Proceedings of the 8th Australian-New Zealand Conference on Geomechanics, Hobart
Tasania. pp. 179-186. February 15-17, 1999

Changes in Clay Structure and Behaviour due to Wetting and Drying

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Summary A synthesis is presented concerning the mechanisms associated with clay structure and behavioural changes during wetting and drying. Generic units forming soil structure are identified as soil particles, particle associations and aggregations and particle clusters. It is evident that the clay structure and behavioural changes are controlled primarily by the changes in the pore size distribution. For young soils, the growth and rearrangement of particles and particle aggregation will produce a dense and stiffer structure during drying. For heavily overconsolidated soils, initially denser structures can regenerate to produce relatively loose structures. During drying, the frequency of macropores increases, whereas during wetting, the majority of the macropores close and transform into intercluster and intracluster pores. The development and the response of cracks are dependent on the restraint conditions placed on the soil and the initial stress state of the soil. The changes in pore system as well as the associated soil properties appear to stabilise as the number of wet/dry cycles increases.

1. INTRODUCTION

Surficial clay soils are of interest in agricultural, geotechnical and environmental applications. These clay soils play an integral role in the natural hydrogeologic systems by controlling evaporative and evapotranspirative losses and recharge. Since surficial soils are directly exposed to seasonal changes in climate, distinct differences in structure and behaviour generally result between the surficial and underlying natural soils. For example, surficial clay soils commonly develop desiccation (shrinkage) cracking, which has a significant influence on rates of infiltration and solute transport. Similarly, during seasonal climatic changes, clay soils can undergo swelling and shrinkage posing difficulties in both engineering and agricultural applications. It is clearly evident that the shrink/swell or wet/dry cycles can change the clay structure in these soils leading to changes in soil behaviour.

The literature covers a range of aspects of clay structural development in surficial soils, and can be found in several disciplines (e.g., Soil Science, Geotechnical Engineering, Geology, and Agricultural Science). These aspects include climatic changes (or wet/dry cycles), weathering, leaching of chemicals, oxidation, biological activity and vegetation. The current paper presents a synthesis on the clay structure and behavioural changes during wet/dry cycles.

2. BASIC CLASSIFICATIONS RELATED TO CLAY STRUCTURE

2.1 Clay Structural Units

Brewer (1964) defines the "clay structure" as the size, shape and arrangement of the soil particles and voids including both primary particles to form compound particles and the arrangement of compound particles themselves. The term fabric is commonly used to refer to the arrangement of soil particles. In addition to the fabric, the structure takes into account the stability of the particle arrangements and associations under various physical and chemical stresses. A variety of terms are used to refer to soil structural features (e.g., Collins and McGowen, 1974). In order to present the following synthesis in a simplified and a consistent way, only a limited number of terms are used in the following explanations.

The generic structural unit of the clay structure is termed a clay particle. The clay particle consists of preferentially aligned individual layers of clay mineral units (platelets). The number of interlayer units forming a particle can depend on a range of factors including the mineral type, matric potential and pore chemistry. The next level of structural unit is termed an aggregation representing an association of clay particles. Sometimes, the particle associations and aggregations are considered as two separate units. In this description, the aggregations also represent various particle associations such as domains (Quirk and Aylmore, 1971), quasicrystals (Quirk and Aylmore, 1971) and tactoids (Blackmore and Miller, 1961). Clay aggregations and other particles can combine to form larger units known as clusters (Olsen, 1962). Clustering can lead to stable aggregates, which generally develop after several wet/dry cycles (Hussein and Adey, 1995), and also other units such as clods and peds (Mitchell, 1993). The terms "macrostructure" and "microstructure" are used to differentiate between large and small structural features.

2.2 Pore Categorisation

The micropores are considered to be the smaller capillaries and pores within interaggregations whereas macropores are the much larger intercluster voids. The cracks also come under macrostructure and are sometimes referred to as planar pores. However, the boundary between micropores and macropores is arbitrarily chosen in the literature with vague criteria. Several authors have attempted to classify the soil pore structure on some rational basis (e.g., Beven and Germann, 1982; Luxmore, 1981; Quirk and Murray, 1971). Many of these classifications make use of the desaturation of a capillary pore under an assumed negative pressure. Various arrangements of particles can give rise to different pore types within the soil structure as shown in Figure 1.

