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Swelling potential and swelling pressure calculation methods: A comprehensive review

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Abstract: Expansive soils, characterized by volume changes due to variations in water content, significantly affect geotechnical engineering. Proper assessment of swelling potential and swelling pressure is essential for improving foundation design on expansive soils, enabling a reduction in risks arising from soil expansion. Different methods for measuring and calculating swelling potential and swelling pressure have been developed, ranging from empirical to analytical approaches, many of which are based on laboratory tests and analysis of soil properties. The paper presents a new classification of these methods, categorizing them into qualitative, semi-qualitative, and quantitative methods. Indirect methods of swell classification are qualitative and semi-qualitative approaches, which may be either single or multi-index methods. In contrast, quantitative approaches are direct methods based on laboratory or field test results. This review will provide researchers and engineers with an easy evaluation of the expansion potential of expansive soils using various methods.

Keywords: *Empirical methods, Expansive clay, Swelling potential, Swelling pressure.*

1. Introduction

Expansive clay soils, also known as shrink-swell soils, are one of the major geotechnical problems because they normally exhibit volumetric changes with variations in moisture content. Such soil consists of several minerals that can absorb water. They increase in volume by absorbing water and shrink on losing moisture; this cycle may cause significant structural damage to the pavements and foundations built on expansive soils [1-4]. In addition, the behavior of expansive soils depends mainly on the type and amount of clay minerals, the size and distribution of clay particles, or other external factors such as temperature or additional moisture content. Of these, the mineral montmorillonite exhibits outstanding swell-shrink capacity. Other clay minerals are illite and kaolinite, which cause expansiveness in soil but only to a very minor degree. According to Chen [5] the swelling potential and the swelling pressure are the major factors to be considered in geotechnical engineering applications dealing with expansive clays impacting the structures' performance or stability. The swelling potential depends on the clay mineral types and amounts, the initial dry unit weight of soil correlated to the void ratio, the soil moisture content, the stress history of soil (succession of wet-dry cycles), and the composition of the soil pore fluid especially the presence of cations or salts [3, 6].

Two of the major properties of expansive soils that are related to the behavior with changing moisture conditions are the swelling potential and the swelling pressure. The potential for swelling is a measure of how much the soil will expand on wetting, while the pressure exerted when the expansion is restrained is known as the swelling pressure. Therefore, both can have practical applications in construction by exerting effects on building stability and strength [7-9]. This property is particularly pronounced in soils with high clay content, especially those rich in smectite minerals. Smectite has a unique lattice structure that accommodates large proportions of water between its layers [10]. Swelling

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pressure is the force developed by soil in expanding, and the magnitude of swelling pressure has become an important factor in the evaluation of stress imposed on structures and their foundations. Inadequate attention to soil expansion during the design and construction can lead to severe structural damages [1, 3, 4].

The different techniques to assess the swelling potential and swelling pressure for soils are mainly based on oedometer cells for direct measurement or soil suction measurements, as well as on empirical correlations, predictive models, numerical modeling, and field test methods. For measuring the swelling pressure, three recognized and standardized tests using an oedometer cell exist: the consolidation swelling (CS) method, the constant volume (CV) method, the swell overburden (SO) method described by Al-Shamrani and Al-Mhaidib [11] that refer to ASTM_D4546 [12]. The three methods usually give various swelling pressure values: the CS test gives the higher values, the SO test the lowest ones, and the CV test gives intermediate results [13]. On the other hand, the empirical correlations may be used to estimate the swelling pressure based on soil characteristics such as plastic limit, liquid limit, and clay content [14-16]. The matric suction methods use soil-water characteristic curves (SWCC) to estimate the swelling pressure based on the soil moisture content relationship [17, 18].

The consolidation tests with suction control and numerical modeling (i.e., finite element modeling) can simulate the soil behavior and their swelling pressure under different scenarios. However, models appear rather complex and usually require calibration [19-21]. Sometimes, back-analysis from field data may help to estimate the swelling pressure undergone by existing structures. The methods to estimate the impact of soil swelling remain numerous. Each method presents advantages and limitations that need to be detailed: in-situ tests provide direct but scale-limited measurements, empirical methods offer rapid but imprecise estimation, numerical models deliver detailed projections but require expert calibration, and field data analyses yield practical insights potentially confounded by numerous variables. Engineers combine these approaches to ensure structural integrity on expansive soils.

Various methods have been developed for measuring and calculating swelling potential and swelling pressure, ranging from empirical to analytical approaches, most of which are based on laboratory testing and soil property analysis. This paper proposes a new classification system for these methods, namely qualitative, semi-qualitative, and quantitative. Indirect swell classification methods include qualitative and semi-qualitative approaches based on single or multiple index techniques. Quantitative methods, on the other hand, comprise direct assessments based on the results obtained from laboratory or field tests. This paper aims to carry out a critical review of the methodologies for swelling potential and swelling pressure. Therefore, this review would give the researchers and engineers a comprehensive framework in which the expansion potential of expansive soils using various methods can be efficiently evaluated.

2. Swelling Potential and Swelling pressure Calculation Methods

In geotechnical engineering, swelling pressure and swelling potential will become conceptual parameters relevant to expansive soils that swell under wetting and shrink on drying. Such volume changes may cause relevant damages to work and overlays built onto or inside such soils [1, 5, 22]. The two most important parameters involving protective measures concerning a construction project to be executed on expansive soils in any geotechnical investigation are selling pressure and potential. Proper assessment and mitigation strategies should be provided to measure against or reduce structural damages through soil swelling, which may involve the replacement of soils by less expensive ones, chemical stabilization, or specially designed structural foundations and/or moisture control systems.

Swelling potential is a critical geotechnical property that foretells the maximum possible volume increase of expansive clay soils upon wetting. High contents of expansive minerals like montmorillonite can cause appreciable changes in volume with fluctuations in moisture. Soils with high swelling potential can cause appreciable amounts of uplift and movement in structures, leading to cracking and other damage. This will be a critical consideration in designing foundations and other civil engineering structures [2, 5].

Swelling pressure is the pressure developed by the soil when it is permitted to swell under restrained conditions. It usually relates to expansive clays with high water absorption capacity. This is one of the very critical parameters for designing foundations and other structures so that they are resistant to the forces exerted by the swelling soils. The computation and estimation of swelling pressure thus become of critical relevance in designing different foundations and other structures built on expansive soils. Swelling pressure is normally measured in the laboratory using oedometer tests, where a soil sample is subjected to controlled conditions, and the pressure required to prevent swelling is measured [2, 5].

In geotechnical engineering, the swelling potential and swelling pressure become critical parameters of soils to achieve stable designs with respect to expansive soils. The various methods used for the evaluation of such properties can then be broadly categorized into qualitative, semi-qualitative, and quantitative methods. All these classifications have different purposes and offer different extents and levels of detail on information and accuracy. Only by understanding these methods and their uses will geotechnical engineers be able to manage and mitigate expansive soil risks properly. The development of a proper understanding of soil behavior will be possible only based on qualitative methods for initial assessments, semi-qualitative methods to make preliminary design estimates, and quantitative methods that go into detailed analysis and validation. Through this multi-tiered approach, engineers are better placed to make informed decisions, create safe and stable structures, and allow for effective mitigation strategies to deal with the difficulties expansive soils can create.

