International Journal of GEOMATE, Dec., 2024 Vol.27, Issue 124, pp.112-119
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2024.124.4735
Geotechnique, Construction Materials and Environment

VALIDATION OF SWELLING ESTIMATION METHODS USING A LABORATORY-SCALED INSTRUMENTED SOIL COLUMN

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*Corresponding Author, Received: 23 Sep. 2024, Revised: 14 Oct. 2024, Accepted: 29 Oct. 2024

ABSTRACT: Damages to lightweight structures due to expansive soils present a significant global challenge in arid and semi-arid regions. These areas are highly susceptible to climatic changes that alter moisture conditions in expansive soils, leading to swell-shrink behavior. The complexity of ground movements induced by moisture (suction) variations is exacerbated by many factors influencing the process, making accurate prediction a formidable task. Various swelling prediction methods are currently employed worldwide, each with its own limitations and varying degrees of success. Consequently, validating any heave prediction method before its application to specific soil types is crucial. This validation can be accomplished through either a field instrumentation program or a laboratory-scaled model to simulate actual field conditions, with the last being preferable due to its cost-effectiveness and ability to control boundary conditions. However, there is a significant lack of studies investigating the applicability of current swelling prediction methods to Queensland soils. This study proposed the development of a long-term operable instrumented soil column (ISC) subjected to four phases (wet-dry-wet-dry) to examine the climatic-induced hydro-mechanical responses of unsaturated expansive grey Vertosol, which is widespread in South-East Queensland. The observed ISC data validated the widely applied current heave prediction methods. Aitchison and Peter (1973) and Oedometer-based methods demonstrated consistency in estimating movements in all four phases compared to other selected methods. The findings of this study provide confidence for accurately predicting expansive soil movements in Queensland's expansive soils, thereby minimizing associated damages and maintenance costs.

Keywords: Expansive soil, Shrink-swell, Swelling Prediction, Instrumented soil column

1. INTRODUCTION

Expansive soil damages have become a substantial global challenge for geotechnical and structural engineers because the associated costs are estimated to reach several billion dollars annually [1,2,3]. Expansive soils are widely distributed in more than 60 countries, especially within arid and semi-arid climatic regions, including the USA, China, Australia, South Africa, and India [4,5]. About 20% of Australian land areas, particularly 50% of Queensland soils, exhibit expansive properties [6,7]. Expansive soils are highly sensitive to climate change-induced soil moisture variation [8,9]. During the wet season, these soils swell; during dry seasons, these soils shrink back [10,11,12]. This cyclic shrink-swell behavior is the leading cause of damage to lightweight structures, such as shallow foundations, pavements, culverts, irrigation structures, and shallow-depth buried pipes [13,14].

Similar to other states of Australia, in Queensland, the low-volume road networks that link regional communities are one of the most vulnerable infrastructure types [15,16,17] because the high costs associated with traditional stabilizers are not economically feasible on these roads [18,19,20] and pose environmental concern [21,22,23]. To overcome these noteworthy concerns, various innovative approaches are being developed, such as the use of geosynthetics [24,25,26], the utilization of waste materials and by-products of manufacturing industries, for example, recycled asphalts [27,28], recycled concrete [29,30], tires and glass wastes [31,32], and the development of advanced road design methods [33,34,35]. Although numerous design, construction, and stabilization techniques have been developed and practiced, the success of these methods mainly depends on the reliability of swelling pressure or expansive soil movement estimations [36,37].

Accurate ground movement predictions can be achieved through long-term field instrumentation programs or numerical models. However, field instrumentation programs are often complex, time-consuming, and costly [38,39,40]. Also, numerical modeling of unsaturated expansive soil behavior is a complex process, and geotechnical engineering researchers are still actively working on it [41]. Therefore, these two methods are not ideal for practitioners, and that is the main reason why analytical methods are most popular among practicing geotechnical engineers.

