STUDY OF CONE PENETRATION IN SILICA SANDS USING DIGITAL IMAGE CORRELATION (DIC) ANALYSIS AND X-RAY COMPUTED TOMOGRAPHY (XCT)

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ABSTRACT

Cone penetration in sands is a complex process: it contains several challenges that geomechanicians face, such as large displacements, large strains, strain localization, and microscale phenomena such as particle crushing and sand fabric evolution. In order to gain a deeper understanding of the penetration process and the mechanisms controlling penetration resistance, capturing these displacement and strain fields and microscale phenomena is necessary. Furthermore, as more sophisticated theoretical models become available for the simulation of the cone penetration problem, the experimental validation of those methods becomes vital.

This dissertation presents a multiscale study of the cone penetration process in silica sands. The penetration problem is investigated using a combinational approach consisting of calibration chamber experiments, digital image correlation (DIC) analysis, and X-ray computed Tomography (XCT) scans. Three silica sands with different particle characteristics are used in the experimental program. These three sands have similar particle size distributions; however, they differ in particle morphologies and particle strengths. These differences allow a study of the effect of microscale sand properties on the macroscale response of the sands to the cone penetration process. The three silica sands used in this research are fully characterized using laboratory experiments to obtain particle size distributions, particle morphologies, particle crushing strengths, minimum and maximum packing densities, and critical-state friction angles. Subsequently, both dense and medium-dense samples of the three sands are compressed in a uniaxial loading device placed inside an X-ray microscope (XRM) and scanned at multiple stress levels during uniaxial compression. Results from uniaxial compression experiments indicate that: (1) the compressibility of the sands is closely tied to particle morphology and strength, and (2) the anisotropy in the orientations of interparticle contact normals generally increases with axial stress; however, this increase is limited by the occurrence of particle crushing in the sample.

Subsequently, cone penetration experiments are performed under different confinement levels on dense samples of the three sands in a special half-cylindrical calibration chamber equipped with DIC capabilities. For each penetration experiment, incremental displacement fields around the cone penetrometer are obtained using DIC analysis, and these incremental displacement fields are further analyzed to compute the incremental strain fields. A novel methodology is developed to obtain the shear-band patterns that develop around the penetrometer automatically. Furthermore, differences in the shear-band patterns in deep and shallow penetration environments are also investigated. Results show that strain fields tend to localize intensely near the penetrometer tip, and the shear bands tend to develop along the inclined face and near the shoulder of the penetrometer. Significant differences in the shear band patterns in deep and shallow penetration environments are also observed.

After each cone penetration experiment, a specially developed agar-impregnation technique is used to collect *minimally disturbed* sand samples from around the penetrometer tip. These agar-impregnated sand samples are scanned in the XRM to obtain 3D tomography data, which are further analyzed to quantify particle crushing around the penetrometer tip. The results show that: (1) for a given sample density, the amount of crushing around the cone penetrometer depends on the confinement and the sand particle characteristics, (2) the level of crushing is not uniform around the penetrometer tip, with more severe crushing observed near the shoulder of the penetrometer, and (3) the regions with more severe particle

crushing around the penetrometer approximately overlap with regions of high shear strain and volumetric contraction. A framework is also proposed to obtain the ratio of penetration resistance in more crushable sands to penetration resistance in less crushable sands. Furthermore, a novel resin-impregnation technique is also developed to collect *undisturbed* sand samples from around the penetrometer tip. The resin-impregnated sand sample collected after one of the penetration experiments is scanned in the XRM to obtain the 3D tomography data, which is then analyzed to obtain the distribution of interparticle contact normal orientations at multiple locations around the penetrometer tip. These analyses indicate that the interparticle contact normals tend to orient themselves with the incremental principal strains around the penetrometer: below the penetrometer tip, the interparticle contact normals orient vertically upwards, while closer to the shoulder of the penetrometer, the interparticle contact normals become more radially inclined.

Data presented in this dissertation on penetration resistance, incremental displacement fields, incremental strain fields, particle crushing, and interparticle contact normal orientations around the cone penetrometer are aimed to be useful to researchers working on the multiscale modeling of penetration processes in granular materials and aid in the further development of our understanding of penetration processes in sands.