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ENGINEERING PROPERTIES OF VERTISOLS

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Abstract

Vertisols are deep clayey soils, with more than 45% clay, dominated by clay minerals such as smectites, which expand upon wetting and shrink upon drying.

The most important physical characteristics of Vertisols are a low hydraulic conductivity and stickiness when wet and high flow of water through the cracks when dry. They become very hard when dry and in all the time are difficult to work. During the rainy season, the cracks disappear and the soil becomes sticky and plastic with a very slippery surface which makes Vertisols hardly trafficable when wet.

Water movement in soil that change volume with water content is not well understood and the management of swelling soil remains problematic. Swelling or shrinking result in vertical displacement of the wet soil, which involves gravitational work and contributes to an overburden component to the total potential of the soil water. Many swelling soils crack and the network of cracks provides pathways for rapid flow of water, which prejudice application of theory based on Darcian flow. One – dimensional flow of water in a swelling system requires material balance equation for both the aqueous and solid phases.

The analytical data offers some values of particle – size distribution, compression, swelling degree and pressure, plasticity index, elastic modulus, triaxial shear, angle of shear and load carrying capacity in order to realize a foundation study for some constructions.

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1. INTRODUCTION

Vertisols occupy significant areas in India (approx. $7.9*10^5 km^2$), Australia (approx. $7*10^5 km^2$) and Sudan (approx. $5*10^5 km^2$), while China, Ethiopia, and the USA each have approximately $1.5*10^5 km^2$ (Smiles D., Raats P., 2005). They tend to be chemically fertile, but physically they are generally very intractable; they become very hard when dry and sticky and plastic when wet. Volume change accompanying water movement is a central activity. The physics of swelling soils has much to offer in engineering soils to support built structures.

The magnitude of the soil solution - soil matrix interactions depends to a large extent upon the types and amounts of inorganic and organic soil colloids. The presence of smectite minerals imparts a considerable cation exchange capacity and/or specific surface area to soils from arid and semiarid regions. Furthermore, smectite minerals are capable of considerable expansion at moderate - to - high exchangeable sodium levels in the presence of relatively low salt soil – solution

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concentration. High concentrations of exchangeable sodium produce a soil structure breakdown which reduces permeability, aeration, infiltration rate, and soil workability.

The smectite group consists of minerals with the 2:1 structure already discussed for mica and vermiculite, but with a still lower charge per formula weight, namely 0.6-0.2. An idealized formula for a common soil smectite, the mineral beidellite, is: $M^{+}_{0.33}Al_2(Si_{3.67}Al_{0.33})O_{10}(OH)_2$, where M^+ represents exchangeable cations, typically Ca^{2+} and Mg^{2+}.

The most common smectite mineral range in composition between three end-members: montmorillonite, beidellite and nontronite. All are dioctahedral, but they differ in the composition of the tetrahedral and octahedral sheets. Smectites do not fix K^+ as readily as do vermiculites because smectites have a lower layer charge, but smectites swell more extensively than vermicultite. This is illustrated in figure 1 by the larger spacing between the 2:1 layers.

Smectites are important minerals in temperate-region soils. Many plant nutrients are held in an available form on the cation exchange sites of soil smectites. Soils rich in smectite tend to be very effective at attenuating many organic and inorganic pollutants because of the high surface area and adsorptive properties of the smectites. Smectites shrink upon drying and swell upon wetting. This shrink-swell behavior is most pronounced in the Vertisol order and in vertic subgroups of other soil orders. The shrink-swell properties lead to cracking and shifting problems when houses, roads and other structures are built on smectitic soils.

Vermiculite has a layer charge of 0.9-0.6 per formula unit and contains hydrated exchangeable cations, primarily Ca and Mg, in the interlayer (figure 1). A typical formula for an idealized vermiculite weathered from muscovite is: $M^{+}_{0.75}Al_2(Si_{3.25}Al_{0.75})O_{10}(OH)_2$, where M^+ represents exchangeable cations. The high charge per formula unit gives vermiculite a high cation exchange capacity and causes vermiculite to have a high affinity for weakly hydrated cations such as K^+, NH^{+}_4 and Cs^+.

Vermiculites in soils are believed to form almost exclusively from the weathering of micas and chlorites. Vermiculite does not swell as extensively as smectite and this is shown in figure 1 by the presence of only two planes of water molecules surrounding the hydrated cations in the interlayer space.

