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学　位　論　文　題　目	Study on the Unloading Shear Behavior of Granular Materials with Different Particle Shapes
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【学位論文内容の要旨】

This study aims on unloading shear behavior of cohesionless granular materials. The unloading is often seen in underground engineering such as tunneling, open cutting, slop cutting. It is known that unexpected deformation often happened during these constructions. For purpose of understanding the basic mechanical behavior of unloading shear behavior, a series of experiments and numerical simulation were performed with influence of particle shape, relative density being discussed. Moreover, small-scale retaining wall model tests were performed to investigate the unloading shear behavior by change of boundary conditions.

First, plane strain compression experiments were performed. Four types of granular material including two sands and two glass beads with different particle shape and particle size were selected. For the two sands, one has angular particle shape while another has sub-angular particle shape. Unloading shear experiments were performed considering confining pressure and relative density. The unloading shear was implemented by plane strain compression tests under decreasing confining pressure (shorted for PSCD), where the vertical axial stress is kept constant and the confining pressure is reduced until failure occurs. A well-known general plane strain compression test (shorted for PSC) was also performed to make a comparison. The PSC test The main different point between the two tests is the mean stress on the test specimen decreases in the PSCD test while it increases in the PSC test. In other word, the PSCD reflects unloading while the PSC reflects loading from physical viewpoint. Photographs of specimens during shear process were taken and local deformations of specimens were analyzed by digital image analysis method. Stress-strain relationship and local deformation analysis results obtained from the experiments were shown as below.

In general, sands showed different shear behavior from glass beads. Under the same test condition, the sand with angular particle shape showed the highest shear strength and dilatancy.

Shear behavior in both sands and glass beads is influenced by stress path, however the influence was found different. For the shear behavior of sands, the maximum principle stress ratio and initial stiffness of stress ratio ~ deviatoric strain were found generally higher in the PSCD test than those in the PSC test. The differences are more significant in dense specimens than those in loose specimens. Moreover, shear bands appeared earlier in the PSCD tests for sands. The sands were strongly influenced by stress path and stress level compared to glass beads. Development of shear bands, final inclination angle and width of shear bands were observed by image analysis. Generally, the onset of shear bands occurs prior to the specimen reaching its maximum principal stress ratio for both dense and loose specimens. Between the peak in shear strength and the end of strain softening, the local maximum shear strain grew approximately linearly with the global axial strain. For the same material, the growth rate of the local maximum shear strain became smaller with wider shear band. The shear band width became smaller when the particle shape of materials with similar mean particle size gets more angular, and it decreased with increase of confining pressure regardless of particle shape. Moreover, the measured shear band inclination angles were compared with prediction values by Coulomb and Roscoe equations having been often used in past study. It is found that the shear band inclination angles in sands matched well with those estimated by Coulomb's formula, while Roscoe's formula predicted shear band inclination angles relatively close to the corresponding measured values in dense glass beads.

Then, based on the analysis of elemental experiment results, discrete element method (DEM) was used to investigate underlying mechanism from micro viewpoints. Biaxial compression (loading) and decompression (unloading) tests were performed. Two types of particle model, round disk model and angular clump model were used in the simulation. The simulation results generally reflected the influence of particle shape, relative density and stress path in the elemental experiments. Through micro behavior analysis including coordination number, contact distribution, fabric inside specimens, the reason of different contact variations in specimens that resulted in different macro shear behavior was found. Moreover, strain energy variations at particle contacts were analyzed in detail. Strain energy variation with the mean stress was compared for the two types of shear test and isotropic consolidation test. It is found that strain energy variation rate is the highest in unloading shear test. Under the same test condition, the variation rate is higher in the loose specimens than in the dense specimens, and is also higher in disk specimen than in clump specimen. The behavior was considered to be influenced by the interlocking among particles. The interlocking is stronger in angular particles than that in round particles, and also stronger in dense specimens than that in loose specimens. When particles are interlocked, the relative displacements between particles shall become difficult and thus strain energy varies little. As a result, the stiffness of specimens behaves strong. In the loading shear test with mean stress increased, the interlocking developed until the peak strength and then failed. Instead, for the shear test with decreasing confining pressure, variation of interlocking gets smaller from the beginning. Thereby, the particle shape effect is different on the different stress path and the difference is more significant in dense specimens.

Finally, unloading retaining wall model tests were performed to investigate particle shape effect and boundary effect on unloading shear behavior. The same two sands and one glass beads were used again. Investigation was focused on the failure mode behind the wall and transition process to the active state. It is found that the particle shape has influence on the resultant force of retaining wall. The more angular particle shape of sand, the resultant force was smaller and the displacement of wall until the final active state was larger. Shear band inclination angle and width were influenced by particle shape and relative density, while the progress shear band pattern is dependent on the wall movement mode regardless of particle shape. Within a limited range of wall speed in this study, shear band became wider and local deformation became larger with increase of wall speed.

