Clay swelling of Quaternary and Paleogene deposits in the south-eastern flanks of West Siberian iron ore basin

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Abstract. Revealing soil swelling and estimation of swelling rate are of great importance at the initial survey stages as well as the bases for further determination of more accurate factors used for selection of recovery methods and facility design. The paper states briefly the most conventional prediction express-methods and determination of swelling indicators, the results of laboratory research in clay composition and properties, free swell index of Quaternary and Paleogene clays in the south-east of West Siberian iron-ore, gives the estimates of the swelling rate. The results have been statistically analyzed, revealing the relationship of properties, on the basis of which the correlation dependencies are suggested to predict the free swell index as well as to apply it for frost heave prediction.

1. Introduction

When changing the temperature-humidity conditions swelling clay poses a serious problem for construction as, when steeping, one observes a transition from solid and semi-solid phases to plastic one, density reduction, several time decrease in strength properties, and increase in maximum swelling pressure up to 2 MPa that can result in partial or complete facility destruction. In accordance with the normative techniques used in geological engineering survey [1], swell index is determined for soils of natural humidity, which depends on the test time and may be significantly different depending on weather conditions at different time of the year. Even slight humidity changes are enough for the same soil to be classified differently in terms of relative swelling ε_{sw} according to [2]. Therefore, revealing of swelling clays is one of the most important tasks of a geological engineer for further detail study.

The purpose of the paper is to reveal the distribution of soils prone to swelling in the profile of south-eastern part of West Siberian iron ore basin.

The objectives include the review of previously conducted research in geological engineering conditions of the area to establish the presence of smectite and hydromica minerals, study the prediction methods of expansive soil behavior and its classifications, selection of express-methods to determine swelling characteristics, sample preparation and laboratory soil tests; statistical data processing and establishment of relationship between the values of their composition and properties.

2. Materials and methods

The review of previous local research [4-6] as well as some authors' studies [7, 8] has proved the presence of swelling minerals in the deposits. Swelling is known to develop in smectites and mixed-layer illites as well as silt-loam soil (non-swelling at water saturation) while steeping with chemical flows or process solutions. The maximum swelling is typical for montmorillonite-hydromicaceous minerals, the least one – for kaolinite-quartz-hydromicaceous minerals, but for the former swelling process is 3-6 times longer than for the latter [9].

The upper part of the profile includes genetic stratigraphic sequences of quaternary, Paleogene, and Cretaceous deposits. Cretaceous deposits of marine and coastal-marine genesis of Coniacian-Maastricht formation in the upper part includes Kuznetsov, Ipatov, and Gankin suits, in composition of which clay minerals of smectite, kaolinite, hydromica groups as well as mixed lattice minerals are found. Paleogene deposit includes Lyulinvorsk marine, Urkov coastal marine, montmorillonite, and hydromica. In stratigraphic-genetic sequence of lacustrine-alluvial deposits of Lagerno-Tomsk suit the value of relative clay swelling changes from 0.01 до 0.1 at the humidity 0.27-0.36 unit fraction [4]. Engineering geology of the USSR [4] presents the data on content of hydromica, montmorillonite (with the exception of higher level), kaolinite, and illite in all Quaternary deposits. In Upper Neopleistocene alluvial terrace deposits fine-dispersed fraction consists of hydromica as well as kaolinite, and, probably, montmorillonite [4], the recent alluvial deposits of flood-plain terraces contain hydromica with admixed montmorillonit, sometimes halloysite [5], in subaerial blanket formation clays include hydromica with admixed kaolinite [4].

Presence of clays is revealed by X-ray diffraction, chemical, spectral, differential thermographic analysis, electron microscopy, determination of cation exchange capacity, soil examination in thin sections and immersion, and other methods. In geological survey the mineral clay composition is not a mandatory value [9] due to the high cost of mentioned analyses, labour intensity, and low equipment availability. In terms of the methods used [1], tests of expansive soil are performed by soil free swell devices and odometers *at natural humidity* to determine the indicators: free swell ε_{sw}, swelling under pressure ε_{swp} and swelling pressure p_{sw}. At the initial survey stages the prediction is made using natural humidity and dry soil density [11]. Hence, these soil research methods do not take into account probability of humidity change, therefore, the methods of swelling soil research including dry condition (in powder) are of particular interest [11-13].

