博 士（工 学） コフマノヴァ　ニコル

学位論文題名

Influence of the soil fabric on the mechanical behaviour of unsaturated and saturated clays

（土構造が不飽和および飽和粘土の力学特性に与える影響）

学位論文内容の要旨

Bentonite, a smectite clay, is widely used in geotechnical engineering as drilling mud, liner material, and it has been proposed as buffer and backfill material for high-level nuclear waste disposal. Landfills are used worldwide as a means of municipal solid waste disposal, and are at times built in close proximity to urban zones, and overtop groundwater resources, leading to potential contamination of potable and industrial water supplies. Liners are used to create an impermeable layer beneath landfills to prevent the leachate, created by water percolating through the waste, from escaping the landfill and contaminating the surrounding soil and water. Nuclear waste disposal is also a growing concern due to the increase in radioactive waste around the world. Facilities are designed to store radioactive waste containers, also known as canisters, several hundreds of meters below ground level in intact rock surrounded by buffer material. The basic function of the buffer material is to immobilize the containers while creating a low permeability layer around them. This allows the waste to be isolated from the surrounding environment, limiting the access of water to the containers, preventing the migration of waste materials, and transferring the heat from the nuclear waste to the host rock (Tripathy et al. 2004). Engineered clay barriers have been proposed as suitable buffer materials as they provide "low hydraulic conductivity, low ion diffusivity, [and] good self-sealing capacities" (Marcial et al. 2002).

Bentonite is an attractive material for clay liners and buffer materials due to its unique self-healing behaviour, low permeability, and its ability to adsorb and prevent the migration of contaminants/radionuclides. Recent studies have shown that the hydraulic conductivity of bentonite is mainly determined by the dry density (γ t). However, conventional geotechnical practice has shown that the behaviour of clays is governed by stress history such as the maximum consolidation pressure (pmax) and the soil microstructure.

Therefore the study of the microstructure formation of bentonite, limited at this time, would not only provide a better understanding of its rheological properties, and but would also enable the development of a methodology capable of predicting its behaviour when exposed to water. The objectives of this study were to gain an understanding of the effects of varying degrees of saturation on the soil fabric of clay, and the effects that the soil fabric has on the mechanical properties. Two types of clays were used in this study, Kunigel-V1, a bentonite, and NSF Clay, a non-swelling clay used to provide a comparison between swelling and non-swelling clay behaviour. The effects of the degree of saturation on the soil fabric were studied by looking at the soil fabric through Scanning Electron Microscopy (SEM), Mercury Intrusion Porosimetry (MIP), and X-ray Computed Tomography (X-ray CT). Three types of samples were tested: unsaturated samples, submerged samples, and consolidated samples, all of which provided a range of degrees of saturation, ranging from dry (0 percent) to fully saturated (100 percent). The effect of the soil fabric on the mechanical behaviour, namely the compression, which affects the permeability, and strength, was studied though Constant Rate of Strain (CRS) Consolidation and Constant Volume Direct Shear

(CVDS) testing. Additionally, the effects of different types of compaction on the soil fabric of clays were also examined through static and dynamic compaction. Static compaction was carried out using CRS Consolidation, while dynamic compaction was carried out using Japanese Proctor Compaction.

A study of the microstructure revealed that in a dry state, NSF Clay was dispersed, while Kunigel-V1 was slightly aggregated. This aggregation is attributed to the mining methods of Kunigel-V1, and also its' higher natural water content, 5.0 to 6.2 percent versus 0.2 to 0.5 percent for NSF Clay. The introduction of water resulted in the formation of aggregates in both clays. The formation of aggregates caused air and water to become trapped between the particles, resulting in the formation of micro-pores (inter-aggregate pores) and macro-pores (inter-aggregate pores).