2.1. Qualitative Methods

Qualitative methods provide initial, broad assessments based on observations and empirical indicators. These methods are almost entirely based on visual inspections, field observations, and simple tests yielding preliminary knowledge regarding soil behavior. For instance, engineers can study the cracking patterns at the surface of the soil, notice the changes in texture and color of the soil, or even use simple thumb-press tests that give them an idea about the plasticity of the soil [23, 24]. These qualitative assessments are very useful in rapidly delineating problem areas that may need further investigation. Indeed, they are relatively inexpensive preliminary screening tools that enable engineers to group soils into such general categories as low, medium, high, and very high expansive soil [25, 26]. However, qualitative methods are not precise and subjective since they depend on the experience and judgment of the observer. Furthermore, qualitative methods provide an approximate prediction for the swelling potential of soils without necessarily involving broad laboratory tests and detailed quantitative analyses [27, 28]. These methods are based on observational techniques and simple empirical classifications, which can rapidly be applied in the field. Such qualitative approaches, though relatively imprecise compared to the quantitative methods, may be very useful in preliminary studies for pointing out areas that may call for more detailed investigation.

Qualitative methods for classifying swelling potential and swelling pressure of soils are important in understanding and subsequently predicting the behavior of soils under different moisture conditions. Qualitative methods for estimating the swell potential and swelling pressure of soils require extensive use of soil index properties. The key properties include liquid limit, shrinkage limit, and percent clay size composition of soils. The plasticity index and the shrinkage index are especially useful indices. The plasticity index, obtained by subtracting the plastic limit from the liquid limit, is considered to measure the range of moisture content over which the soil is plastic. It also strongly indicates swell potential; high values in the plasticity index are considered indicative of a higher swell potential. These properties can be used by engineers and geologists to present qualitative estimates of swell potential. These qualitative methods, though less accurate compared to quantitative approaches, give very useful preliminary assessments that guide further detailed investigations and inform engineering decisions in construction and land development projects. The main qualitative methods for assessing the swelling potential and swelling pressure through Atterberg limits, particle size, suction-water content, standard penetration test (SPT), and empirical correlations derived from the observed behavior of soils provide preliminary evaluations that become very important in geotechnical engineering practices and construction projects.

2.1.1. Single Index Methods

2.1.1.1. Liquid Limit (LL)

Table 1 compares the swelling potential classifications (low, medium, high, and very high) based on the liquid limits (LL) by Chen [29] and Snethen, et al. [30]. Some important differences exist regarding threshold or criteria for low, medium, and high swell potential. Chen's classification included a very high swell potential category at a liquid limit greater than 60%, which was not given in the classification framework of Snethen, et al. [30]. For low and medium categories with broader range values, Snethen, et al. [30] take more on the conservative side. In addition, the LL has been used conventionally as a critical parameter for the assessment of the swelling potential of soils. However, inadequacies in classification criteria have prevented it from providing a universally appropriate assessment for applications in geotechnical engineering. A comparison of some of the classification systems presented by Chen [29]; Snethen, et al. [30] and Dakshanamurthy and Raman [31] indicates considerable discrepancies regarding the level of swelling potential categories.

Table 1.
Swelling soil classification based on the liquid limit.

Swell level	**Chen [29]**	**LL [%] Dakshanamurthy and Raman [31]**	**Snethen, et al. [30]**
Non	-	0 – 20	-
Low	< 30	20 - 35	< 50
Medium	30 – 40	35 - 50	50 – 60
High	40 - 60	50 -70	> 60
Very high	> 60	70 - 90	-
Extra high	-	> 90	-

2.1.1.2. Plasticity Index (PI)

Table 2 compares soils' swelling potential using PI values from Holtz and Gibbs [32] and Chen [5]. According to Holtz and Gibbs [32], the threshold values for low, medium, high, and very high swell potentials are <18%, 15-28%, 25-41%, and >35%, respectively. For Chen [5], they are 0-15%, 10-35%, 20-55%, and >35%. This comparison shows variations in the classification criteria over time. The narrower ranges of PI by Holtz and Gibbs [32] enable the classification of soils to be more specific, while the broader thresholds of Chen [5] introduce flexibility but with attendant inconsistencies, especially in view of the overlapping categories Medium and High being 10-35% and 20-55%, respectively. Both frameworks coincide on the definition of more than 35% for Very High swell potential and unity on extremely expansive soils. Although PI is better correlated with swelling potential than LL, the integration of other parameters, such as shrinkage limit, suction, and particle size distribution becomes imperative. Establishing a standardized, multi-index classification method will enhance accuracy and dependability in geotechnical engineering.

Table 2.
Swelling soil classification based on plasticity index.

Swell level	**PI [%] Holtz and Gibbs [32]**	**PI [%] Chen [5]**
Low	< 18	0 - 15
Medium	15 - 28	10 - 35
High	25 - 41	20 - 55
Very High	> 35	>35

2.1.1.3. Shrinkage Limit (SL)

Table 3 presents a classification of swell based on the shrinkage limit by Holtz and Gibbs [32]. Soils with a shrinkage limit greater than 15% will have low swell potential; medium and high swells are

10-16% and 7-12%, respectively, and very high, less than 11%. This classification helps determine soil behavior with changes in moisture. Although the SL provides a good framework for classifying swell potential, it is not satisfactory to rely only on SL in the evaluation of expansive soils. It is necessary to incorporate more factors into the evaluation, apart from SL, for better and more reliable assessments.

Table 3.
Swelling soil classification based on shrinkage limit [32].

Swell level	Shrinkage limit
Low	> 15
Medium	10 - 16
High	7 - 12
Very High	< 11

2.1.1.4. Shrinkage Index (SI)

The shrinkage index is the numerical difference between a soil's plastic limit and shrinkage limit and defines the range of moisture content over which the soil changes volume. Table 4 classifies the swell classification by the shrinkage index, as proposed by Seed, et al. [33]. Soils with a shrinkage index of less than 20% have low swell potential; those with 20-30%, 30-60%, and greater than 60% have medium, high, and very high swell potential, respectively. Depending on the SI alone for the classification of swelling is very rudimentary in the expansive soil classification because it provides a very limited view with regard to soil behavioral responses. Combining SI with other parameters, such as PI and SL, will provide a wider and more reliable method for classifying and understanding expansive soil potential.

Table 4.
Swelling soil classification based on shrinkage index [33].

Swell level	Shrinkage index
Low	< 20
Medium	20 - 30
High	30 - 60
Very High	> 60

2.1.1.5. Particle size

Table 5 compares the swelling potential of soils based on particle size defined by Chen [29] and Holtz and Gibbs [32]. In Chen's classification, the emphasis is given to the particles less than 0.002 mm. According to that, soils with low swell potential have less than 18% of such particles, medium between 15-28%, high between 25-41%, and high above 35%. Holtz and Gibbs apply a threshold value of less than 0.001mm with finer particle size and classify soils as low swell potential with 0-15%, medium with 10-35%, high with 20-55, and very high above 35%. This observation thus points out the variations in the criteria applied by the two studies regarding the impact of particle size. The particle size is not a good index for the classification of swell, as the type of clay minerals considered plays an important role in the expansion of the soil. A soil containing a low amount of clay but a high proportion of expansive minerals, such as montmorillonite, can have greater swelling potential than a soil with higher clay content and less expansive minerals, making particle size alone an unreliable criterion for swell level classification.

