Swelling of compacted expansive clays interpreted in terms of Tezaghi effective stress

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ABSTRACT: Experimental data on nine different sodium and calcium bentonites from literature are examined. Specific experiment types are selected so that we evaluate the behaviour of microstructural units (aggregates) rather than the global behaviour of compacted bentonite, which is influenced by its double structure. We show that it is possible to uniquely represent the unconfined water retention curve, swelling pressure tests, swelling under constant load tests and mechanical unloading tests in the space of dry density of clay aggregate vs. mean Terzaghi effective stress. Our analysis implies that the Terzaghi effective stress is applicable for description of the expansive clay aggregate behaviour and it is reasonable to consider the behaviour of aggregates to be reversible. In addition, for a broad range of suctions, they can be considered as fully saturated.

1 INTRODUCTION

Compacted bentonites – clays with high smectite content – have received considerable research attention in the past, particularly thanks to their application in engineered barrier systems of high-level radioactive waste repositories. Models of different types have been developed to reproduce their swelling behaviour. The models include purely empirical models, diffuse double layer models and continuum thermodynamics-based models. These models relate the swelling pressure/water potential to inter-particle distance. They assume homogeneous particle distribution, so that the inter-particle distance can be calculated from the clay specific surface area and global dry density. The actual structure of a compacted clay is, however, more complex. It is formed by clay platelet clusters (hereafter referred to as aggregates or microstructure), which form the primary component of a rather complicated structure. To predict the mechanical response of such a material, models that explicitly consider two structural levels have been developed by different authors (by example, Gens and Alonso 1992, Alonso et al. 1999, Mašín 2013). The double structure models typically assume a simple representation of the aggregate response; that is (1) validity of the Terzaghi effective stress is assumed, (2) the behaviour of aggregate is assumed to be reversible elastic and (3) aggregate is assumed to be fully saturated. These assumptions are often put forward without any justification, but the researchers admit that the aggregate behaviour is most likely to be more complex.

In this work we wish to elaborate more on this issue. Instead of studying the material under general stress conditions using double structure approach, we select specific experiments, where the global response is predominantly governed by the behaviour of aggregates. We show that, subject to reasonable assumptions, different features of the bentonite behaviour can be predicted solely on the basis of unconfined water retention curve data. Among other consequences, our findings imply validity of the Terzaghi effective stress principle to represent the clay aggregate behaviour. Theoretical analysis of this consequence can be found in a journal paper (Mašín & Khalili 2013). Our evaluation is directly applicable to specific suction range only, in which the microstructure remains saturated and macrovoids are either dry, or they are effectively closed thanks to the high compaction level.

2 STUDIED SOILS

Experimental data on a number of different compacted clays, mostly Na- or Ca-montmorillonitic bentonites, have been studied. The investigations include five primarily sodium montmorillonitic bentonites,

three primarily calcium montmorillonitic bentonites, and one bentonite composed of an interstratified calcium beidellite and kaolinite. Experimental data have been obtained from the following sources:
– Avonseal bentonite: Graham et al. (1989).
– FEBEX bentonite: Villar (2002).
– FoCa7 bentonite: Cui et al. (2002), Delage et al. (1998) and Van Geet et al. (2009).
– Bavaria bentonite: Baille et al. (2010).
– Kunigel V1 bentonite: JNC (2000), Komine (2004).
– Volclay bentonite: Komine (2004).
– Kunibond bentonite: Komine (2004).
– Neokunibond bentonite: Komine (2004).
– MX-80 bentonite: Johannesson et al. (1999).

Primary chemical and mineralogical compositions of the soils are summarised in Table 1.

Table 1: *Mineralogical and chemical composition of the soils studied. References to the composition data are given if different from experimental data sources. M – montmorillonite, B – beidellite, K – kaolinite, CEC – cation exchange capacity.*

bentonite	smect. cont. [%]	dom. smect. min.	dom. ex. cation	
Avonseal[1]	79	M	Na	
Bavaria	60	M	Ca	
FEBEX	92	M	Ca	
FoCa7[2]	80	B+K[3]	Ca	
Kunibond	80	M	Ca	
Kunigel V1[4]	48	M	Na	
MX-80[5]	83	M	Na	
Neokunibond	76	M	Na	
Volclay	69	M	Na	
	CEC $\left[\frac{\text{meq.}}{100\text{g}}\right]$	Na $\left[\frac{\text{meq.}}{100\text{g}}\right]$	Ca $\left[\frac{\text{meq.}}{100\text{g}}\right]$	Mg $\left[\frac{\text{meq.}}{100\text{g}}\right]$
Avonseal[1]	82	41	35	6
Bavaria	74		65	
FEBEX	111	25	47	36
FoCa7[2]	69	3	63	
Kunibond	80	12	59	7
Kunigel V1[4]	73	41	29	3
MX-80[5]	88	67	8	5
Neokunibond	104	62	33	6
Volclay	101	57	29	13