Various analytical heave prediction methods have been developed and are being employed by different countries. Available heave prediction methods can be divided into four main categories: Empirical, odometer test, soil moisture, and Soil suction methods [42]. Empirical relationships are typically developed based on limited test data from a specific region and cannot account for in situ conditions [43]. In contrast, oedometer test-based methods can control loading conditions, moisture content, and dry density, allowing for more accurate replication of field conditions to some extent [43]. Suction-based methods are considered more reliable as they are based on information about the stress state (i.e., suction). However, measuring the suction profile is time-consuming, and using the predicted profile can be erroneous [43]. Therefore, validation of analytical heave prediction methods is crucial, as it allows for the confident application of these methods to specific regions.

Validation of any heave estimation method can be performed by comparing the observation of the field instrumentation program with the results of the analytical methods. However, conducting a long-term field instrumentation program is a really challenging task. Laboratory-based model setups are often used to overcome the difficulties associated with field instrumentations [44,45]. Further, these models are beneficial for parametric analyses due to the flexibility of controlling conditions [45,46]. Based on the knowledge grown over time, monitoring the topmost one meter of soil for a long period would give a better insight into the hydro-mechanical response of expansive soil under the land climate interaction [47,48]. Therefore, an instrumented expansive soil model with a height of 1m or more can be deemed a practical physical model that can effectively represent real expansive soil behavior [49,50].

A review [51] on soil column tests has revealed that most tests in the literature are smaller in dimensions as well as on sandy soils. Only a few studies with large-scale, instrumented, reactive clay model setups are available in the literature. A study [52] has conducted a similar ISC for only one wet-dry cycle of 8 months and did not incorporate the effect of cracks when simulated for multiple wet-dry cycles.

A study by Authors [53] attempted to validate the Richards (1967) [54] heave prediction equation through both field instrumentation and numerical analysis, which is one of the accepted equations in Texas, USA. A Similar study was conducted by Author [55] to validate the applicability of Aitchison & Peter's (1973) method [56] in Melbourne, Australia, which is the most widely accepted method in Australia. However, there was no study found in the literature conducted for Southeast Queensland soil to validate the applicability of different analytical heave prediction methods that are popular in Australia with the support of the instrumentation program to fully monitor the expansive soil behavior. The same ISC column is previously used to validate the oedometer-based expansive soil shrink estimation method [6]. Compared to the previous studies, this study was conducted to validate the five heave estimation methods, provide an alternative method for conventional field instrumentation, and develop a comparatively large ISC, and ISC undergoes a few wet-dry cycles.

The primary objective of this study is to validate the applicability of the widely used five analytical expansive soil heave estimation methods for southeast Queensland's expansive soils. To achieve this primary objective while addressing identified gaps in the literature, this study developed a long-term operable instrumented soil column (ISC) with 1.0 m in height and 0.2 m in radius, capable of long-term monitoring of vertical displacements, moisture, and suction variations to assess the climate-responsive swelling behavior of grey Vertosol soils. Then, ISC observations and results of the oedometer test series were used to validate the widely used five analytical heave estimation methods. Ultimately, this study aims to minimize the expansive soil-related damages and maintenance costs and enhance the geotechnical and pavement engineers' confidence in applying analytical heave prediction methods.

2. RESEARCH SIGNIFICANCE

This study presents a highly applicable analytical method for estimating swell in South East Queensland, aiming to increase practitioners' confidence in accurate heave prediction, enhance safety, and significantly reduce maintenance costs associated with expansive soil damage. An alternative laboratory-based instrumented soil column (ISC) approach was introduced to validate analytical heave prediction methods. Additionally, the ISC operated over an extended period under alternating wet-dry cycles to simulate climate-induced expansive soil responses. This new approach reduces the cost, time, and operational challenges typically associated with conventional field monitoring programs used for validating heave prediction methods.

3. MATERIALS

This study utilized expansive grey soil extracted from Sherwood, Queensland, Australia. These grey Vertosol soils are widespread across Southeast Queensland and represent the sub-soil conditions found in Brisbane. Basic soil properties were identified based on the Australian Standard (AS) test methods and are shown in Table 1. This soil is classified as high plasticity clay (CH) according to the Unified Soil Classification System (USCS).

