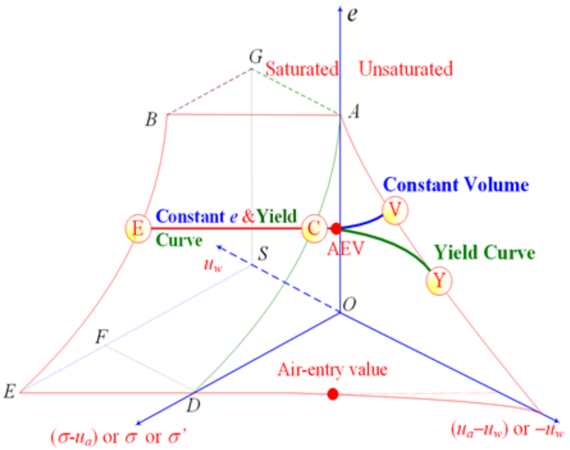


Fig. 6. MSSA View of Transition from Saturated to Unsaturated

4 Shape of the Yield Curve

One important application of the MSSA is to determine the shape of yield curves and their evolution, as discussed by Zhang et al. [40]. Within the MSSA framework, modifications to the expression used for the yield curve are based solely on the shape of the elastoplastic surface, and thus does not require classification of the soil as either collapsible or expansive – and any transition in response (e.g., collapse response at higher confining stress) is automatically handled. Because unsaturated soil behavior is closely related to the shape of yield curve, better representation and a unified approach to describing the yield curve is needed to simulate wetting-induced swelling at a low confining stress and wetting-induced collapse at a high confining stress.

The MSSA is a framework that defines the relationship between the form of the normal compression lines in the *v: p* plane and the shape of the yield curve as it expands in the *s: p* plane. The MSSA defines the yield curves as the intersection of the elastic and plastic surfaces. The evolution of the yield curves forms the elastoplastic surface or, one can say that the elastoplastic surface is a "trace" of the yield curves. Consider that the three suction-controlled compression test specimens of Fig. 5 do not have the same stress history. The tests could, for example, be ABC, D'VF, and G'XI as shown in Fig. 5c, resulting in determination of the three yield points B, V, and X, belonging to three different yield curves, LY_1, LY_2, and LY_3 (Fig. 5a).

As can be seen in Fig. 5c, in the three-dimensional *p-s-v* plot the virgin normal compression curves BC, VF, and XI will fall on a unique elastoplastic hardening surface while the elastic compression curves AB, D'V, and G'X belong to different elastic surfaces. The shape and position of the elastoplastic surface is unchanged during yielding (but the range of the plastic hardening surface will change). Consequently, the plastic hardening surface obtained from the three soil specimens with different stress histories, BCFIXV, is a subset of BCFIHE obtained from the testing of the three hypothetically identical stress history specimen tests (ABC, DEF, and GHI). Using the principles of the MSSA, the virgin compression curves BC, VF, and XI establish the shape of the plastic surface, in spite of the use of non-identical soil specimens in the laboratory testing. The elastic surface (shown here under an assumption of planar shape) is obtained from laboratory compression tests. Provided the shape of the elastic and elastoplastic surfaces are well-fit by smooth functions, the shape of the yield curve is determined by their intersection, and its evolution is established by a downward shift of the elastic surface.

Zhang and Lytton [24] analyzed the possible shape of yield curve for unsaturated expansive soils. The yield curve is the boundary separating the elastic and elastoplastic zones. Moving along the yield curve is a neutral loading process and will not generate plastic deformation. In an incremental formulation, the yield curves can be expressed as follows:

On the yield curve,

$$d\varepsilon_v^p = \left(m_1^s - m_1^{se}\right)dp + \left(m_2^s - m_2^{se}\right)ds = 0 \qquad (2)$$

where m_1^s = coefficient of total volume change with respect to mechanical stress in the elastoplastic zone, $m_1^s = \dfrac{1}{1+e_0}\dfrac{\partial e}{\partial p}$,

e_0 is the initial void ratio,

m_1^{se} = coefficient of volume change with respect to mechanical stress in the elastic zone , or bulk modulus of the soil in the elastic zone,

$$m_1^{se} = \frac{1}{1+e_0}\frac{\partial e^e}{\partial p}$$

m_2^s = coefficient of total volume change with respect to changes in the matric suction in the elastoplastic zone, $m_2^s = \dfrac{1}{1+e_0}\dfrac{\partial e}{\partial s}$, and

m_2^{se} = coefficient of volume change with respect to changes in matric suction or coefficient of expansion due to matric suction change in the elastic zone

$$m_2^{se} = \frac{1}{1+e_0}\frac{\partial e^e}{\partial s}.$$

Application of equation (2) to stress states associated with volume increase upon wetting (expansion), gives yield curves on which suction decreases are associated with an increase in the net total stress in the expansive soil zone as shown in Fig. 7. For stress states corresponding to volume decrease upon wetting (collapse), equation (2) will result in yield curves on which suction increases are associated an increase in net total stress in the collapsible soil zone, as shown in Fig. 7.

Equation (2) is sufficiently general to accommodate volume change of expansion, collapse, or both [24]. The MSSA can be used to model both unsaturated expansive and collapsible soils in a unified system by adopting a plastic hardening surface that is warped similarly to that shown in Figs. 1 and 4, and along which soil behavior can smoothly change from expansive at a low confining stress to collapsible at high confining stress level.

Thu et al. [41] conducted isotropic suction-controlled compression tests and constant confining stress soil-water retention data to determine the BBM LC and SI yield curves using conventional data interpretation methods, as shown in Fig. 7. The MSSA, and equation (2) were used by Zhang and Lytton [24] to reanalyze the Thu et al. data, producing the yield curves shown in Fig. 7.

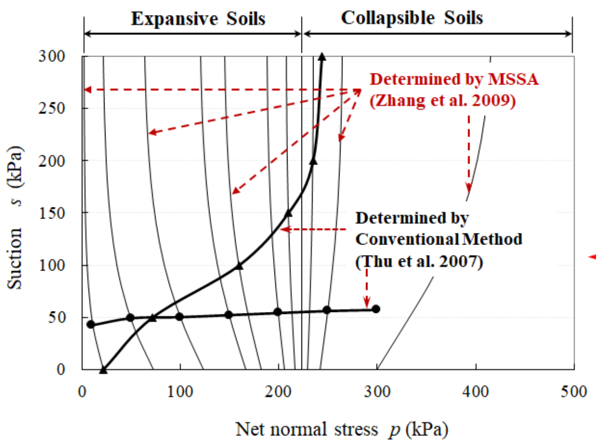


Fig. 7. Comparison between yield curves obtained from different methods, from [16]

To understand the stark difference in yield curve results of Fig. 7 requires review of assumptions of the BBM. In the original BBM the preconsolidation pressure p_0^* is restricted to be greater than any given reference pressure p^c to avoid a decrease in the preconsolidation stress with an increase in the matric suction on the yield curve, considered illogical by [12, 39]. Zhang and Lytton [24] present arguments for removal of this BBM restriction on p_o*, citing limitations of use of restricted stress path testing (isotropic compression test at constant suction and SWCC at constant confining stress).

By removing this restriction (i.e., $p_0^* > p^c$) the SI yield curve in the BBM can be discarded while expansive soil behavior can still be simulated [16, 24].

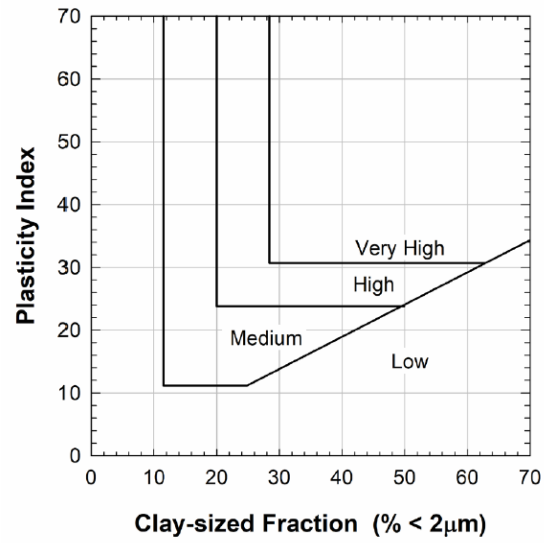
The MSSA framework can be used to simulate wetting–induced swelling at a low confining stress and wetting-induced collapse at a high confining stress for unsaturated soils. Under isotropic conditions, the MSSA only requires separation of the conventional void ratio state surface into an elastic surface and an elastoplastic virgin loading surface, and to obtain a smooth function for these surfaces. Thus, the MSSA is a unified unsaturated soil volume change framework that provides a smooth bridge between the traditional state surface approach and elastoplastic constitutive models for unsaturated soils.

