Free swell of compacted plastic soils

Ivan Gratchev^{1*} and Somayeh Saeidi²

1) Senior Lecturer, Griffith School of Engineering, Griffith University, Australia.

*Corresponding author. Email: ivangratchev@gmail.com

2) PhD candidate, Griffith School of Engineering, Griffith University, Australia

Abstract. Compacted soils are used in engineering practice due to their higher strength and low permeability. However, when they come in contact with water, such soils may swell and pose significant threats to structures. This paper presents and discusses the data from a series of oedometer tests, in which the potential swell of 26 natural soils compacted to their maximum dry density and optimum water content was studied. The obtained results were analysed to establish relationships between the swelling characteristics and geotechnical properties of soils. Drawing on the experimental outcomes and available literature, a new chart and expansion criteria, which would allow engineers to quickly estimate the swelling potential of compacted soils based on their field placement conditions, were proposed and discussed.

Kew words: swell, expansive soil, compacted soil, optimum moisture content, expansion criteria

1. Introduction

Expansive soils have been one of the major geotechnical challenges in the past decades. The available literature indicates that the damage to engineering structure caused by the swell-shrink behaviour of expansive soils can be enormous and worth millions (Al-Rawas et al., 1998; Al-Mhaidib, 1999; Shi et al., 2002). It is not surprising that a good deal of research has been conducted up-to-date to understand the expansive soil behaviour (Holtz and Gibbs, 1956; Seed et al., 1962; Rao et al., 2000; Sridharan and Gurtug, 2004; Fityus et al., 2004; Rao et al., 2011), revealing that the swelling potential depends on soil properties, including clay mineralogy, and environmental conditions. In addition, several researchers have used experimental data to qualitatively estimate the potential volume change of expansive soils and establish empirical correlations between swell values and soil characteristics such as plasticity, clay content, activity, dry unit weight, soil suction and/or cation exchange capacity (Seed et al., 1962; Ranganatham and Satyanarayan, 1965; Raman, 1967; Nayak and Christensen, 1971; Chu and Mou, 1981; Chen, 1983; Basma, 1993; Rao et al., 2004; Yilmaz, 2006; Çimen et al., 2012; Puppala et al., 2014). The detailed summary of these studies can be found in Yilmaz (2006), Ashayeri and Yasrebi (2009), Rao et al. (2011). However, practice shows that these correlations give reasonably good results when applied to particular soils for which they were developed while they typically lack generality necessary to cover a broad range of soil types (Nayak and Christensen, 1971; Muntohar, 2006).

A few attempts have been made to provide engineers with more general criteria to estimate the swelling potential of soil based on its plasticity, clay content, activity and/or cation exchange capacity (Holtz and Gibbs, 1956; Seed et al., 1962; Dakshanamurthy and Raman, 1973; Chen, 1983; Hamberg, 1985; Yilmaz, 2006). However, despite some similarities, these classification schemes tend to produce different results (Snethen et al., 1977) as the sample conditions (i.e., undisturbed, remoulded, compacted, artificial or natural soils) and moisture boundaries (i.e., dry or wet) in these criteria varied considerably. For this reason, it has been extremely difficult to produce a single criterion/chart that would be universal for all types of expansive soil.

This work deals with compacted soils which are commonly used in fills and soil subgrade for highways. When compacted to its maximum dry density, these soils provide better engineering properties such as higher strength and low permeability. However, when being in contact with water, they may swell, causing some damage to structures built on such soils. For example, Sridharan and Gurtug (2004) noted that the swelling behaviour of compacted

soils caused by moisture changes may result in excessive heave and severe damage to pavements since they are lightly loaded.

Nayak and Christensen (1971) noted that empirical equations developed for natural soils may not be applicable to compacted soils in general as the initial conditions such as dry density and moisture content may be different. Among all engineering classifications of expansive soils, only the criteria proposed by Seed et al. (1962) were intentionally developed for compacted soils. Yet, the soil samples tested by the researchers were artificial mixtures of clay and sand, which may have different properties compared to natural soils. In addition, the Seed's classification chart does not provide information about the compaction characteristics of soil as it is mostly related to soil plasticity and activity. In practice, it would be beneficial for engineers to use a chart that will allow them to quickly estimate the swelling potential of compacted soils based on field placement conditions such as maximum dry density (MDD) and/or optimum moisture content (OMC).

The purpose of this study is to estimate the swell properties of natural soils and establish relationships between their swell potential, plasticity and compaction characteristics. To achieve this goal, 26 natural plastic soils from South East Queensland, Australia were examined and their geotechnical properties were analysed. On the basis of the obtained results, a new engineering chart, which provides a qualitative expansion rating of compacted soils based on their OMC and MDD, was proposed. This newly-developed chart also includes experimental data from the available literature, making its use more universal.

2. Soils used and test procedure

Soil samples were collected from a depth of 1 to 1.5 m from different construction sites in the Brisbane and Gold Coast area (Queensland, Australia) as part of a study on expansive soils conducted at Griffith University (Liu et al. 2017; Gratchev et al., 2018). Physical properties of these soils such as liquid limit (LL) and plastic limit (PL) (ASTM D4318-05, 2005), linear shrinkage (LS) (AS 1289, 2008), maximum dry density (MDD) and optimum water content (OMC) (ASTM D698-00a, 2003) were measured as per guidelines provided in their respective standards. The summary of the test results are given in Table 1.

