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Technical Note

Volumetric deformability and water mass exchange of bentonite aggregates

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ABSTRACT

A constitutive model of the volumetric behaviour of bentonite aggregates is proposed. The model is based on a state function to define the inter-aggregate (microstructural) void ratio and on a mass transfer function to calculate the mass exchange between macrostructural and microstructural water. Although both functions have been used previously for clay soils, their application beyond the range for which they were derived is proposed. To evaluate whether this extrapolation is valid, data on the swelling of individual bentonite aggregates are analysed. This novel aspect of this study is significant because it is not common to analyse microstructural data directly without introducing any hypothesis about the behaviour of the macrostructure. Despite the lack of a more intensive validation, which will be conducted when more experimental data become available, the results obtained have been satisfactory.

1. Introduction

Expansive bentonite is a clay soil with significant engineering applications, especially in the construction of municipal and industrial waste landfill liners (US EPA, 1993) and barriers for the storage of spent nuclear fuel (see, for instance, Pusch, 1992; Gens et al., 1998; Yong, 1999b; Cui et al., 2002; Chegbeleh et al., 2008; Pusch and Weston, 2012). Important contributions to the modelling of the bentonite behaviour have been made. Particularly relevant are the advancements presented at important conferences, such as the 3rd International Conference on Expansive Soils held in 1973 in Haifa (Israel), the International Symposium on Soil Structure, held the same year in Stockholm (Sweden), and the workshop 'Microstructural modelling of natural and artificially prepared clay soils with special emphasis on the use of clays for waste isolation', which was held in 1998 in Lund (Sweden) (Issues 1 and 2 in volume 54 of Engineering Geology; Pusch, 1999; Yong, 1999a). At this last workshop, Alonso et al. (1999) presented the 'Barcelona Expansive Model' (BExM), which was based on the conceptual approach proposed by Gens and Alonso (1992). The model is based on the idealisation of the bentonite structure as having two structural levels, a macrostructure and a microstructure. BExM has proven to be a powerful tool for characterising the behaviour of bentonites (see, for instance, Lloret et al., 2003), thereby demonstrating the power of conceptual models based on double porosity approaches.

It is therefore of great interest that progress is made in the macroscopic characterisation of the microstructure behaviour of bentonite. This is not a simple task because it is not easy to obtain isolated information about microstructure behaviour, i.e., information about the microstructure that is not coupled to macrostructural processes. Data on bentonite aggregate deformability available from Montes-H (2005), Montes-H et al. (2003a, 2003b, 2005a, 2005b), Farulla et al. (2010), and Romero et al. (2011) are consequently very useful. In those studies, environmental scanning electron microscopy (ESEM) was combined with digital image analysis to identify individual bentonite aggregates, characterising their area variation as a function of environmental relative humidity.

ESEM images are sensitive to working conditions. Particularly, when monitoring microstructural changes along drying and wetting paths with varying gas pressures (as done by Montes-H and co-workers), it is important to maintain a constant monitoring distance (Romero and Simms, 2008). However, if the ESEM images are obtained carefully, they provide information that is valuable for understanding the behaviour of soil microstructure (Romero and Simms, 2008). In the following sections, a constitutive model for the volumetric behaviour of bentonite aggregates is proposed, and the experimental results obtained by Montes-H (2005) and Montes-H et al. (2003a, 2003b) are used to assess its range of applicability and limitations.

2. Aggregate concept and aggregate deformability

A bimodal pore size distribution is evidenced in compacted bentonite from mercury intrusion porosimetry (MIP) tests (Collins and McGown, 1974; Pusch, 1982; Collins, 1984; Alonso et al., 1987) (see Figure 1). The predominant smaller pore sizes are in the vicinity of 10 nm and correspond to pores inside clay aggregates. The predominant larger pore sizes of the MIP-bimodal distribution depend on the dry density, which

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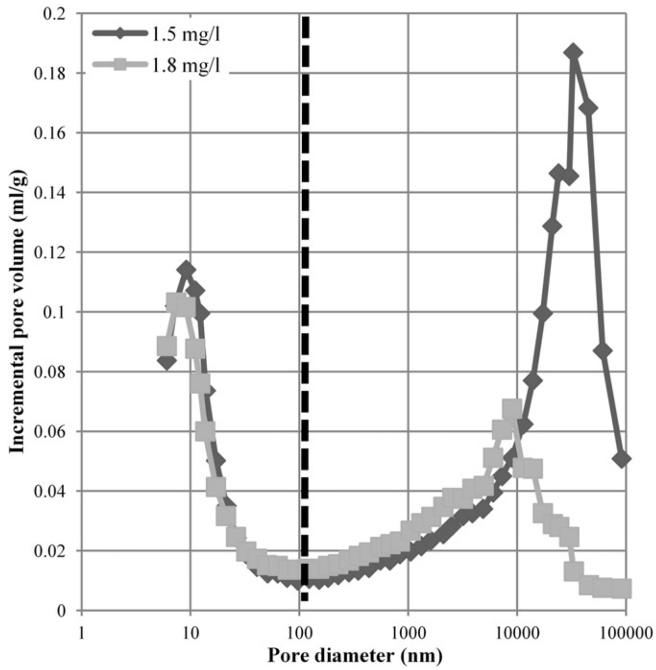