Table 5.
Swelling soil classification based on particle size.

Swell level	Particle size < 0.002mm [29]	Particle size < 0.001mm [32]
Low	< 18	0 - 15
Medium	15 - 28	10 - 35
High	25 - 41	20 - 55
Very High	> 35	>35

2.1.2. Multi Indexes Methods

2.1.2.1. PI and SL

Table 6 classifies the swelling potential of soils based on the PI and SL. The soils having a PI of less than 15% and SL greater than 12% are classified as low swelling potential. In the same line, the medium swelling potential is put at PI 15-30% and SL 10-12%. Soils with PI greater than 30% and SL less than 10% are of high swelling potential. The PI is a good and reliable index of the swelling potential, especially in combination with the SL. However, the SL ranges given by Sowers and Sowers [34] do not correspond fully to the PI values, leading mostly to inconsistent swell classifications. Therefore, the SL framework needs revision so that there is correspondence with the ranges of PI for coherent and dependable expansive soil classification.

Table 6.
Swelling soil classification based on PI and SL [34].

Swell level	PI [%]	SL [%]
Low	< 15	> 12
Medium	15 - 30	10 - 12
High	> 30	< 10

2.1.2.2. PI and SI

Table 7 categorizes the swelling potential of soils into four classes: low, medium, high, and very high. The classification is based on the Plasticity Index and Shrinkage Index. Soils with PI less than 18% and SI of 0-15% are rated to have low swelling potential. The higher the values of PI and SI, the higher the swelling potential: very high, with PI greater than 35% and SI above 35%. A combination of PI and SI thus gives a reliable index for the classification of the swelling potential of expansive soils, which may provide a good basis for preliminary assessment. It helps in the preliminary assessment of soil expansiveness, where the higher the PI and SI values, the higher the swelling potential. However, for geotechnical design, it is crucial to determine the swelling potential and swelling pressure of the soil stratum to ensure both safety and effectiveness regarding the design of structures within influences of soil shrinkage and swelling.

Table 7.
Swelling soil classification based on PI and SI [35].

Swell level	PI [%]	SI [%]
Low	< 18	0 - 15
Medium	15 - 28	10 - 35
High	25 - 41	20 - 55
Very High	> 35	>35

2.1.2.3. PI and LL

Figure 1 shows the relationship between PI and LL in classifying soil swell potential. The A-line and the U-line are provided within the chart, which provides boundaries separating categories of soil behavior. In general, higher values in both the liquid limit and plasticity index give higher swell potential, from low to extra high. Although PI and LL are good indications in classifying the swell level in expansive soils, the current classification framework ranges in such a way that PI becomes minor due to dependence on the variations of LL. Because LL varies in higher values and the swelling level increases by variation in LL, the potential role of PI becomes negligible; therefore, it is less influential in the overall classification.

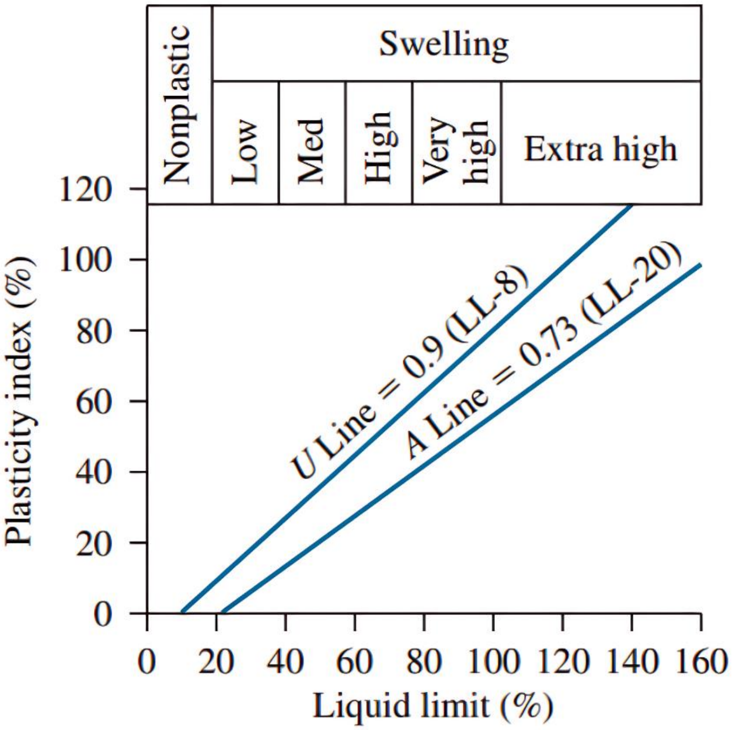

Figure 1.
Swelling soil classification based on the liquid limit and plasticity index after Das and Sivakugan [36] Figure 15.19 (b), pp. 621.

2.1.2.4. Suction and Soil Water Content

Figure 2 illustrates the relation of soil water content versus suction for five different classes separating the expansiveness of soils. The range of these five distinct categories goes from non-expansive, V, to a special case, I, where the expansiveness is very high. An increase in the water content of the soil will reduce suction and, hence, expansiveness in the soil. Suction and soil water content have been reliable indicators for classifying the swell potential of expansive soils since they reflect the moisture retention and behavior of the soil. However, the suction measurement is difficult to perform since it requires advanced instruments and highly specialized techniques. This is more helpful for an indirect evaluation or preliminary study but not widely applicable for routine geotechnical investigations since it is quite complex.