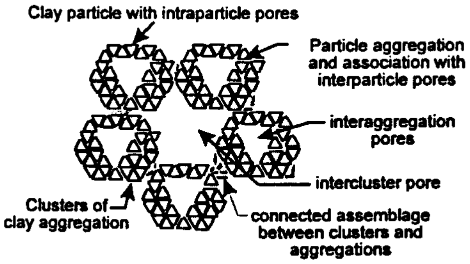

Figure 1. Structural elements and pore types (modified from Shear et al., 1993).

The arrangements shown in Fig. 1 can be categorised as intraparticle, interparticle (intraggregation), interaggreation (intracluster) and intercluster pores. To aid in the following synthesis, broad size ranges are assigned to these categories on the basis of evidence from literature.

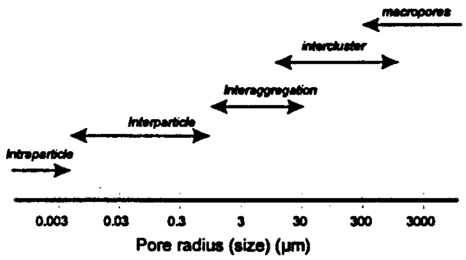

Figure 2. Pore categories and sizes

The intraparticle pores are controlled by the size of the double layers (Mitchell, 1993). Coulombe et al. (1996) indicated that, for heavy clays, the intraparticle pore size could be 0.003 to 0.004 µm. A study by Collins and McGowan (1974) using silty clays indicated that interparticle pore spaces can be as large as 1 µm, but the work of Coulombe et al. (1996) indicates that the pore sizes can be as small as 0.025 µm for heavy clays. The interaggregation pore sizes can be of several tens of micrometers in diameter (up to about 30 µm). Flow through these pores will be much higher than intraparticle pores.

The intercluster pores are much larger and depend on the sizes and type of clusters formed (aggregate, peds, clods etc.). The intercluster pores can be viewed as being similar to the mesopores (10 µm to 1mm) described by Luxmore (1981), although the pore size can sometimes be larger than 1 mm. In addition, cracks and other voids such as root holes and worm holes can also come under intercluster pores shown in Figure 1. These pores will dominate the liquid flow through the soil. To be consistent with the general use, cracks and other voids are referred to as macropores in the following discussion. On the basis of available evidence, the macropores are considered to be 300 µm and higher. The developed pore spectrum and associated pore size ranges are shown in Figure 2.

3. STRUCTURE CHANGES DURING WET/DRY CYCLES

3.1 Structure of Young Soils

Young soils are considered to be the soils that have formed relatively recently (in geological time scale) and have not been significantly subjected to post depositional processes such as over-consolidation, weathering, shearing and cycles of wetting and drying. The structure and structural development of young soils has been extensively studied. (e.g., Collins and McGowan, 1974; Mitchell, 1993). The dominant factors in the clay structure development of young soils are the mode of deposition and electrochemistry of the pore fluid. The face to face stacking of clay particles is a common structural pattern for young soils, but other forms such as "cardhouse", "bookhouse", dispersed and flocculated structures can exist.

There is significant body of evidence to indicate that the structure of young surficial clay soils usually changes when subjected to wet/dry cycles (e.g., Dalrymple and Jim, 1984). In the soil science literature, this has been referred to as the "ripening of soils" particularly in relation to heavy clays (Rijniersce, 1984; Bronswijk, 1990). It is suggested that many soils develop a stable structure when the soil ripens under repeated wet/dry cycles (e.g., Quirk and Murray, 1971; Collis-Geroge, 1991).

3.2 Synthesis of Mechanisms in Clay Structural Changes during Wetting and Drying

3.2.1 Phases of Soil Drying

Three phases of soil drying can be identified as normal shrinkage, residual shrinkage and zero shrinkage, and can be shown on a plot of void ratio against (volumetric) water content as shown in Figure 3.