5 Implications of Stress Path Method for Soil Index Property Methods

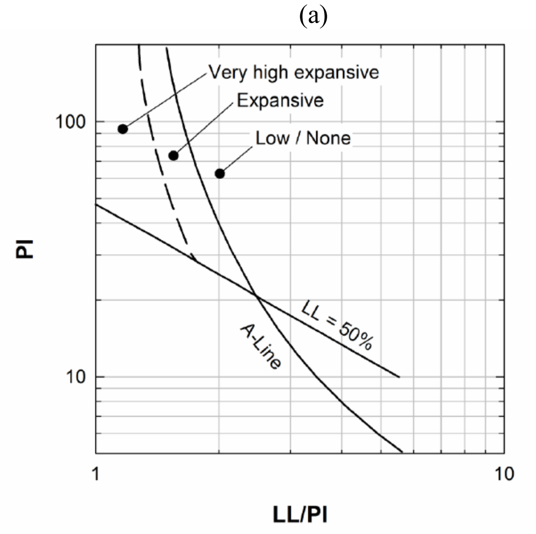
Although emphasis of the Stress Path Method is commonly placed on past and future stress (net total stress and suction) and stress path, it is equally important to capture the specimen for testing in a state as fully representative of field conditions as possible. While it is acknowledged that index-based correlations play a major role in geotechnical engineering, such correlations cannot account for effects of confining stress (net total stress) or initial soil state (density, water content, suction, structure). However, due to their simplicity, expansive and collapsible soil property correlations persist in practice [42]. Essentially every geotechnical engineering textbook presents correlations between Atterberg limits and identification (qualitative and semi-quantitative) of expansive soils. Index properties and simple correlations for collapsible soils are also common, typically involving Atterberg limits and dry density data. Index-property based correlations almost always require classification of soils as either expansive or collapsible.

A sampling of the many soil index property-based approaches to semi-quantitative assessment of moisture-changed induced volume change of unsaturated soils are presented in Figs. 8 and 9. A more comprehensive listing and discussion can be found in Holtz et al. and Vanapalli and Lu [43, 44]. There are numerous soil index property-based methods for expansion response, and relatively fewer for collapse response.

Olaiz, et al. [45] present a series of suction-controlled oedometer tests performed on clay soils exhibiting predominantly expansion response to wetting, with the data demonstrating that empirical relationships based on soil index properties alone are inadequate for making quantitative volume change estimates due to heavy dependence of the suction volume change index on stress history. Fig. 10 presents volume change indices (slope of the straight-line portion of the void ratio versus log suction) for various groupings of weighted PI (wPI = percent passing #200 multiplied by PI). Within a given category (intact or thoroughly remolded and recompacted), the suction-change index increases with increase in wPI. However, at a given range of wPI, the suction indices for intact specimens is substantially lower than for remolded specimens. Given the number of cycles of loading that intact specimens undergo in the field, intact specimens are more likely, within the range of an axis-translation suction-controlled oedometer device, to exhibit elastic response and reduced hysteretic response to wetting (and therefore lower suction - change indices). Remolded specimens are more likely to exhibit structure change for the first wetting cycle (and therefore larger suction-change indices).

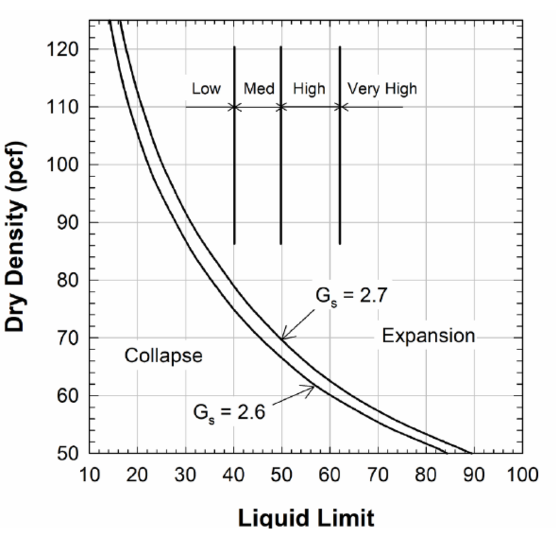


(a)



(b)

Fig. 8. Index Property-Based Correlations for Expansive Soils from [42].



(1 pcf = 0.157 kN/m^3)

Fig. 9. Index Properties and Dry Density Correlations for Collapsible and Expansive Soils [42].

Counter to the findings of Olaiz, et al., Gaspar, et al. [46] report little difference in the swell response of undisturbed and recompacted very high plasticity clays (PI=55), provided the initial void ratio and water content were comparable. Olaiz, et al. did not test companion compacted and intact specimens prepared at the same void ratio, however the intact and compacted datasets considered were relatively large and contained quite comparable ranges in specimen initial void ratio. A plausible reason for the Gaspar et al. findings is that it is relatively more difficult to affect structure change during recompaction of clays having very high montmorillonite content (high PI) compared to clays having greater proportion of kaolinite, for example, and lower PI. This is because the soil structure is affected by particle arrangement (macro-structure) as well as cementation and physicochemical interactions [46]. The Olaiz, et al. data represent a wide range in soil plasticity and clay mineralogy. Thus, for the more general case, the Olaiz data show the importance of using field-representative specimens in laboratory and field testing for unsaturated soil volume change.

An index property-based correlation developed using intact specimens could be totally inappropriate for application to compacted specimens. For example, at a given confining stress an undisturbed high PI fat clay (CH) may exhibit significantly lower expansion potential than a recompacted lower PI sandy clay (SC) or lean clay (CL). A similar problem arises from the use of dry density and PI for evaluation of collapsible soils (Fig. 9).

Laboratory oedometer tests that do not use representative soil specimens or field-appropriate net total stress loading are little-better than approaches based on simpler index tests such as Atterberg limits, gradation, and/or dry density. For example, the Expansion Index (EI) oedometer test ASTM D4829 [47] uses specimens compacted to approximately 50% degree of saturation under a typically non-representative vertical confining stress of 7 kPa. EI is widely used to evaluate expansion potential in a semi-quantitative way using the correlation shown in Table 1. Given the non-representative specimen and confining stress of the EI test, in general, semi-quantitative ratings of expansion potential, such as low, medium, or high, can be nonrepresentative of volume change response. Where clay soils of relatively high plasticity are encountered, the expansion index (EI) is often required by government agencies. Unfortunately, the EI test is often used as an option to stress-path appropriate oedometer tests, regardless of the ASTM committee "significance and use" comments that the EI test is solely for qualitative assessment of expansion potential [47].

Table 1. Potential Swell Based on EI [47]

Expansion Index, EI	**Potential Expansion**
0-20	Very Low
21-50	Low
51-90	Medium
91-130	High
>130	Very High

Further demonstrating that the EI test is little better than a soil index test, Fig. 11 by Zapata, et al. [47] shows a reasonably good correlation between the Arizona EI (EI_{AZ}) and wPI. The EI_{AZ} test is performed at 5 kPa total vertical stress on specimens compacted to 95% of Standard Proctor at water content 2% below optimum and bears a very strong correlation with the ASTM D4829 EI test. At first glance such a correlation as Fig. 11 may seem like a useful tool. Afterall, gradation and Atterberg limits test are easier to perform than oedometer tests. However, as demonstrated above, such correlations cannot be used to make quantitative or even semi-quantitative estimates of unsaturated soil volume change. Further, use of very light confining stress in performance of the EI test fails to consider the possibility of collapse of clay soils at high confining stress.

Similar criticisms can be made of the Collapse Index Test, ASTM D 5333 [49]. The collapse index is an oedometer test wherein the specimen is first loaded at field water content to a vertical stress of 200kPa, and then inundated. The collapse strain observed upon

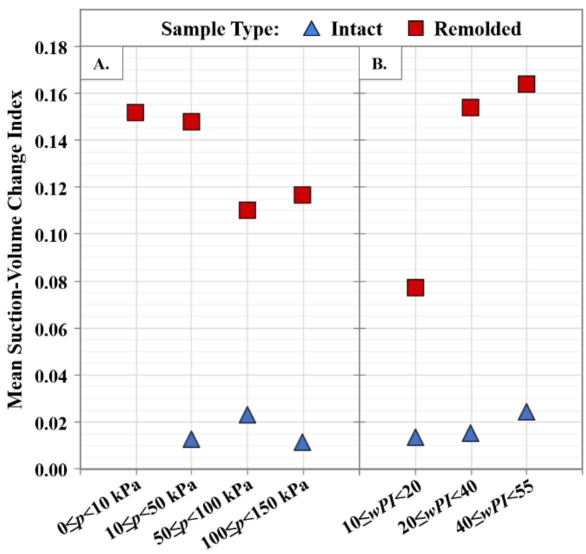


Fig. 10. Suction-volume change indices for intact and remolded specimens (modified from [45])

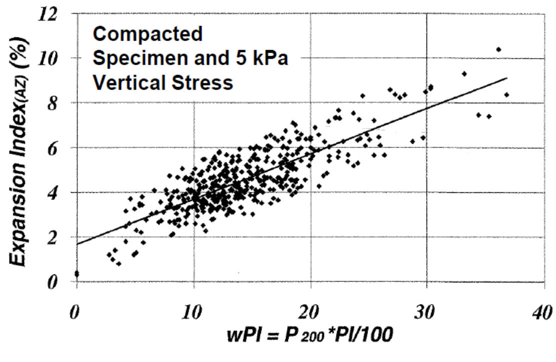


Fig. 11. Correlation between Oedometer Arizona-Expansion Index and Simple Soil Index Parameter (modified from [47])

inundation is referred to as the collapse potential. Although ASTM D5333 does not appear in the current book of standards and was withdrawn in 2012, the index test is cited by Loehr, et al. [50] as the most accepted collapse test and is used still used as a semi-quantitative indicator of collapse potential. Table 2 presents the semi-quantitative interpretation most often adopted for the Collapse Index. Because the Collapse Index test is performed at a fix confining stress level of 200 kPa, the test suffers from failure to adhere to field-appropriate stress conditions. The Collapse Index is not useful for making quantitative analyses of collapse settlement, in general. Without regard to confining stress conditions, even the semi-quantitative interpretation of collapse potential (i.e., slight, moderate, severe) is potentially misleading.