4. METHODS

This study contains a laboratory-simulated large ISC developed and operated to monitor the swell behavior of expansive grey Vertosol under wetting conditions. Simultaneously, a series of oedometer-based swelling tests were carried out to predict the actual ground swell. Then, the actual swell value measured from the ISC was compared with the predicted swell values from the oedometer-based swelling tests and a few other widely used swelling prediction methods.

Table 1. Properties of the test soil

Tested parameter	Results
Grain size distribution	% finer than 75 mm > 77%
Fraction of clay	39%
Atterberg limits	LL = 67.0%, PI = 37.2%
Linear shrinkage	13.4%
X-ray diffraction (XRD)	Smectite group
Specific gravity (Gs)	2.67
Sat. hydraulic conductivity	5×10^{-10} ms^{-1} (compacted soil)
Activity value (Ac)	0.95

4.1 Laboratory Simulated ISC

An ISC (Fig 1.) was developed to simulate the actual field conditions. Further, to replicate the climate conditions, the ISC test was conducted for a period of 575 days (two wet-dry cycles). The operational program of wetting and drying cycles and the periods of each phase are tabulated in Table 2.

Table 2. Implementation of wet-dry cycles in the ISC

Phase	Wet/ Dry Cycle	Start Date	End Date
Phase 1	Wet 1	Day 1	Day 165
Phase 2	Dry 1	Day 166	Day 325
Phase 3	Wet 2	Day 326	Day 425
Phase 4	Dry 2	Day 426	Day 575

The soil column was built up by compacting 50 mm layers, and initial conditions were selected according to the field observation, in which dry density and gravimetric moisture contents are 1.2g/cm^3 and 15%, respectively. Table 3 outlines the types and respective functions of the sensors embedded in the ISC. The climatic parameters surrounding the ISC were observed using an evaporation pan (Potential Evaporation), VP4 sensors (Relative Humidity and Air Temperature), and Therm-EP sensors (Air Temperature).

Table 3. Type of sensors used in this study

Parameter	Sensor	Remark
Soil displacement	LVDT	Shrink-swell behaviour
Soil moisture	MP-406 EC-5	Spanned moisture content Point moisture content
Soil suction	GT-3 MPS-6	Low suction values Low/ high suction values
Soil temperature	Therm-EP	Subsoil temperature

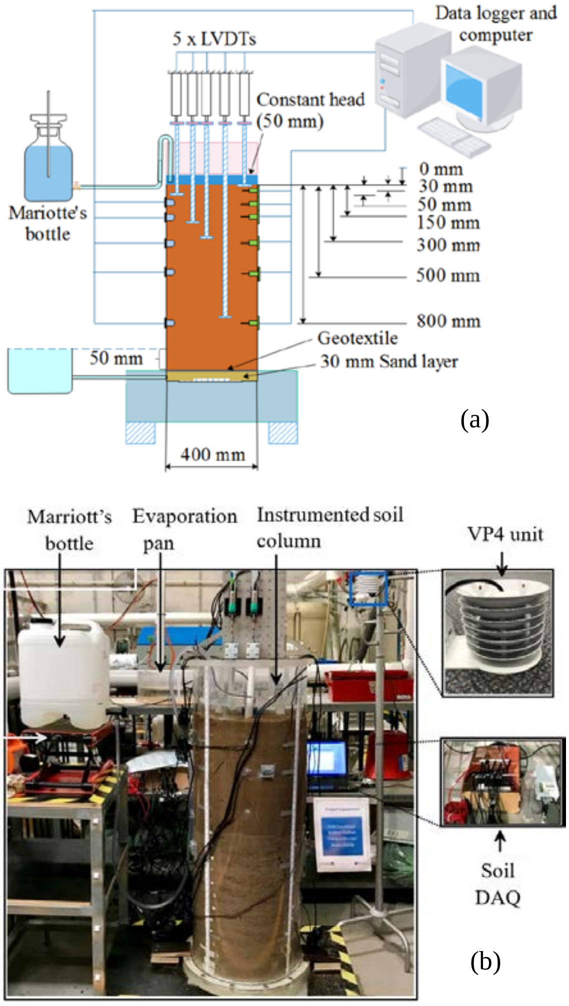

Fig. 1 Soil column during wetting: (a) Schematic diagram (b) Physical set-up

4.2 Swelling Prediction and Validation

Heave prediction methods that are selected for this study are listed in Table 4. Empirical methods were not selected for this study because empirical methods are developed for a specific region with a limited amount of data.