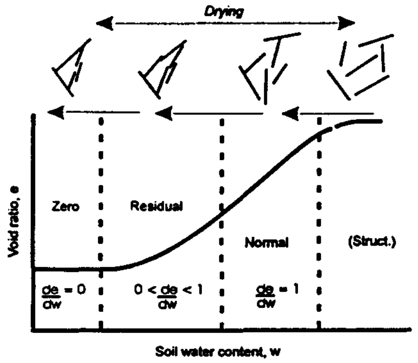

Figure 3. The three shrinkage phases of clay aggregates upon drying

Normal shrinkage is similar to consolidation under negative pore-water pressures where the volume decrease in the soil is equal to the volume of water loss. Residual shrinkage is the next phase where water loss is greater than the soil volume decrease. Air can enter the pores of the soil during this phase. During zero shrinkage, soil particles have reached their densest configuration and a further decrease in the soil volume does not occur. Figure 3 also gives a two-dimensional illustration of the particle rearrangement that takes place during the three shrinkage phases of soil drying.

It is evident that water is primarily lost through interparticle and interaggreation pores during drying (e.g., Quirk and Murray, 1991; Kutilek, 1996). Generally, the diffuse double layer would appear to have relatively little role to play in the wetting and drying of clays. For example, Wilding and Tessier (1988) indicated that dehydration of Mg and Ca smectites results in intraparticle water loss only at soil suction potentials greater than 5000 kPa and can be as high as 10,000 to 100,000 kPa. Under field conditions, where soil suctions rarely become greater than 2000 kPa (Wilding and Tessier, 1988), it is reasonable to expect that the swelling/shrinkage of clay soils occurs predominantly due to addition/loss of water from the interparticle, intergggregation and, of course, from intercluster and macropores (if present).

3.2.2 Particle Aggregation

The major mechanism involved in structure development during drying is the growth and aggregation of soil particles to form a stiffer structure (e.g., Allam and Sridharan, 1981; Dalrymple and Jim, 1984; Wilding and Tessier, 1988). Particle aggregation is driven by soil suction that develops as water is removed from the soil pores during the drying process. A cardhouse or bookhouse type structures can collapse because of the instability created by soil suction. The tendency is to develop a more flocculated or random structure at a given void ratio because this structure is stronger, particularly under isotropic volume change (Lambe, 1958). One of the most stable basic structural units is the triangular (or open pyramidal) arrangement of particles. In this geometrical configuration, attractive and repulsive force fields are symmetrically distributed without any structural redundancy. While a variety of stable and unstable structural aggregations can co-exist during the initial stages of drying, it may be reasonable to infer that more and more stable structural units such as pyramidal units and a combination of those, will form as more wet/dry cycles take place.

The thickness of a clay particle is generally higher in *a* and *b* axes than in *c* axis. The growth of a particle can be more extensive along *a* and *b* axes than along the *c* axis (Coulombe et al., 1996). It may be possible that the relative dimensions of particles along these axes vary during wet/dry cycles. However, in the assessment of clay structural stability, the complex attractive and repulsive forces among clay particles and aggregations, as well as electrical and mechanical bonding, at the particle contact points should be considered. These force fields can give rise to some structural shapes that may otherwise be unstable.

It is expected that the reverse of particle aggregation would occur during wetting. Wetting can lead to the instability of some structural units due to the softening of the particle rigidity and the breakage of particle contact bonds. This can result in the swelling of the bulk soil volume as the water, being a polar liquid, accumulates over the increased particle surface area (Wilding and Tessier, 1988). As the soil water content increases, structural instability tends to drive particles towards a face-to-face clay alignment and a more dispersed structure. However, if the soil has previously undergone drying, then additional bonding that is generated between the particle contacts as well as the stiffening of particles resists the total failure of the developed structure. While some aggregations can collapse or soften, others might resist the change without undergoing total collapse. This process can be viewed as being analogous to the pre-consolidation soil experienced through drying and subsequent unloading. The end result represents a more stable structure. When further drying events take place, more and more of the structure becomes stable and resists total collapse during wetting events. Eventually, it can be expected that soils "ripen" to achieve a more stable structure where structural changes during drying and wetting are significantly reversible.