Hydroxyl-interlayered vermiculite and smectite can be considered a solid solution with vermiculite or smectite as one end-member and chlorite as the other. Hydroxyl-interlayered minerals form as Al^{3+} released during weathering hydrolyzes and polymerizes to form large polycations with a postulated formula of $Al_6(OH)^{3+}_{15}$ (or similar) in the interlayers of vermiculite and smectite. The interlayer hydroxyl Al is not exchangeable, therefore it lowers the cation exchange capacity of smectite or vermiculite almost linearly as a function of the amount of Al adsorbed in the interlayer.

Interlayer hydroxyl Al prevents smectite from shrinking and swelling as it normally would. The positively charged hydroxyl interlayers also provide potential sites for anion adsorption. Hydroxyl-interlayered vermiculite and smectite are most common in Alfisols and Ultisols. Within a given profile, they tend to be most abundant near the soil surface.

Three mechanisms operate to transport solutes in soils and aquifers (Sukop M., Perfect E., 2004). **Advection** refers to the movement of chemicals with soil fluids and groundwater. Diffusion is the omnidirectional spreading of a chemical that result from thermal motion of the fluid and solute molecules.

Dispersion results primarily from variations in fluid velocity that occurs at all scales. Dispersion is anisotropic and enhanced in the overall direction on flow. Flow through the vadose zone requires study of saturated and unsaturated flow through variably saturated media.

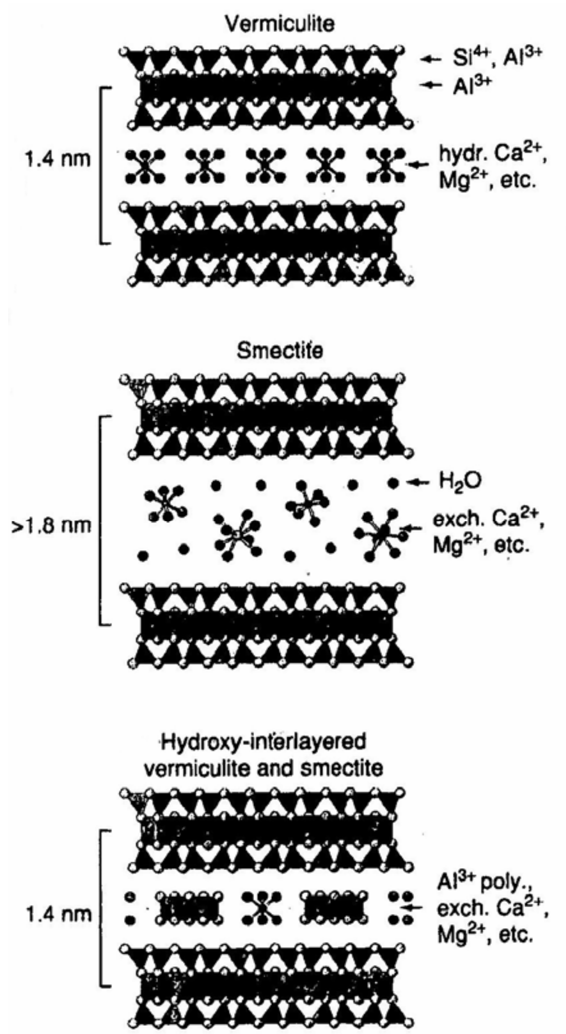

Figure 1. Structural scheme of soil minerals

Both saturated and unsaturated flow problems may be steady – state or transient. Solutes can interact strongly with soil surfaces by physical or chemical adsorption and their transport can be appreciably slowed in a process known as **retardation**. Flow through the vadose zone requires study of saturated and unsaturated flow through variably saturated media.

The follow equations describe the movement of water:

- Steady-state flow through a ***saturated medium***:

The Darcy equation can be written as:

$$q = -K \frac{\Delta(z + \Psi)}{\Delta L}$$

Two-dimensional flow in the x-^{z} plane is described as:

$$qi = -K_{i,j} \frac{\Delta(z+\Psi)}{\Delta x_j}$$

- Transient flow through a ***saturated medium***

Substituting the specific storage into the mass balance equation gives:

$$\frac{\partial}{\partial_{xi}}(K_{i,j}\frac{\partial_\psi}{\partial_{xi}}) = S_s \frac{\partial_\psi}{\partial_t}$$

This form of the equation describes the transient response of a porous medium to changes in the applied pressure head.

- Steady – state flow through an ***unsaturated medium***

The derivate of the matric flux potential is related to the flux as:

$$\frac{\partial_\phi}{\partial_x} = q_x$$

- Transient flow through an ***unsaturated medium***

Transient unsaturated flow is underlying of the Richards equation:

$$\frac{\partial}{\partial_{xi}}(K_{i,j}(\theta)\frac{\partial_{(z+\psi)}}{\partial_{xi}}) = \frac{\partial_\theta}{\partial_t} \quad (1)$$

Water movement in soils that change volume with water content is not well understood, and management of swelling soils remains problematic. Swelling or shrinking accompanying soil water content change results in vertical displacement of the wet soil which involves gravitational work and contributes an overburden component, to the total potential of the soil water.