Of course, index tests, including soil classification, provide a basis for comparison across various regions and soil profiles, and therefore can be useful in preliminary site assessments for identification of possible unsaturated soil volume change problems. Index tests are useful for planning site characterization and laboratory testing. However, design and analysis questions surrounding unsaturated soil volume change problems cannot be addressed via index testing alone. Regarding index oedometer tests, such as the EI and Collapse Index, given that such tests are just as time-consuming and expensive as stress-path appropriate oedometer tests, the recommended use of such indicators in geotechnical standards, agency requirements, and building codes is questionable.

Table 2. Collapse Potential Based on Collapse Index Test, ASTM D5333 [49]

Collapse Index at 200 kPa Vertical Total Stress	**Degree of Collapse Potential**
0	None
0.1 – 2.0	Slight
2.1 – 6.0	Moderate
6.1 – 10.0	Moderately Severe
>10.0	Severe

6 MSSA and Stress Path View of Common Oedometer Tests for Moisture Increase-Induced Volume Change

6.1 Background and Assumptions

As demonstrated above, there are obvious negative implications for use of non-representative test specimens for making quantitative, or even semi-quantitative analyses for wetting-induced volume change of unsaturated soils. In the follow section it is assumed that representative soil specimens are used (i.e., undisturbed or as-field-compacted). It is assumed that sampling methods are good, and that the specimen is well-returned to its in-situ state upon reloading the undisturbed specimen to field total stress conditions under constant water content loading. In practice, empirically based sample disturbance corrections to oedometer test results may be appropriately applied [51, 52].

Despite use of high-quality representative specimens and appropriate corrections for sample disturbance, complexities of unsaturated soil volume change response require careful consideration of stress and stress path. Review of common non-suction-controlled oedometer tests within the MSSA framework can reveal stress path appropriate testing and analyses for unsaturated soil volume change, as well as demonstrate potential errors where non-stress path approaches are used.

6.2 Double Oedometer Test and Interpretation

Routine engineering for expansive and collapsible soils depends heavily on non-suction-controlled testing, particularly oedometer testing. One such test is the double oedometer test, requiring two "identical" test specimens. The double oedometer test was originally presented by Jennings and Knight [52] as a means of estimating collapse stains. Shown in Fig. 12a, one specimen is compressed at in-situ moisture conditions (in-situ moisture curve, Figs. 12a), and the companion specimen is first soaked under light load, and then compressed (consolidated) to higher stress levels (soaked curve, Fig. 12 a). The collapse strain is estimated as the difference between the wet and dry compression curves.

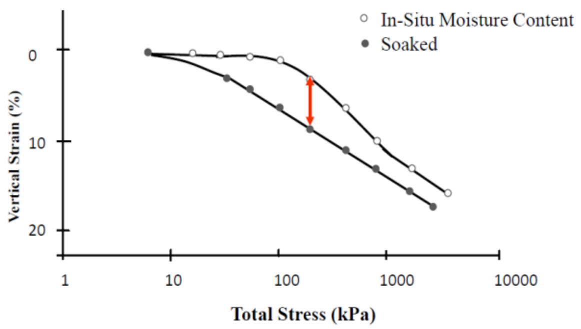


Fig. 12a. Double oedometer test on compacted soil exhibiting collapse

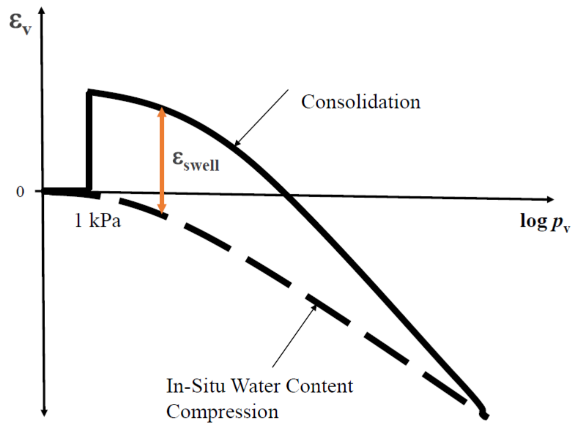


Fig. 12 b. Double Oedometer expansion response to wetting using two identical specimens

The double oedometer test is also used to estimate swell potential [54]. Two "identical" companion specimens are loaded to a nominal 1 kPa load. One specimen is soaked and allowed to swell freely, and then compressed incrementally by increasing total stress. The second specimen is compressed under in-situ moisture conditions (dry). At high stress level, the dry specimen curve is adjusted vertically to merge with the soaked curve, and the swell potential is estimated as the difference between the soaked and dry curves. This shift is apparently intended to compensate for disturbance effects and would be unnecessary under the assumption of "identical" specimens.

Snethan, et al. [55] caution that the double oedometer test may be overestimated heave when total stress levels are increased to a point where the soil would exhibit collapse upon wetting. Justo, et al. [7] present data demonstrating path-dependency of wetting-induced unsaturated soil volume change, and criticize the double oedometer test for leading to serious overestimates of swell potential under load, noting that the field stress path (typically involving wetting after loading) is violated by allowing token-load (1 kPa) free swell of the specimen.

6.3 MSSA View of Oedometer Test Procedures for Expansion Response

The literature is replete with studies comparing various oedometer methods for determination of swell pressure and swell potential for soils [56-61]. Swell potential is most often determined by first applying a fixed vertical total stress (ranging from a token load to field overburden or greater) to the dry (in-situ moisture state) specimen, and then wetting (soaking) the specimen to $s=0$ conditions. The swell potential (free swell for token total vertical loading and restricted swell for higher vertical stress loadings) is the vertical strain resulting from the wetting process. Alternatively, a double oedometer test, as described in the previous section, may be used to estimate swell potential. Swell pressure test methods include: (a) *constant volume (zero swell)* tests conducted by first applying a load to the specimen and then increasing load as the specimen is wetted to keep the specimen volume constant. (b) *load-back (swell-consolidation)* test conducted by first applying a load to the specimen, allowing the specimen to swell under the applied load under soaking conditions, then compressing (consolidating) the soaked specimen by increasing total vertical stress until the specimen is compressed to its initial, prior-to-soaking, void ratio. This method is the same as ASTM D4546 Method A or B swell potential, followed by Method C loading-after-wetting [62]. (c) *Multiple-specimen swell-after-loading (restricted swell)*, conducted on multiple "identical" specimens allowed to swell upon submergence after loading. The multiple specimen swell potential data are used to project the loading pressure that would be required to just prevent specimen swell. This methods is the same as ASTM D 4546, Method A. (d) *Double oedometer test*, wherein the swell pressure is estimated to be the total stress level at which the compressive strains of the dry specimen are equal in magnitude (and opposite in sign) to the token-load (1kPa) free swell of the soaked specimen [61].