Soils No. 7, 11, 14, 16, 17 and 26 were collected from the Thagoona area of South East Queensland where ground deformations at a railway track were observed. More detailed

investigation of these soils including soil mineralogy and grain-size distribution (Table 2) was performed to study the effect of mineral composition and clay content on the swelling potential. As these soils were collected from the same area, their mineralogical composition (including smectite, illite and kaolinite) was similar; however, some difference in soil grading was observed.

A series of standard oedometer tests (ASTM D4546-14, 2014) were performed to determine swelling characteristics of soils. For each test, oven-dried soil was thoroughly mixed with a determined amount of distilled water to achieve the OMC, sealed in a plastic bag and allowed to rest for 1 day. The moist soil was then placed in the oedometer ring (diameter of 50 mm, height of 20 mm) and compacted in two layers to its MDD. After the ring was positioned in the oedometer apparatus with an overburden pressure of 1 kPa, water was added to initiate the swelling process. The measurements in the specimen's height were performed during testing to estimate the percentage of swelling (S , %), which was defined as the ratio between the change in the height and the initial height of the specimen. For most of soils, the test continued for 5-7 days, and it was terminated where no changes in the specimen height were recorded for 24 hours. In this study, the swelling potential was defined as the maximum swell recorded at the end of the test.

3. Results and discussion

3.1. Test results

Results from oedometer tests on three different specimens are plotted in Figure 1 to demonstrate typical behavior of plastic soils during the soil-water interaction. Soils 4, 21 and 25 with different LL (33.9%, 63.5%, and 74.5%, respectively) were compacted to their MDD and OMC and then subjected to wetting for several days. The obtained data indicate different degrees of swelling; that is, the soil with the lowest LL (Soil 4) swelled only 2.8% while Soil 25 with the highest LL expanded as much as 22.5%.

To better understand relationships between the swelling potential and soil properties, the obtained data from Table 1 were re-plotted in Figure 2 as the swelling potential against LL, LS, OMC and MDD. It is evident from this figure that a) soils with higher LL and LS tend to have higher values of swelling potential, and b) the swelling potential of soil has higher levels of correlation with LL ($R^2=0.91$) and LS ($R^2=0.77$). It is noted that available literature also

suggests that LL can be a better indicator of soil swelling characteristics (Snethen et al., 1977; Weston, 1980). The laboratory data from Figures 2c,d indicate a relatively lower degree of correlations obtained for OMC and MDD ($R^2=0.40$ and $R^2=0.29$, respectively), which are two parameters that represent the placement conditions of compacted soils. The scatter can be attributed to the fact that soils with very similar values of MDD or OMC may have different degrees of plasticity, thus exhibiting different levels of swell.

3.2 A chart to estimate the potential swell of compacted soils

Considering the aforementioned results, a new chart was developed to quickly estimate the swelling potential of compacted soils based on their LL and field placement conditions (MDD or OMC). This chart summarizes the laboratory data from this study (Table 1) as well as the data reported by other researchers who examined the swell behavior of plastic soils compacted to their MDD and OMC (Table 3). Some interpolation was performed to define the areas with the same swell values.

The use of LL in this chart has several advantages: a) from the aforementioned discussion it is clear that LL is a good indicator of soil swell; b) LL depends on soil mineralogy and clay content which are variables that also determine the swell potential of soil; and c) it is easier and less time-consuming to obtain LL, compared to other soil properties such as clay content, clay mineralogy and cation exchange capacity which are used in other classification schemes but require special equipment.

The charts in Fig. 3 provide ranges of values for probable percentage of volume change as well as a qualitative expansion rating (i.e., low, medium, high and very high). For example, soil with LL=50% and OMC=16% may swell as much as 5% in the field when allowed to remain in contact with water for a period of time. To relate this chart to the one that was developed by Seed et al. (1962) for compacted soil mixtures, the same boundaries (i.e., 1.5, 5 and 25%) were used to define the expansion criteria.

3.3 Chart use and limitations

As this chart provides a quick estimation of soil's swell potential, engineers can use it at an initial investigation stage to minimize the laborious and time-consuming experimental work. While utilizing this chart, the following needs to be considered:

- The amount of swell that may be realized in the field also depends on environmental conditions including the amount of precipitation and duration of dry and wet periods. Soils may not reach its maximum swell value if not sufficient amount of water and time are provided.
- The proposed chart combines data from different sources, and for this reason, caution must be exercised when applying it to specific site conditions.
- The chart uses data on plastic soils which were compacted to their maximum dry density using a standard compactive effort. It may not be applicable for soils which were compacted by a modified effort.

3.4 Comparisons with existing charts

The swell potential of soils from the Thagoona area (Table 2) was estimated using three different classification charts which provided qualitative assessments of the expansion degree (i.e., low, medium, high and very high). The obtained results are summarized in Table 4.