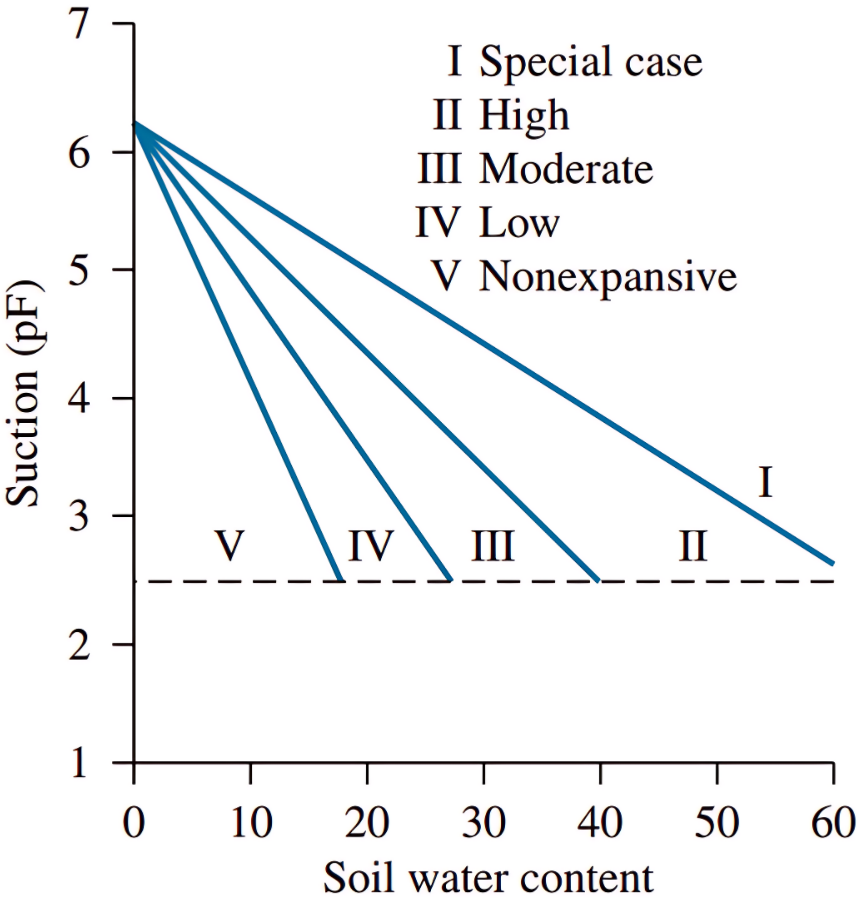

Figure 2.
Swelling soil classification based on the soil water content and suction after Das and Sivakugan [36] Figure 15.19 (d), pp. 621.

2.1.2.5. Percent of Clay and PI

Figure 3 gives the relation of the PI of soil to the percentile of clay particles (2 μm) in that sample. It separately categorizes soils into four classes with respect to their swelling potential: low, medium, high, and very high. This means that as the percentage of clay particles increases, so does the PI, hence swelling potential. The percentage of clay and PI are effective indicators in the classification of swell potential in expansive soils. Together, they form a reliable classification system since the framework considers the combined influence of clay content and PI on swelling behavior. This would ensure a more accurate classification of swells since the interaction between the expansive properties of the clay and its plasticity is considered rather than relying on either parameter individually.

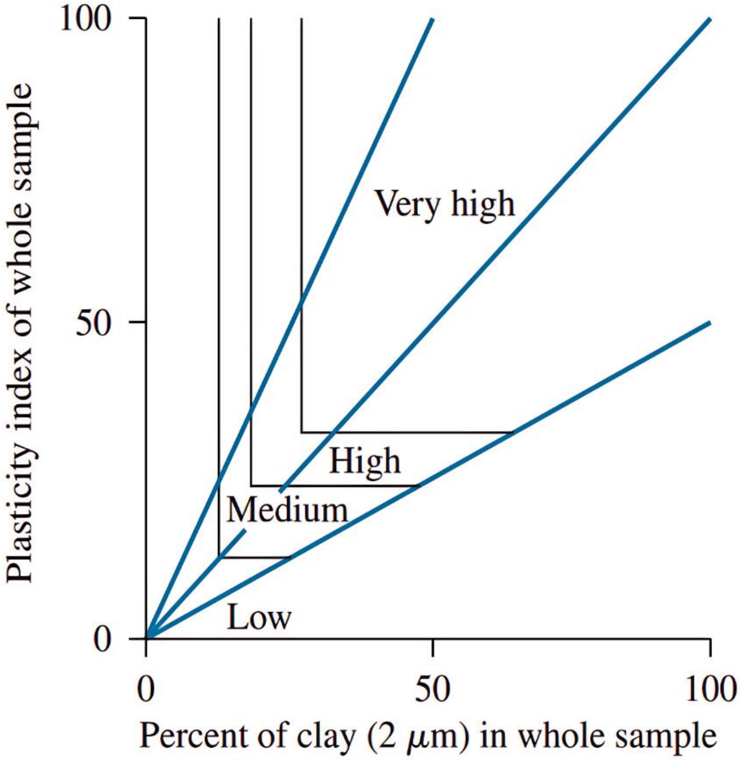

Figure 3.
Swelling soil classification based on the percent of clay and PI after Das and Sivakugan [36] Figure 15.19 (c), pp. 621.

2.1.2.6. Total Suction-Water Content Index and the Suction Compression Index

Table 8 classifies the swelling potential of soils based on their relation of the total suction-water content index to the suction compression index. Soils with a total suction-water content index between -13 to -20 and corresponding suction compression indices less than -0.040 have low swelling potential. Their swelling potential is very high for soils with indices (the total suction-water content index and the suction compression index) greater than -6 and above -0.227 [37]. The total suction-water content index and suction compression index are effective indicators for the classification of swell potential in expansive soils, as they reflect the moisture and compressibility behavior of the soil. However, these indices require advanced instruments and specialized techniques for measurement and calculation, which are difficult to carry out in practice. Thus, only indirect preliminary assessments can utilize this approach, but it is rarely applicable to practical geotechnical investigations.

Table 8.
Swelling soil classification based on the total suction-water content index and the suction compression index [37].

Swell level	Total suction-water content index	The suction compression index
Low	-13 to - 20	< -0.040
Medium	-10 to -13	-0.120 to -0.040
High	-6 to -10	-0.227 to -0.120
Very High	> -6	> -0.227

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2.2. Semi-Qualitative Methods

Semi-qualitative methods provide estimations that combine empirical data with theoretical principles, offering a more detailed assessment than qualitative methods. These methods use empirical correlations derived from historical data to estimate swelling behavior. For example, empirical formulas that relate the PI, LL, and SL to swelling potential can provide reasonably accurate predictions. Design charts and nomographs, which integrate empirical data with theoretical adjustments, are also commonly used. Semi-qualitative methods balance the simplicity of qualitative methods and the rigor of quantitative methods. They are particularly useful for preliminary design calculations, where detailed experimental data may not be available, but reliable estimates are needed to inform design decisions. Nevertheless, the accuracy of these methods can be limited by the specific conditions and contexts from which the empirical data were derived. In semi-qualitative methods, the volume change of the soil sample is generally calculated through laboratory tests.

2.2.1. Single Index Methods

This method defines swelling potential using some special characteristics of soils, usually by a single index such as an expansion index. In this approach, the swelling potential of soils will be classified based on measuring the soil volume changes in laboratory testing. Controlled tests are conducted to quantify soil response to moisture variations and then classify the swelling potential. This method is useful in geotechnical engineering for initial site assessment in situations requiring quick, cost-effective estimation of soil expansiveness to guide foundation design and construction planning.

2.2.1.1. Swell Tests

Table 9 compares the swelling potential of undisturbed and remolded samples under a 6.9 kPa load. Holtz and Gibbs [32] classify undisturbed samples into low, medium, high, and very high swelling potential according to percentage swelling, which falls within the range of less than 10% to over 30%. Seed, et al. [33] provide another similar classification system for remolded samples, with 0-1.5% swelling percentages corresponding to low and very high corresponding to over 25%. In addition, the oedometer test result-based classification of swelling potential provides a more realistic and reliable method than the qualitative approach, as the oedometer test result gives the exact behavior of the soil samples in the laboratory. However, significant differences were noticed in the oedometer-based classification method between the undisturbed and remolded samples concerning the ranges for the low, medium, and high swell levels. For instance, the medium swell potential varies from 10-20% for undisturbed samples to 1.5-5% for remolded samples. The discrepancy in the values indicates that further studies are needed to revise or standardize these ranges of classification for consistency and reliability.