In Kunigel-V1 swelling and aggregation of the existing aggregates was observed, resulting in a non-homogenous soil fabric in the unsaturated samples. The higher the water content, the larger the aggregates formed, and thus the larger volume and size of macro-pores present, as seen in the SEM and MIP results. A further addition in water, in the form of sample submergence, resulted in the collapse of the aggregates, and the eventual formation of a homogenous mixture, as the particles tried to arrange themselves in face-to-face aggregation.

In NSF Clay the aggregation of aggregates also occurred, but at higher water contents (higher than 30 percent) a homogenous soil fabric was observed, resulting in a decrease in the initial void ratio, compression index, and the pore entrance diameter during CRS testing and MIP, respectively. SEM images also showed the collapse of NSF clay aggregates with an increase in water content and the development of face-to-face aggregation.

The effect of the soil fabric on the mechanical behaviour, namely the compression, and strength was also observed in this study. An increase in pressure (compression) resulted in the dissipation of air and movement of water from the macro-voids to the micro-voids, in addition to a rearrangement of the particles and the collapse of the aggregates, shown by the decrease in void ratio in CRS testing, and the decrease in pore size in MIP, SEM imaging, and X-ray CT images. In NSF Clay, compression resulted in face-to-face aggregation of the particles, while in Kunigel-V1 the soil fabric remained non-homogenous. Due to the low permeability of Kunigel-V1, drainage did not occur during testing, resulting in sample extrusion in unsaturated samples at higher pressures as samples could not be compressed further.

In unsaturated samples, the formation of aggregates through an increase in water content, resulted in an increase in the undrained shear strength in both clays. In NSF Clay however, at 50 percent water content a decrease in shear strength was observed due to the formation of the homogenous structure.

The effects of the soil fabric on the dilatancy revealed that the formation of aggregates resulted in positive dilatancy due to the resistance of the aggregates to shearing. It is believed that the stiffness of the aggregates increased due to large matric suctions, resulting in behaviour that is similar to a compacted dense granular material. At high water contents, aggregates were easily broken down, resulting in contractive behaviour during shearing and a decrease in strength. In NSF Clay this trend was only slightly apparent, due to the tendency to form a homogenous sample at lower water contents.

In unsaturated Kunigel-V1 samples, a change in the water content had no effect on the friction angle (40.4°). The submergence and saturation of Kunigel-V1 resulted in a lubricating effect on the particles, thus decreasing the shear strength, and most importantly, the friction angle (20.4° and 9.5° , respectively), as the friction between particles decreased. Alternatively, in NSF Clay the friction angle experienced slight changes, including a decrease with saturation, however, these changes were small in comparison to Kunigel-V1.

The study of effects of different types of compaction (static and dynamic) on the soil fabric of clays revealed that the pore size is determined by the initial water content and does not depend on the compaction method used or the dry density of the sample. The dry density however is affected by the change in energy, or pressure used during compaction, increasing with an increase in pressure. Additionally, static compaction was more effective than dynamic compaction in achieving a higher dry density.

学位論文審査の要旨

主査　教授　田中洋行
副査　教授　三浦清一
副査　教授　蟹江俊仁
副査　准教授　石川達也

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ベントナイトはボーリングの削孔やシール材として広く土木分野で用いられている. 特に最近では核廃棄物処分場のシール材として注目を浴びている. ベントナイトを使用する最大の目的は, その低透水性であり, 所用の透水性を確保するために乾燥密度を高める試みがなされている. しかしながら, 地盤工学の知見に照らし合わせると, 土の透水性は, 土の乾燥密度だけではなく, 先行圧密荷重などの応力履歴や, 土の微視構造などに大きく影響されることが知られている. そこで, 本論文では, 種々の含水比の下で土の微視構造を形成し, この微視構造がベントナイトの力学挙動にどのような影響を与えるかを明らかにしている.

