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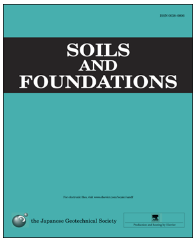

Shear banding in torsion shear tests on cross-anisotropic deposits of fine Nevada sand

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Abstract

A series of torsion shear experiments was performed on large hollow cylinder specimens of Fine Nevada sand with major principal stress directions relative to vertical, α, varying from 0° to 90° and with the intermediate principal stress, σ_2, varying from σ_3 to σ_1 as indicated by $b=(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$. The Fine Nevada sand was deposited by dry pluviation, thus producing a sand fabric with horizontal bedding planes and cross-anisotropic characteristics. The various stress conditions were achieved by varying the pressures inside and outside the hollow cylinder specimen relative to the shear stress and the vertical deviator stress according to a pre-calculated pattern. All stresses and all strains were determined from careful measurements so that analysis of the soil behavior could be made reliably. The soil behavior was determined for a pattern of combinations of α varying with increments of 22.5° from 0° to 90° and b varying with increments of 0.25 from 0.0 to 1.0. Thus, 25 test locations were established, but many tests were repeated to study the consistency of the results. The friction angles varied considerably with α and b, thus indicating the importance of the intermediate principal stress and the principal stress directions relative to the horizontal bedding planes. The observed shear bands essentially followed the expected directions, but due to the cross-anisotropy shear bands were also observed in the direction of the major principal stress in regions with high b-values. The strength variation was also influenced by the flexibility of the boundaries in these regions.
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Keywords: Cross-anisotropy; Sand; shear banding; Shear strength; Three-dimensional strength; Torsion shear; True triaxial tests (IGC: D6)

1. Introduction

The effects of principal stress direction relative to the bedding planes and the effects of the relative magnitude of the intermediate principal stress on the direction of shear banding in cross-anisotropic sand deposits is of interest. Therefore, a series of torsion shear tests on large hollow cylinder specimens prepared by dry pluviation was performed. To study the variation in shear strength and in direction of shear banding for all directions of the major principal stress relative to vertical, α, and all relative values of the intermediate principal stress, as expressed by $b=(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$, a systematic program consisting of 25 drained torsion shear tests was performed. Since several of these experiments were repeated to check for accuracy and scatter, a total of 44 torsion shear tests were performed on Fine Silica sand deposited by dry pluviation, which creates cross-anisotropic deposits similar to those found in-situ. Situations in which the

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influence of principal stress direction can be isolated, while other parameters are held constant can be created and studied in a torsion shear apparatus, in which both the direction and magnitude of principal stresses can be controlled. With these devices, which allow for creation of three different principal stresses, it is possible to apply continuous, controlled increments and/or rotations of principal stresses in the vertical plane of the hollow cylinder specimen. The tests performed in this experimental program had different, varying internal and external pressures and therefore, were able to cover constant intermediate principal stress ratios as expressed by b, and principal stress directions, as expressed by α.

2. Shear strength components in granular materials

The shear strength of granular materials derives from different components as identified earlier (Rowe, 1962; Bishop, 1966; Lee and Seed, 1967). Thus, the measured friction angle consists of contributions from basic sliding friction between particles, energy input to overcome dilation, energy for rearrangement of particles (remolding) at constant volume and energy for particle crushing. The basic friction angle is considered to be constant at all confining pressures. While the basic friction and the dilation effects can be measured and quantified, the effects of remolding and crushing are not quantifiable. It is however, possible to calculate them as the difference between the measured friction angle and the effects of dilation. In undrained tests remolding at constant volume results in an additional contribution to the shear strength above the basic friction effect. The crushing component is small at low confining pressures where dilation is important, while the effect of dilation vanishes at high confining pressures, where particle crushing is prevalent. Thus, particle crushing is dominant at high confining pressures and volume changes, which are so important for soil behavior at low confining pressures, are suppressed and the shear strength is caused by the crushing strength of sand particles. The resulting friction angle is constant at these high confining pressures and the shear strength is simply proportional to the confining pressure (Lade and Yamamuro, 1996, Yamamuro and Lade, 1996). While the friction angle for dense Cambria sand varied with confining pressure due to the contribution of dilation at lower confining pressures, it became constant at confining pressures higher than 15 to 20 MPa (Yamamuro and Lade, 1996). The friction angle at high pressures represents the intrinsic shear strength of the sand and does not involve any effects of dilation or remolding at constant volume.

These components of shear strength do not have directional values, except the dilation angle. Thus, all cross-anisotropy relates to the variation of the angle of dilation obtained for different directions. This in turn is dependent on the particle fabric or structure in the soil.

3. Previous studies of cross-anisotropy

Studies of cross-anisotropy as influenced by the sand fabric were initially performed in triaxial compression on specimens in which the sand was deposited with bedding planes inclined at different angles, α, to the vertical axis of the specimen from 0° to 90°. These studies (Oda 1972a, 1972b, 1981; Oda et al., 1978; Tatsuoka et al., 1986; Lade and Wasif, 1988) indicated that the maximum strength was mobilized when the major principal stress was applied perpendicular to the bedding planes with a transition to lower strengths observed when the major principal stress was aligned with the bedding planes. While these tests were all performed with b=0.0, cross-anisotropy has also been studied in true triaxial equipment to investigate the effects of $b > 0.0$ (e.g. Yamada and Ishihara, 1979; Haruyama, 1981; Ochiai and Lade, 1983; Lam and Tatsuoka, 1988; Abelev and Lade 2003, 2004; Lade and Abelev 2003, 2005). The accumulated evidence shows that under monotonic conditions, when loading and deposition directions coincide, and when no rotation of principal stresses occurs, then the initial anisotropic fabric largely controls the deformation process and the peak shear resistance, especially in sands with elongated particles. This fact has been utilized in testing programs to study the influence of inherent cross-anisotropy on the failure criterion for such soils. The results obtained by Ochiai and Lade (1983), as well as those obtained by Yamada and Ishihara (1979), clearly showed cross-anisotropic stress–strain behavior. The failure surfaces, on the other hand, indicated only minor effects and were less clearly influenced by cross-anisotropy.

Only few studies have been performed to find the influence of b and α on the friction angle of sands for various combinations of these two variables. This may be done in directional shear or in torsion shear equipment with different pressures applied inside and outside the hollow cylinder specimen. Limited and sporadic experimental results have been provided in this respect by Arthur and Menzies (1972), Arthur and Phillips (1975), Hight et al. (1983), Miura et al. (1986), Pradel et al. (1990), Naughton and O'Kelly (2007), O'Kelly and Naughton (2009) and by Chairo et al. (2013). While these studies indicated some variation in the friction angle, none provided a complete picture.

4. Shear band orientations in isotropic soil

It does not appear to be possible to intentionally create isotropic deposits of granular materials, i.e. a laboratory method does not exist by which isotropic specimens of granular materials can be produced. In fact, deposits generated by dry pluviation always behave as cross-anisotropic materials, because the particle contact points favor the vertical direction, and the deposit is therefore stiffer and stronger in the vertical direction. However, just as friction angles from conventional, vertical specimens are calculated and employed in most analyses procedures with the assumption that the soil is isotropic, angles of dilation are calculated from the principal strains with the assumption that the soil behaves as an isotropic material. Thus, the intermediate principal strain does not enter into the calculation of the dilation angle and therefore does not affect its value.

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