Table 4. Selected analytical swell prediction methods

Swell prediction method	Category
Direct oedometer test	Oedometer method
Aitchison & Peter (1973)	Soil suction method
Dhowian (1990)	Soil moisture method
Fityus & Smith (1998)	Soil moisture method
Briaud, Zhang, and Moon (2003)	Soil moisture method

The method proposed by Aitchison & Peter (Eq. (1) & Eq. (2)) is a soil suction-based heave prediction method [56], which is the basis of the heave prediction method proposed in AS2870: Australian

Standard for residential slabs and footings [57].

$$\Delta H = \frac{1}{100}\int_0^{H_s} I_{pt}\,(\Delta u)(\Delta h) \tag{1}$$

$$I_{pt} = \varepsilon_y/\Delta u \tag{2}$$

Where, ΔH is defined as the amount of swell, H_s is active depth, I_{pt} is instability index, Δu is design suction change, Δh is layer thickness and ε_y is vertical strain.

Dhowian's method (Eq. (3) & Eq. (4)) is a water content-based method [58] and contains parameters, namely, moisture index ($C_{w,dry}$), initial water content (w_i), final water content (w_f), Compressibility factor (α) Specific gravity (G_s), and initial void ratio (e_0).

$$\Delta H = C_{w,dry}\cdot H\cdot(w_f - w_i) \tag{3}$$

$$C_{w,dry} = \frac{\alpha\cdot G_s}{1+e_0} \tag{4}$$

Heave can be predicted using Eq. (5) prediction, according to the Fityus and Smith proposed method [59]. The Swell value derived from this method is a function of the active depth (H), empirical factor for confining stress (α), volume index (I_V), and gravimetric water content variation ($w_f - w_i$).

$$\Delta H = \sum\{H\cdot I_V\cdot\alpha\cdot(w_f - w_i)\} \tag{5}$$

Briaud, Zhang, and Moon's proposed method is based on the variation in gravimetry water content [60]. Swell can be predicted using Eq. (6) and Eq. (7). This model required parameters, namely, layer thickness (h), axial strain for unit volumetric strain (f) and shrink-swell modulus (E_w).

$$\Delta H = \sum\left\{\frac{h\cdot f\cdot(w_f - w_i)}{E_w}\right\} \tag{6}$$

$$E_w = \frac{\Delta w}{\Delta V/V_0} \tag{7}$$

Equation (8) was used to estimate the swell based on the direct oedometer method. Where the parameter H is active depth, Δw is soil moisture variation and $\left(\frac{\Delta\varepsilon}{\Delta\theta}\right)$ is the ratio between the change of vertical strain and volumetric water content that is obtained from the oedometer swell test.

$$\Delta H = \sum\left\{H\times\left(\frac{\Delta\varepsilon}{\Delta\theta}\right)\times\Delta w\right\} \tag{8}$$

For the other methods, oedometer-based shrinkage tests were performed, and the resulting data were used to obtain the soil-dependent parameters required in swell prediction methods. Soil moisture contents and soil suction measurements were obtained from the ISC. Then, the estimation of swelling was conducted using the selected prediction methods. Finally, the results were compared with the actual swelling values recorded from the ISC during the two wetting periods. The Validation process is illustrated in Fig. 2.