There is evidence that the particle aggregations can form soil clusters (commonly known as aggregates and peds in soil science literature), as the number of wet/dry cycles increases (e.g., Wilding and Tesier, 1988; Ringrose-Voase, 1991). This process depends on the clay content in the soil as well as the mineralogy of the clay, and is more clearly seen in heavy clays or Vertisols.

3.2.3 Separation of Different Fabric Units

Jim (1990) reviewed fabric development and separation of different fabric units (i.e. plasma separation) in clays under various stress regimes. It was noted that under isotropic swelling and shrinking, clays develop a predominantly spherical, asepic (i.e. randomly oriented clay) and skelsepic (oriented clay around coarse particles such as quartz) fabrics. For skelsepic fabrics, sand particles generally are not in contact with each other, but are connected by clay aggregations (or buttresses) at the contact zones (Dalrymple and Jim, 1984). When a clay soil is swelling or shrinking, the displacement of different fabric units will depend on their relative stiffnesses. This appears to be a primary mechanism for plasma separations. These separations can be assisted by the presence of organic matter and other cementing agents. The plasma separations can lead to generation of large pores such as intercluster pores (Darlymple and Jim, 1984).

3.2.4 Influence of Stress and Restraint Conditions

The structural changes reported in the literature commonly relate to soils undergoing free (unrestrained) shrinkage under isotropic internal compressive stresses. However, the actual field stress and strain condition can be anisotropic where the lateral stress/strain not equal to the vertical stress/strain. The lateral stress/strain can also become tensile which can lead to particle separation or cracking. Similar anisotropy can arise during wetting, where the lateral stress can become higher than the vertical stress due to laterally restrained swelling. Under anisotropic stress regimes, particle arrangement can differ from the isotropic state and particle aggregations tends to squash more in the direction of major stress or even undergo shear failure (Kirkpatrick and Rennie, 1973). Under anisotropic swelling/shrinkage, the soil fabric is characterised by elongated and oriented clay aggregations reflecting the stress history (Jim, 1990). Similarly, the confining stress in the field conditions can also significantly influence the structure development and the soil behaviour of clays under wet/dry cycles (Fredlund and Rahardjo, 1993).

4. INFLUENCES ON SOIL BEHAVIOUR

4.1 Pore Size Distribution

One of the most important features of clays and particularly for heavy clays, is the dependency of the pore size distribution with the water content of the soil system. This generally has implications on all aspects of soil behaviour and in particular, on the hydraulic conductivity and the soil-water characteristic curve.

Using mercury porometry data, Kutilek (1996) indicated that the pore size distribution (on the basis of the frequency of equivalent radii) could be skewed with secondary peaks depending on the water content (Figure 4a and 4b). It is clear that the proportion of various pore sizes changes with the water content. Figure 4a indicates that during drying up to 1.5 MPa of suction, the frequency of the pores with equivalent radii in the range 0.003 to 0.03 μm (e.g., interparticle and intraparticle) increased slightly. On the other hand, the frequency of pores in the range from 0.03 to 30 μm (e.g., some interparticle and some interaggregation) decreased substantially. The pores larger than 30 μm (e.g., some interaggreagation, intercluster and higher) increased substantially. Figure 4(b) is based on the same results but includes the macropores. This figure shows that, during drying, the frequency of macropores increase, whereas during wetting, the majority of the macropores close and transform into intercluster and intracluster pores. Similarly, during wetting, the intercluster pores can reduce in size. Nevertheless, it can be argued that the changes in pore system eventually stabilise as the number of wet/dry cycles increases.

