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Stress drop effects in time dependent behavior of quartz sand

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ABSTRACT

Time effects in granular materials relate to crushing of grains, which is a time dependent process. Depending on the proximity of the load applied to a grain relative to the instantaneous failure load of the grain, the time increases as the load is decreased below the failure load. A study of grain crushing associated with stress drop-creep and stress drop-stress relaxation experiments on dense Virginia Beach sand consisting mainly of quartz grains is presented. In these experiments the triaxial specimens are isotropically consolidated to 8000 kPa, sheared at a constant rate up to a given deviator stress followed by either creep or stress relaxation over a given time period. After dismantling the triaxial specimens, the grain size distributions are determined and their changes, as expressed through Hardin's relative breakage factor, are related to the amount of energy input. Results of the stress drop-creep tests and the stress drop-stress relaxation tests show that creep deformations and the amount of stress relaxation are considerably reduced with increasing amounts of stress drop. Depending on the amount of stress drop, a delay is detected before creep deformation or stress relaxation is initiated. Multiple stress drop-creep experiments are also performed. Structuration effects, which describe changes in yield surface location during creep or stress relaxation and are due to change in grain configuration and interlocking with time, are not observed in the specimens of Virginia Beach sand.

1. Introduction

Creep in granular materials have been shown to relate to crushing of particles (Lade, 2007; Lade and Karimpour, 2010, 2013; Karimpour and Lade, 2010, 2013; Karimpour, 2012; Michalowski and Nadukuru, 2012), which is a time dependent process referred to as static fatigue or delayed plasticity (Lemaitre and Chaboche, 1994; Callister, 2005). Grain size distributions before and after creep experiments clearly showed the connection between energy input to the soil specimen and the amount of grain crushing as expressed by Hardin's (1985) relative particle breakage factor. Stress relaxation behavior of the granular material has also been suggested to be related to particle crushing. However, since particle crushing experienced during stress relaxation is less pronounced than what observed during creep, a clear change in grain size distribution has not been identified using sieve analysis.

Effects of stress drops (i.e. quick reduction in deviator stress level or quick unloading) on subsequent creep or stress relaxation have been studied for crushed coral sand by Lade et al. (2009, 2010). While it was apparent that the grains had crushed at the end of the experiments, grain size distributions were not determined at the end of the tests, because the soil grains were too small and too friable to obtain trustworthy grain size distributions by sieve shaking. Thus, the amounts of grain crushing were not quantified for the experiments on crushed coral sand.

Presented here is a study of grain crushing associated with stress drop followed by creep or by stress relaxation experiments on dense Virginia Beach sand consisting mainly of quartz grains. In these experiments the triaxial specimens are isotropically consolidated to 8000 kPa, then sheared at a constant rate up to a given deviator stress at which deviator stress reduced quickly, and followed by either creep or stress relaxation over a given time period. After dismantling the triaxial specimens, the grain size distributions are determined and their change as expressed through Hardin's relative breakage factor, are related to the amount of energy input.

The results of sieve analysis confirm that creep behavior is related to crushing of particles. Since the possible particle crushing during stress relaxation cannot be measured using sieve analysis, relation of stress relaxation behavior and particle crushing is a hypothesis. It is believed that the proposed mechanistic picture presented herein can adequately connect the time effects and crushing of particles.

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2. Previous studies

Aging effects and rate effects in granular material have been widely referred to in the literature. Aging effects are explained as the material stress–strain relation change with time that could be due to actual change in material (i.e. bonding or weathering).

Experimental programs have been carried out by different researchers (Daramola, 1980; Joshi et al., 1995; Al-Sanad and Ismael, 1996; Baxter and Mitchell, 2004) to investigate aging effects in granular materials and possibly suggest mechanisms that would explain such behavior.

Schmertmann (1987) and Mesri et al. (1990) suggested that grain reorientations during secondary compression in sands can describe time-dependent gain in horizontal stress and purely frictional increase in stiffness and strength with time. Schmertmann (1991) also related the time dependent increase observed in penetration resistance in granular material to the non-uniform distribution of stress and consequent arching effects. In a similar manner, force chain buckling and stress redistribution in soil medium with time was suggested by Bowman and Soga (2003) to describe time-dependent behavior of granular materials.

Mitchell (2008) provided a comprehensive literature review on aging phenomena in sand and proposed particle rearrangements, interparticle stress adjustment and redistribution among grains, accompanied with small volumetric contractions as the main roots of aging phenomena. It was also suggested that sand type and its initial state, the applied stress state and micro-biological processes can contribute to the aging phenomenon.

