Characterization of expansive soils for the foundation of an irrigation canal in the Peruvian Andes, Cabana-Mañazo case

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Abstract. Alterations in water content in swelling soils cause volume variation, which implies constructive, socioeconomic and environmental damage. This paper characterizes the swelling soil located in an irrigation canal of the Peruvian Altiplano and its behavior of the properties by addition of lime in 5, 10, 15 and 20% of the total weight. Finding that the sample of the station 6+575 has combined presence of montmorillonite clays in a percentage of 13.52% together with the group of kaolinite in a percentage of 1.31%, consequently, it makes expandable clay of high plasticity. The soils of the station 6+250 have the characteristics of kaolinite clay, which distinguishes it as having low plasticity. In the swelling tests the high expansiveness was found, in the station 6+575, which has decreased with the addition of lime. Considering that concrete canals are generally of small thickness it would be important to consider the slightly dangerous effects on irrigation infrastructure.
1. Introduction
An expansive soft soil or rock tends to swell or shrink under changes in ambient humidity, especially from dry to wet [1]. Problems with foundations on expansive soils have included lifting, cracking and breaking pavements, building foundations and sloping slabs [2,3].

Irrigation canals are primary hydraulic infrastructures from an agricultural point of view, and their performance depends largely on the efficiency and durability of their coatings [4]. Canals located in expansive soils [5] and in regions with severe winters [6,7] must be lined with membranes or compacted soil. Significant substrate movements can induce considerable cracks and displacements, resulting in the settlement or rotation of the slope and banks. [8,9] mention structural methods to restrict the difficult behavior of an expansive soil such as stone columns, geo-synthetic earth platforms supported by piles, the sand mattress technique, bell pillars, granular pile anchors. However chemical stabilization that includes chemical treatment, the mixing of chemical agents with the soil, received much attention through numerous studies [10,11], so it's more promising. In general the improvement occurs in the increase of the resistance of the soil, the rigidity of the durability and the reduction of the plasticity of the soil and the potential swelling [12].

Therefore, it is necessary to control the contraction behavior of the swelling of the expansive soil to limit its harmful impact. In this study, a site was selected in the area of the main canal Cabana, analyzing the physical and chemical properties of the soil from the geotechnical point of view, because very little is known about the presence of expansive clay soils in the Peruvian Altiplano, this work has a very important significance. Thus, its objective is characterizing and determine expansion potential of 02 samples of clay soils found in the Cabana-Mañazo Irrigation project, which are soils typical of a semi-arid climate of the Andes and will allow to foresee the dynamics of the expansive phenomenon of clay soils.

2. Materials and methods
2.1 Study Area
The research work is located in the station 6+250 and 6+575 of the Cabana main canal of the Cabana-Mañazo irrigation project that is part of the Lagunillas Integral System, in the Puno region, Peru. Geographically it is at 15º 38' 54" S, 70º 19' 11" W and altitude of 3901 m.a.s.l. This main canal is 24 km long, which in turn is divided into 02 branches Cabana and Mañazo, being the canal under study the Cabana that mostly crosses the natural terrain in cut. For a flow of 5.50 m$^3$/s. During the construction process, there were lifting of the concrete slab, in a section of 250 meters.
2.2 Methods
The methodology consisted of taking the unaltered samples extracted from an exploratory boring of the slope adjacent to the canal, being covered with paraffin for conservation and transferred to the soil mechanics laboratory of the Faculty of Agricultural Engineering of the Universidad Nacional Agraria La Molina (UNALM) and X-ray laboratory of the Geological Mining and Metallurgical Institute (INGEMMET) in Lima Peru.

2.3 Characterization of Soils
To determine the physical and mechanical properties of the soil, Atterberg limits tests were performed, test method for particle-size analysis of soils according to NTP 339.128/ASTM–D 422, analysis by the hydrometer method according to ASTM–D 421–58 and D422–63. Tests were also performed to determine maximum dry density using the modified Proctor, which may influence the swelling potential.

2.4 Soil Chemical Analysis
To determine the influence of the chemical compounds of the clay soil on its expansivity, we proceeded to diagnose the content of chlorides, sulfates, total soluble salts and pH.

2.5 X-Ray Diffraction Analysis (XRD)
To identify and determine the crystallochemical parameters of the different minerals present in the clay fraction, the X-ray diffraction analysis was used, for which the Cu tube was used in a SHIMADZU diffractometer model XRD-6000, with energy of 40 Kv 30 mA from INGEMMET.