Table 9.
Classification of swelling potential based on swell tests using an oedometer.

Swell level	% Swelling (Under 6.9 kPa-undisturbed sample) [32]	% Swelling (Under 6.9 kPa-remolded sample) [33]
Low	< 10	0 – 1.5
Medium	10 - 20	1.5 - 5
High	20 - 30	5 - 25
Very High	> 30	>25

2.2.1.2. Expansion Index

The expansion index (EI) is a critical soil parameter that can be used to evaluate the potential volume swell of the soil when in contact with water. The parameter here is measured by the amount in which a soil specimen expands under controlled conditions, and values are usually dimensionless. A high EI signifies great soil expansion, which can be very hazardous to most country infrastructures, particularly the foundation of structures. The EI is obtained through standard testing [12] and categorizes soils with very low to very high expansion potential. Table 10 classifies soil expansion potential in regard to the EI into five classes: very low, low, medium, high, and very high. The values of this index for expansion range from 0 to 20 for very low potential to over 130 for very high potential.

Table 10.
Swelling soil classification based on expansion index.

Swell level	EI
Very Low	0 - 20
Low	21 - 50
Medium	51 - 90
High	91 - 130
Very High	> 130

2.2.2. Multi-Index Methods with Percent of Swelling Potential

This method categorizes the swelling potential of soils by considering multiple soil properties at once. These include plasticity ratio, percent of clay, activity, particle size, PI, LL, and SL. In this approach, laboratory tests are conducted where volume changes in soil samples are measured under controlled conditions. The integration of various soil indices rules out such a method for a better assessment compared with single index methods for the expansiveness of soils. It further allows a nuanced understanding of soil behavior, increasing swelling potential predictions' accuracy. This is especially useful in geotechnical engineering, where every assessment is critical to the design of stable foundations and infrastructure.

2.2.2.1. Plasticity ratio

This method defines the plasticity ratio (PR) as the ratio of PI to PL and uses such a ratio to establish a relationship with the measured swell of soils. The PI is only a numerical difference between LL and PL and can only indicate the plasticity characteristics of the soil. The PR calculates the relative plasticity of the soil; the ratio gives a quantifiable measure of the potential of the soil for volume changes due to variations in its moisture. High PR generally indicates higher swell potential (see Table 11).

Table 11.
Swelling soil classification based on plasticity ratio (PR) and potential volume change [38].

Swell level	PR	Volume change [%]
Low	< 0.6	< 3
Medium	0.6 - 1	3 - 10
High	1 - 2	10 - 50
Very High	> 3	> 50

2.2.2.2. Percent of Clay And Activity

Figure 4 shows the relation between soil activity and the percentage of clay sizes finer than 0.002 mm, which can be used to classify soils under different swelling potential categories: low, medium, high, and very high. Activity, being the ratio of PI to the percentage of clay, decreases as the percentage of finer clay particles increases. High-activity soils with a high percentage of fine clay particles have very high swelling potential. In addition, percent clay, soil activity, and swelling potential can be considered effective indicators for classifying the swell level of expansive soils. Since activity decreases with the increasing proportion of finer clay particles, its consideration in classification will involve their integrated effects. This results in correct swell classification based on the consideration of the clay content as well as its expansive behavior, not based on one factor only.

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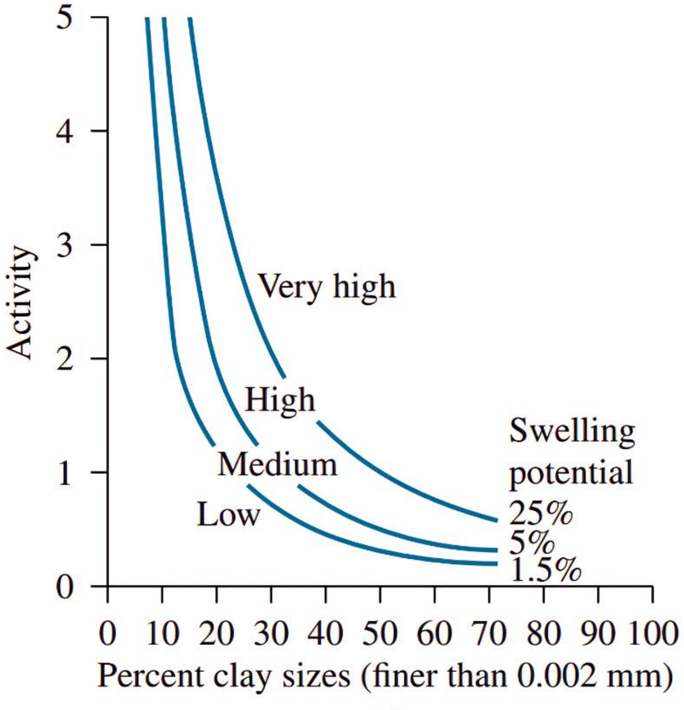

(a)

Figure 4. Swelling soil classification based on the percent of clay and activity after Das and Sivakugan [36] Figure 15.19 (a), pp. 621.

2.2.2.3. Shrinkage limit and linear shrinkage

Table 12 classifies the swell potential of soils into noncritical, marginal, and critical categories based on the percentage swell, shrinkage limit, and linear shrinkage. Noncritical soils have a percentage swell of less than 0.5%, shrinkage limit above 12%, and linear shrinkage below 5%; thus, the soils are nearly not expansive. Marginal soils have a probable swell ranging from 0.5% to 1.5%, a 10-12% shrinkage limit, and linear shrinkage between 5% and 8%. Critical soils generally have a percentage swell of more than 1.5%, shrinkage limit below 10%, and linear shrinkage above 8%. This classification, developed from the remolded samples under a 6.9 kN/m^2 surcharge, gives a practical working basis for appraising soil expansiveness in geotechnical engineering.

Table 12.
Swelling soil classification based on SL and linear shrinkage [Altmeyer (1955), as cited in Das and Sivakugan [36].

Swell level	Swell [%]	SL [%]	Linear shrinkage [%]
Noncritical	< 0.5	> 12	< 5
Marginal	0.5 – 1.5	10 - 12	5-8
Critical	> 1.5	< 10	>8

2.2.2.4. Particle Size, LL, SPT, Volume Change, and Swelling Pressure

Table 13 classifies the swelling potential of soils into four categories: low, medium, high, and very high. The classification system is based on key geotechnical parameters like particle size finer than 0.075 mm in percentage, liquid limit (LL), standard penetration test blows per foot, volume change percentage, and swell pressure. Soils with a low swelling potential are those with less than 30% fine particles, LL below 30%, SPT values below 10 blows/ft, volume change of less than 1%, and swell pressure below 1 ksf. As these parameters increase, the swelling potential of the soil increases. Very

High swelling potential soils would have more than 95% fine particles, LL above 60%, SPT values over 30 blows/ft, more than 10% volume change, and a swell pressure higher than 20 ksf. This classification system provides an overall good framework for evaluating the swelling potential of soils. However, its application requires detailed site investigation in which all relevant parameters are measured accurately for reliable predictions of soil behavior for the design of effective foundations in expansive soils.

