博士（工　学）　サハポン　ティムポン

学 位 論 文 題 名

SMALL STRAIN SHEAR MODULUS EVALUATION OF VOLCANIC COARSE-GRAINED SOILS WITH PARTICLE BREAKAGE

（破砕性火山灰質粒状体の微小ひずみレベルにおける変形特性の評価法に関する研究）

学位論文内容の要旨

Abstract

The shear modulus of soils at a small strain level (0.0001 – 0.001%) is normally a required parameter in many geotechnical aspects such as when evaluating dynamic soil response, when modeling the non-linear stress-strain relationship and in soil-structure interaction analyses. It has become common practice in laboratory testing to evaluate the soil stiffness at small strain level by bender element test and cyclic triaxial test with strain-controlled type equipment. The bender element test is a simple technique and is noted as effective tool to determine the small strain shear modulus of soil by measuring the velocity of propagation of a shear wave through a soil specimen. This may be due to the simplicity of the test procedure and its non-destructive nature, which allow us to measure the small strain shear modulus at any stress state. Many researches on the small strain shear modulus of cohesive soils and sands with the implemented bender element measurement in triaxial cell and oedometer have been performed. However, the shear modulus of volcanic coarse-grained soils with particle breakage evaluated by bender element test has not been fully investigated.

Volcanic coarse-grained soils, distributed widely in all regions of Japan, are one of the problematic soils in geotechnical engineering. This is because their origin and formation process are very different from those cohesive soils and sands. Sedimentary structure, distributional area and degrees of the weathering greatly differ with the depositional environment. Therefore, it is anticipated that the mechanical property of volcanic soil grounds will be diverged. For many years, liquefaction related phenomena were thought to be limited to sands. However, according to the earthquake observations in Japan, for example, the 1993 Hokkaido Nansei-Oki, the 1994 Hokkaido Toho-Oki and the 2003 Tokachi-Oki earthquakes, the liquefaction also occurred in volcanic soil grounds. The earthquake generated serious damage to the ground composed of volcanic soils, embankment structures, road pavement, port structures, and many other facilities. Because volcanic soils have been widely used as a construction and fill materials, in order to prevent damage arising from the earthquake and to determine the appropriate geotechnical engineering routine design for volcanic soils ground, the research on deformation-strength behavior of volcanic coarse-grained soils with particle breakage has to be made. This dissertation composes of seven chapters as follows:

Chapter 1 provides the general introduction and objective of this research.

Chapter 2 contains a literature review of previous research on the small strain shear modulus of soils, determination of travel time of shear wave in the bender element test, variables effect on the small strain shear modulus, and a brief review of the recent earthquake damages in volcanic soil grounds in Hokkaido, Japan.

Chapter 3 describes geological aspects of volcanic coarse-grained soils in Hokkaido, location of the sampling sites and physical properties of the volcanic coarse-grained soils used in this research. These volcanic soils are Mori, Sapporo, Tomikawa, Touhoro and Kitami volcanic soils with widely different potential for particle breakage. In addition, some tests on Toyoura sand with no particle breakage were also performed for comparison. Particle breakage is an important phenomenon of the mechanical behavior of volcanic coarse-grained soils, since their particles contain porous and fragile materials, which start breakage at a low stress level. In this research, the amount of particle breakage or

particle crushability for volcanic coarse-grained soils was measured by the increment of fines content, which was estimated by performing sieve analysis before and after tests.

Chapter 4 describes the laboratory testing program, test apparatus and test procedures. The shear moduli of volcanic coarse-grained soils were investigated in bender element test and cyclic triaxial test (strain-controlled type equipment). The preparation of soil specimen, saturation and consolidation process and test procedure were performed according to the Japanese Geotechnical Society (JGS) standards. In bender element test, the travel time of shear wave was taken as the average value obtained by start-to-start and cross-correlation methods as described in the chapter 2.

In Chapter 5, the small strain shear moduli obtained from bender element tests were compared with those obtained from the cyclic triaxial tests in order to reveal the difference between test methods. The shear modulus was measured under different effective confining pressures for various states of packing, represented by different void ratios after consolidation. The use of bender elements in triaxial test, made it possible to evaluate the small strain shear modulus of volcanic coarse-grained soils. A reasonable agreement between the shear modulus obtained from the bender element and the strain-controlled cyclic triaxial tests can be observed. It can be concluded that for a given volcanic soil, the different testing methods have no significant effect on the measurement of the shear modulus. The effects of strain dependency, particle breakage, effective confining pressure, void ratio and fines content on small strain shear modulus are examined and discussed in this chapter. The test result showed that the shear modulus of volcanic coarse-grained soils with crushable particles is lower than that of Toyoura sand with no particle breakage. The shear modulus of volcanic coarse-grained soils depends strongly on the crushability of their particles. The lower particle crushability shows a higher shear modulus for a given stress. The dependency of shear modulus ratio, G_{eq}/G_0 on shear strain level for volcanic coarse-grained soils is usually lower than that of Toyoura sand. This behavior could be attributed to the fact that the damping ratio, h for volcanic soils is lower in comparison with Toyoura sand.

