論 文 の 内 容 の 要 旨

論文題目　Disk Transducer for Elastic Wave Measurement
and its Application to Unsaturated Sandy Soils
（弾性波速度測定センサーの開発とその不飽和砂質土供試体への適用）

氏　　名　スワル　ラクシュミ　プラサド

Investigations on the laboratory are traditionally being important and pertinent on several kinds of analyses and design in engineering field. Advanced technologies and dedicated scholars enrich the geotechnical engineering field with the numerous laboratory tests methods. Geotechnical engineers are increasingly being known the importance of elastic wave for characterizing soil stiffness and deformation behaviors. Generally, piezo-ceramic elements are customized as transducers on the measurement of mechanical properties in engineering field. A single flat disk shaped piezo-ceramic transducer, so called disk transducer, for measuring both compressional and shear wave on an identical soil specimen has been developed. Two types of piezo-ceramic elements, one for measuring P wave and the other for S wave, were placed together in a metal housing, which worked as a wave measuring transducer installed in a triaxial apparatus. Several shape patterns of surface coating were initially considered to ensure the firm contact between the transducer and tested material. Flat surface coating was adopted in this study because it was found to show better performance than corrugated or sand-papered surfaces. In addition, the disk transducer was examined to confirm the frequency ranges of its applicability. Following to previous researchers, the interpretation based on rising of signal in transmitter to rising of signal in received signal at zero crossing was employed in study. Elastic wave propagation through soil is recently getting popular amongst the researchers. However, the acquisition of both the compressional and the shear waves in parallel are unheard in geotechnical engineering sector. Extending the applicability of newly developed disk transducer method, both compressional and shear waves were propagated on a single specimen simultaneously and signals were successfully acquired at same time.

Several kinds of tests were carried out to become acquainted with recent development on elastic wave measurement system, Disk Transducer method. The whole study was broadly categorized in two groups:

1. *Elastic properties evaluation of granular materials at small strain:* Accurate evaluation of small strain stiffness of the soil is essential for reliable analysis and prediction of the deformation while subjecting static and dynamic loading of structures upon it. Investigations of elastic properties in laboratory

specimens are becoming important for study of deformation characteristics of the geo-materials. Poisson's ratio of the material reflects the transverse deformation characteristics. It is generally accounted as the lateral deformation due to application of load along longitudinal direction. Elastic properties; small-strain stiffness and Poisson's ratio, of three sorts of granular materials, fine, medium coarse and coarse sands were investigated at isotropic and anisotropic stress states in laboratory. Resembling fine sand, Toyoura sand was tested. Axial and lateral strains were locally evaluated by Local Deformation Transducer (LDT) and clip gauges. Small strain stiffness and Poisson's ratios were directly evaluated employing small strain (≈0.001%) cyclic loadings in vertical direction. With simultaneously acquired compressional and shear waves, elastic parameters were indirectly determined in both isotropic and anisotropic stress states. Interpretable waveforms were observed during parallel measurement of both the compressional and the shear waves. The cyclindrical specimen of standard dimension, 150 mm in height and 75 mm in diameter were tested in both isotropic and anisotropic stress states. The elastic parameters were investigated subjecting the specimen from lower isotropic stress state (50 kPa) to higher isotropic stress state (400 kPa). In case of anisotropic stress state, two types of loading sequences were employed. The ratio of vertical and radial stresses was kept equal to two in first loading sequence in anisotropic stress state where the vertical stress was increased form 50 kPa to 400 kPa. In second sort of loading sequence, stress anisotropy was generated increasing axial stress at constant radial stress (25 kPa). Similarly, silica sand and Hime gravel were tested representing medium and coarse grained materials. The findings of the experiments are summarized as;

- The elastic properties, small strain stiffness and the Poisson's ratios of three sorts of granular materials, Toyoura sand, Silica sand and Hime gravel were evaluated by both statically applying small strain cyclic loadings and dynamically employing Disk Transducer method in isotropic and anisotropic stress states.
- The results, obtained by static method and elastic wave measurement by disk transducer have shown; the young's modulus in vertical direction be a unique function of vertical stress {($\mathbf{E}_v = \mathbf{A}.\ \boldsymbol{\sigma}_v^{m}v$),(Hardin, 1978)} and the shear modulus be a unique function of both vertical and horizontal stresses { $\mathbf{G}_{vh} = \mathbf{A}.\ (\sigma_v\ .\sigma_h)^{m/2}$}
- The stiffness; young's modulus and shear modulus determined by disk transducer method were around 10% - 20% higher than statically measured at stress states of 50 kPa and closeness was increasing in higher stress states
- The stiffness; young's modulus and shear modulus evaluated by both static and disk transducer methods on Toyoura sand, silica sand and Hime gravel have shown the following order; {*Silica sand* < *Toyoura sand* < *Hime gravel*}. The trends of merging both static results and the results by wave measurements were found in higher stress states.