Table 13.
Swelling soil classification based on particle size, LL, SPT, volume change, and swelling pressure [5].

Swell level	Percentage of Particle size < 0.075 mm	LL [%]	SPT Blows/ft	Volume change [%]	Swell pressure [ksf]
Low	< 30	< 30	< 10	< 1	< 1
Medium	30 – 60	30 – 40	10 – 20	1 – 5	3 – 5
High	60 – 95	40 – 60	20 – 30	3– 10	5 – 20
Very High	> 95	> 60	> 30	> 10	> 20

2.2.2.5. Particle Size, PI, and SL

Table 14 classifies the swelling potential of soils into four categories: low, medium, high, and very high. The classification is based on the following key parameters: particle size finer than 0.001 mm, Plasticity Index, Shrink-Swell Limit, and potential volume change. Soils of low swelling potential will have less than 15% fine particles, PI below 18%, SL greater than 15%, and volume change under 10%. With the increase in these parameters, so is the swelling potential, and for very high swelling potential soils, more than 28% fine particles, PI above 35%, SL below 11%, with a volume change of more than 30% are present. The expansion percentages are based on a vertical loading of 1.0 psi. This detail is critical because it sets the context for the conditions under which the expansion potential is measured. Different loading conditions might indicate different degrees of expansion; therefore, understanding this baseline is paramount in correctly applying the table's data to practical scenarios. This classification becomes important in predicting the behavior of these soils and thus constructing them in those areas with expansive soils.

Table 14.
Swelling soil classification based on particle size, PI, SL, and potential volume change by Holtz [39].

Swell level	% Particle size < 0.001mm	PI [%]	SL [%]	volume change [%]
Low	< 15	< 18	> 15	< 10
Medium	13 - 23	15 – 28	10 – 16	10 – 20
High	20 - 31	25 – 41	7 – 12	20 – 30
Very High	> 28	> 35	< 11	> 30

2.2.2.6. LL, PI, and soil suction

Table 15 categorizes soil swell potential into low, marginal, and high classifications. The classification is based on four key soil properties: LL, PI, soil suction measured in tons per square foot (tsf), and swelling potential of the soils given in percentage. Soils that are categorized have a low potential for swelling, i.e., soils with lower than 50% LL and less than 25% PI, suction is below 1.5 tsf, and swelling potential is below 0.5%. As these values increase, the swelling potential changes from marginal to high, and high-classification soils will have more than 60% LL, over 35% PI, over 4 tsf soil suction, and over 1.5% swelling potential.

Table 15.
Swelling soil classification based on LL, PI, soil suction, and linear shrinkage [30].

Swell level	**LL [%]**	**PI [%]**	**Soil Suction [tsf]**	**Swelling potential [%]**
Low	< 50	< 25	< 1.5	< 0.5
Marginal	50 – 60	25 - 35	1.5 - 4	0.5 - 1.5
High	> 60	> 35	> 4	> 1.5

2.3. Quantitative Methods

Quantitative methods will deliver more precise and elaborate results through controlled experimental and analytical techniques. Such methods will be conducted in both the laboratory and the fields; they will achieve precise numerical values for parameters in relation to both swelling potential and swelling pressure. Examples include oedometer tests, triaxial compression tests, and several field tests, such as the SPT and the Cone Penetration Test. These tests provide detailed data on soil properties and their response to various conditions, essential for detailed design and analysis. Other quantitative methods involve advanced numerical models and simulations that superimpose experimental information over theoretical principles to predict soil behavior accurately. However, the quantitative approaches are the most detailed and accurate ones, though they are very expensive in terms of time and money. Additionally, the results may be specific to the samples tested and might not fully represent broader soil conditions, necessitating careful interpretation and potential additional testing.

2.3.1. Oedometer Test-Based Methods

The oedometer test is one of the most conventional laboratory tests used for measuring swelling potential. During the oedometer test, a sample is laterally confined in a rigid ring and subjected to a controlled vertical load, representing the overburden pressure. It measures the vertical deformation of a sample under conditions of monotonic wetting and loading [12, 41]. This test allows the acquisition of very useful information about the swell potential and swell pressure of the soil, which are most important in designing foundations in expansive soils. Several methods for interpreting test results of the oedometer have been developed by researchers to assess free swell characteristics. The swell index, for instance, is a parameter derived from the oedometer test and expresses the rate of vertical swell per unit increase in moisture content. This index becomes very crucial in predicting the behavior of expansive soils under field conditions.

Expansive clay soils exhibit complex behavior during their volume variations with changes in their moisture content, creating different problems related to geotechnical engineering. Free swelling of this soil is essential information that has been previously obtained through various methods based on oedometer tests. Free swelling means that the volume of expansive clay soils increases upon the absorption of water without any external constraint. This behavior is majorly attributed to the high water affinity of the clay minerals. The volume of such soil increases due to the expansion of the interlayer spaces while absorbing the water. This property makes it very sensitive while under construction, and it has potential ground movement that may cause damage to structures. Furthermore, the free swell index (FSI) is used in soil mechanics to indicate the swelling potential of soils, particularly expansive clays, in contact with water [12, 40]. This index is very important in interpreting how particular types of soils will respond and change in volume as they take on moisture.

Determination of free swelling of expansive clays is very important, more so in areas where such soils are widely available. An assessment of the accuracy of oedometer tests makes it helpful and ideal for designing structures that experience or counteract changes in soil volume for the safety and durability of the structure. The study of free swelling of expansive clay soils is one of the most important research areas in geotechnical engineering, particularly in oedometer test-based. It provides essential insights for the safe and efficient design of structures in areas affected by these challenging soil conditions. Besides, these two techniques are often used when compared to the other approaches for making predictions. Oedometer tests are among the major factors used to identify one-dimensional

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heave, which is measured using oedometer test techniques [41]. These techniques are summarized in Table 16.

Table 16.
Summary of total heave calculation based on oedometer test methods.

Reference	**Equation**	**Remarks**
Fredlund [42]	$\Delta H = C_s \frac{H}{1+e_0} \log \frac{P_f}{P_s'}$	$P_f = \sigma_y + \Delta\sigma_y - u_{wf}$
Picornell and Lytton [43]	$\Delta H = \sum_1^n f_i \frac{\Delta v}{v_i}$	
Dhowian [44]	$\Delta H = H \frac{C_s}{1+e_0} \log \frac{P_s}{P_0}$	
Nelson and Miller [2]	$\Delta H = H \frac{C_\rho}{1+e_0} \log \frac{\sigma_f'}{\sigma_{cv}'}$	
Nelson, et al. [45]	$\Delta H = H \cdot C_H \log \frac{\sigma_{cv}'}{\sigma_{v0}'}$	$C_H = \frac{\%S_A}{\log \frac{\sigma_{cv}'}{(\sigma_i')_A}}$
Vanapalli, et al. [41]	$\Delta H = C_s \frac{H}{1+e_0} \log \left\{ \frac{K \cdot P_f}{10^{\left(\frac{C_s \cdot \Delta w}{C_w}\right)}} \right\}$	$P_f = \sigma_y + \Delta\sigma_y - u_{wf}$

Note:
ΔH = total heave; C_s = swell index; H = thickness of soil layer; e_0 = initial void ratio; P_f = final stress state; P_s' = corrected swelling pressure; σ_y = total overburden pressure; $\Delta\sigma_y$ = change in total stress; u_{wf} = final pore-water pressure; f_i = factor to include the effects of the lateral confinement; $\Delta v/v_i$ = volumetric stain; P_s= swelling pressure; P_0 = effective overburden pressure; C_ρ = heave index; σ_f' = vertical stress at the midpoint of the soil layer for the conditions under which heave is being computed; σ_{cv}' = swelling pressure from constant volume swell test; $\%S$ = Percent of swell; (σ_i') = inundation stress; K = correction parameter; C_w = suction modulus ratio; Δw = change in water content.