The following swelling indicators are used abroad: Free Swell Index [14], Potential Volume Change (PVC) и Swell Index, lb/ft^2 [15]; Percent swell CBR (%) [16]; COLE and LE (%) [17], Expansion Index [18]. There are also indirect prediction methods of soil volume change in terms of Atterberg's limits – Liquid Limit (LL), Plastic Limit (PL), Shrinkage Limit (SL), plasticity index, colloidal content, soil behavior, dry soil humidity and density, sum water intake value and many other factors [12, 22-26]. One should note the difference in methods for determining the consistency index in domestic and foreign standards, for comparison of the results of which it is recommended to apply dependencies given in the work [26]. To estimate the expansion rate for one or several indicators mentioned above the classification have been developed. These prediction methods do not account for soil mineral composition, therefore, cannot predict their swelling adequately. Free Swell Index *FSI*, unit fraction or % allows revealing expansive soils more accurately yielding additional information on the behavior of clay minerals [10]. The method of *FSI* determination was suggested by Holtz and Gibbs (1956) [14]: dry soil of 10 cm^3 volume (V_0) is sieved through the mesh № 425 μm, filled in the cylinder of 100 cm^3 volume, poured with water, then in 24 hours soil volume (V) is measured and swelling percentage is determined:

$$FSI = \frac{V - V_0}{V_0}\ 100.$$

The authors suggested that soils with free swell index lower than 100 % can cause serious structural damage producing maximum pressure on foundation. If the index is lower than 50%, such soil can hardly cause a volume change even at low pressure [14].

According to IS: 2720 [26] *FSI* is defined according to the following formula:

$$FSI = \frac{V_d - V_k}{V_k} * 100.$$

where V_d – the volume of dry soil deposit of 10 g weight sieved through the mesh 425 μm and placed in 100 ml measuring cylinder with distilled water, V_k – deposit volume of 10 g soil placed in the cylinder with kerosene (carbon tetrachloride). If soils are heavily swelled, 5 g of soil sample or cylinder of 250 ml volume are taken.

The methods yield negative values of FSI for soils rich in kaolinite [10], the other disadvantage consists in rough measurement of initial volume. To eliminate the problem the researchers offer modified free swell index (*MFSI*) equal to the relationship of deposit volume (V_d) of the dry soil of mass 10 g in 100 ml cylinder of water to the dry soil mass

$$MFSI = \frac{V_d}{10}.$$

The research was based on experiment works at soil composition and properties obtained in accordance with methods of exsiting specification documents [8, 27]. The following parameters were defined: grain-size distribution, water content (w), clay soil water content at plastic and liquid limits (w_L and w_p), density (ρ), solid particle density (ρ_s), dry soil density (ρ_d), porosity factor (e), porosity and maximum water capacity were calculated. To determine *FSI* the method was chosen [14] with insignificant difference in procedure: soil dried in the furnace is grained in the mill, then filled in the flask of 3 ml (V), poured with distilled water up to 10 ml mark, thoroughly mixed and stirred up. The volume of soil deposit (ΔV) is measured in a day or more, depending on the suspension transparency. Finally, the swell index is determined: $FSI = \Delta V/ V_0$, unit fraction or *%.* In authors' opinion, negative values of the kaolinite clay index can be used to predict soil frost heaving, which is rather relevant for the West Siberian area.

