Synopsis

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Instabilities in Granular Media with Flexible Boundaries

Instability in granular media is associated with the emergence of non-uniform deformation modes suddenly from its state of uniform material behaviour. It is manifested in the form of localized strain accumulation (shear banding), surface buckling, bulging, liquefaction ("solid-fluid") and volume instability. Such instabilities act as precursor to failure influencing material strength owing to which, investigation regarding its inception is of prime concern in geomechanics research. Onset of diverse instability modes can be attributed to several factors viz. inherent heterogeneity of the material medium, type of loading, boundary and drainage conditions. One needs to have an idea of handling the global material response in the post-bifurcation regime with its first stepping stone being assertion of instability onset strain since, the material behaviour does not remain uniform ("single element" behaviour) with instability outset. Initiation of non-uniform material response in Plane Strain (PS) conditions has been explored numerically within a continuum elastoplastic framework with the aid of a nonassociative generalized 3D material model that takes into account kinematic hardening. Emergence of instabilities have also been probed at the grain scale level within a discrete (discontinuum) framework that incorporates actual grain morphology while experimental findings augmented with digital image analysis techniques unravel local strain evolution in soil specimens subjected to different boundary conditions.

Since most of the geotechnical structures encountered in the field are idealized as plane strain problems (viz., slope stability, strip footing etc.) with their strength parameters still being estimated from axisymmetric triaxial tests, soil behaviour has been explored in PS conditions ($\epsilon_2 = 0$) in the present study. Existing PS testing of granular media (sands) have been restricted to rigid boundaries (frictional and lubricated to some extent) in the loading direction. Interestingly boundary conditions in laboratory experiments significantly influencing the mechanical response resulting in triggering of various non-uniform deformation modes suddenly from its homogeneous material behaviour, the present study employs flexible boundaries (FBs) in PS testing of sand specimens. FB-PS tests thus becomes imperative for development of material models and yield or failure criteria so that they can be employed to mimic field conditions which may result in more realistic predictions.

Onset of instability in sands has been explored in this study at different length scales from numerical as well as experimental perspectives. Coupled (diffusion) undrained instability analysis (globally undrained locally drained) in sands have been executed in ABAQUS v6.14 with the implementation of a user defined material model (UMAT). Instability onset within a numerical framework was found to be a mesh dependent phenomenon for a particular magnitude of inhomogeneity. Perturbation (required to trigger instability within any numerical framework) was introduced in terms of initial void ratio (e_0) of the sand specimen locally in a few elements and its magnitude was found to significantly influence the instability onset strain. Influence of patch area of perturbation on instability onset was found to be relatively insignificant.

Furthermore, in order to resolve "pathological mesh dependence" with "phenomenological" material models, instability onset and its signatures have been captured within a discontinuum framework. Macroscopic response obtained from FB-PS test simulations are in good agreement with the experimental findings and the markedly comparable resemblance of the deformed sand specimens gives confidence on high reliability of the discrete element simulations. Localisation initiation was observed at smaller axial strain levels that manifested into distinct zone of shear strain accumulation at large strains with multiple shear bands (in conjugate arrays) at later stages. These zones were also associated with significant grain rotation asserting that sand grains undergo significant rotation inside shear band(s).

A multiaxial cubical device with provisions of FB-PS testing has been developed with three-axis electro-pneumatic Proportional-Integral-Derivative (PID) based real-time feedback control system. Transparent plexiglass in (imposed) PS directions allowed images to be taken at regular intervals during shearing stage of the specimen in order to characterise the local strain evolution in sand specimens. A customised software has also been developed in this regard which can automate various processes including consolidation and shearing stage along any predetermined stress or strain path in the generalised stress space. A series of FB-PS tests have been carried out by pre-compressing the sand specimen to a desired mean stress state and then by shearing it along a pre-determined stress path following a particular stress ratio ($\Delta\sigma_3/\Delta\sigma_1$). A simplified yield function in 2D stress space has also been proposed that is in good agreement with the experimental findings along different stress paths with constant $\Delta\sigma_3/\Delta\sigma_1$. Local strain evolution in the material domain has also been examined by employing image analysis techniques during a set of carefully performed FB-PS tests and triaxial compression tests on cuboidal sand specimens so as to segregate the deformation modes encountered in these two conditions. An attempt thus has been made in the present study to characterise how instabilities and localisation emerge in pressure-dependent granular media and what are their various signatures across different length scales viz., continuum, discrete and laboratory "single element" scale.