In summary, a series of experiments and numerical analysis were performed in this study to investigate the fundamental unloading behavior of granular materials with different particle shapes. Based on the study, particle shape effect on the macro mechanical behavior was presented and further investigations were made on micro mechanical behavior and its relevance to the macro behavior. Particularly, unloading shear behavior was found to be clearly different from the general loading shear behavior and influence of particle shape and relative density on the difference between the behaviors was revealed. The influence was considered rooting in the interlocking effect, which was qualitatively discussed from micro viewpoint.

【論文審査結果の要旨】

地盤工学において土の除荷せん断挙動の理解はきわめて重要である。これは、地下開発のための掘削や切土のための斜面掘削、トンネル掘削などのような除荷により、新しい地表面が造られ、境界の変形や安定性の評価が工学的な課題となるためである。このような掘削に伴う除荷では、新しい地表面となる地盤近傍において特定の応力変化が生じる。この応力変化に対する土の挙動の理解は、掘削時時の力学特性を評価するうえできわめて重要といえる。加えて、土のような粒子の集合体である粒状体の挙動は、粒子形状に大きく影響を受けることが知られている。

本研究では、粒子形状の異なる粒状体の除荷せん断挙動を明確にするために、土質要素試験、数値解析、模型実験による一連の検討を行っている。本論文の第１章では研究の背景、目的および論文の構成が示されている。第２章で、４種類の粒状体に対する平面ひずみ条件での要素試験を実施し、実験的に除荷せん断挙動を把握するための検討を行った。第３章では、２次元個別要素法解析を用い、円形と非円形粒子が二軸圧縮シミュレーションにおける除荷せん断挙動に与える影響を考察している。第４章では、第２章で用いた粒状体について擁壁の倒壊に対する小型模型実験を行い、模型地盤の挙動における粒子形状の影響を議論している。

第２章の平面ひずみ条件での要素試験においては、除荷せん断挙動に与える粒子形状、密度、圧力レベルの影響について考察するとともに、圧縮せん断挙動と比較を行っている。これから、角張りのある砂の方が、剛性やピーク強度は高く、体積変化挙動はより膨張するという結果を示すとともに、応力経路や圧力経路依存性を顕著にうけることを示した。また、画像解析からせん断中の局所化の進行やせん弾帯の特性を詳細に観察し、粒子形状の複雑な砂の方が、せん断帯の幅は小さくなること、拘束圧の増加に対する変化は大きいこと、せん断帯の傾斜角が高くなることを示した。さらに、局所

化の進行が早く、ピークから残留までの変形量が小さいことなどを明らかにした。

第３章では個別要素法解析を行い、第２章で明らかにした巨視的な挙動を再現できることを示すとともに、内部の微視的な挙動について分析している。その結果、粒子形状の複雑なモデルの方が、平均粒子接点数が多く、粒子接点角分布の変化が大きく、粒子接点角分布の異方性が顕著になることを示した。また、除荷せん断の方が、異方性が明確に現れることや、ピーク直前までの挙動が弾性的であることを示した。さらに、粒子形状の複雑な粒状材料ではインターロッキング効果が現れることが指摘されていることに対して、粒子接点での弾性エネルギーの変化が小さく、より安定な状態にあることを見出し、内部構造的により強固な状態にあることを説明した。

第４章では小型模型土槽を用いて矢板の倒壊挙動について説明している。ここでは、第２章で現れた力学挙動と境界値問題との関連性について検討するとともに、倒壊時の境界条件による挙動の変化について考察した。実験から、角張った粒子形状を有する地盤モデルの方が、倒壊のモードによらず小さな壁の変位で主働状態に到達すること、主働土圧が小さくなること、せん断帯の幅が小さく主働崩壊角が大きくなること等を示した。また、倒壊モードによってせん断帯の出現の仕方がかわることやせん断速度によっても主働崩壊の範囲が異なる結果になることを示した。

第５章は、各章で得られた知見を取りまとめて、結論としている。

公聴会における主な質問内容は、

平面ひずみ条件における除荷せん断の載荷方法、
除荷せん断と圧縮せん断に現れる粒子形状の影響と応力経路依存性や拘束圧依存性の捉え方、
せん断帯幅の評価方法とその粒子径の影響、
粒子径の大きな試料のダイレタンシー挙動、
インターロッキング効果を示す粒子形状を評価するパラメータ

について等であった。いずれの質問に対しても発表者から的確な回答がなされた。

以上より、本研究は、独創性、信頼性、有効性、実用性ともに優れ、博士（学術）の論文に十分に値するものと判断した。