2.6 Degree of Expansion
2.6.1 Indirect methods
The swelling potential was determined using the Dakshanamurthy &Raman criterion [13], Van der Merwe [14] and Seed et al [15] using the equation suggested by [16], who have developed different methods to identify expansive soils based on the percentage of clay content (< 0.002 mm), plasticity index, liquid limit and activity. Consequently, soils are classified into low, medium, high and very high degrees of expansion (Figures 1a, 1b and 1c). There may be other criteria as indicated [17–19]. For the soil-lime mixture, lime was added to 5, 10, 15 and 20%.

2.6.2 Direct methods
Swell index (SI) test were applied, in accordance with the procedure specified in ASTM D 4829-95, measuring the expansion of the soil, under the state flooded in water, the soil sample was submerged for 24 hours and subjected to the action of a constant vertical pressure of 6.89 kN/m2 (1 psi). Similarly, one-dimensional
swell or Lambe test was carried out, according to the standard (ASTM D 4546), determining the swelling pressure of the soils under a known vertical pressure. The test was developed in a first stage loading the sample in factory conditions, and a second where the sample is saturated by flooding. The test ended when the sample reached saturation and there was no change in the vertical deformation of the sample for 24 hrs. The sample was then extracted, measuring its dimensions and water content.

The swell index (SI) is given by equation (1) [20]:

$$SI(\%) = \frac{\Delta H}{H_0} \times 100$$  \hspace{1cm} (1)

Where: $\Delta H$ is the vertical displacement and $H_0$ is the initial height of the sample.

The free expansion of a clay soil, according to [21], it is estimated according to equation (2).

$$FE(\%) = \frac{V - V_0}{V_0} \times 100$$  \hspace{1cm} (2)

FE = Free expansion %
V = Final volume of soil
$V_0$ = Initial volume of soil

**Table 1. Classification of Swelling Potential [20]:**

| Swelling Potential | Swell Index (\%) |
|--------------------|------------------|
| Very low           | 0 – 20           |
| Low                | 21 – 50          |
| Medium             | 51 – 90          |
| High               | 91 – 130         |
| Very High          | >130             |

**Table 2. Classification of the degree of expansion [21].**

| Degree of expansion | Free Expansion (\%) |
|---------------------|---------------------|
| Very high           | >100                |
| High                | >100                |
| Medium              | 50 – 100            |
| Low                 | <50                 |
Direct methods such as the free expansion test and the one-dimensional swell test are the most reliable for determining the degree of swelling, because their measurements are more direct in the laboratory. The procedures for determining the swell index and the free expansion using direct methods can be calculated using equations (1) and (2). We can correlate the swell index values with the swelling potential as shown in Table 1. Also, Holtz and Gibbs [21] have correlated the degree of expansion with values of the free expansion as presented in Table 2.

3. Results and Discussions

3.1 Soil Characterization

3.1.1 Physical and mechanical properties

The physical characteristics of clay soils are shown in Table 3, whose results indicate that the sample of the station 6+250, has a lower index of plasticity with respect to the sample of the station 6+575, being verified in the Unified Soil Classification System (USCS) of CL and CH respectively.

Table 3. Geotechnical soil characteristics of stations 6 + 250 and 6 + 575

| Properties                  | Station 6+250 | Station 6+575 |
|-----------------------------|---------------|---------------|
| Specific gravity (Gs)       | 2.782         | 2.782         |
| Unit weight [gr/cm3]        | 2.54          | 2.33          |
| Dry unit weight [gr/cm3]    | 2.5           | 2.31          |
| Water content ω [%]         | 1.51          | 6.5           |
| Saturated humidity ωsa [%]  | 3.23          | 5.4           |
| Specific weight [gr/cm3]    | 2.78          | 2.803         |
| Gravel content [%]          | 0             | 5             |
| Sand content [%]            | 8             | 10            |
| Fines content [%]           | 92            | 85            |
| Content <0.002mm [%]        | 24            | 46            |
| Liquid limit (wL) [%]       | 31.63         | 51.81         |
| Plastic limit [(wP) %]      | 18.13         | 19.95         |
| Shrinkage limit (wα) [%]    | 14.27         | 37.06         |
| Plasticity index (IP) [%]   | 13.5          | 31.86         |
| Classification USCS         | CL            | CH            |
| Maximum dry density [gr/cm3]| 1.99          | 1.75          |