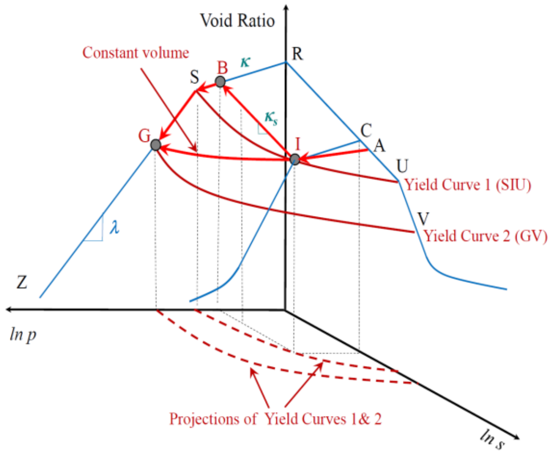
6.4 MSSA View of Constant Volume and Load-Back Tests

The MSSA provides an elastoplastic framework for evaluation and comparison of the stress paths followed under various laboratory swell pressure and swell potential testing methods. Consider the laboratory testing of a field specimen located on a yield curve (point I, Fig. 13a). It is assumed here that the field specimen exists on yield curve 1 (SIU). The specimen is unloaded during sampling from I to A along an elastic surface (URS). Using ASTM D4546 Methods A and C, the *load-back* swell pressure is determined by first reloading the specimen to field overburden stress from A to I along a constant water content path in the elastic surface, and then submerging the specimen under load (reducing suction to zero along elastic path I to B). The strain resulting from I to B is the swell potential obtained following the field stress path for 1-D Ko wetting to zero suction under overburden stress conditions. The soaked specimen is then loaded (consolidated) along BSG (points I and point G have the same void ratio). Path IBS is in the elastic surface, and SG occurs along the virgin loading, elastoplastic surface. The vertical total stress at point G is the load-back swell pressure. Projections of yield curves SIU and GV shown in Fig. 13a are consistent with expansion response to wetting curves obtained from the MSSA (Fig. 7), where suction decreases are associated with an increase in the net total stress.

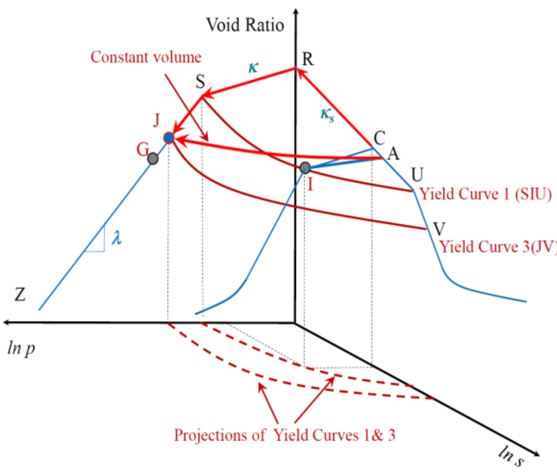
Also shown in Fig. 13a is a *constant volume* swell pressure test performed by first loading the specimen along a constant water content path AI to point I, and then loading while wetting to $s=0$ so as to keep the void ratio constant along path IG. Path IG is a constant void ratio path, not a yield curve (see Fig. 6). The constant volume swell pressure test results in specimen yield along path IG, and associated lowering of the elastic surface. Ultimately, Yield Curve 2 is reached at $s=0$, corresponding Point G having void ratio equal to point I. Neglecting sampling disturbance and hysteresis, the MSSA view shows that, starting from point I, the constant volume and load-back swell pressures should be the same, whether the soil exhibits elastic or elastoplastic response to wetting.

Fig. 13b depicts a token-load constant volume swell pressure test, along constant void ratio path AJ. Also shown is the token-load free swell and load-back swell pressure test, ARSJ. The token-load swell pressure corresponds to the vertical total stress (p) at point J, having void ratio equal to A. Note that the token load swell pressure at J is less than the overburden-swell pressure at G. Theoretically (neglecting hysteresis), the swell pressure at J (from path AJ) is less than that at G (from path IG), as found by Singhal, et al. [59]. Justo et. al. [7] also found that constant volume swell pressure increases with increasing net total stress applied prior to commencement of soaking.

Unrelated to the elastoplastic path-dependence discussed above, Gaspar, et al. [46] asserted that the load-back swell pressure, for practical application purposes, could be assumed to be relatively insensitive to the applied vertical stress prior to wetting. Justo, et al. [7] reported that load-back swell pressures were not highly sensitive to load applied prior to soaking, except for very light confinement during free swell (less than 5 kPa) which resulted in J being a larger vertical net total stress, sometime much larger, than the net total stress of G when following the load-back path ARSJ. A plausible explanation of the Justo, et al. observation is that soil structure changes occur when fat clays (e.g. high montmorillonite content) are allowed to swell under very light confinement; wetting the specimen under very light load allows a type of specimen disturbance (structure change) this is not related to elastoplastic unsaturated soil volume change response discussed here. In general, soaking a specimen under token load may result in excessive and undesirable soil structure change, depending on the soil mineralogy. Montmorillonite (high PI clays) are likely most sensitive to structure change upon soaking under token load compared to low PI soils. Consistent with the above discussion, Singhal, et al. [59] computed higher coefficient of variability for token load swell pressures compared to overburden swell pressures.



(a)



(b)

Fig. 13. Oedometer Swell Pressure and Expansion Response to Wetting Tests (a) Field vertical stress (ASTM D4546 Method B) [16] and (b) Token vertical stress.

The load-back swell pressure test procedure is easy to perform and holds some advantages over the constant volume swell test. Where the load-back test is performed on a representative specimen first loaded to field total stress level (ASTM D4546 Method B), a subset of the test provides stress-path appropriate full-wetting volume change. Absent Servo-control, the constant volume swell test is difficult to perform, and even the very small allowed vertical strains or system compliance errors from load-measurement can result in significantly variable measured swell pressure. Indeed, constant volume swell pressure is often reported to be lower than swell pressure obtained by other methods, particularly the load-back [60, 61]. Difficulties in test performance and in obtaining consistent swell pressure resulted in withdrawal of the former ASTM standard for the constant volume swell pressure test. Further, the constant volume test provides no stress path appropriate data for estimation of volume change.

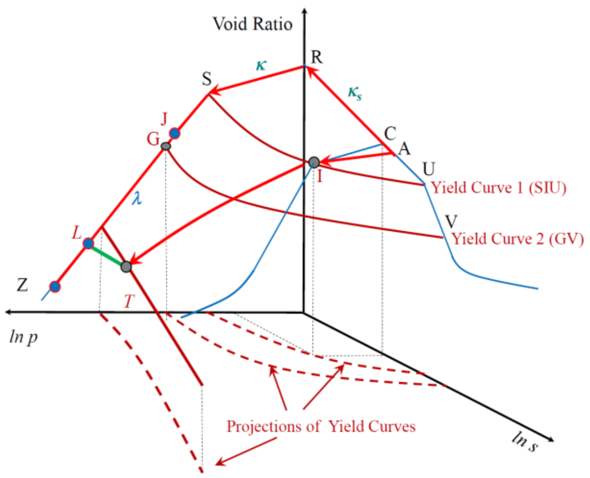
In consideration of the MSSA view of the swell potential and swell pressure estimation methods, a stress-path appropriate and practical approach to laboratory testing where expansion response to wetting is anticipated is to use ASTM D4546. Swell potential is obtained using Method B (wetting from field vertical total stress, e.g., path IB), then load-back of the wetted specimen (BSG) is used to obtain an estimate of swell pressure (p at point G).

6.5 MSSA View of Double Oedometer Test

The *double oedometer* procedure for estimation of swell pressure is shown in Fig. 14. Two "identical" specimens are tested. The first specimen follows along path ARSZ. The second test specimen is loaded along constant water content path AIT. The swell pressure is interpreted as p at point T along the AIT path where the compressive strain is equal in magnitude to the expansion strain observed at point R [61]. In this interpretation of the double oedometer test, it is assumed that wetting form T under constant p will result in a constant void ratio path from T to L. This assumption is, however, not directly demonstrated through laboratory testing, and Kayabali and Demir [61] found that the double oedometer test over-estimates the constant volume swell pressure (token load, J, and overburden load, G).

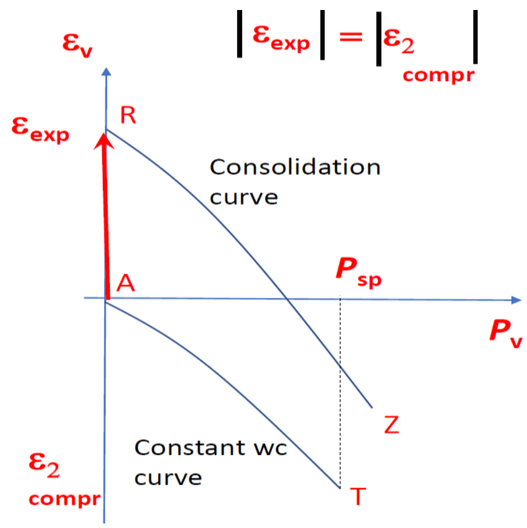
In the interpretation of the double oedometer test, at any given p, the difference in void ratio between the soaked specimen consolidation curve and the dry specimen compression curve is taken to be the swell potential [54]. Justo, et al. [7] and Snethan, et al. [55] report that the double oedometer test over-estimates swell potential. Other researchers find that the double oedometer test results in reasonable estimate of swell potential [54, 63].