[1]JNC (2000); [2]Saiyouri et al. (2000); [3]FoCa7 clay composed of kaolinite interstratified with the beidellite in equal proportion (Van Geet et al. 2009); [4]Komine (2004); [5]Karnland et al. (2006).

3 ORIGINAL EXPERIMENTAL DATA

3.1 *Unconfined water retention curve*

The water retention curve (WRC), in unconfined conditions, is a relationship between the water content and suction at zero net stress. Available are experimental water retention curves of FEBEX, Kunigel V1, MX-80 and FoCa7 bentonites; see Fig. 1. We evaluate wetting branches of water retention curves, for consistency with the other experimental data types. In Fig. 1 and in the following text, s_m denotes matric suction, s_π denotes osmotic suction and $s_t = s_m + s_\pi$ is total suction.

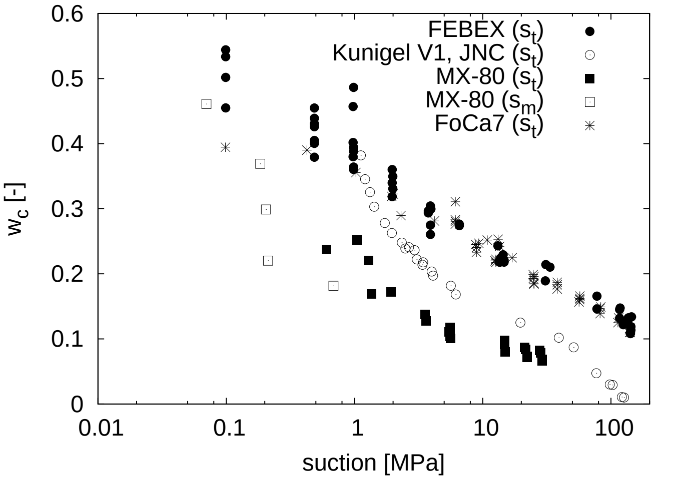

Figure 1: Wetting branches of water retention curves of soils investigated, original experimental data. w_c is gravimetric water content.

To interpret the WRC in a unified manner, we take advantage of findings by Romero et al. (2011). They observed that the water retention curve is in the higher suction range ($s_t > 2$ MPa for Boom clay by Romero et al. 2011) independent of the initial global relative density. In this case, the macrostructure may effectively be considered as dry. In addition, we assume consistently with the double structure modelling full saturation of aggregates. Dry density ρ_d (solid mass over aggregate volume) and void ratio e calculated from the global water content then represent dry density and void ratio of aggregates. It turns out that

$$\rho_d = \frac{G_s}{G_s w_c + 1}\rho_w \qquad e = G_s w_c \tag{1}$$

where $G_s = \rho_s/\rho_w$ is solid specific gravity, $w_c = m_w/m_s$ is gravimetric water content, and m_s, m_w, ρ_s and ρ_w are solid and water masses and densities respectively. In the evaluation of experimental data, $G_s = 2.7$ (Mitchell & Soga 2005) and $\rho_w = 1000$ kg/m^3 has been adopted throughout. A simplification is thus introduced here, as the intercrystalline water may have a slightly higher density than the free water (Mitchell & Soga 2005) and we neglect eventual uncertainty in G_s. The above WRC evaluation is limited to suction range in which macrovoids remain dry and microstructure is fully saturated.