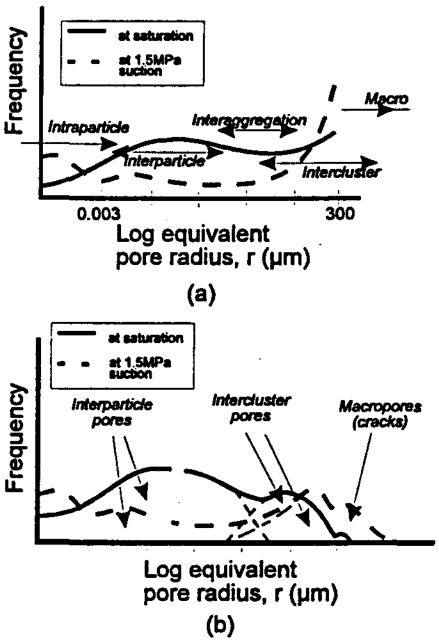

Figure 4. Pore size distribution after wetting and drying

4.2 Hydraulic Conductivity

Depending on the severity of the pore structure changes, saturated clay hydraulic conductivity can increase over a wide range, spanning several orders of magnitude during wet/dry cycles. The macropores, which are mostly cracks, are mainly responsible for these large increases. The unsaturated hydraulic conductivity, however, is not influenced that much by macropores because the cracks desaturate at a low suction. For example, a crack 1 mm in the width desaturates at 0.3 kPa suction. Subsequently, the crack has no significant influence on the unsaturated flow rate (e.g., Kutilek, 1996). However, if the structural changes have generated intercluster pores, their influence can spread over a wider range of suctions depending on the pore size.

The reason for large difference in hydraulic conductivity that is usually observed at dry and wet of optimum water contents for compacted clays is also attributed to intercluster pores (or interclod pores) present at dry of optimum (Olsen, 1962). Clod is usually used to refer to clusters that have not undergone wet/dry cycles. The air-drying of undisturbed clay soil samples to various water content levels was undertaken by Shear et al. (1993) who studied the change of saturated hydraulic conductivity on desiccation. It was found that on a plot of hydraulic conductivity against void ratio, the resulting curve shifted upwards while maintaining the same general shape as desiccation progressed. This result shows that at a particular void ratio, the saturated hydraulic conductivity increased with desiccation, indicating an increase of larger pore sizes and a decrease of smaller pore sizes.

The authors have not encountered direct measurements on the change in the saturated hydraulic conductivity with the number of wet/dry cycles. However, Day (1994) studied the volume change of compacted clays (wet of optimum) during wet/dry cycles. It was found that the change in volume decreased with each cycle and became stable after about seven cycles. This behaviour was explained in terms of a soil structure that reached a stable pore distribution after several cycles. Therefore, the saturated hydraulic conductivity attained a larger but stable value.

When external work is done on compacted soils either by drying/wetting the structure appears to soften and increase the sizes of the pores to achieve a stable condition. This phenomenon is referred to as the "regeneration of soils" in the soil science literature where compacted (by agricultural machinery) soils soften and become suitable for plant growth after exposure to wet/dry cycles (Hussein and Adey, 1995; Pessaran, 1998).

4.3 Moisture Retention

The moisture retention capacity of soils is commonly displayed in terms of the soil-water characteristic curve (SWCC), which involves plotting the (volumetric or gravimetric) water content against suction. It is established that this characteristic is closely related to the clay soil structure and the associated pore size distribution. There is evidence to indicate that normally consolidated clays or unconsolidated slurries tend to stiffen and become over-consolidated as the number of wet/dry cycles increase, and eventually reach a stable soil-water characteristic curve (Wilding and Tessier, 1988; Pessaran, 1998). Similarly, initially overconsolidated heavy clay soils (i.e. compacted soils) can "regenerate" so that the soil structure becomes loose. This is accompanied by a corresponding shift in the soil-water characteristic curve (Pessaran, 1988). In addition, the hysteresis of the soil-water characteristic curve is also influenced by pore size changes and appears to decrease with the number of wet/dry cycles.

4.4 Soil strength

It is well established that wet/dry cycles progressively increase the soil strength and this is also similar to the overconsolidation of soils. For example, Allam and Sridharan (1981) carried out a series of consolidated, undrained triaxial tests on statically compacted clay soil specimens that displayed low shrinkage properties. The soil specimens were subjected to differing numbers of wet/dry cycles. The results indicate that the soil displayed a transformation from normally consolidated to over-consolidated clay behaviour as the number of wet/dry cycles increased. There was also an increase in the initial stiffness of the soil fabric. These increases, however, appeared to stabilise as number of cycles increased. It is possible that the initial level of compaction and the swell/shrink potential of the soil influence this behaviour. On the basis of an experimental program using soil aggregates of a heavy soil, Husein and Adey (1995) reported that the tensile strength of soil decreased with the number of wet/dry cycles, but can stabilise after about 2 to 3 cycles.