As shown by the MSSA view of Fig. 14, where response of the soil is elastoplastic, given that neither test specimen of the double oedometer test follows field-appropriate loading path (IB, Fig. 13a), it should not be expected that the double oedometer test would consistently return reasonable results. Failure of the double oedometer test to follow appropriate stress path was also cited by Justo, et al. [7]. Further, there is an implicit elastic and saturated soil effective stress approach to the interpretation of the double oedometer tests, where volume change from point A upon wetting to zero suction (AR) is equated (in terms of equal magnitude, but opposite sign) to volume change arising from constant water content loading from point A to T in determination of swell pressure. Provided the soil remains saturated and in the elastic range during the entire test series, the double oedometer test interpretation would be expected to provide good estimates of both swell pressure and swell potential. Such a circumstance, although not generally applicable, is possible where the soil is of very high PI and where the soil specimen has previously experienced greater loading (in terms of p and s) compared to laboratory and field loading. In general, however, the double oedometer test approach cannot be relied on to return good estimates of swell potential or swell pressure.



(a)

Fig. 14a. MSSA View of Double Oedometer Tests for Two identical specimens.



(b)

Fig. 14b. Double Oedometer Tests swell pressure interpretation

6.6 MSSA View of Multiple Specimen Loaded Swell Test

The multi-specimen test follows the expected field stress path if the swell pressure is defined as the net vertical stress that would have to be applied to the field specimen so that there was zero response to wetting (no expansion and no collapse) upon full wetting to zero suction. This definition of swell pressure is arguably the most used in geotechnical practice.

The MSSA view of the multi-specimen test ASTM D4546 [62], method A, is shown in Fig. 15. In the multi-specimen test, a series of identical specimens are loaded along the constant water content path AIXMQ to various levels of confinement (*p*), and then submerged under these differing constant vertical stress levels. Because wetting under low confining pressure for expansion response is unloading, wetting paths IB and XD occur on elastic surfaces, but the elastic surface of path XD is different and lower from the elastic surface of path IB. The yield curves associated with points I and X are consistent with expansion response to wetting, as more easily seen in the yield curve projection for points I and G of Fig. 15 (point X falls on a yield curve intermediate between SIU and GV and therefore is also expansive). Wetting of a third specimen under high confining stress from point Q results in collapse (point K on the *s=0* plane). Points Q and K fall on a plastic surface which is consistent with collapse response where increase in suction is associated with increase in *p* along the yield curve.

A curve BDK connecting the full wetting swell or collapse response void ratio points could be drawn in the *s=0* plane, but such a curve is not a state surface because point D is on an elastic plane below the state surface. Justo, et al. [7] report that loading after soaking curves (e.g., BSK, Fig. 15a) stay above the soaking under loading curve (e.g., curve BDK) in the swell zone (consistent with point D falling below the state surface, Fig. 15a) due to expansion being an elastic unload process. Zhang and Lytton [24] also report that soaking under loading curves fall below loading after soaking in their reanalysis of the Brackley [26] expansive soil data.

As depicted in Fig. 15b, the measured strains at B, D, and K are used in the multiple specimen test (ASTM D4546, Method A) to estimate point M (zero strain upon wetting), corresponding to the stress level *p* that would be required to be applied at the field specimen I to avoid any response to wetting (no expansion and no collapse). If, starting from point A, the specimen were first loaded to M along the constant water content path, wetting of the specimen under constant total vertical stress would result in zero change in void ratio (i.e., a constant void ratio path would be followed from point M to virgin loading surface on the *s=0* plane). The yield curve at point M, as shown in the projection on Fig. 15a, is consistent with slight collapse response. This is because wetting under constant net total stress from point M causes a tendency for specimen expansion corresponding to unloading along an elastic surface, and this tendency towards expansion is balanced by a tendency towards collapse of the macrostructure resulting from wetting-induced softening at particle contacts. Consistently, Schreiner, Burland and Gourley [56] discuss that changes in soil structure associated with collapse take place simultaneously with swelling due to absorption of water by particles.

The stress level, *p*, at point M is the swell pressure for the multi-specimen test series (soaking after loading). Neglecting sample disturbance and hysteresis, the swell pressure for the multi-specimen tests would be expected to be somewhat greater than the load-back or constant volume swell pressure (point G, Fig. 15b). This observation is consistent with Gaspar, et al. [46] where an average multi-specimen test swell pressure value of 360 kPa compared to an average load-back swell pressure of 280 kPa. Justo et al. [7] also found that swell pressure by constant volume was somewhat less than that by multi-specimen testing.

The multi-specimen test using identical specimens is argued to be, theoretically, the best stress-path consistent approach to determination of swell pressure. However, it is challenging, particularly for natural soil deposits, to obtain representative "identical" specimens. For compacted soils where the entire fill is prepared using one compaction specification, the multiple specimen test also provides an estimate of expansion potential, and if sufficiently high confining stresses are applied, collapse potential, over a wide range of fill depth. Natural deposits are unlikely to be of sufficient uniformity, in general, for the multiple specimen test to be generally useful for estimation swell potential for any depth within the profile other than that associated with (or very proximate to) the depth of sample collection.

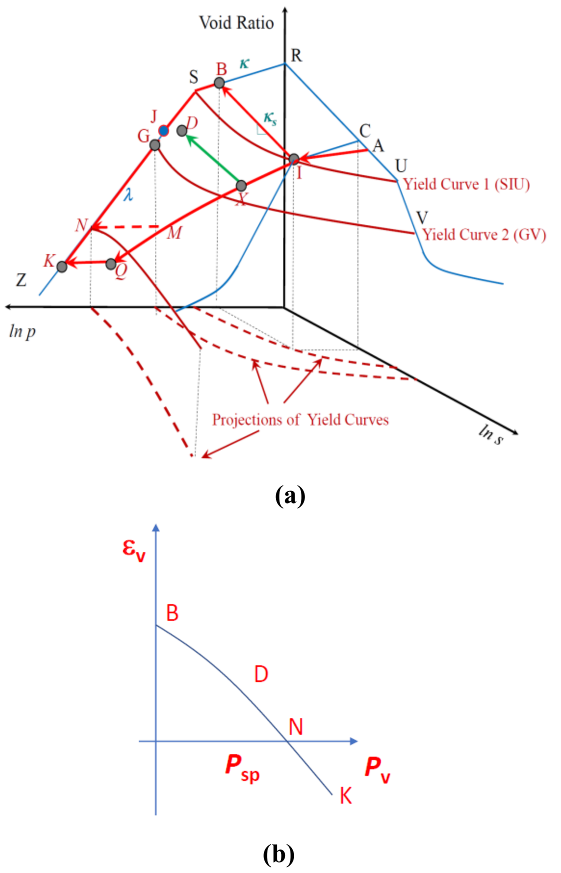


Fig. 15. MSSA View of Multiple Specimen Test ASTM D4546, Method A (a) Swell Potential, and (b) Swell Pressure

6.7 Oedometer Tests for Collapse Response

6.7.1 Common Test Procedures

The most-used oedometer tests for quantification of field collapse settlements are: (1) wetting after loading (e.g., ASTM D4546, A or B) and (2) the double oedometer (loading after wetting of one specimen and loading at in-situ moisture on a second "identical" specimen). These testing methods are explored below within the MSSA and Stress Path Method frameworks.

6.7.2 ASTM D4546- Wetting After Loading

Consider an unsaturated soil specimen in the field with stress state corresponding to point I in the elastic range, Fig. 16. One test specimen, starting from point V, is loaded along a constant water content path (VW) to field-level total vertical stress, corresponding to point I. The specimen is then wetted to $s=0$, following path ITB. The change in void ratio from I to T is negligible and elastic while change in void ratio from T to B is the more substantial elastoplastic part of the full-wetting volume change response termed the collapse potential (ITB). Path ITB follows the stress path anticipated for field conditions when total stress levels remain constant, and subsequently wetting occurs. Thus, the collapse strain resulting from full wetting (path ITB) gives the best-estimate of field strains that would occur at point I if the soil suction is reduced to zero (e.g., by rising groundwater table). For collapse response to wetting, point B is guaranteed to fall on the unique virgin loading surface YZ. Consistent with collapse resulting in yield, Justo et al. [7] observed little to no path dependency for response-to-wetting of clay soils in the collapse zone.

The single-specimen procedure ASTM D4546, Method B, is used for estimation of response-to-wetting of natural soils. Although suggested for compacted specimens, ASTM D4546 Method A, the multiple specimen test, can also be used for natural soils, but it may be more challenging to obtain an "identical" companion specimen. The multiple specimen test procedure can be used to provide an estimate of the total vertical stress corresponding to the cross-over from collapse to expansion, analogous to determining swell pressure for soils exhibiting primarily expansion response (Fig. 15b). In Fig. 16, the field response-to-wetting of specimen I is collapse, and therefore the second test specimen is wetted at a reduced total vertical stress level (lower than that at I) to reduce the amount of collapse. Where the second test specimen exhibits slight collapse upon soaking, point G remains on the virgin loading surface. However, if stress level reduction is sufficient to bring the specimen into the expansion response range, point G (at $s=0$) would fall on the elastic surface (XY) of Fig. 16. Of course, it is likely that there is either expansion or collapse for wetting along constant p from any point J, in which case a procedure of plotting full wetting vertical strain for specimens I and J can be used to estimate the zero strain upon wetting cross-over stress between expansion and collapse.