3. Results and discussion

To solve the set problems more than 200 samples are selected from clay soil from the depth of 160-200 m of Quaternary and Paleogene deposits. *In clays of Quaternary age* the fraction content is less than 0.002 mm, on average amounts 48.5%, changing from 25 to 52% (10 samples); in loam clay from 18,9 to 27%, on average 22% (6 samples). Water content of loam clay amounts from 20.5 to 30%, the minimal value of clay is 26.5%, maximum – 40%. Water content at the loam clay liquid limit is from 37 to 41%; clay from 42 to 51%. Water content at loam clay plastic limit is from 20.2 to 26.4%, clay from 19.4 to 31%. The liquidity index of loam clay is from 0.02 to 0.33%, that of clay is from 0.25 to 0.53%, respectively, loam clay is in semi-solid and low-plastic state, clay consistency is from low- to high-plastic. Loam clay density changes from 1.89 to 1.97 g/cm^3; clay – from 1.82 to 1.96 g/cm^3. The loam clay particle density amounts from 2.71 to 2.77 g/cm^3; clay – from 2.63 to 2.75 g/cm^3. Dry soil density of clay loam is from 1.47 to1.57 g/cm^3, clay – from 1.31 to 1.53 g/cm^3.

In Paleogene deposits the fraction conent in clay is less than 0.002 mm, amounts on average 34.6%, changing from 28.2 to 51.8% (60 samples), in loam clay on average 19,0%, ranging from 10.0 to 29.9% (60 samples), in dust sand and sand clay it amounts 1.6 to 14.7% of fraction content, the average content being 3.9% (40 samples). The clay water content has the minimal value – 11.9%, maximal – 44.5%, that of loam clay is from 19.1 to 61.7%; that of sand clay – from 19 to 42.3%; that of dust sand – from 14.7 to 40.4. Water content at the clay liquid limit is from 42 to 77%; loam clay – from 28.5 to 59%; sand clay – from 33 to 48%. Water content at clay plastic limit changes from 18.7 to 47%; loam clay – from 18.7 to 45%; sand clay – from 26.7 to 42.6%. The clay density changes from 1.70 to 2.04 g/cm^3, loam clay – from 1.73 to 2.15 g/cm^3; sand clay – from 1.77 to 2.06 g/cm^3; sand – from 1.73 to 2.35 g/cm^3. The clay particle density changes from 2.50 to 2.82 g/cm^3; loam clay – from 2.53 to 3.03 g/cm^3; sand clay – from 1.58 to 2.96 g/cm^3; sand – from 2.50 to 3.09 g/cm^3. Dry soil density of clay loam accounts for from 1.16 to 1.77 g/cm^3; clay – from 1.18 to 1.65 g/cm^3; sand clay – from 1.27 to 1.65 g/cm^3, sand – from 1.25 to 1.86 g/cm^3. Hence, Paleogene dispersive soil is characterized by higher density in contrast to soil of quaternary deposits, clay soil consistency is various and includes all types from solid to liquid. According to [9], swelling is found at clay particle content in the amount of more than 40–60%, dry soil density – more than 1.5–1.7 g/cm^3, water content – less than 0.20–0.30 unit fraction. Hence, the data obtained allow determining soil composition and properties as low- and medium swelling.

As a result of experiments the following *FSI* values were obtained:

- in clay of quaternary deposits they vary from 0.23 to 0.87 %, the average is 0.59, in loam clay it is from 0.10 to 0.73, the average – 0.42% (4 samples of every type),

- in clay of Paleogene deposits they vary from minus 0.03 to 0.23 %, the average is minus 0.10% (20 samples), in loam clay – from minus 0.13 to 0.47, the average – 0.23% (20 samples), in sand clay they are from minus 0.17 to minus 0.03, the average being minus 0.10, in dust sand they are from minus 0.10 to 0.33, the average being 0.02%.

In general, *FSI* distribution in the section is shown in Figure 1 where expansive soils in green claystone-like deposits of Lyulinvorsk suit are clearly seen, in the interlayer of bluestone and loam clay of Novomikhailovsk and Lagerno-Tomsk (swell index is up to 0.50 unit fractions), three maximum values are observed in Quaternary deposits. Negative values of *FSI* are established in soils of Novomikhailovsk, Lagerno-Tomsk, and Urkov suits, therefore, these soils shouls be studied in terms of relative heaving deformation. According to the classifications [8, 26] the studied soils are referred to low and medium swelling indexes. According to the classification [12] the results obtained are of serious concern, as at *FSI* < 10 soils are non-expansive, low-expansive within the range 10-15%, medium-expansive at 15-20%, high-expansive soils are within the range 20-40%, and more 40% - very high.

