Abstract

Four decades after it was investigated experimentally for the first time, the influence of multi-directional shearing on soil behaviour, especially the undrained behaviour of saturated sands, remains one of the least understood areas in geotechnics. This study developed a new test database on Hostun sand with the modified multi-directional simple shear testing apparatus. The results of uni-directional tests were examined under available analysis frameworks to validate the performance of the adopted testing techniques. Multi-directional tests were analysed and compared with their uni-directional counterparts to illustrate the remarkable change in soil response when loading paths change from uni-directional to multi-directional.

A three-dimensional $\tau - \sigma_v'$ space was established as the extrapolation of the 2D $\tau - \sigma_v'$ plane, with a 3D conical failure surface derived from 2D failure lines. The concept of the failure cone was validated by the tests with various loading paths. The failure cone hypothesis explain the unsolved questions, including why bi-directional linear stress paths do not reach the failure line in the 2D $\tau - \sigma_v'$ plane and why an inverse correlation exists between the limiting excess pore pressure ratio and shear stress amplitude.

A bimodal phenomenon was identified in terms of the phase transformation of sand under multi-directional shearing conditions. Phase transformation states form a conical surface, like failure states, in the tests with circular, oval and figure-8 loading paths but do not fall on a cone in uni-directional and bi-directional linear tests.

The effects of multi-directional loading on soil liquefaction were further investigated from the perspective of liquefaction criteria, liquefaction resistance, development of excess pore pressure and shear strain, as well as the degradation of shear modulus. The definitions of shear stress, shear strain and shear modulus were re-examined in multi-directional loading scenarios. Liquefaction resistance assessment based on $N - CSR$ curves was examined and potential alternative discussed. The shear modulus degradation predictions of Hardin and Drnevich (1972) were found to fit with the newly-proposed multi-directional secant shear modulus.

This study provides novel perspectives to understand the undrained soil behaviour under multi-directional loading and has useful implications for future potential modelling research.