3.1.2 Mineralogical identification

In Table 4, it is shown that the structure of the clay soil of the station 6 + 575 has among the main compounds silica (Quartz) in 60.25%, as well as minerals of the group of carbonates (Calcites) in 17.05%, with characteristics of the smectites group (Montmorillonite), common in sedimentary soils, presenting with Calcium, Magnesium, Silica and Alumina ions in the form of oxides and hydroxides, it
presents Montmorillonite \([\text{CaO}_2(\text{Al}, \text{Mg})_2\text{Si}_4\text{O}_{10}(\text{OH})_2.4\text{H}_2\text{O}]\) in a percentage of 13.52%, together with Kaolinites \([\text{NaO}_3\text{Al}_4\text{Si}_6\text{O}_{15}(\text{OH})_6.4\text{H}_2\text{O}]\) in a percentage of 1.31%, which would make it an expansive clay with high plasticity. With an influence on the potentiality of their expansion, due to the negative electric charge, the bond strength between them, the cation exchange capacity and the water absorption capacity of the montmorillonites, as expressed \([22–24]\).

Regarding the sample of the station 6 + 250, according to its basic structure the clay minerals belong to the group of Kaolinites (4.23%), with a strong presence of Dolomite (56.66%) and Quartz (23.68%) and other minerals, which characterizes it as a low plasticity clay.

Table 4. Mineralogical components of the analyzed soil.

| Mineral          | Formula                                                                 | Station 6+250 | Station 6+575 |
|------------------|-------------------------------------------------------------------------|---------------|---------------|
| Dolomite         | \(\text{CaMg(CO}_3\text{)}_2\)                                         | 56.66         | -             |
| Cuarzo           | \(\text{SiO}_2\)                                                        | 23.68         | 60.25         |
| Calcite          | \(\text{CaCO}_3\)                                                      | 1.06          | 17.05         |
| Montmorillonite  | \(\text{CaO}_2(\text{Al,Mg})_2\text{Si}_4\text{O}_{10}(\text{OH})_2.4\text{H}_2\text{O}\) | -             | 13.52         |
| Muscovite        | \((K,\text{Na})(\text{Al, Mg,Fe})_2(\text{Si}_{3.1}\text{Al}_{0.9})\text{O}_{10}(\text{OH})_2\) | 3.74          | 2.62          |
| Hematite         | \(\text{Fe}_2\text{O}_3\)                                              | 1.54          | 2.54          |
| Orthoclase       | \((K,\text{Ba, Na})(\text{Si Al})_4\text{O}_8\)                        | 4.59          | 2.05          |
| Kaolinite        | \(\text{Na}_{0.3}\text{Al}_4\text{Si}_6\text{O}_{15}(\text{OH})_6.4\text{H}_2\text{O}\) | 4.23          | 1.31          |
| Albite           | \(\text{Na}\text{Si}_3\text{Al}\text{O}_8\)                           | 3.17          | 0.66          |
| Magnetite        | \(\text{MgCO}_3\)                                                     | 1.33          | -             |

3.1.3 Soil Chemical Analysis

Table 5. Chemical constituents of clay soil

| N° Campo | T.S.S. (ppm) | Cl\(^-\) (ppm) | SO\(^4-\) (ppm) | pH | Ca (%) | Mg (%) | Na (%) |
|----------|--------------|----------------|-----------------|----|--------|--------|--------|
| Sample 6+250 | 160.00     | 23.80         | 25.92           | 8.28 | 5.37   | 0.10   | 0.29   |
| Sample 6+575 | 230.00     | 32.20         | 26.40           | 8.14 | 4.84   | 1.76   | 0.18   |

Lime
- - - - 33.20 - -

Table 5 shows the chemical composition of the station 6+250 and 6+575 samples, Total Soluble Salts (TSS), Chlorides (Cl), Sulfates (SO\(^4\)). Both samples are strongly basic soils (Alkaline), because they are within the 8.1-8.5 range, that is, due to the presence of Calcite (\(\text{CaCO}_3\)) (17.5%), so that alkalinity would be retaining the mineral salts of the structure in the soil, open, and therefore are soils
susceptible to swelling. Likewise, in terms of total soluble salts, chlorides and sulphates, the sample of the station 6+575 has higher values than the sample of the station 6+250, and is in a slight degree.