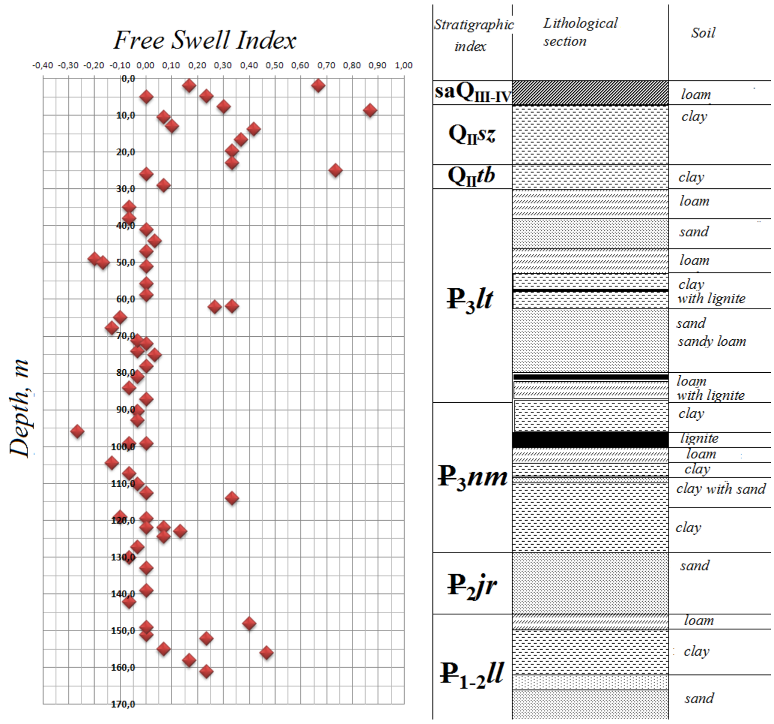

Figure 1. Changes in free swell index FSI with depth.

The statistical analysis has revealed the relationship between the soil properties and *FSI*, the closest dependencies are registered between *FSI* and plasticity index *IP* (correlation coefficient *r* = 0.66), particle number of size less than 0.002 mm $C_{<0.002}$ (*r* = 0.63), more than 0.05 $C_{>0.05}$ (*r* = –0.34), within the range 0.05–0.002 mm $C_{0.05–0.002}$ (*r* = 0.24), water content at plastic limit *PL* (*r* = –0.43), water content at liquid limit *LL* (*r* = 0.21), liquid indicator *IL* (*r* = –0.23), internal friction angle *φ* (*r* = –0.26). Based on the established relationships of *FSI* with composition and properties the regression equations are obtained:

$$FSI = -0.262+0.021\cdot IP,$$
$$FSI = -0.223 + 0.014\cdot C_{>0.002},$$
$$FSI = -0.149+0.006\cdot LL,$$
$$FSI = 0.492-0.014\cdot PL.$$
$$FSI = 0.263-0.009\cdot \varphi.$$

4. Conclusion

Hence, the research results confirmed the common occurrence of expansive soil in the sections of Quaternary and Paleogene deposits at the South-Eastern flanks of West Siberian iron ore basin. Their properties are not always taken into consideration when choosing a method of mineral deposits development which might result in undesirable effects because the soil swell index increases 2-3 times at soil structure disturbance [9]. The work performed is the first step in research of clay properties including problem statement and determination of relationships to predict swelling. The next step should be a more detailed study in swelling soil behavior allowing their qualitative estimation based on comparison of the obtained results with more detailed soil tests. Simultaneously, the database would be enlarged that would become a base for local classification in terms of free swell index. Similar procedures would be performed to study soil heaving properties with negative values of *FSI*. Finally, it is important to note that *free swell index should be a mandatory value* at any geologic survey.

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