4.5 Volume Change

A primary feature of clay soils is that they undergo changes in bulk soil volume during wetting and drying. The amount of volume change is, in fact, a reflection of the degree of structural change that is taking place. The volume change of heavy clays can be significantly larger than the volume change of lean clays or clays with a substantial proportion of larger non-clay particles (e.g., sand or silt). Natural heavy clays can display volume changes as high as 49% (Bronswijk and Evers-Vermeer, 1990). It is observed that for clay-sand mixtures, the volume change during wetting and drying becomes relatively unimportant when the sand percentage increases above a certain value. This behaviour seems to occur when the abundance of sand is high enough to cause direct contact of individual sand particles. Consequently, a stiffer structure is developed, which is more resistant to the changes in suction.

The estimates of soil volume change should correspond to the suction range likely to occur in the field otherwise unrealistic estimates can result. Bronswijk and Evers-Vermeer (1990) reported that Dutch heavy clays, which display substantial variations in the shrinkage behaviour, can commence to desaturate at suctions ranging from 1 kPa to 1600 kPa. This means that some soils can display substantial normal shrinkage before desaturation. It also indicated that partially ripened soils could display significant residual shrinkage that will decrease with ripening. The amount of likely volume change is a key indication of the cracking potential of a clay soil.

4.6 Desiccation Cracking

When a drying soil is restrained not allowing volume change to take place predominantly isotropically(or free shrinkage is not allowed), the soil suction can lead to development of tensile stresses in the restrained directions. When the tensile stresses exceed the tensile strength of the soil, clay soils tend to crack (i.e. primary cracking) releasing the strain energy developed in the soil. Once the soil is cracked, the restraints placed on the soil are partially released and soil can undergo further volume change more isotropically. However, during subsequent drying, soil suction can build up to higher levels to cause further cracking (i.e. secondary and tertiary cracking). Eventually a cracking pattern can develop subdividing the soil into blocks of various sizes.

Usually, drying soil is restrained laterally (i.e. horizontal directions). This condition relies on the continuity of the structural fabric units to maintain zero lateral strain in the soil. Therefore, prior to cracking, the volume change in the soil must take place primarily vertically (i.e. one-dimensionally). The amount of one-dimensional shrinkage prior to cracking will depend mainly on the overall stiffness or the compressibility of the soil structure. For example, clay slurry will undergo higher vertical shrinkage than compacted clay prior to cracking.

Desiccation cracks can have a paramount influence on the structure development of clay soils. Cracks can bypass infiltrating water directly to the bottom of the cracks. Wetting of the dry soil from the bottom of a crack can cause swelling of the soil in a restrained environment. High lateral stresses can build up in the soil causing soil to fail in shear, and to heave the ground surface surrounding the crack. This process seems to be responsible for the formation of surface undulations in clay soils known as gilgai micro-relief formations (Knight, 1980).

5 CONCLUDING REMARKS

A synthesis is presented concerning the mechanisms associated with clay structure and behavioural changes during wetting and drying. Generic units forming soil structure are identified as soil particles, particle associations and aggregations and particle clusters. It is evident that the clay structure and behavioural changes are controlled primarily by the changes in the pore size distribution. For young soils, the growth and rearrangement of particles and particle aggregation will produce a dense and stiffer structure during drying. For heavily overconsolidated soils, initially denser structures can regenerate to produce relatively loose structures. During drying, the frequency of macropores increase, whereas during wetting, the majority of the macropores close and transform into intercluster and intracluster pores. The development and the response of cracks are dependent on the restraint conditions placed on the soil, severity of the drying cycles and the initial stress state of the soil. The changes in pore system as well as associated soil properties appear to stabilise as the number of wet/dry cycles increases.

6 ACKNOWLEDGEMENTS

The first author wishes to thank Victoria University of Technology, Melbourne for facilitating Outside Study Leave (OSP) during with this study was undertaken. The support by NSERC is also acknowledged. Thanks are also rendered to Drs. M. Mermut, de Jong, Sai Vanapalli and Mr. Reza Pesaran for valuable discussions and information.

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