用いた試料は, スメクタイトを多く含む Kunigel-V1 と, ベントナイトを含まない非膨潤粘土の NSF 粘土である. 微視構造を表現するために, 走査線型電子顕微鏡 (SEM), 水銀圧入試験 (MIP) および X 線トモグラフィー (X-CT) を用いた.3 つの状態 (不飽和, 水潤および飽和) で試験を行った. 行った力学試験は圧縮性を求めるための定率ひずみ圧密試験 (CRS), およびせん断強さを測定するための定体積直接せん断試験 (CVDS) である. さらに, 締固め方法の違いが土も構造に与える影響を調べるために,CRS による静的締固めと, プロクターによる動的締固めによって供試体を作成し, これらの方法によって形成された試料の微視構造の比較を行った.

両粘土とも含水比の増加によって, 土の骨格が形成され, これらの骨格は微小間隙 (micro pore, inter-aggregate pores) と通常間隙 (macro pores, inter-aggregate pores) に分類される.Kunigel-V1 では, 含水比の増加に伴い大きな土骨格が形成されるため土の不均一性が顕著になり, さらに含水比が大きくなると, これらの土骨格が破壊し, 均一性が増大し, また土粒子は平行に配置 (Face-to-face aggregation) する傾向にあることが,SEM および MIP によって確認できた. 一方,NSF においても同様な傾向が認められたが, 高い含水比においても試料は比較的均一であった. すなわち, 形成された土骨格の大きさは Kunigel-V1 と比べて小さいことを示している.

不飽和土の供試体が圧縮されると, 大きな空隙がつぶれ水分は大きな間隙から微少な間隙へと移動する. この様子は SEM と MIP によって観察することができた.Kunigel-V1 の場合は大きな間隙

が形成され，圧力によってこれが簡単につぶれるので大きな圧縮性を示す.Kunigel-V1 の場合は透水性が低いので，空隙だけが圧縮され，水分は排水されない．このため，高い圧縮性を示した後に更に圧力を増加させた場合には圧縮性は小さくなる．すなわち，間隙と対数でプロットした圧力,e-logp 関係は，著しい非線形性を示す．一方,NSF の場合は，骨格の発達は Kunigel-V1 より顕著に認められず，また透水性が高いので空隙がつぶれるばかりではなく水も排水される．したがって,e-logp 関係は Kunigel-V1 と大きく異なる．

土のせん断特性を調べるために，排水条件を明確にする必要がある．すなわち，完全排水条件か完全非排水条件下でせん断試験を実施するのが普通である．しかし，不飽和土の場合は，供試体内に空隙を有するために，定体積で三軸試験を行うことは難しく，また Kunigel-V1 の場合は透水係数が非常に小さいので排水条件で行うことも不可能である．本研究では，一面せん断試験を用いて定体積条件の下で不飽和土のせん断特性を調べた.Kunigel-V1 の不飽和土を対象とした試験の結果から，全ての条件で内部摩擦角 ϕ は 40.4 澆犯羈單　腓　蔽佑終┓垢，定体積条件下のせん断強さは含水比(飽和度) によって大きく異なった．すなわち，飽和度によって土の骨格構造が大きく異なり，構造が発達した場合にはダイレタンシーが正となるため，高い強度を有する．しかしながら，この状態で供試体を水潤させると，ϕ は 20.4 澆砲覆，さらに飽和状態で試料を作成した場合には,9.5 澆膨祺爾垢．すなわち，ベントナイトは土粒子周りの水分によって ϕ が大きく変化する．これは，現在不飽和土の力学に用いられているマトリックサクションの考え方が適用できないことを示している．

これを要するに著者は，ベントナイトは不飽和土の状態では土の骨格構造によって力学特性が大きく変化するという，重要な特性を見いだしている．核廃棄物処分場の場合には，ベントナイトは不飽和の状態で施工され，飽和するまでには長い歳月が必要である．その間における処分場の安定性を検討するためには，本研究で得られた知見は必要不可欠であり，地盤工学の発展寄与するところ大なるものがある．

よって著者は，北海道大学博士 (工学) の学位を授与される資格があるものと認める．