Under the assumption of full aggregate saturation, matric suction can be associated with negative pore water pressure, and the Terzaghi effective mean stress p is equal to the matric suction s_m. In the higher suction range, suction is in the experiments imposed by controlling the relative humidity of the system, representing total suction. In what follows, matric suction has been estimated from the experimental data using $s_m = s_t - s_{\pi 0}$ as first approximation. A value of $s_{\pi 0} = 0.41$ MPa has been adopted in evaluating all the data available. This value was obtained by Romero (1999) as the osmotic suction of pore water of compacted Boom clay prepared by mixing it with demineralised water. As the osmotic suction is reported to increase slightly with increasing matric suction (Miller & Nelson 2006), the values of the effective stresses obtained represent an upper bound for the likely correct values. $s_{\pi 0}$ depends on pore water chemistry and it is thus expected to differ in different soils tested. It has been checked that the actual value of $s_{\pi 0}$ has only minor effect on the evaluation results.

3.2 *Confined wetting (swelling pressure) tests*

The confined wetting test (swelling pressure test) is an important method for characterising the swelling properties of compacted soils, as it resembles the situation encountered in the engineered barriers, where the bentonite blocks are hydrated under confined conditions. The experiments are typically performed from the as-compacted state at hygroscopic humidity. The soil is soaked, and the resultant total stresses due to confined wetting are measured. Available are swelling pressure test results on FEBEX, MX-80, Bavaria, Avonseal, FoCa7, Kunigel V1, Volclay, Kunibond and Neokunibond bentonites.

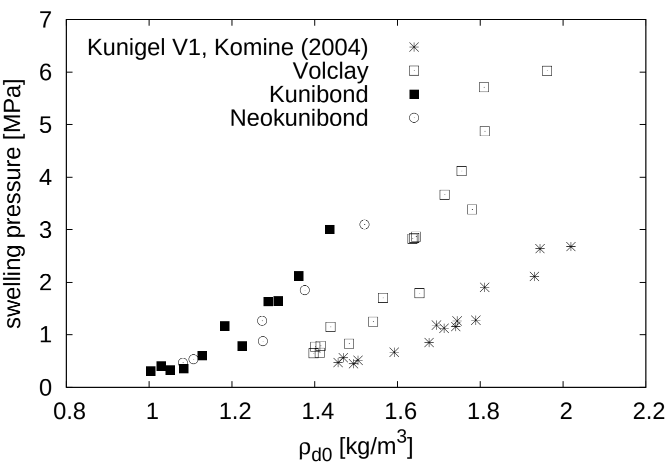

Figure 2: Swelling pressure tests, example of original experimental data.

Figure 2 shows example experimental data from the swelling pressure test results plotted in the plane of the initial global dry density ρ_{d0} (solid mass over total soil volume) with respect to the final swelling pressure at zero matric suction. In the initial as-compacted state, the global dry density does not represent dry density of aggregate due to the presence of effectively dry macrovoids. After saturation, however, experimental observations by different authors (e.g., Monroy et al. 2010, Romero et al. 2011) suggest that the porosity distribution becomes monomodal, particle orientation changes and a more uniform pore size distribution is attained. As global dry density is constant during the swelling pressure test, the initial global dry density of the sample represents the aggregate dry density at full saturation. By the test specification, matric suction is nil at the end of the swelling pressure test, and the swelling pressure thus represents the effective stress within the soil specimen.

3.3 *Mechanical unloading tests on saturated soil*

The next experimental data represent mechanical unloading tests on saturated soils or at constant value of suction. Experiments starting from high stress levels (of the order of tens of MPa) are relevant for our evaluation only. In this case, macroporosity is very low and the global dry density (global void ratio) represents dry density (void ratio) of aggregates. Consistent with double structure modelling, macroporosity does not substantially open up during subsequent unloading. Oedometric unloading test data at saturated conditions are available for FEBEX and Bavaria bentonites (Fig. 3a). Isotropic loading-unloading tests at extremely high cell pressures and different suctions are available for FoCa7 bentonite (Fig. 3b). In addition, we include isotropic compression results on reconstituted Avonseal bentonite (Fig. 3a).