2.3.2. Empirical Methods

Swelling potential and swelling pressure are critical parameters in the study of expansive clay soils, which are known for their significant volume change in response to moisture variations. The swelling pressure is usually calculated to act in the right designs of foundations and other structures in areas with expansive soils, constituting geotechnical engineering. The method that is usually employed for this purpose is oedometer test-based. Besides, the oedometer test is a laboratory procedure used to simulate the conditions that expansive soil would experience in the field. It consists of applying vertical stress to the cylindrical ring and the sample. This test is mainly applicable in measuring the vertical deformation of soil caused by variations in the moisture content and state of stress. Swelling pressure is one of the basic principles in the utilization of soil in the formation of building swells, lanes, and drains, as it can determine the stress required to prevent the soil sample's swelling in this direction. Table 17 presents and summarizes swelling pressure by different researchers using various oedometer test-based methods.

Swelling pressure in expansive clay soils is one of such fundamental issues in geotechnical engineering, specifically in the design of foundations or structures where these soils become predominant. The swelling pressure represents pressure developed by soil during heave under restraint conditions. This parameter is very important to ensure that the structure resists such forces exerted due to swelling soil. The oedometer test is a standard laboratory technique for measuring swelling pressure [12]. In the oedometer test, a soil sample is permitted to swell under controlled conditions, and the pressure required to prevent further swelling is recorded. This test gives invaluable data for understanding the behavior of expansive soils and for the proper design of structural foundations.

The swelling pressure could be calculated through empirical correlations and other methods, including the soil suction method, predictive models, or field test methods; however, oedometer testing remained one of the primary methods because of its standardized procedure and reliability. Three primary types of oedometer test-based methods are recognized and standardized to measure swelling pressure: consolidation Swelling (CS), at Constant Volume (CV), and Swell Overburden (SO). These techniques are outlined in ASTM_D4546 [12]. All of them are distinctive, with tendencies to give different results in swelling pressure. Furthermore, the CS method allows for initial swelling of the soil under a small load, and extra load can be applied in such a way that there is re-consolidation back to its virgin volume, thereby giving an indication of the maximum potential swelling of the soil. On the other hand, the CV method maintains a constant volume of the soil sample during the swelling process and measures the pressure required to prevent any further swelling. This method is therefore revered to offer conditions closer to field conditions by simulating the natural restriction to soil swelling by surrounding structures. Finally, the SO method applies a pressure representative of the in-situ overburden pressure under which the swelling pressure has to be measured; the closer to real conditions, the more weight from overlying or superficial soil that is taken into account. Each one delivers useful data related to the swelling behavior of expansive soils but correlates with field scenarios to different degrees.

Assessment of which method of oedometer test CS, CV, or SO best simulates the field conditions is a very critical consideration in geotechnical engineering. The reason this evaluation is extremely important is that the conditions in the laboratory may differ far from those in the field; then, the choice of methods would be effective in the design and safety of structures founded on expansive soils.

- Consolidation Swell (CS) Method: This test generally gives the upper bound of swelling pressure. While they give an idea about the maximum possible swelling of the soil, they may not represent field conditions, which are usually restrained by overburden and surrounding soil mass on the swelling of the soils.
- Constant Volume (CV) Method: The CV method is considered to give a more realistic approximation to field conditions than the CS method since it measures the pressure required to prevent any volume change in the soil sample. Because, in most field situations, swelling of the soil is somewhat restrained, similar to constant volume conditions in the laboratory, by surrounding soil and structures.
- Swell Overburden (SO) Method: The SO method is generally accepted as closest to the actual field conditions because it simulates the in-situ overburden pressure. It considers the weight of overlying soil, which is a very critical parameter in actual field conditions. However, this may underestimate the swelling pressure if the overburden pressure applied is not representative of the entire depth of the expansive soil layer.

The loading and unloading sequence, surcharge pressure, sample disturbance, and equipment compressibility should all be considered for a reliable estimate of the swelling pressure. Furthermore, the determination of index parameters, such as swelling index (Cs) and heave index (C_H), and their application in heave prediction equations have greatly influenced the development of heave prediction techniques utilizing oedometer testing. Moreover, Burland [46] introduced the concept of estimating heave by calculating the slope of the rebound section of the consolidation swell curve. According to Fredlund [47], the slope of the unloading curve produced by consolidation-swell testing is nearly identical to the slope of the rebound curve determined by constant volume tests.

Fredlund [42] and Nelson and Miller [2] calculated index parameters based on oedometer test results from both CS and CV tests. Almost the same equation as that suggested by Fredlund [42] is used by Nelson and Miller [2] method (see Table 3). Feng, et al. [48] performed a comparison study of swell pressure for a series of laboratory swelling pressure tests on a highly expansive clay using the oedometer test techniques (loading after swell, swell under load, constant volume, and unloading methods). Furthermore, Nelson, et al. [49] and Bonner [50] proposed a technique for calculating the index parameter (CH) based only on consolidation swell test results. For the purpose of finding the percent swell as a function of inundation pressure, Nelson, et al. [45] improved and enhanced the approach utilizing odometer test data acquired from both CS (Method A) and Cv (Method C) tests that were based on ASTM D 4546.

During the CV test, the sample is submerged in the oedometer while placed under a nominal pressure of 7 kPa (1 psi). The load applied to the sample was raised in order to avoid any volume growth or swelling of the sample during the experiment. The swell pressure is the greatest applied pressure necessary to maintain a constant volume condition. An incremental increase in the applied load is performed in a manner similar to that of a traditional consolidation test when the specimen no longer shows swelling tendencies.

Table 17.
A summary of the different empirical methods that have been published in the literature.

