

Micro–Macro Mechanisms of Waveform-Dependent Sand Liquefaction Based on DEM Simulations

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With rapid urbanization and increasing infrastructure density, sand liquefaction has become a critical challenge for the future of urban engineering geology, as it poses severe threats to buildings, lifelines, and transportation systems during earthquakes. In saturated sandy ground underlying urban areas, liquefaction can induce a sudden loss of shear strength, leading to ground deformation and cascading engineering failures. While past studies have extensively investigated liquefaction behaviour, the influence of waveform has received little attention. In particular, the connection between macroscopic mechanical behaviour and microscopic fabric evolution remains largely underexplored. To address this limitation, this study employed the Discrete Element Method (DEM) to simulate a series of undrained cyclic triaxial tests. The results revealed that rectangle waves caused the most severe liquefaction as a result of greater loading acting for a longer duration and produced unconventional liquefaction behaviours, as compared to sine and triangle waves. With coordination number (C_N) and the deviatoric part of the second invariant of the fabric tensor ($J2$), this study demonstrates that both C_N and $J2$ can effectively capture the liquefaction process. However, $J2$ exhibited two distinct peaks at loading reversal points within the same cycle, expressing the inherent asymmetry in fabric anisotropy. A new indicator $J2R$ was thus proposed to quantify the difference in peaks and a unified threshold value was identified, being a consistent marker for distinguishing liquefaction stages. Finally, a unified 3D liquefaction path was constructed integrating $J2$, stress ratio (η), and shear strain (ε_d). This unified framework provides deeper insights into the interplay between macromechanical response and microscopic fabric, offering a comprehensive perspective on liquefaction mechanism.

Keywords: Sand Liquefaction, Discrete Element Method, Cyclic Triaxial Test, Fabric Characteristics, Anisotropy Degree