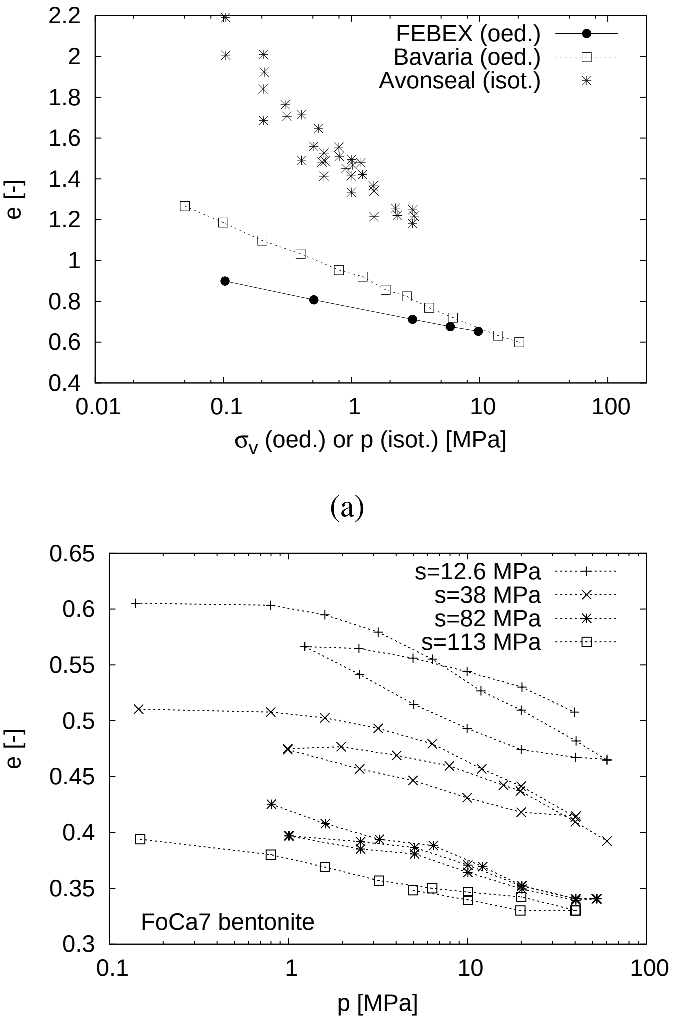

Figure 3: Mechanical unloading and compression tests; original experimental data. (a) tests at $s = 0$, (b) isotropic tests at different suctions.

Evaluation of oedometric unloading tests is complicated by the fact that the measured vertical stress does not represent the mean effective stress within the sample. For the purpose of our evaluation, the value of K_0 (ratio of horisontal and vertical stresses) has been estimated using the Mayne & Kulhawy (1982) empirical relationship

$$K_0 = (1 - \sin \varphi_c)\text{OCR}^{\sin \varphi_c} \quad (2)$$

where OCR denotes the overconsolidation ratio, calculated as the ratio of maximum preconsolidation vertical stress and current vertical stress. The value of φ_c was not available for Bavaria bentonite. $\varphi_c = 25°$, reported by Gens et al. (2009) for FEBEX bentonite was also used for the Bavaria bentonite. Test data on Avonseal and FoCa7 clays represent results of isotropic unloading tests, where the mean stress is measured directly.

3.4 *Wetting under constant load tests*

The last type of experiments evaluated are wetting-induced swelling tests at constant vertical load. The tests were performed under oedometric conditions on unsaturated soil samples compacted to different known initial global dry densities. The soil was then soaked and left to swell under constant vertical load. The experimental data relate the swelling strain ϵ_s to the sample initial global dry density. Data are available for FEBEX, Kunigel V1, Volclay, Kunibond and Neokunibond bentonites (example experimental data are in Fig. 4).

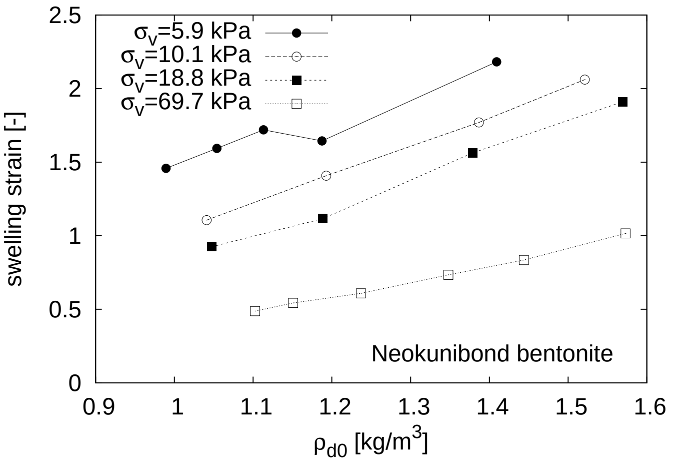

Figure 4: Swelling under constant load, example of original experimental data.