Equation	**Reference**	**Initial surcharge**	**Soil Sample**	**Remarks**
$SP = 0.00216\, PI^{2.44}$ $SP = 0.0036\, PI^{2.44}$	Seed, et al. [33]	7 kPa (1 psi)	Undisturbed Disturbed	$PI = LL - PL$
$SP = 0.000413\, {I_s}^{2.67}$	Ranganatham and Satyanarayana [51]	7 kPa (1 psi)	Disturbed	$I_s = LL - SL$
$Log\, P_s = -2.132 + 0.0208\, LL + 0.000665\, \rho_d - 0.0269\, w_0$	Komornik and David [52]		Undisturbed	$\rho_d\ [kg/m^3]$ $P_s\ [kg/cm^2]$
$SP = 0.0229\, PI^{1.45}\, \frac{c}{w_i} + 6.38$ $P_s = 0.035817\, PI^{1.12}\, \frac{c^2}{{w_i}^2} + 3.7912$	Nayak and Christensen [53]	7 kPa (1 psi)	Disturbed	$P_s\ [psi]$
$LogSP = \frac{1}{12}\,(0.4\, LL - w_i + 5.5)$ $Log\, SP = \frac{1}{19.5}\,(\gamma_d + 0.65\, LL - 130.5)$ $LogP_s = \frac{1}{12}\,(0.4\, LL - w_i - 0.4)$ $Log\, P_s = \frac{1}{19.5}\,(\gamma_d + 0.65\, LL - 139.5)$	Vijayvergiya and Ghazzaly [54]	10.5 kPa (1.5 psi)	Undisturbed	$\gamma_d\ [Ib/ft^3]$
$LogSP = 0.9\, \frac{PI}{w_i} - 1.19$	Schneider and Poor [55]		Undisturbed	
$SP = 0.2558\, e^{0.08381\, PI}$	Chen [5]		Disturbed Soil and Free Swell Test	$\gamma_d\ [kN/m^3]$
$SP = 7.5 - 0.8\, w_i + 0.203\, c$ $Log\, P_s = -2.89 - 7\, w_i + 6.65\, c$	McCormack and Wilding [56]		Undisturbed	
$SP = 2.77 + 0.131\, LL - 0.27\, w_i$	O'Neill and Ghazzaly [57]		Undisturbed	
$SP = 23.82 + 0.7346\, PI - 0.1458\, H - 1.7\, w_i + 0.0025\, PI \cdot w_i - 0.00884\, PI \cdot H$	Johnson [58]		Undisturbed	$For\ PI \geq 40$
$SP = -9.18 + 1.5546\, PI + 0.08424\, H - 0.1\, w_i - 0.0432\, PI \cdot w_i - 0.01215\, PI \cdot H$	Johnson [58]		Undisturbed	$For\ PI \leq 40$
$SP = 0.00411\, (LLw)^{4.17}\, q^{-3.86}\, {w_i}^{-2.33}$	Weston [59]	1 kPa	Undisturbed	LLw = (% of passing sive N0. 40/100) *LL
$SP = 0.00001114\, {A_c}^{2.559}\, c^{3.44}$	Bandyopadhyay [60]		Undisturbed	

$SP = 41.161\, A_c \ + 0.6236$ $SP = 0.0763\, \psi_i - 339.03$	Erdal [61]		Disturbed	$\psi_i\ [kPa]$
$Log\ P_s = \ -4.812 + 0.01405\, PI + 2.394\, \rho_d - 0.0163\, w_i$ $Log\ P_s = \ -5.197 + 0.01405\, PI + 2.408\, \rho_d - 0.819\, LL$ $Log\ P_s = \ -5.020 + 0.01383\, PI + 2.356\, \rho_d$	Erzin and Erol [62]		Disturbed	
$P_s = 63.78\, e^{0.1528\,(SP)}$ $P_s = 48.32\, (SP)$	Sridharan and Gurtug [63]		Disturbed	
$SP = 1 + 0.006\, (c + PI - \ w_i\,)$ $P_s = 135 + 2\, (c + PI - w_i\,)$	Sabtan [64]		Undisturbed	
$P_s = 12.5\, (0.001\ \ \psi)^{0.25}$	Thakur and Singh [65]		Disturbed	Bentonite, $\psi\ [kPa]$
$P_s = 25\, (0.001\ \ \psi)^{0.25}$	Thakur and Singh [65]		Disturbed	Montmorillonite, $\psi\ [kPa]$
$P_s = -8.04 + 0.0177 PI + 4.39\ \ \gamma_d + 0.54 \log \psi$	Erzin and Erol [17]		Disturbed	
$SP = 24.5\, q^{-0.26}\, (PI \cdot c)^{1.26}\, [F_i - 7.1\, q^{0.22}\, (PI \cdot c)^{0.78}]$ $P_s = 249\ \ (PI \cdot c)^{1.18}\, [F_i - 0.84\, q^{0.22}\, (PI \cdot c)^{-0.96}]$	ME Zumrawi [66]		Disturbed	
$P_s = 0.0552\, PI^{2.385}\, {I_c}^{1.757}\, {I_a}^{0.397}$ $SP = 0.3\, PI^{0.2}\ \ {I_c}^{0.3}\, {P_s}^{0.3}$	Pruška and Šedivý [67]		Undisturbed	$P_s\ [kPa]$
$P_s = 369 - 272\, \rho_d + 1.78\, w_i + 1.10\, PL + SP$	Djellali, et al. [68]		Undisturbed	
${P_s}^{0.5} = 2.166\, \gamma_t + 1.029\, LL - 0.866\, w_i - 0.665\, c - 26.98 - 20.78\, F_\gamma$ $SP^{0.5} = 0.20656\, w_i - 0.001060\, \gamma_t \cdot H + +0.000003\, PI \cdot H^2$	Mawlood and Hummadi [69]		Disturbed	$F_\gamma = e\ \dfrac{\gamma_w}{\gamma_d}$

Note:
SP = Swelling Potential, [%]; PI = Plasticity Index, [%]; LL = Liquid Limit [%]; PL = Plastic Limit [%]; IS = Shrinkage Index; SL = Shrinkage Limit [%]; P_s = Swelling Pressure; P_d = Dry Density; W_0 = Initial Water Content [%]; C = Percent Of Clay; Γ_d = Dry Unit Weight; H = Thickness Of Soil Layer; Ll_w = Weighted Liquid Limit [%]; A_c = Colloidal Clay's Activity; Ψi = Initial Total Suction Ψ = Total Suction; Q = Surcharge Pressure [Kpa]; Fi = Is The Initial State Factor; Ic = Consistency Index; I_a = Colloidal Activity Index; F_γ = Unit Weight Factor; Γ_t = Total Unit Weight.

3. Conclusions

This comprehensive review has discussed different methods for the assessment of swelling potential and swelling pressure, which are the two most important parameters for understanding and mitigating the challenges of expansive soils. Expansive soils show considerable volumetric variations with changes in their moisture content and, thus, are highly hazardous to structures and infrastructure. Proper assessment of such properties is a key task in the design of safe and durable foundations and in mitigation strategies for the potential damage caused by soil expansion.

The methods reviewed were systematically categorized into qualitative, semi-qualitative, and quantitative approaches. Qualitative approaches are inexpensive and fast but provide only preliminary insights based on empirical observations and simple indices. Semi-qualitative approaches bridge the gap by integrating empirical data with theoretical principles, offering moderate accuracy for preliminary design applications. Quantitative methods give precise and detailed results based on advanced laboratory tests and field investigations.

Qualitative methods work perfectly for a preliminary site assessment, semi-qualitative methods provide reliable estimates during the initial design phase, and quantitative approaches are essentially needed during the detailed analysis and verification phases. Combining them allows engineers and researchers to evaluate expansive soil behavior in varying conditions comprehensively.

This review gives a structured framework that will enable researchers and engineers to choose the most suitable methods based on the specific requirements of their projects. By understanding the capabilities and parameters of each approach, they can make informed decisions to ensure structural stability and durability.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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