In the case of collapse response to wetting, wetting under constant load (e.g., along path TB, Fig. 16) results in specimen yield. This is consistent with the shapes of the yield curve for collapse response regions of the virgin loading surfaces shown in Fig. 7 and in Fig. 16 (yield curve YW), where increase in suction is associated with increase in p. The wetting after loading test, ASTM D4546, Method B, represents a common 1-D, Ko field stress path condition wherein collapse strains occur due to post-construction wetting events. ASTM D4546, Method B, provides a best-estimate of 1-D, Ko full-wetting collapse potential in the field. A second companion test (such as would be used for ASTM D4546, Method A) is not required for assessment of full-wetting collapse potential.

6.7.3 Double Oedometer Test

The double oedometer test requires testing of two "identical" specimens. Double oedometer test specimen 1 follows VJIW constant water content path (Fig. 16). Double oedometer specimen 2 is wetted under token load along path VX, then consolidated along the $s=0$ path XYZ (Fig. 16). The collapse strain is computed from the difference in void ratio, at any given p, between the specimen 1 and specimen 2 curves (Fig. 12a).

Neither specimen of the double oedometer test follows the field stress path. However, when the applied confining stress is such that the response to wetting is collapse, the specimen yields such that the full-wetted position is always on the unique virgin loading surface (YZ). In other words, the virgin loading portion of the soaked specimen curve is unique, and therefore collapse strains for full wetting conditions are not path dependent. Neglecting sample disturbance, the double oedometer test would be expected to provide the correct full-wetting collapse potential in the collapse zone confining stress range. For low stress levels (expansion zone), the double oedometer method cannot be expected to provide field-appropriate response to wetting results.

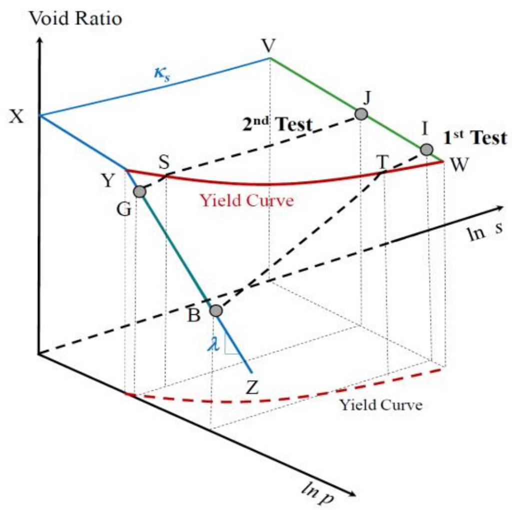


Fig. 16. MSSA View of Collapse Response to Wetting Using ASTM D4546 (modified from [16])

For cemented collapsible soils the constant water content loading path, VW is quite flat, such that only minimal volume change occurs. Under this scenario, where the dry loading curve results in significant compression of the specimen, sample correction measures are required for correct test interpretation, and the best estimate of full wetting collapse potential is obtained by taking the difference between the initial (unloaded dry specimen) void ratio and the void ratio observed after soaking [51]. This recommendation is based on the observation of many large to medium scale field plate load tests which show that dry loading curves exhibit more or less insignificant strains (for engineering applications), especially when some cementation is present – which is very often the case.

6.8 Summary from MSSA Views of Common Oedometer Response-to-Wetting Tests

Because collapse response to wetting results in yield of the soil, the "wetted curve" for soils exhibiting only collapse response will always be along the virgin loading surface, regardless of the stress level applied prior to wetting. The "classical" collapsible soil is highly structured, at least somewhat cemented, and of low PI. Such soils may not exhibit noticeable expansion response, even under very light confining stress. The fact that the collapse "wetted curve" follows along the unique virgin loading surface explains why, for collapsible soils, the wetted curve has been observed to be more or less unique and independent of stress level applied prior to wetting [7, 51, 64].

In the collapse zone, stress-path was found by Justo, et al. [7] to have little effect on the final ($s=0$) void ratio (i.e., the soaked curve for collapse response zone was found to be more or less path independent). Experimental data show that loading after soaking curves stay above the soaking under loading curve in the swell zone [7, 24]. Consistent with these laboratory findings in the expansion zone, wetting under constant load (e.g., IB and XD, Fig. 15) occurs along an elastic (unloading) surface, such that point D, at $s=0$, falls below the virgin loading elastoplastic surface. Thus, path dependence of wetting induced volume change is expected in the expansion zone, when the MSSA framework and elastoplastic behavior are considered.

As seen in the Figs. 13, 14, and 15 MSSA views of oedometer tests, yield of an unsaturated soil can occur in response to changes in p and/or s. Of particular note is that a constant volume swell test (path IG, Fig. 13a) can result in specimen yield and advancement of the yield curve along the virgin loading (elastoplastic) surface. This is consistent with demonstrated divergence of the yield curve and constant volume curve for unsaturated soil conditions (Fig. 6). Within the MSSA framework, neglecting hysteresis, wetting under constant net total vertical stress in the expansive zone is elastic and does not change the yield stress. Fig. 13a and b MSSA views of the constant volume swell pressure and load-back swell pressure show that these swell pressures are the same when hysteresis and sample disturbance are neglected. However, both the load-back and constant volume swell pressure increases with increasing pre-soaking applied confining stress.

Swell pressure definitions vary among geotechnical engineers. An observation from the MSSA views of oedometer tests for expansive soils is that different testing methods and interpretations result in differing values of swell pressure. For example, the MSSA shows that swell pressures J (token load constant volume), G (field overburden constant volume), and M (multiple test specimen) should be expected to be different (Fig. 15a). The swell pressure could also be viewed as the net total stress, along a constant initial field suction plane, that separates wetting induced expansion from wetting induced collapse (corresponding to a p slighter less than p at point M, Fig. 15a). Depending on how swell pressure is used in foundation design and analyses, such differences in swell pressure may or may not have engineering significance.

Most geotechnical engineers would define swell pressure as the overburden plus structural load that would need to be applied to a clay soil to just prevent swell upon wetting to zero suction (full wetting). Under this definition, the multi-specimen test series (ASTM D 4546, Method A) is the only stress-path based method for obtaining swell pressure. However, difficulties in obtaining identical test specimens results in some resistance to use of ASTM D4546, Method A, particularly for natural soils. Hence, use of ASTM Method B, single specimen swell potential test followed by Method C, swell pressure by load-back, is very appealing for practice, and is stress-path appropriate for determination of swell potential when the soil specimen is loaded to field total stress levels prior to wetting. Arguably, the most important result from an oedometer testing program is swell (or collapse) potential, and swell pressure is a relatively less important. Following the Stress Path Method, representative specimens from various depths within the soil profile are obtained and tested for response to wetting under field-appropriate stress path [21]. Thus, the Stress Path Method does not rely on testing of "identical" soil specimens.

7 A Direct 1-D, K_o Suction-Controlled Method for Volume Change

7.1 Partial Wetting

Any Stress Path Method for estimation of volume change of unsaturated soils must account for field stress paths with respect to both net normal stress and soil suction. In the traditional oedometer device soil suction is not measured, and therefore the moisture state of the soil specimen can only be known or estimated at the initial and final state. To estimate the initial soil suction, various techniques are available, including as examples, the WP4C (Meter Group, Inc.), filter paper, or high capacity tensiometer. Although constant water content loading of a natural water content sample results in some change in soil suction, it is typically assumed that a measurement made prior to "dry" compression provides a sufficiently accurate initial suction estimate for routine engineering applications. When the oedometer specimen is submerged (soaked) in water, it is assumed that sufficient time is allowed for the soil to absorb as much water as required to bring the soil matric suction value to essentially zero (full wetting).

Traditional oedometer testing of unsaturated soils involves wetting of the soil to *s=0*, but for field conditions it is common that wetting results in some, but not complete, relief of suction [65]. Because suction-change is the primary unsaturated soil volume change driver, it is a necessary part of stress-path-appropriate volume change methods to estimate soil suction along the wetting path in the laboratory as well as in the field.

7.2 Use of the OPPD – An Approach for Shrink/Swell and Collapse Response

Oedometer devices that provide for measurement and/or control of soil suction and net total vertical stress, allowing stress-path testing for 1-D, K_o conditions, are available to the practice community. One such device is an oedometer pressure plate device (OPPD), which uses axis-translation suction-control methods [45]. Other suction-controlled oedometers include osmotic suction-control and high capacity tensiometer measurement methods [66-69]. Suction-controlled oedometer devices are rarely used for routine foundation design problems.

The oedometer pressure plate device (OPPD) will be discussed here as an example of a suction-control oedometer testing method that is useful for 1-D, Ko stress-path testing whether expansion or collapse response results from wetting. One significant advantage of the suction-controlled oedometer device is that it can be used for expansion, collapse, and shrinkage [70]. Disadvantages of suction-controlled oedometers include typically lengthy test times and required careful attention to detail in testing to ensure accurate suction and water content measurement [71, 72].