The experimental data were evaluated in the following way. First of all, it was assumed that at saturation the pore space distribution is monomodal, similar to the confined swelling pressure tests. The soil final dry density ρ_d thus represents the aggregate dry density at full saturation. The experimental sources, however, are normally presented in terms of the initial dry density vs. swelling strain. The soil final dry density may be calculated from the initial global dry density ρ_{d0} and swelling strain ϵ_s by a simple relationship $\rho_d = \rho_{d0}/(1 + \epsilon_s)$ (note that under oedometric conditions the measured vertical strain equals to the volume strain). As in the case of the oedometric unloading tests, the oedometric conditions imply development of horisontal stresses, which are not measured. In our evaluation, we adopted a fixed value of $K_0 = 1.5$. This value appeared to be reasonable estimate for the given experiments. As the value of K_0 was uncertain, we also investigated sensitivity of the results on the selected K_0 value and concluded its effect was not substantial.

4 UNIFIED INTERPRETATION OF THE EXPERIMENTAL RESULTS

All the above experiments have been plotted in the space of effective mean stress p vs. aggregate dry density ρ_d. Results for all soils and test types are given in Figs. 5 to 7. It is observed that the data form distinct bands in the p vs. ρ_d space. This supports the proposed unified representation. It is, however, pointed out that the data themselves are relatively scattered and thus unique representation cannot be fully proved.

The unified representation has important practical consequences. For example, swelling pressures and swelling strains of densely compacted bentonites may be estimated from a single unconfined water retention curve without a need to resort to more complex material modelling.

Note that similarity between the swelling pressure and water retention behaviour evaluated under the assumption of full saturation has also been shown experimentally by Dueck et al. (2010) and Johannesson et al. (1999), and explained in terms of the continuum thermodynamic model by Dueck & Börgesson (2007).

5 CONCLUDING REMARKS

In the paper, we re-interpreted experimental data from the literature on different compacted smectitic clays. There appeared to be a unique relationship between the clay aggregate dry density (void ratio) and the mean Terzaghi effective stress. It implied that for a broad suction range the Terzaghi effective stress was applicable for description of the expansive clay aggregate behaviour, they could be assumed as fully saturated and their volumetric behaviour was reversible.

As a practical consequence of our findings, it was possible to estimate swelling pressures, swelling strains under a constant load to zero final suctions, as well as the unloading mechanical response based solely on unconfined water retention data. Our approach needs to be adopted with caution, however, as the experimental values are scattered and any conclusion drawn are valid within the scatter only. In addi-