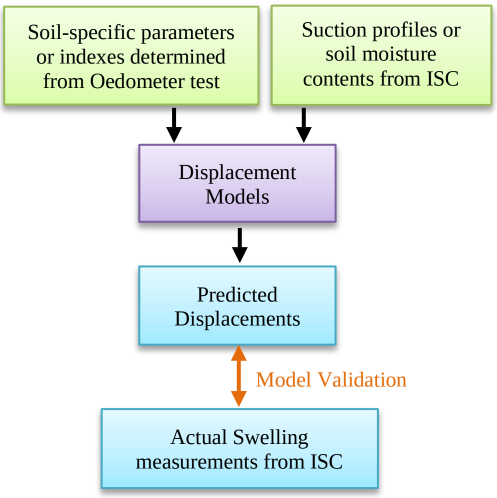

Fig. 2 Analytical swelling prediction methods validation process

5. RESULTS AND DISCUSSION

Variations of soil suction and soil moisture profiles of each phase during two wet-dry cycles are shown in Fig. 3 and Fig. 4. Based on the suction profiles shown in Figure 3, climatic influence depth (active zone) of ISC can be identified as 500mm. The drying and wetting phases follow very similar moisture variations at all depths. However, soil suctions only at 150mm depth show significant differences compared to other locations at the end of two drying phases. The ISC observation of this study could be different from that of the responses of the undisturbed sample. However, this may more accurately reflect real ground responses in an environmentally stabilised state maintained by the alternating wetting and drying phases.

Comparison of predicted swell values and ISC observed actual swell values during two wetting periods are illustrated in Fig. 5 and Fig. 6. As shown in Fig 5., All four models, except the Dhowian model, underestimated the heave observed at the end of the first wetting period. Oedometer and Aitchison methods show comparatively better estimation (less than 15%) compared to the other three models. Fityus and Briaud's models clearly show a 46% deviation from the ISC results. The Dhowian model demonstrated 139% overestimation, which implies the Dhowian model is unsuitable for heave prediction related to the expansive fill or newly compacted grey vertosol soil. With these observations, Oedometer and Aitchison's methods are the most appropriate for swelling predictions during prolonged rainfall.

The second wetting period was conducted to assess the responses to the climate variability in cracked vertosol. As the second wetting period began after a 160-day-long dry period, the topmost soil layers were cracked significantly. In this phase, soil column heave was reduced drastically. As depicted in Fig. 6, the Dhowian model consistently exhibits significant overestimation, while the oedometer and Aitchison models also demonstrate notable overestimations. These discrepancies are likely due to the effect of crack closure during this phase. Consequently, applying realistic adjustment factors could enhance the alignment of the results with the Oedometer and Aitchison models for cracked grey Vertosol soils. In contrast, the Fityus and Briaud models continued to be underestimated. Furthermore, the Dhowian model was confirmed to be unsuitable for the tested soil.