The suction-controlled oedometer device can be used to obtain a complete void ratio surface, as shown in Fig. 17 [73]. In addition to the wetting tests of Fig. 17, Singhal performed OPPD tests on a series of clay specimens following constant total vertical stress wetting and constant total vertical stress drying (shrinkage) paths. It is often assumed that the vertical strains observed during OPPD drying test on clays cannot be used directly to determinate volumetric strains due to radial shrinkage away from the side walls. Singhal found that application of net total vertical stress to the specimen often prevented radial shrinkage, and that compacted specimens were much less likely to exhibit radial shrinkage under load compared to slurry specimens. Fig. 18a shows the absence of radial shrinkage on a disassembled OPPD test for a compacted clay specimen subjected to 25 kPa vertical total stress; Fig. 18b shows substantial radial shrinkage for an lightly confined slurry specimen dried to 400 kPa suction; Fig. 18c shows the relative lack of radial shrinkage for a PI=42 compacted clay dried from a soaked state to 400 kPa suction. The pictures of specimens in Fig. 18 suggest that the typical practice of performance of laboratory shrinkage tests under zero confinement conditions should be re-evaluated in the context of stress-path methods.

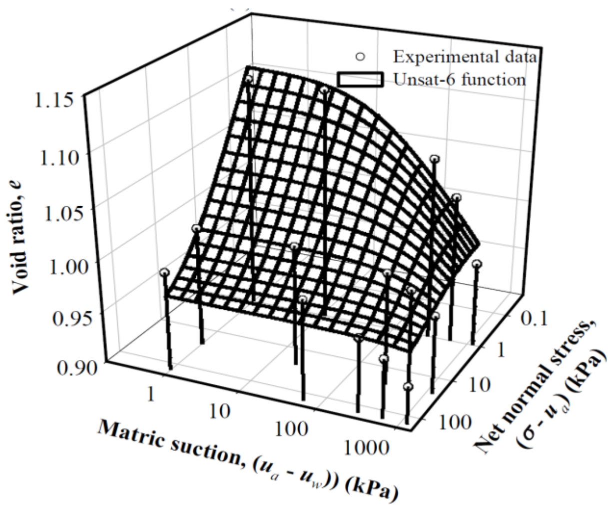


Fig. 17. OPPD determined expansion response to wetting for a compacted clay soil using Unsat-6 fit to surface [73]

Fig. 18a. Net normal vertical stress 25 kPa; PI=27, compacted specimen, dried to suction of 400 kPa [73]

Fig. 18b. PI=42 specimen dried from slurry to 400 kPa suction under total vertical stress of 3 kPa [73]

Fig. 18c. PI=42 compacted specimen dried from *s=0* to 400 kPa suction under total vertical stress of 3 kPa [73]

Notwithstanding obvious advantages of suction-controlled for stress-path appropriate testing, there are substantial obstacles to use of suction-controlled testing in routine geotechnical engineering practice. Until progress is made in suction-controlled testing with respect to testing difficulties and test duration, traditional oedometer testing will prevail in the routine practice methods used to quantify unsaturated soil volume change. It is therefore of value to pursue approaches to unsaturated soil volume change analyses that are based on theoretically sound unsaturated soil principles yet make use of traditional non-suction-controlled laboratory tests.

8 A Unified Practice-Based Stress Path Method for Partial Wetting Unsaturated Soil Volume Change under 1-D, K$_0$ Loading Conditions – The SPM

The Surrogate Path Method (SPM) is appropriate for soils exhibiting expansion, collapse, or both, and uses laboratory results from conventional oedometer devices having no suction control or measurement capability [16, 65, 73]. As such, it is a unified approach to computation of moisture-change induced expansion or collapse volume change of unsaturated soil. The SPM remains as true as possible to the MSSA representation of unsaturated soil elastoplastic response while using routine oedometer test results [16]. Laboratory tests following field-appropriate stress paths are used, and the laboratory testing approach is an integral part of the SPM. Because the method is based on ASTM D 4546 A and/or B, the SPM could also reasonably be thought of as a Stress Path Method, which could, coincidentally, also be abbreviated SPM.

Because suction is not controlled in the SPM laboratory test, suction can only be estimated for initial and final test conditions. In the SPM, a surrogate path in the $s=0$ plane is obtained through a mapping process of the actual stress path to estimate wetting induced volume change for less than full saturation (to suction values between initial and $s=0$). Although not required for using the suction interpolation approach of the SPM, the mapping onto the $s=0$ plane provides a comfortable format for geotechnical practitioners who have become accustomed to using methods of unsaturated soil volume change analyses (e.g., most heave computation methods) that are presented in the $s=0$ plane. Because suction-change is the driving mechanism of primary interest for most unsaturated soil volume change problems (particularly those of expansion and collapse), it is essential that field profiles of the initial suction and the final design suction be estimated in the quantification of moisture-changed induced volume change of unsaturated soils. Discussion of measurement and estimation of initial and design suction values is beyond the scope of this paper, but approaches are available for use in practice for certain limited applications (e.g., [74]).

The suction-based mapping from the s-p space to the $s=0$ plane is a unique feature of the SPM which anchors the result of the volume change computation to fall between the full-wetting ($s=0$) strain (ASTMD-4546 single specimen test) and zero strain for the case of no wetting. In addition to the D-4546 test result, the mapping process requires an estimate of the net total stress corresponding to zero volume change upon wetting (e.g., the swell pressure for expansive soils). The initial field suction and the final field suction must also be known or estimated.

Fig. 19 shows the SPM surrogate path BG with slope λ_{sp} for wetting under constant load from point I. Point B is obtained from ASTM D4546, Method B (wetting under field overburden load). Point G (swell pressure), is most often obtained by load-back of the Method B specimen, but could also be obtained using the multiple specimen method, ASTM D4546 Method A. The results of the SPM are not very sensitive to the method used to estimate swell pressure [65, 73]. Mapping from path IFB (the actual path) to GB (the surrogate path) is accomplished through a simple ratio of initial and final soil suction, with the intent that, for partial wetting, the void ratio at point Q on the surrogate path matches the void ratio at point F on the actual path.

Following is a brief overview of the SPM computation for expansion response to wetting, considering the Fig. 20, $s=0$ plane view.

$$\sigma_p = \sigma_o + R_w (\sigma_{cv} - \sigma_o) \tag{3}$$

where, R_w = suction ratio = s_f / s_i
s_i =initial matric suction
s_f =final matric suction
$R_w = 1$ for no wetting
$R_w = 0$ for full wetting
σ_p = surrogate final stress corresponding to final suction.
$\varepsilon_{pw} = (C_H)_{SP} \log (\sigma_{cv}/\sigma_p)$ = partial wetting swell strain.
where $(C_H)_{SP}$ =slope of the Surrogate Path on the p (net total stress) and $s=0$ plane.

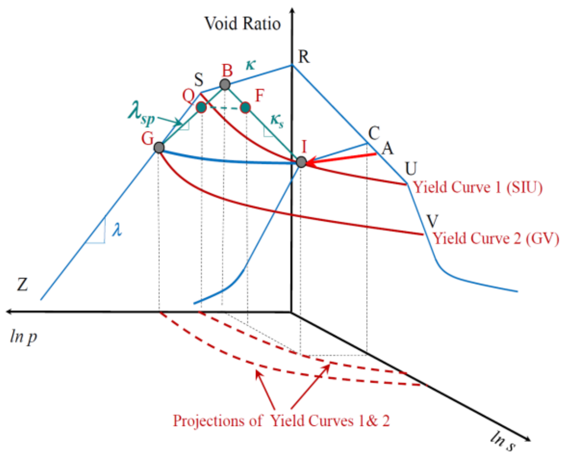


Fig 19. MSSA view of the Surrogate Path Method (SPM) for expansion response-to- wetting

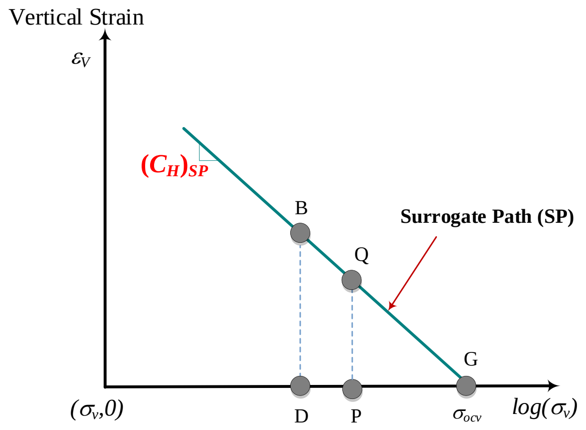


Fig. 20. Surrogate Path Method (SPM) on $s=0$ plane

The SPM mapping approach has been shown through some limited amount of OPPD testing to result in reasonably good agreement between swell strain (void ratio) at points F (on the actual path) and void ratio at point Q (on the surrogate path) [65, 73]. Additional checks on this simple mapping function for expansion and collapse response are encouraged. However, whether the mapping is "excellent" or not, the computed strain is always guaranteed to be reasonable, falling between the full wetting strain and zero, and avoiding gross over-estimates or underestimates that are known to occur with some other volume change estimation procedures [16, 73].