The small strain shear modulus of volcanic soils increases with an increase in the effective confining pressure but tends to decrease with an increase in the void ratio. The dependency of shear modulus on void ratio for Tomikawa and Touhoro volcanic soils is less significant than that of Mori, Kitami and Sapporo volcanic soils. This is due to the existence of many intra-particle voids in Tomikawa and Touhoro volcanic soils. The shear modulus of volcanic soils decreases as the amounts of non-plastic fines content increase. At fines content less than 15%-20% the fines can be accommodated in the voids of the parent material so the effect of the shear modulus may be minimal if intergranular void ratios remain intact. As the fines content increases to more than 40% the parent material flows with the fines matrix and the fines begin to play a rather important role so the effect of the shear modulus increases. From the test results, the shear modulus decreased to about a haft of the initial value at a fines content of 100%.

In Chapter 6, time-dependency behavior of small strain shear modulus of volcanic coarse-grained soils was investigated. In general, the small strain shear modulus of volcanic coarse-grained soils depends on particle crushability, confining pressure, void ratio and amount of fines as explained already in the chapter 5. Although the influence of variables on the shear modulus can be readily obtained in laboratory testing, it is time consuming to investigate the time-dependent behavior of the shear modulus. Therefore, the minimum testing period required to predict the long-term values of shear modulus in the laboratory, and the developed correlations between shear modulus and consolidation period have to be established. In order to gain an understanding of the time-dependency of shear modulus in volcanic coarse-grained soils with particle breakage, a series of bender element and cyclic triaxial tests was performed on volcanic coarse-grained soils with different degrees of particle breakage. The bender element test, a non-destructive test, allows the variation between shear modulus and consolidation time to be monitored during consolidation. Because the cyclic triaxial test is a destructive test which means that the specimen will be damaged due to liquefaction, in order to clarify the effect of consolidation time on small strain shear modulus, it is necessary to perform the test on many soil specimens at various consolidation times. Therefore, some test techniques have to be developed in order to minimize time consumption in laboratory testing. In this research, the simplified method of cyclic triaxial test was proposed in order to investigate the effect of consolidation time on the shear modulus.

From test results, it is possible to investigate the time-dependency behavior of small strain shear modulus in volcanic coarse-grained soils from the simplified cyclic triaxial test. An essentially good agreement among the test results obtained from the simplified cyclic triaxial test, conventional cyclic triaxial test and bender element test can be observed. The small strain shear modulus of volcanic coarse-grained soil gradually increases with the consolidation time and overconsolidation ratio, the increase rate of small strain shear modulus depends strongly on the degree of particle breakage. A lower degree of particle breakage shows a lower increase rate in small strain shear modulus. In addition, the increase rate of small strain shear modulus also depends on the stress level, the increase rate of small strain shear modulus tends to increase with stress level.

Finally, the significant findings in this research are summarized in Chapter 7, along with recommendations for future research. The bender element test results show a good repeatability, and reasonable agreement of the small strain shear modulus can be recognized between the bender element and the strain-controlled cyclic triaxial tests, implying that it is possible to evaluate the small strain shear modulus of volcanic coarse-grained soils using the bender element technique. The crushability of soil particles has large effects on the mechanical behavior of granular material with pumice particles. Larger size particles are more likely to break because the probability of intra-particle voids in a given particle increases with its size. The amount of particle breakage tends to increase with stress level, and under constant states of stress, the amount of particle breakage tends to increase with time. The proposed equations as the function of effective confining pressure and void ratio based on the experimental results of the current research can be used for the small strain shear modulus evaluation in geotechnical engineering routine design. In addition, the shear modulus under a constant effective confining pressure for a long-term period can be predicted using the proposed empirical equations obtained from the present research.