### 3.2 Degree of Expansion Analysis

Using indirect criteria, the sample of the station 6+250 using the Van Der Merwe criterion [14] it has a medium swelling potential (Figure 1a); with the criteria of Dakshanamurthy & Raman [13] and Seed et al. [15] it has a low swelling potential (Figure 1b and Figure 1c respectively); while the clay soil of the station 6+575 is located in a high swelling potential by the three criteria (Figure 1a, Figure 1b and Figure 1c).

**Figure 1.** Criteria commonly used to determine swelling potential: a) Van Der Merwe (1964); b) Dakshanamurthy and Raman (1973); c) Seed et al. (1962)

Subsequently, through the free expansion test, two tests were performed for the sample of the station 6+250, obtaining an expansion of 0.46 and 0.15 mm (see Figure 2a), where we consider the largest 0.46 mm, this result, provides a swell index of 18.4% calculated using equation (1) and places it with a very low swelling potential. According to Holtz and Gibbs [21], which estimates the degree of expansion of a clay soil through the free expansion, shown in equation
(2), for the expansive clay of low plasticity of the station 6 + 250, a degree of expansion between very low and medium.

In the same way, for the sample of the station 6+575, 1.25 and 0.97 mm were obtained as expansion values, (see Figure 2b), of which we consider the largest 1.25 mm. Determining a swell index of 50%, the result places it with a low to medium expansion potential. Also, according to [21] we attribute the degree of swelling of the clay soil, a medium degree of expansion.

Finally, through the one-dimensional swell test. For the sample of the station 6+250, a swelling pressure of 0.5884 kN/m² (0.006 kg/cm²) was obtained, which is less than 19.6 kN/m² (0.2 kg/cm²), therefore, its swelling potential is low. In the same way, for the sample of the station 6+575, a swelling pressure of 1976.04 kN/m² (20.15 kg/cm²) was obtained, this being greater and therefore characterizing it with a high swelling potential, as reported [17,25], having a very high potential to generate damage to structures [18].

3.3 Soil-lime mixture
Using the direct method of free expansion in a remolded sample, in the clay soil of low plasticity of the station 6+250, mixing with lime in percentages of 10, 15 and 20%, an expansion index of 8%, 10 % and 14% was obtained respectively, (see Figure 3a), namely, it can be seen that the lower the percentage, the lime acts better as a stabilizer of the expansive clay. As can be seen in Figure 3a, if we compare the expansion index of unstabilized clay (18.4%) at 0% lime, with that of clay mixed with 10% lime (8%), it is evident that the swell index was decreased by 56.5%.

In the same way, we tested the remoulded samples of high plasticity clay of the station 6+575, mixing with lime in percentages of 5, 15 and 20%, a swell index of 6%, 12% and 10% was obtained, (see Figure 3b), it can also be said that as the percentage of lime in the mixture with the clay increases, the free expansion also increases slightly, except for the mixture with 20% lime.
Comparing the swell index of unstabilized clay (50%) at 0% lime, with that of clay mixed with 5% lime (6%), it is evident that the swell index was decreased by 88%.

![Figure 3. Variation of the swell index with lime content: a) Expansion under constant pressure 6+250; b) Expansion under constant pressure 6+575](image)

The stabilization of the clay with lime, mixed with different percentages, shows that the swell index determined through the free expansion test, in all cases is lower than that of the unstabilized clay, the percentage of lime to be added being lower 5% to achieve a better stabilization of the clay. Therefore, it can be concluded that lime is a good stabilizer, thus reducing the degree of expansion of clay soils considerably.

4. Conclusions
The soil of the station 6+575 has the physical-chemical characteristics of a Montmorillonite in a percentage of 13.52% together with the group of kaolinites in a percentage of 1.31%, consequently, it is expansive clay of high plasticity, with a high swelling potential. While the soil of the station 6+250 has the characteristic of a basic structure of clay minerals belonging to the Kaolinite group, with 4.23% that characterize it as clay with low plasticity and a medium swelling potential.

Using the free expansion methods, a swell index was obtained for the sample 6+575, which configures it as a clay soil with a medium to high degree of expansion, while the sample 6+250 places it with a very low degree of expansion. By the one-dimensional swell test, in the sample of the station 6+250 a swelling pressure of 0.5884 kN/m² was obtained, less than 19.6 kN/m², therefore, its swelling potential is low. And for the sample of the station 6+575, an expansion force under controlled load of 1976.04 kN/m² was obtained; this is greater and therefore has a high degree of expansion, which makes it highly dangerous with harmful effects and consequences for irrigation infrastructure.
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