Fig. 1. Distribution of incremental pore volume for two compacted bentonite samples at different dry densities.
Adapted from Lloret et al. (2003).

depends of the compaction load (e.g., 10 μm for dry density $\rho_d = 1.8\ g/cm^3$ and 40 μm for dry density $\rho_d = 1.5\ g/cm^3$) (Romero, 1999; Romero et al., 1999; Lloret et al., 2003). Despite the pore size distribution being a continuum, a boundary between the two pore families, that is, between the intra-aggregate porosity and inter-aggregate porosity, has been identified at approximately 100 nm by different authors (Romero, 1999; Lloret et al., 2003; Romero and Simms, 2008). Pores smaller than this size do not appear to be affected by the level of the compaction load (Romero, 1999; Lloret et al., 2003; Montes-Hernandez et al., 2006). As other authors have done (see, for example, Pusch, 1982; Romero, 1999; Romero et al., 1999; Pusch and Moreno, 2001; Lloret et al., 2003; Romero and Simms, 2008) and as proposed by Gens and Alonso (1992), the bimodal pore size distribution of the soil is idealised in this study using a double porosity model.

Macroporosity is associated with the inter-aggregate pores. The soil deformation is due to the rearrangement of the granular-like skeleton formed by the aggregates. Therefore, its behaviour may be described by 'conventional' models for the unsaturated soil mechanics (Lloret et al., 2003), as the Barcelona Basic Model (Alonso et al., 1990).

The microstructural level is associated with intra-aggregate porosity due to inter-sheet voids as well as interstack voids. One sheet is 'the smallest building of clay'. A montmorillonite sheet has a 2:1 structure and is formed by an octahedral aluminium oxide layer sandwiched between two tetrahedral silicon oxide layers (see van Olphen, 1977). The sheets are approximately 1 nm thick and are typically between 50 and 300 nm long in the other directions (Neretnieks et al., 2009). A number of sheets held together mostly face to face are known as a 'stack' (Figure 2a and b). When sodium is the dominant counterion, the stacks consist of one sheet or a few sheets (Cadene et al., 2005). When calcium dominates, the stacks typically consist of 5 to 15 sheets or more (Pusch and Yong, 2006). Aggregates are formed by the agglomeration of stacks that are held together more loosely than the sheets in stacks.

As Fig. 2c shows, the stacks are not necessarily arranged in a parallel mode inside the aggregates. In addition, heterogeneities can be produced in the interior of the stacks, as shown in Fig. 2a and b. Therefore, the interior of the aggregates has a complex topology that is difficult to characterise. It is reasonable to expect two hierarchical levels, interlamellar and interstack voids using the notation in Neretnieks et al. (2009). However, as with the formulations derived by Gens and Alonso (1992), the approach taken in this paper does not characterise that topology. Only one macroscopic variable, the microstructural void ratio e_m (e_m = volume of voids in the microstructure per volume of clay mineral), is used in this study to describe the intra-aggregate porosity (microporosity). The aggregate is treated as a microstructure

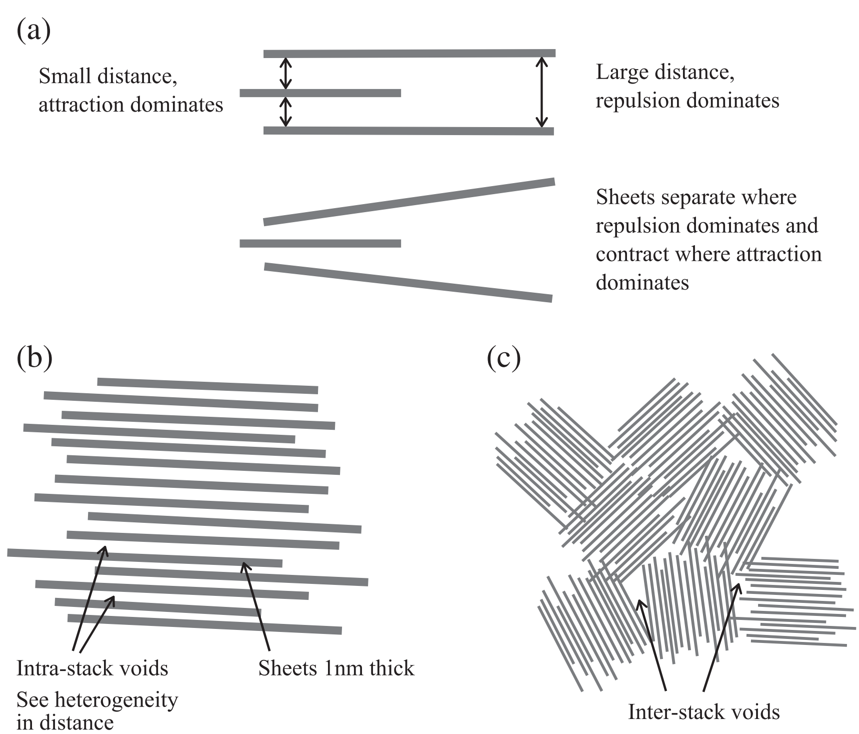

Fig. 2. (a) Sheets defining heterogeneity in the interior of a stack. (b) Arrangement of sheets forming a stack. (c) Arrangement of stacks in a compacted bentonite.
Adapted from Neretnieks et al. (2009).