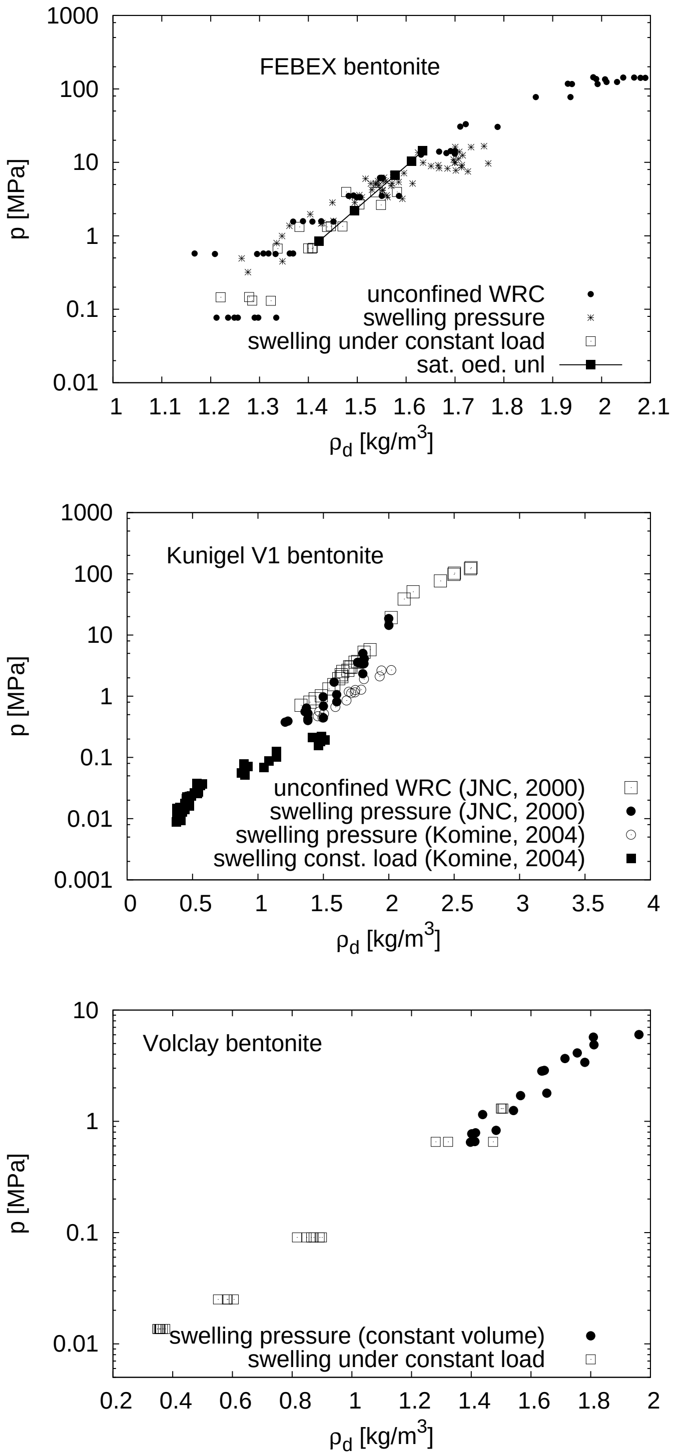

Figure 5: Experimental data re-plotted in the ρ_d vs. p space, part 1.

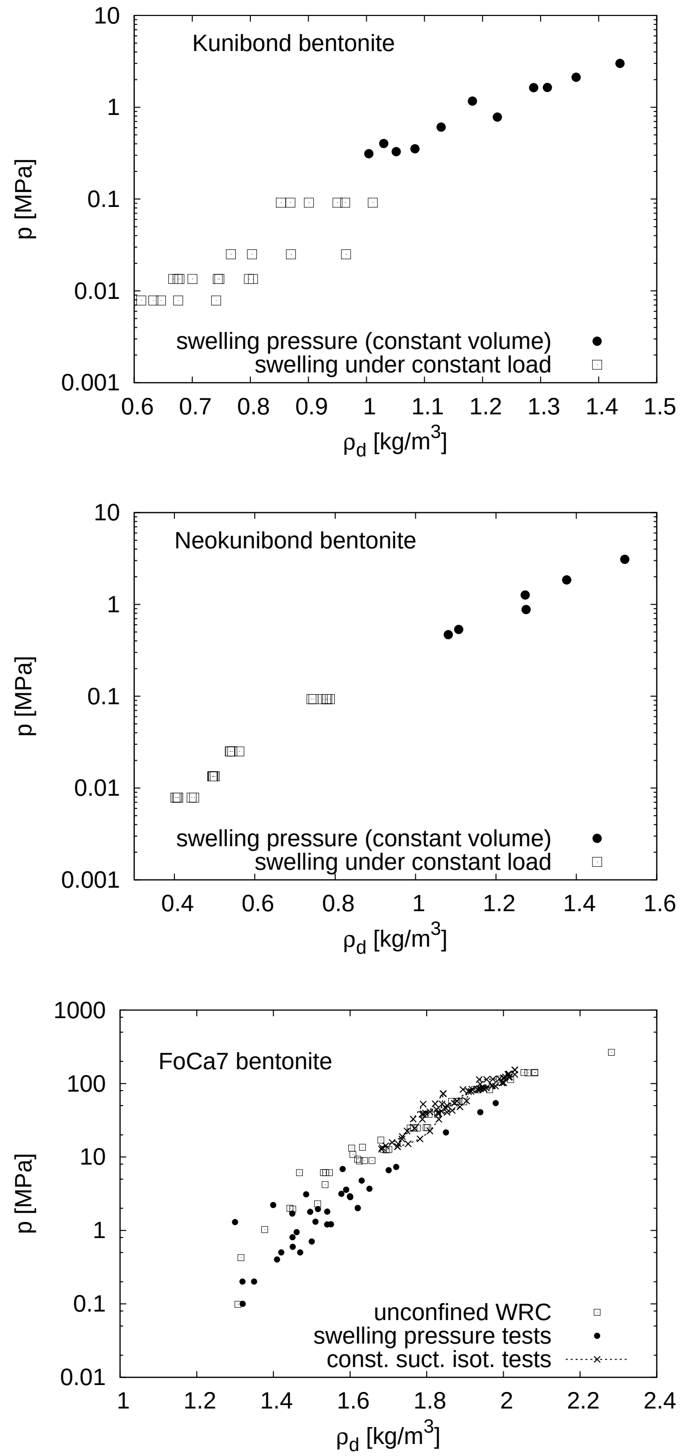

Figure 6: Experimental data re-plotted in the ρ_d vs. p space, part 2.

