APPLICATION OF MIXED-MODE FRACTURE MECHANICS IN GEOTECHNICAL ENGINEERING

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ABSTRACT

The physical properties of stiff clays and cemented sands are characterized by brittleness. Although there is no single reason for this behavior, past studies have shown that the presence of flaws, fissures, cracks and joints have significant influence on the overall stiffness, stability and strength behavior of these materials. While classical geotechnical analysis techniques are based on traditional strength concepts, it has been shown that failure of stiff-fissured earth structures in weakly cemented sands, sch as embankments and slopes to a large extent is governed by fracture mechanics , which is the appropriate technique for analyzing such materials and related systems. However, the use of fracture mechanics concepts in weakly cemented sands is faced with the difficulty in obtaining relevant parameters, because fracture parameters and predictions are highly dependent on the material constituents and laboratory specimen configuration. The paper describes experiments on three different sizes of four-point beam specimens, which are comprised of cemented granular materials having three different grain sizes. The same cementing agent was used in all the experiments. It was found that the fracture behavior of cemented sands is highly dependent on the grain size of the constituent material as well as the size of the specimen, which provides data for a specific size-effect law. The 25 four-point beam specimens, which were conducted, did not provide for a pure Mode II condition but rather a mixture of Modes I and II. The analysis of the experiments as accompanied by detailed fracture-mechanics finite element studies.

1 INTRODUCTION

Analysis of foundation systems and slopes in stiff soils, especially overconsolidated clays and cemented sands, presents challenges due to the brittle nature of the material and failure mechanisms, which vary significantly from those explained in terms of traditional strength of materials concepts. While the stability of most geotechnical and geomechanical systems is frequently determined by means of classical limiting equilibrium, limit plasticity of nonlinear continuum computational modeling techniques, it appears that fracture mechanics concepts in many cases are more appropriate, especially where tensile cracking or rupture, as well as progressive failure mechanisms appear to dominate. Although there is no single reason for progressive failure and fracture behavior, past studies have shown that the presence of flaws, fissures, cracks, joints, etc. have significant influence on the overall stiffness, stability and strength behavior of cemented sands and overconsolidated clays. Terzaghi (1936), Skempton (1964), Sitar et al. (1980), Vallejo (1989), and Sture et al. (1999) described failure phenomena and the progressive nature of material failure in stiff-fissured soils, which clearly indicate that the appropriate explanation of overall behavior is best achieved by means of classical or nonlinear fracture mechanics methods. However, the use of fracture mechanics concepts in weakly cemented granular soils is faced with the difficulty in obtaining relevant parameters, because fracture parameters and predictions are highly dependent on the material constituents, boundary conditions and laboratory specimen configuration. In this paper we describe experiments on three different sizes of four-point bending specimens, which are comprised of weakly cemented granular materials having three different grain sizes. In addition to gaining an understanding of basic phenomena, the purpose was also to ascertain the role of any scaling relations related to overall geometry as well as material constituents, which also remain important issues in explaining fracture processes in cementitious composites such as concrete (Bazant and Planas, 1998).

2 EXPERIMENTAL TECHNIQUE AND RESULTS

In order to investigate mixed Modes I and II fracture behavior in weakly cemented sands, we adopted the four-point beam specimen configuration, which was first described by Iosipescu (1967), which has emerged as the most stable, versatile and generally applicable experimental technique employed in structural mechanics. Although the four-point beam specimen typically does not develop a pure Mode II condition, regardless of the beam specimen's geometry and related aspect ratios, the technique provides nearly constant shear and almost zero moment across the main central section; it facilitates double notching; the experimental fixtures (supports) readily prevents overall rotation of the beam specimen; and, post-peak behavior can be monitored by employing Crack Mouth Sliding Displacement (CMSD) techniques (Kim, 2003). Three different quartz sands having different grain sizes, but with similar surface texture, while maintaining very uniform distributions, with average grain sizes (d_{50}) of 0.31 mm, 1.10 mm and 1.90 mm, respectively. The specific mass for the quartz sand was in the range 2.63 to 2.65. Rather than using a naturally occurring cemented sand, which would involve a high degree of variability in strength throughout the volume of a specimen, it was decided to employ an artificial cementing agent to produce specimens with uniform properties. Three sets of different size porous (perforated) polycarbonate molds, which contained the different size beam specimens, were submerged in a concentrated sugar-water mixture for short periods of time and then left to drain and dry for prescribed time periods. Residue of crystallized sugar-cement was left at the grain contacts, while the granular structure overall remained relatively porous. Thus, it appeared that the primary form of bonding was of the grain-contact category, rather than the void-bonding category that characterizes most cementitious composites, including concrete, although data scatter in some of the tests and post-experiments surveys indicate that void-bonding did occur in some instances. This technique has successfully been used in the past (Mould, 1983; Sture et al., 1999), and it provides straightforward control and measurements of the constituents and basic properties. The specimens were geometrically similar, and the configuration of the specimens ensured that approximate plane strain conditions were maintained in the central regions (ASTM E399-74). The ratio between width to length was kept at approximately 1:4. The average dimensions (Length, Width, Depth) of the three different sized beams were as follows:

Large size beams:	L: 812 mm,	W: 94 mm,	D: 203 mm
Intermediate size beams:	L: 406 mm,	W: 97 mm,	D: 102 mm
Small size beams:	L: 203 mm,	W: 51 mm,	D: 51 mm

Twenty-five successful experiments were conducted in the various categories in a structurally stiff experimental fixture, and overall loading was performed in a displacement - servo controlled universal hydraulic testing machine (MTS). The loading positions in the four-point beam specimens were in all cases kept at a distance D/12 from the centrally located double-notches, which were monitored by high sensitivity CMSD clip-gages. The overall loading rate in all the experiments was maintained at 0.05 mm/min. Experimental control and data acquisition was performed by National Instruments, Inc., LabView and related control routines. Loading-unloading-reloading cycles were conducted frequently in all tests both prior to and after peak capacities were reached. The CMSD corresponding to peak load for the small and large size specimens were in the range of 0.098 mm and 0.190 mm respectively. All specimens displayed a high degree of brittleness in terms of steep descending load-displacement response behavior. It was observed that specimen size and the size of the constituents have a profound effect on the fracture properties and overall capacity and load-displacement response behavior. It was found that none of the many size-effect laws or models described by Bazant and Planas (1998) adequately accounted for load-displacement behavior and overall capacity. In terms of the standard size-effect diagram representation, which is represented in terms of nominal stress vs. size, it was established that the negative slope was in the range of 0.67.

4 SUMMARY

The investigation established that the four-point beam bending configuration can successfully be used to obtain fracture properties of weakly cemented geomaterials, such as weakly cemented sand, although it was difficult to maintain overall stability and control for the large-size specimens due to self-weight effects. Analysis and observations ascertained that the inelastic zone, process zone, etc. in front of the crack tip was relatively small and at the scale of one grain, which can readily be explained by the grain-contact bond vs. the void-bond feature. The cracks propagated in an inclined manner, rather than straight up-and-down, which indicated mixed-mode behavior. Linear Elastic Fracture Mechanics (LEFM) and Crack Mouth Opening Displacement (CMOD) concepts appear to be applicable for large size specimens or weakly-cemented earth-structures, although the CMOD approach seems to be overly conservative for small-grain-size materials. Clearly, LEFM and CMOD techniques do not account for effects due to grain size, and the proposed modification (Kim, 2003) is applicable.

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