The MSSA view of the SPM for collapse response is shown in Fig. 21. For this case, the field specimen is assumed to exist at point I, on the elastic plane WVXY. Test method ASTMD4546, Method B, follows the actual field path ITFB, and the surrogate path in *s-p* space is IFB. Due to transition from elastic to elastoplastic response at point T, the surrogate path deviates slightly from the actual path. However, the surrogate path still represents a very good approximation of the actual path. A second "identical" specimen is tested at a reduced stress level, following path JSG. Assuming, for convenience in this discussion, that there is essentially no volume change along path JSG, p at point J represents the transition between expansion and collapse for the field soil. The surrogate path in the $s=0$ plane is GB, and the partial wetting collapse strain at point F (on the actual stress path) is estimated from point Q on the surrogate path using the initial and final soil suction ratio-based mapping similar to that discussed above for expansive soils, except $\sigma_p = \sigma_G + (1\text{-}R_w)\,(\sigma_{ob} - \sigma_G)$ is used because σ_{ob} is greater than σ_G. It is likely that the void ratio at Q provides a very good approximation of the void ratio at F. However, partial wetting strains are guaranteed by the SPM to provide reasonable results and are always anchored between zero at point I for no wetting and B for full wetting.

The SPM has been compared to other common oedometer methods for estimation of volume change of expansive soils [16, 73]. The SPM can also be used for collapse response to wetting [65]. The primary advantages of the SPM are: (1) it is a Stress Path Method, (2) the procedure is the same whether the response to wetting of the soil is expansion or collapse, (3) the procedure accounts for partial wetting in terms of the stress state variable, soil suction, (4) the partial wetting strains from the SPM are always guaranteed to be reasonable because the results are anchored to the ASTM D4546 Method B volume change at full wetting and to zero for no wetting, and (5) the SPM-computed volume change is not overly sensitive to the estimated value of the cross-over pressure separating expansion and collapse response to wetting.

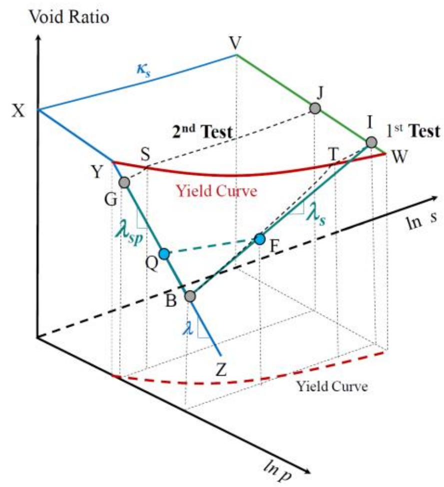


Fig. 21. MSSA view of the SPM for collapse response to wetting [16]

9 Conclusions

Currently, due to the proliferation of methods for laboratory testing and modeling of heave or collapse, a wide range of professional opinions regarding volume change potential at a given unsaturated soil site can typically be found. Indeed, it is even possible that one engineer projects net heave at a site while another engineer projects net settlement. Such discrepancies are not in the best interest of the geotechnical profession or our clients. Unsaturated soil response to wetting under load may be expansion, collapse, or both, depending on the total stress (confinement) range of interest. It is not necessary to categorize unsaturated soils as either exclusively expansive or exclusively collapsible, and such over categorization can lead to unexpected volume change response in the field and poor performance of engineered systems (e.g., foundations, compacted fills, and embankments).

There are unified approaches for moisture-induced unsaturated soil volume change testing and analyses that are appropriate whether the response is expansion, collapse, or both. Recommended procedures share the use of the Stress Path Method [22]. The complexity of unsaturated soil volume change response requires stress-path-based laboratory testing methods for routine practice. Although emphasis is commonly placed on a soil wetting path under constant confining stress conditions, use of field-appropriate net total stress is essential whether the soil volume change is due to wetting or drying. Observations presented here of oedometer suction-controlled specimens suggest that the typical practice of performance of laboratory shrinkage tests under zero confinement conditions should be re-evaluated in the context of stress-path methods. Overall, adoption of a Stress Path Method in routine practice will help bring consistency to unsaturated soil volume change estimates among geotechnical practitioners.

In view of current theory and understand of unsaturated soil behavior, it seems time to discard over simplified and highly empirical approaches to unsaturated soil volume change problems. It is difficult to support continued over reliance on index- and non-stress-path-appropriate laboratory tests. Our geotechnical engineering solutions require thinking beyond such simplifications as labeling soil as having high, moderate or low collapse or shrink-swell potential, as well as use of more fundamental constitutive models applicable beyond limited regions or soil-type.

Where 1-D, Ko loading conditions are adequately representative, consideration should be given to use of oedometer devices that allow control or measurement of both net total stress and soil suction. For routine applications where laboratory direct suction measurement or control is not practical, Stress Path Methods, applicable to both expansion or collapse response to wetting are available. For monotonic wetting under constant load (a common practical scenario), the Surrogate Path Method (SPM) is recommended. The SPM uses stress-path appropriate ASTM D4546, Methods A and B (Standard Test Methods for One-Dimensional Swell or Collapse of Soils) test results obtained using conventional non-suction-controlled oedometer equipment. The ASTM D4546 test (A and B) is also known as the wetting under load test, where the applied vertical stress is representative of field conditions. The ASTM D4546 test methods are appropriate for use whether the soil response is expansive or collapsible, or both. Although suction is not measured for the SPM laboratory oedometer tests, the SPM does require measurement and/or estimation of initial and final soil suction.

In solving unsaturated soil volume change problems, it cannot be ignored that suction change (water content change) is the primary driving mechanism from an engineering significance perspective. Suction controlled testing may be time consuming and/or difficult – or equipment is simply not widely available to practitioners. The SPM provides a means of estimation of partial wetting strains, which is critical given the very common field situation of partial wetting. The SPM estimates of partial-wetting unsaturated soil volume change are forced to remain within a reasonable range, because the results are anchored to zero strain when there is no suction change and the ASTM D45456 test response for full wetting ($s=0$). Thus, the only source of error in the partial wetting result derives from the algorithm used to interpolate between these fixed endpoints. Based on available studies for soils exhibiting expansion response, linear interpolation with respect to suction has been found to be quite adequate for engineering applications.

For unsaturated soils, the Modified State Surface Approach (MSSA), a simple macro-level elastoplastic framework, is analogous to and compliments the Stress Path Method. The MSSA provides a unified framework for understanding complex volume change response of unsaturated soil, whether the soil exhibits collapse, expansion, or both. The MSSA perspective provides a clear picture of elastoplastic unsaturated soil volume change response, and a window into laboratory observations. The MSSA takes advantage of the uniqueness of the virgin loading surface and represents the yield curve as the intersection between elastic and elastoplastic response. Following are some important findings from MSSA views of common oedometer laboratory tests for soil expansion and collapse due to wetting.

Path independence of the “wetted (soaked) curve” in the collapse zone supports uniqueness of the virgin loading surface for unsaturated soils, and is a direct result of elastoplastic response of unsaturated soils and the fact that collapse response results in specimen yield and outward expansion of the yield curve (increasing p at yield). Path-dependence of the “wetted (soaked) curve” in the expansion zone is directly related to elastoplastic soil behavior and the fact that expansion is an unload process occurring along elastic surfaces that move downward as yield occurs. The primary point is that path dependency may or may not affect results from laboratory tests, and it may be possible to “get away with” not following the appropriate stress path for some volume change problems (e.g., the double oedometer test may provide reasonable results in some cases). However, failure to follow the field stress path in the laboratory is not worth the risk because it is not known, a priori, if there will or will not be path dependency of engineering significance, or whether, in general, the soil will exhibit expansion or collapse response under field conditions. It is therefore a slippery slope: (1) to not use the Stress Path Method in laboratory testing, and (2) to assume that an unsaturated soil is exclusively expansive or collapsible with respect to wetting-induced volume change.

As a final comment, herein hysteresis effects have been neglected. When natural soils (or in-place field-compacted soils) that have been subjected to many cycles of wetting and drying are considered, hysteresis effects may not be great – and hysteresis is not an issue for cases of monotonic loading (e.g., monotonic wetting, which is a common circumstance for field conditions). However, for compacted soils subjected to cyclic suction change, hysteresis effects in the first several cycles of wetting-drying could be quite pronounced. Such hysteresis effects relate to soil structure and hydraulic effects. It is not within the scope of this paper to address hysteresis effects in completeness, but it is relevant to note that a Stress Path Method automatically handles hysteresis effects. In other words, provided the laboratory testing follows the same stress path(s) anticipated for field conditions, a laboratory-field matching process can be used to obtain reasonable estimates of field volume change response.

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