Rate effects comprise rate dependency, creep (loading rate of zero) or stress relaxation (loading strain rate of zero). The first experimental study of the strain rate effects was conducted by Casagrande and Shannon (1948) on dense sand using a triaxial testing apparatus with low confining pressures. In similar studies, Seed and Lundgren (1954), Nash and Dixon (1961), Whitman and Healy (1962) and Lee et al. (1969) also examined drained and undrained behavior of loose and dense sand under low and high confining pressures. Other researchers (Yamamuro and Lade, 1993; Matsushita et al., 1999; Santucci de Magistris and Tatsuoka, 1999; Tatsuoka et al., 2000, 2002, 2006; Kuwano and Jardine, 2002; di Benedetto et al., 2003; Augustesen et al., 2004; AnhDan et al., 2006; Kiyota and Tatsuoka, 2006; Lade, 2007; Lade et al., 2009, 2010; Lade and Karimpour, 2010; Karimpour and Lade, 2010, 2013) have also studied stress–strain rate dependency in granular materials.

Creep behavior of granular materials has also been broadly studied. Crawford and Morrison (1996), Komornik et al. (1972), Sweeney and Lambson (1991) and Hannink (1994) have reported long-term settlements of structures built on sand. Murayama et al. (1984), Mejia et al. (1988), Colliat-Dangus et al. (1988), Leung et al. (1996), Lade and Liu (1998), Lagioia (1998), Bowman and Soga (2003), Lade et al. (2009), Karimpour and Lade (2010), Karimpour (2012) and Karimpour and Lade (2013) have experimentally studied creep behavior of granular materials.

Only few investigations have been performed on stress relaxation in granular materials. Lacerda (1976), and Lacerda and Houston (1973) carried out stress relaxation experiments on several types of clay and quartz sand. Their results indicated that once deformation was stopped, there was an initial delay in time before a linear relationship between the logarithm of time and the stress relaxation was observed for both clays and quartz sand and a change in shearing strain rate did not affect the slopes of the stress relaxation curves. Previously, Murayama and Shibata (1961), Vialov and Skibitsky (1961) and Saada (1962) had reported such behavior for clays. Murayama and Shibata (1961) observed that there was a limiting stress for stress relaxation, while others did not report such an observation.

Lacerda and Houston (1973) performed several undrained stress relaxation experiments. The results showed that the amount of generated pore pressure during stress relaxation was small to negligible and this observation was supported by a hypothesis suggested by Lo (1969) according to which pore pressure generation is only associated with the amount of applied strain. Ladanyi and Benyamina (1995) carried out a series of stress relaxation experiments on frozen Ottawa sand with the goal of estimating creep parameters from the relaxation experiments. For the range of confining pressures used (100–300 kPa), they concluded that confining pressure has no influence on the stress relaxation behavior for frozen Ottawa sand.

Lade et al. (2010) performed a series of stress-drop-relaxation tests on crushed coral sand. Significant amounts of stress relaxation were observed at different levels of deviator stresses. Analogous to the creep tests (Lade et al., 2009), close observation of the volumetric strain showed contraction during stress relaxation. Additional loading after each stress relaxation was accompanied by structuration effects i.e., temporary overshoot of the original stress–strain curve once loading is continued after creep or stress relaxation-similar to what Tatsuoka et al. (2008) defined as temporary effects of strain rate and acceleration (i.e. TESRA). Karimpour and Lade (2010) studied the effect of strain rate on the stress relaxation behavior of Virginia Beach sand under a confining pressure of 8000 kPa, where particle breakage was experienced. It was observed that higher initial loading rates produced slightly larger amounts of stress relaxation, but after some time the stress relaxation rate became approximately the same for all initial loading rates. Due to negligible additional energy input and volume change during stress relaxation, insignificant amounts of particle crushing were observed during stress relaxation.

Lade and Liu (1998), Lade (2007), Lade et al. (2009, 2010), Lade and Karimpour (2010) and Karimpour and Lade (2010, 2013, 2015) proposed that changes in the developed force chains in grain assemblies can explain creep and stress relaxation behaviors in sand. This is because different boundary conditions prevail as a consequence of particle crushing due to static fatigue. Static fatigue can be simply described as failure occurring at a lower load than that required to cause short-term failure in brittle materials, such as quartz, due to slow growth of sub-critical cracks to a length at which they will propagate catastrophically. Lade and Karimpour (2010) and Michalowski and Nadukuru (2012) explained this phenomenon in granular materials.

3. Mechanistic picture of time effects in sands

Particle breakage has often been observed to be associated with time effects in granular materials, and a mechanistic picture of time effects may be constructed on the basis of this phenomenon.

Fig. 1(a) shows an assembly of grains that have been loaded up to a given stress difference and either creep or stress relaxation occurs from this point. The diagram shows the force chains down through the assembly. The grain in the middle fractures in the beginning of either of these two types of time effects. The responses of the grain assembly are quite different for the two phenomena. Fig. 1(b) shows what happens during creep in which the vertical stress is held constant. The assembly adjusts its structure to carry the vertical stress. This requires adjustment of the grains and it results in some vertical deformation and new force chains are created to match the externally applied stress. The redundancy in the grain structure allows new force chains to be created and engage other grains that may break. But slowly the amount of breakage will reduce and the creep will slow down with time, just as observed in the experiments.

Fig. 1(c) shows what happens in the stress relaxation experiment. After the grain has broken, the grain structure is not able to