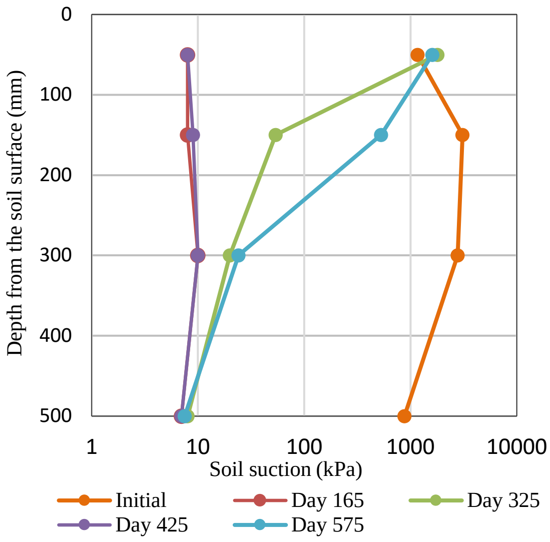

Fig. 3 Suction profile variation during the test period

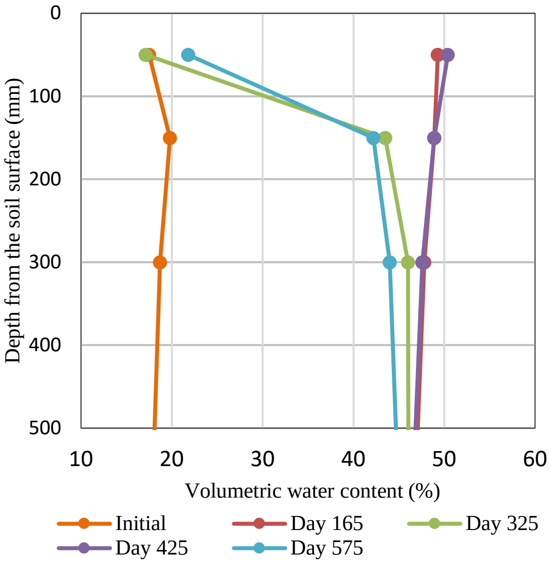

Fig. 4 VWC variation during the test period

The study by Author [55] has previously validated the applicability of Aitchisons's method for the Melbourne region. This further confirms the outcome of this study and proves the validity of the current Australian standard residential slab and fighting design (AS 2870), which, based on Aitchisons's method, is a good method for most of the Australian regions. Further Authors [6] have validated the applicability of oedometer-based shrinkage estimation. Therefore, the oedometer method is suitable for the estimation of both shrink-swell movements of grey vertosol soil in south Queensland, Australia.

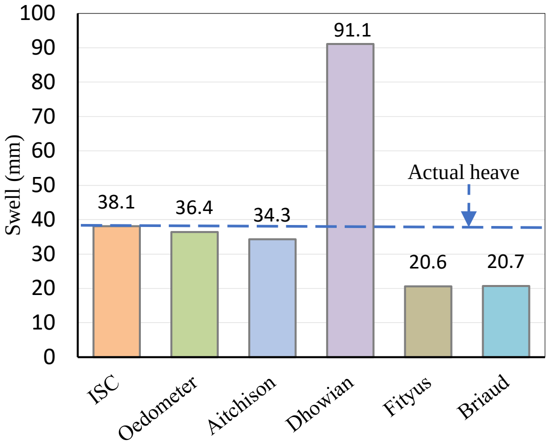

Fig. 5 Comparison of estimated displacements during the first wetting period (Day 1 - 165)

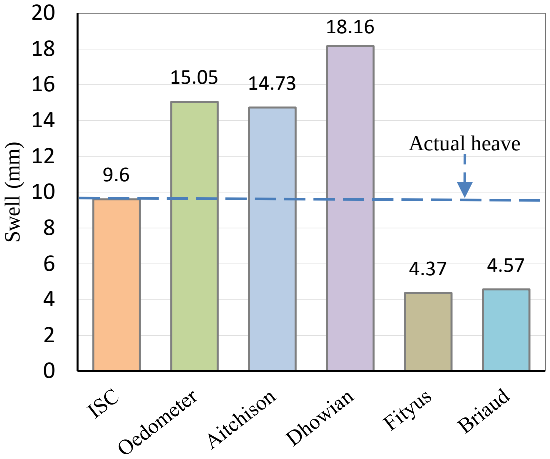

Fig. 6 Comparison of estimated displacements during the second wetting period (Day 326 - 425)

6. CONCLUSIONS

Based on the findings of this study, the following conclusions can be drawn.

- The oedometer method and Aitchison and Peter's (1973) heave prediction [52] methods are the most appropriate methods for predicting the swelling of environmentally stabilized expansive fills or newly compacted grey Vertosol soil.

- Realistic adjustment factors are required when applying these two methods to the cracked soil fills. It is necessary to delineate the swell overestimations caused by the crack being closer when water infiltrates through these cracks.
- Higher swell overestimations associated with Dhowian's [54] method and significant underestimations associated with Fityus and Smith's method [55] and Briaud, Zhang, and Moon's method [56] imply the unsuitability for Queensland's grey Vertesol soil.

7. ACKNOWLEDGMENTS

The authors appreciatively acknowledge the technical staff at Queensland University of Technology (QUT) for providing the on-campus & off-campus (Banyo Pilot Plant) laboratory facilities to conduct the test series. Further, gratitude should be extended to Steve Hackworth from THE SOILTESTERS for providing in-kind support for the project. The authors acknowledge the scholarship for the doctoral degree received from QUT, Australia.

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