Swelling soils crack and the network of cracks provides alternative, preferential pathways for rapid flow of water which prejudice application of theory simply based on Darcian flow (Russo D., 2005). Terzaghi (1961), Richards (1931) applied a diffusion approach to water in clay soils in agricultural context. In addition, Philip analyzed the one-dimensional problem using conventional coordinates. One – dimensional flow of water in a swelling system requires material balance equations for both the aqueous and solid phases:

$$\frac{\partial \theta w}{\delta t} = -\frac{\delta Fw}{\delta z}(1); \; \frac{\delta\theta s}{\delta t} = -\frac{\delta Fs}{\delta z}(2)$$

where z is a distance coordinate, t is the time, Fw and Fs are the volume flux densities of the water and of the solid (cubic meters per square meter per second) relative to the observer and θw and θs are the volume fractions of the water and solid. The volume fractions are defined per unit area of horizontal cross section of the soil and the reference volume includes the cracks.

The total potential θ of the water in swelling systems have been considered from a thermodynamic perspective and mechanistically. Thus θ is the sum of the gravitational potential, z, the unloaded matric or capillary potential, Ψ, the overburden potential, Ω, (representing vertical displacement of the wet soil accompanying unit change in water content at z. The total potential, θ, is defined by the equations:

$$\phi = z + pw = z + \psi + \Omega = z + \psi + \alpha(S_z^T \wp dz + P)\,(3)$$

In eqn (3), $\wp$ is the wet specific gravity of the soil, P is any static load on the soil surface, and α reflects the degree to which the soil is elevated by unit change in water content. In a saturated soil, α= 1; when the soil is unsaturated 1 ≥α; and in a nonswelling soil, α= 0. In civil engineering contexts, P may be very important.

The overburden, Ω, is related to the civil engineers ″effective stress″according to the equation:

$$\Omega = \alpha\delta = \delta^{'} + Pw \, (4)$$

in which δ is the total normal stress and δ′ is the effective or interparticle stress.

2. MATERIALS AND METHODS

Soil mechanics is a branch of science studying in civil engineering and agricultural engineering, the mechanical properties and processes of soils. Soil mechanics can be divided in two branches: mechanical properties – like grain size descriptions, density, bulk density, pore space, void ratio, packing, permeability and rheological properties – like consistency, plasticity, deformation, resistance to shearing, stress – strain, compression, compaction, consolidation, swelling and shrinking, elastic modulus, pressure (Rogobete et al., 2005, Rogobete and Bertici, 2006).

The location for geotechnical and foundation study was situated between Timisoara and Sacalaz village (Timis County). Field trials and sampling from a drilling of 2.80 m depth were conducted in order to realize in the laboratory some analysis and trials. Methods included in Romania Standards were used, such as STAS 1913/12-82, STAS 1913/9-76, STAS 9180-73, STAS 8942-82, STAS 8942/5-75, STAS 8942-71.

The scientific considerations relied on a lot of studies effectuated during 40^{th} years in Banat region, published in many publications.

3. RESULTS AND DISCUSSION

Vertisols occupy large areas in Romania such as:

- in the hilly regions of Banat, Oltenia, Muntenia (piedmonts);
- in the north part of Transylvania (tableland);
- in the subsidence plain, like Aranca Plain, from the west part of Banat;
- in floodplains from Barlad and Suceava Plateaus (in the perimeter of Iasi, Vaslui, Barlad, Roman).

Important contributions for geotechnical studies on soils rich in smectites have been brought in Romania by Andrei S. (1967), Boti N. (1992, 1996, 2002), Siminea I. (1996).

The determination of elastic deformation, in the case of soils with swelling and shrinking phenomena, can be realized with the method of double edometer, either with the theorem of moisture equilibrium.

The method of double edometer consists in the determination of the specific swelling (ε ui) on the grounds on the grounds of compression – porosity curves established behind a parallel trial with two soil samples from the some depth, and consolidated in the edometer, using a classic test.

$$\left(\frac{\Delta h}{h}\right)_{pi} = \frac{eo - ei}{1 + eo} \rightarrow \varepsilon ui = \frac{(\Delta e)i}{1 + eo} \, (5)$$

Totalized the elementary layers, in the presence of a, p, pressure, the swelling of active zone is:

$$Su = \sum_{1}^{n} hi\varepsilon ui \, (6) \quad \text{or} \quad Su = \sum_{1}^{n} hi \frac{(\Delta e)i}{1 + eo} \quad (7)$$

where:

hi – depth of elementary layer; eo – pores index: Δe – porosity variation by swelling; n – the number of elementary layers which constituted the active zone, Hu, (Hu takes 3.00 m from the terrain level).