tion, the analysis is only valid to that portions of water retention curves where macrovoids are dry and aggregates saturated. For more discussion on the validity of Terzaghi effective stress to represent response of aggregates in fine-grained expansive soils, see Mašín & Khalili (2013).

We must emphasize that we did not advocate the use of a simple elastic volumetric model to predict the overall mechanical behaviour of compacted clay. Our conclusions were restricted to specific experiment types, where the state of the aggregates could be interpreted based the global measurements, subject to reasonable assumptions. In other cases, more complex models need to be utilised.

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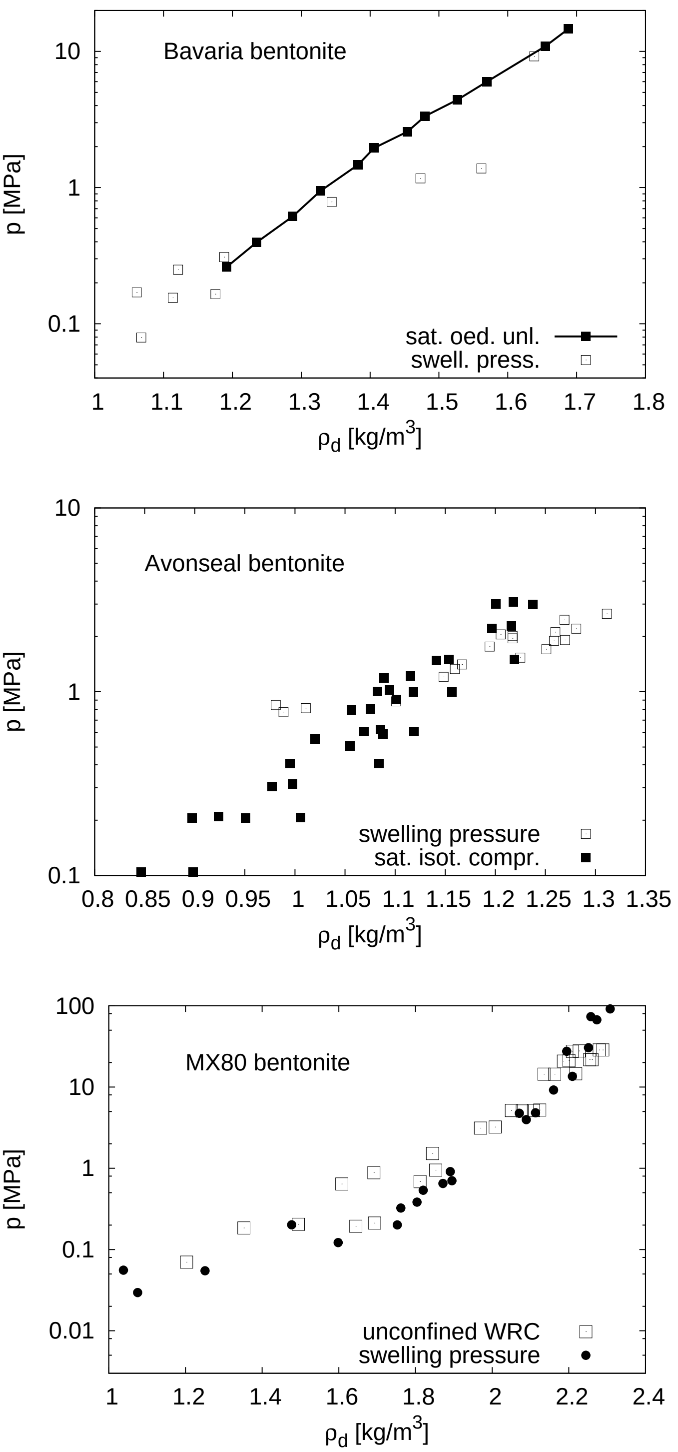

Figure 7: Experimental data re-plotted in the ρ_d vs. p space, part 3.

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