- The Poisson's ratio values were found by both static and Disk Transducer method to be slightly decreasing with increasing isotropic stress states 50 kPa to 400 kPa.
- The statically measured Poisson's ratios applying small-strain cyclic loadings on vertical direction (v_{vh}) were found in ranges; on Toyoura sand specimen, *0.11-0.21*, on silica sand specimen, *0.145 – 0.21*, and on Hime gravel specimen, *0.13 – 0.22*. Mostly, not all, specimen of lesser density have resulted higher values of Poisson's ratio.
- The Poisson's ratio values derived by disk transducer method considering absence of inherent anisotropy were found to be higher than statically derived. Introducing coefficient of inherent anisotropy, the equivalent values of Poisson's ratios were obtained. The coefficient of inherent anisotropy were found to be varied; *1.1-1.3* for Toyoura sand. *1.3-1.6* for silica sand and *1.2-1.5* for Hime gravel. Recorded strains data during isotropic consolidation also showed the existence of inherent anisotropy.

2. *Mechanical properties evaluation on sandy soil containing fines:* Most of the infrastructures are laid within the shallow depth of ground directly exposing to the natural environment. These structures are always suffering from the change of water contents due to seasonal and climatic variations resulting repetitive wetting and drying processes. Rapid and frequent variations of water contents on soil lead to collapse of the earthen structures. Collapse of soil structures is generally known as the additional deformation within the short time period. So collapse is believed to be responsible to damage or fail of many kinds of infrastructures such as embankments, earthen dams, levee and buildings resting on not well compacted soil etc. Many researchers had defined the collapse as; the reduction of volume on unsaturated soil on the infiltration of water at constant applied stress. An initially unsaturated condition is a prerequisite for collapse of soil. Mechanical and dynamic behaviors of unsaturated sandy soil is intended to investigate in this study. Triaxial apparatus was modified enabling to measure elastic waves (body waves) and moisture content with monitoring associated suction. Matric suction was continuously measured applying pressure membrane technique. For monitoring water content in specimen, upper and lower tanks with load cells were employed. Water was fed through the upper tank and outflow was collected in lower tank. Recently developed disk transducer method was employed to measure both compressional and shear waves. Deformations were monitored by local deformation transducer (LDT) and clip gauges in axial and radial directions. Resembling the sandy soils, artificially non-plastic silt and kaolin clay were mixed with Toyoura sand at several proportions. Edosaki sand and sandy soils containing kaolin clay and non-plastic silt were tested to evaluate mechanical properties. After mixing soil homogeneously, the specimen was prepared around 25 kPa of isotropic stress state. Then the stress level was increased upto 50 kPa and kept in creep condition for sufficient time (approximately 10 hrs. –15 hrs.). After creep, the specimen was subjected into wetting and drying cycles. In each step, the small-strain cyclic loading and elastic

wave measurement were conducted. Fine particles in soils were found to be significant and responsible for varying soil's properties. The amount of the fines was found to play significant role on both deformation characteristics and matric suction. Analyses were performed on the test results and findings were summarized as;

- Deformation behaviors of sandy soils containing two types of fines were examined in laboratory. The triaxial apparatus was modified enabling to measure matric suction, elastic waves and other associated parameters in the present study. The triaxial apparatus enabling to measure matric suction, elastic wave including other physical parameters were developed and employed in this study.
- A series of tests on sandy soil containing kaolin clay and non-plastic silt in several proportions as well as Edosaki sand were performed to investigate the properties of unsaturated soil.
- The first infiltration collapse was found to be crucial. The successive infiltration may not lead to reduce significant volumetric strain.
- Toyoura sand containing kaolin clay was found to be deformed significantly higher as compared to Toyoura sand containing non-plastic silt. The higher amount of fines existed in the sand led the higher amount of deformation. Edosaki sand was also found to be deformed significantly.
- Toyoura sand containing 15 % kaolin clay was found to be deformed nearly 8 %, where around 4 % and 1 % (in terms of volumetric strain) in 10 % and 5 % kaolin containing sands at approximately 80 % degree of compaction.
- Toyoura sands containing non-plastic silt were found to be deformed nearly 3 times lesser than Toyoura sands containing kaolin clay.
- The variation of the several parameters; small strain stiffness, elastic wave velocities, matric suction, Poisson's ratios, void ratios and strain anisotropy during repeated drying and wetting cycles were investigated.
- In both sands; containing kaolin clay and containing non-plastic silt, the matric suction was found to be directly proportional to the fine contents in sand. The results of kaolin mixed soil showed the higher matric suction as compared to the non-plastic silts.
- Matric suction was directly related with the degree of saturation. The trend of decreasing matric suction with increasing degree of saturation was investigated on these sandy soils.
- The relationship between elastic wave velocities and degree of saturation as well as the relationship between elastic wave velocities and matric suction were studied on sandy soils.
- The role of the fine content on sandy soil was investigated. The effects of type and quantity of fines on sandy soils were comprehensively studied. The unsaturated soil's properties containing silt or clay were found to be different. The trends of varying these parameters on fine sands containing non-plastic silt and clay were investigated.