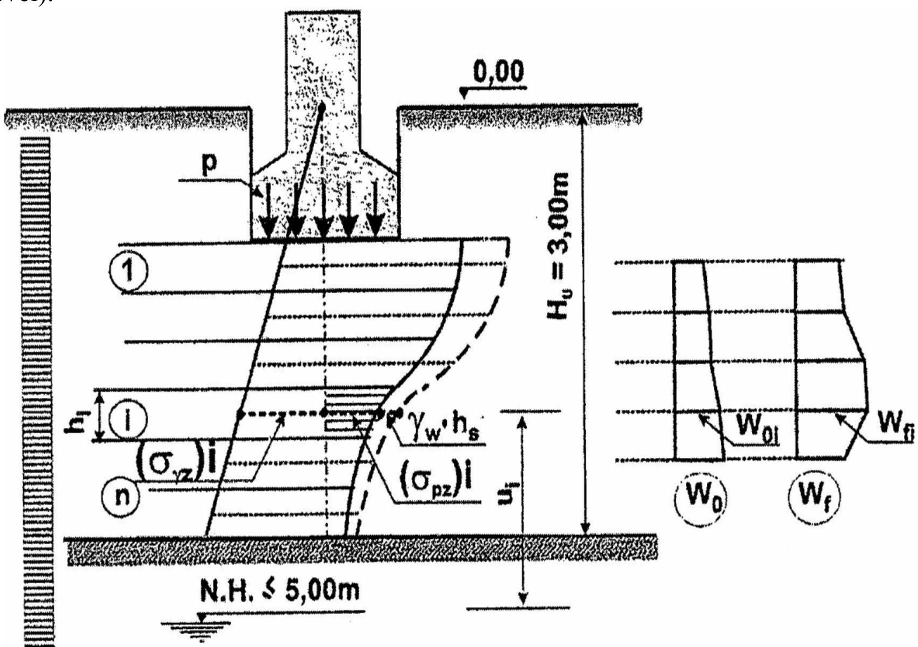

Figure 2. Calculation scheme for swelling estimate

The total pressure on the elementary layer will be estimated with:

$$Ptot = \delta\eta + \delta pz + \delta s \quad (8)$$

where:

Ptot – total pressure; δη- geological load for the elementary layer, calculated from the sole of foundation: δpz – vertical strain of the middle of the elementary layer; δs = mn*y(z+Df), supplementary pressure from the construction dimension.

The value of the subsidence (Sc) determinate by de contraction of foundation terrain, as a result of moisture decrease, can be calculated with:

$$Sc - \sum_{i=1}^{n} hi\varepsilon cimc \quad (9)$$

where:

εci– specific contraction; mc=1.30.

The main results obtained in test of soil sampled in a drilling with 2.80 m depth are presented in table 1:

Table 1. Rheological properties, Sacalaz drilling 1

Depth, m	- 0.50	- 1.10	- 1.90	-2.80
Coarse sand, %	0.50	0.45	0.40	0.65
Fine sand, %	25.30	52.35	26.80	28.20
Silt, %	21.90	20.70	23.43	28.70
Clay, %	52.30	53.50	49.40	42.45
Density, g/cm^3	1.46	1.60	1.62	1.52
Total porosity, %	44	40	41	43.5
Pore index, %	0.78	0.66	0.71	0.77
Penetration resistance, Rp, no knock	21	19	17	9
Plasticity index, Ip, %	59.10	66.10	30.00	28.10
Consistence index, Ic, %	0.91	1.10	0.92	0.91
Volume contraction, Cv, %	51.20	57.96	49.55	44.68
Natural humidity, w,%	24.4	20.65	20.07	19.65
Contraction limit, ws,%	8.6	8.9	9.9	15.4
Optimum humidity for compaction, Proct. 27, %	18.4	19.7	18.3	16.4
Deformation module, M, daN/cmp	60	105	90	44
Cohesion, c, daN/cmp	0.50	0.65	0.65	0.40
Activity index, IA	1.13	1.23	0.61	0.66
Internal angle of response, ϕ^o	9.5	10.0	10.5	15.3
Critical pressure, Pcr, t/m^2	13.65	18.18	18.49	23.13
Admissible pressure, Padm, t/m^2	6.82	9.09	9.24	11.56

In order to evaluate the intensity of the swelling and shrinking phenomena and the presence of the ″active layer″, we present the limits for the main rheological properties.