It is interesting to note that although both Seed's (1962) and Williams (1980) charts utilize the clay content and soil activity as key classification parameters; they still produce slightly different estimates. This can be attributed to the fact that Seed's classification was developed for compacted artificial soil mixtures while the Williams method was suggested for all types of soil. The classification proposed by Dakshanamurthy and Raman (1973) utilizes the plasticity chart and yields the degree of expansion on the basis of LL. The chart proposed in this study provides classification outcomes which are similar to the Dakshanamurthy and Raman (1973) method; however, the proposed chart also gives the quantitative estimates with maximum swell values (in %). Compared to Seed's method, the proposed chart produces higher degrees of soil expansion, which may be attributed to different origin of soil used in both charts (artificial mixtures vs natural soils).

4. Conclusions

The main conclusions that can be drawn from this work are as follows:

1. The results of laboratory tests on natural soils from the Brisbane and Gold Coast area (Australia) indicated that the swelling potential of plastic soils has a high degree of correlation with the liquid limit (LL) and linear shrinkage. Soils with higher LL produce higher values of swell.
2. Classification charts were developed to quickly estimate the swelling potential of natural plastic soils compacted to their maximum dry density and optimum water content. These charts can minimize the laborious and time-consuming experimental routine.
3. The proposed chart gives estimates of soil expansion which are similar to the estimates produced by the Dakshanamurthy and Raman (1973) method. Compared to the Seed et al (1972) chart, which was designed for compacted soil mixtures, the proposed classification yields higher levels of soil expansion.

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Figure captions.

Figure 1. Typical results from oedometer tests on natural soils with different plasticity.

Figure 2. Experimental data plotted as swelling potential against a) liquid limit, b) linear shrinkage, c) optimum moisture content, and d) maximum dry density.

Figure 3. A proposed chart to estimate the swelling potential of soil based on its plasticity and optimum moisture content (a), and maximum dry density (b).

Table 1. Properties of the studied soils

Soil No.	Liquid limit, %	Plasticity index, %	Unified soil classification	Maximum dry density, g/cm ³	Optimum moisture content, %	Linear shrinkage, %	Percentage of swelling, %
1	23.4	9.0	SC	1.88	11.5	7.4	1.1
2	26.3	1.6	SM	1.52	17.5	3.4	0.5
3	30.2	1.2	SM	1.68	17.8	4.3	1.2
4	33.9	8.5	SM	1.81	11.9	6.3	1.4
5	34.3	17.2	SC	1.62	15.2	11.4	2.0
6	34.7	16.9	SC	1.72	17.4	12.7	1.7
7	36.6	18.7	SC	1.81	12.2	10.1	2.8
8	38.6	14.4	SC	1.79	14.9	7.1	1.8
9	38.9	19.3	SC	1.66	18.0	13.8	1.8
10	44.3	21.0	SC	1.62	17.8	10.2	4.2
11	46.8	23.5	SC	1.53	23.5	13.4	5.8
12	46.8	23.1	SC	1.51	18.0	13.0	6.8
13	52.4	28.8	SC	1.65	20.2	18.3	9.6
14	53.5	31.6	SC	1.52	22.0	16.9	7.9
15	54.2	26.8	SC	1.51	20.0	13.9	10.7
16	55.8	28.6	GC	1.47	23.0	16.1	11.2
17	55.8	31.8	GC	1.54	24.4	16.1	4.9
18	57.2	33.9	CH	1.57	18.2	18.6	9.2
19	61.3	39.6	CH	1.71	14.0	14.3	15.6
20	63.1	38.7	CH	1.46	24.0	16.2	14.1
21	63.5	39.9	CH	1.78	15.0	11.7	10.2
22	65.0	37.0	CH	1.61	19.0	17.0	16.4
23	65.2	34.0	CH	1.65	29.0	20.6	16.7
24	69.6	31.9	MH	1.50	22.7	20.3	18.1
25	74.5	38.2	MH	1.45	25.0	19.5	22.5
26	80.1	42.2	MH	1.40	28.0	21.4	23.9

Table 2. Properties of soils collected from the Thagoona area, Queensland (Australia)

Soil No.	Gravel, %	Sand, %	Silt, %	Clay, %	Activity	Major minerals
7	1	52	21	28	0.67	Smectite, Illite, Kaolinite, Quartz, Plagioclase
11	19	38	15	28	0.84	Smectite, Illite, Kaolinite, Quartz, Feldspar, Plagioclase
16	33	22	12	33	0.87	Smectite, Illite, Kaolinite, Quartz, Plagioclase
17	43	28	12	17	1.87	Smectite, Illite, Kaolinite, Quartz, Feldspar
26	0	7	14	79	0.53	Smectite, Illite, Kaolinite, Quartz, Plagioclase

Table 4. Degree of expansion for soils from the Thagoona, according to different classification charts.

Soil No.	Degree of expansion			
	Seed et al., 1962	Dakshanamurthy and Raman, 1973	Williams, 1980	Proposed chart
7	Low	Medium	Low	Medium
11	Medium	Medium	Medium	Medium
16	Medium	High	Medium	High
17	Medium	High	Medium	High
26	High	Very High	Medium	High