学位論文審査の要旨

主　査　　教　授　　三　浦　清　一
副　査　　教　授　　三田地　利　之
副　査　　教　授　　藤　井　義　明
副　査　　助教授　　石　川　達　也

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我が国には、構成粒子が特異な形状・構造を呈する火山灰土が広く分布している。このような地盤ではその工学的性質が極めて多岐にわたっているが、地盤工学的見地に立った系統的な研究は限定されている。特に火山灰質粗粒土の動的力学挙動に関する研究は、この種の地盤における地震等の被災事例が多いにもかかわらず、ほとんどなされていない。たとえば2003年十勝沖地震など最近の北海道域を襲った大地震では、液状化による大規模な被害や構造物の流動破壊が、火山灰質地盤において、誘発されている。また、同年の三陸南地震でも、火山灰質土斜面において大規模な高速長距離地すべりが発生している。一方、火山灰質粗粒土の一種である西日本域のしらす地盤でも、過去に幾多の斜面崩壊や液状化による噴砂の被害が報告されているが、このような動的破壊に至ったメカニズムは不明のままである。これらの被災事例からも明らかなように、火山灰地盤の微小ひずみレベルを含む動態時の力学特性を的確に把握し、その耐震性能の評価手順を確立することが緊急の課題になっている。

このような背景から、本研究では室内三軸試験機にベンダーエレメントによる簡易な供試体弾性波測定装置を具備させ、各種の火山灰土のせん弾弾性係数の測定を試みた。それらの結果を変位制御式繰返し三軸試験装置による精密な測定値と詳細な比較検討を行い、提案するベンダーエレメント試験法の妥当性を明らかにすることを目指した。具体的には噴出源の異なる北海道各地の火山灰地盤より試料を採取し、ベンダーエレメントによる動的変形特性の推定可能性を明示することを目標にした。ここでは、種々の物性を有する火山灰土の地震応答解析に必要な微小ひずみレベルにおける動的力学特性、特にせん断弾性係数の評価がベンダーエレメント試験により所定の精度で求まるかどうかを検討している。さらに、火山灰質粗粒土の動的変形定数に及ぼす構成粒子の破砕、圧密時間、微視構造、硬度等の影響を明確にするとともに、一連の試験結果を詳細に解析し、実堆積地盤で発揮

されているセメンテーション効果についても論述している。

本論文は7章から構成されるが、研究の成果を章毎に要約すると以下のようである。

第1章では研究の背景を示し、本研究の目的と論文の概要が述べられている。

第2章では、ベンダーエレメント試験におけるせん断波到達特性やそれから解析されるせん断弾性係数の値とその工学的意義に関する既往の研究をレビューしている。

第3章では、本研究が対象とした火山灰土の噴出起源や地質条件を示し、火山灰地盤の堆積形成過程を詳述している。なお本章ではさらに、試料の採取法、それらの物理的性質および供試体作製方法が説明されている。また、これらの地盤が受けた地震災害を詳細に紹介するとともに、地盤の耐震性能において懸念される力学的な問題点を明らかにしている。

第4章では、本研究採用したベンダーエレメント試験の原理とその手順を述べるとともに、その特徴や弾性波データの解釈法が論じられ、計測値から動的変形定数等を決定する手法を具体的に説明している。豊浦標準砂などの通常の粒状体を用いた一連の試験から、採用した方法は､より合理的かつ簡便にせん断弾性係数を決定できることを明示している。

第5章では、各火山灰土について実施した一連の試験の結果から、本方法によって得た動的変形定数が、変位制御式繰返し三軸試験装置による精密な測定値に相当する値になることを、火山灰土の種類によらず、見出している。このことは、今までの室内試験法に比べてはるかに簡便な手順で実行される本試験法は、特殊な地盤材料である火山灰土でも、その動的変形特性を正確に見積もることができることを示唆するものである。

第6章では、特異な物性値を有する各種の火山灰質土の動的変形定数が、圧密時間、有効拘束の大きさ、構成粒子の破砕性等によってどのように変化するのかを詳しく検討している。まず、圧密やせん断によって粒子破砕が生じやすい火山灰質粗粒土では、拘束圧の増大に伴うせん断弾性係数の増加は粒子破砕によって抑制される傾向にあることを確認している。また、火山灰土の間隙比は通常の砂よりも著しく高くなるため、せん断弾性係数に及ぼす間隙比の影響は小さなものになっていることを明らかにするとともに、せん断弾性係数の時間依存性を定量的に表示することに成功している。ここで、このような火山灰土の動的変形定数の変化が、その構成粒子の硬度や空隙構造の特異性を考慮することによって合理的に説明できることを示している点は注目される。さらに、任意の圧密時間履歴を有する破砕性火山灰土のせん断弾性係数に及ぼす間隙比や拘束圧の影響を明確にしたうえで、それらの推定式を誘導している。提示された式は、基本的に通常の粒状体のそれと同形式になっており、工学的に有用である。

第7章は結論であり、各章で得られた知見を総括し、今後の展望と課題を述べている。

これを要するに、著者は、特異な粒子構造を有する火山灰質土の弾性係数を簡易な手法であるベンダーエレメント試験によって正確に求め得ることを示すとともに、この種の地盤の地震応答解析等に適用する動的変形定数の評価法の構築について貴重な知見を得ており、地盤工学の発展に貢献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あるものと認める。