Table 2. Classification of the soil with swelling and shrinking

Activity	Clay %	Ip %	I_A %	U_L %	ws %	Cv, %		w15 %	Pu MPa
						matur struct.	modified struct.		
very active	>30	>35	>1.25	>140	<10	>100	>35	>18	>0.4
active	18-35	25-35	1.0-1.25	100-140	14-10	75-100	25-35	13-18	0.1-0.4
less active	15-25	20-30	0.75-1.00	70-100	16-14	55-75	15-25	10-13	0.05-0.1

The ground established for geotechnical study is plane, but with ″gilgai″ elements, and ascertained stability. The first layer, from the surface, Lower Holocene, has 5-6 m thickness and is formed by alluvium materials, which contain clay minerals, such as smectites, that expand upon wetting and shrink upon drying. Under this layer, on 20-40 m thickness, there is a sandy – clay complex, attributed to Medium Pleistocene. The ground water layer is at 1.0 m depth, is rich in bicarbonate, but is not aggressive for concrete. From the survey presented in table 1, it can be noted that the ground has a normal consolidation, a plastic consistence, to plastic viscous, which becomes hard by drying, and in this state occurs a maximum deformation. All rheological indices indicate a great activity with a high pressure on the foundations upon constructions. The minimum depth for foundation is recommended to be: Dmin=1.50 m from the surface. For the foundation layer situated

between 1.90-2.80m we will consider the next indices: bulk density = 1.52 t/mc; c = 0.40 daN/cm^2; Φ= 1.53^o; M = 44 daN/cm^2; pressure adm. = 11.56 t/m^2.

There are necessary measures for water evacuation and support; the ground is integrated at the category – heavy ground, for manual dig.

For soil scientists it is important to define the Vertisols and the index for classification these soils.

An index characterizing quantitatively the soil swelling/shrinking properties, i.e. the volume change of a soil during such processes is CoLE:

$$CoLE = \frac{Lw - Ld}{Ld} = \frac{BDd}{BDw} - 1$$

where CoLE is the coefficient of linear extensibility, and Lw and Ld (m) are respectively the lengths of the soil sample under wet (at 1/3 bar) and dry (oven-dry) conditions, and BDw and BDd (Mg·m^3) are the bulk densities under these two moisture conditions. Vertisols usually have a CoLE of >0.07.

Vertisols in ST and WRB classifications are a soil order or reference soil group with a vertic horizon within 100 cm from the soil surface; ≥30% clay in all horizons to a depth of 100 or more and a layer ≥25% thick that has either slickensides close enough to intersect each other, or wedge – shaped aggregates having their long axis tilted at 10^o-60^o from the horizontal; cracks that open and close periodically, these cracks being ≥1 cm wide.

Vertisols in SRTS – 2012 (Romanian Soil Taxonomy) is a class with two soil types, Vertosol and Pelosol; with >45% clay (rich in smectite) respectively Vertosol, having swelling – shrinking properties (z and y horizons) and Pelosol, having only swelling-shrinking properties (z horizon).

In order to make an evidently difference between Vertosol and Pelosol we propose index from soil mechanics, easily to establish:

- Ip, plasticity index:
  - Y, vertic horizon >35%
  - Z, pelic horizon 25-35%
- $U_{L,}$ free swelling = $100 \cdot \frac{Vf + Vi}{Vi}$ in which: Vf – final volume, Vi – initial volume
  - Y, vertic horizon >140%
  - Z, pelic horizon 100-140%
- I_A, activity index = $\frac{Ip}{Clay}(< 2\mu),\%$
  - Y, vertic horizon >1.25
  - Z, pelic horizon 1.00-1.25

It can be used also, index like:

- w_s – contraction limit; y-<10%; z-14-10%

Cv – volume contraction; y->100%; z-75-100%

4. CONCLUSIONS

Terrains with more than 30% clay, dominated by clay minerals such as smectites, expand upon wetting and shrink upon drying. Volume change accompanying water movement is a central activity. Solutes interact strongly with soil surfaces by adsorption and thus appears the process

known as retardation, and the overburden potential, representing vertical displacement of the wet soil. Soils with swelling and shrinking phenomena are present on large areas in Romania. The total pressure on the elementary layer can be estimated with eq. 8. In order to investigate the rheological behavior some determinations were made. The minimum depth for foundation layer is 1.50 m from the surface. Deformation module M is 44 daN/cm^2, and the admissible pressure, P, is 11.56 t/m^2.

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