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Numerical Simulations on Liquefaction of Iron Ore Fines under Roll Motion of Bulk Carriers Using Fluid Coupling Scheme in DEM

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Numerical simulations are conducted to investigate the dynamics and mechanical characteristics of saturated iron ore fines in bulk carriers by the roll motion using the microscopic fluid coupling scheme devised in the discrete element method. The scheme solves pore water pressure in particle assemblies by the change of void spaces and flows between them. Updated pore water pressure is applied to related particles around void spaces. Two types of bulk carriers are modeled, as well as changing roll conditions for simulations. The results represent liquefaction—that is, the pore water pressure increases while effective stress decreases in particle assemblies as the roll motion proceeds. The relative motion between particles increases especially in the upper area, with particles moving laterally along the surface, such that the surface tilts relative to the lateral direction. In the case of a bulk carrier with a roll angle of 20 degrees, the ratio of excess pore water pressure to initial effective overburden pressure reaches about 70% at a depth of 5 m, and the magnitude of particle velocities is about 5 m/s on the surface; also, the surface tilts about 6 to 8 degrees during the motion. It was verified that the scheme enables one to examine the dynamics and mechanical characteristics of saturated iron ore fines in bulk carriers and could be a more useful tool to guide their safe carriage if further studies for the unsaturated condition are advanced.

INTRODUCTION

The International Maritime Solid Bulk Cargoes Code (International Maritime Organization (IMO), 2015a) states that the gravimetric moisture content of Group A cargoes that may liquefy shall not exceed the transportable moisture limit during the loading and subsequent voyage. Liquefaction occurs as follows: (1) Ship motion causes compaction of the moisture cargoes. (2) Its pore water pressure increases. (3) Its shear strength decreases. (4) A certain number of cargoes turn into viscous fluid. The viscous fluid follows the ship roll motion and moves to one side of the ship. However, the fluid does not completely return to its original position. Consequently, the cargo shifting may result in the ship's loss of stability, followed by capsizing.

After a bulk carrier loaded with bauxite capsized in January 2015 (Bahamas Maritime Authority, 2015), the Global Bauxite Working Group (GBWG) reported that the surface slurry layer, which consists of water and fine particles separated from the bauxite fines, affected the stability of the ship (GBWG, 2017). This phenomenon, which is called dynamic separation, is distinguished from liquefaction. The IMO cautioned that bauxite fines should be treated as a Group A cargo (IMO, 2015b, 2017).

The kinetic properties of fine solid bulk cargoes (e.g., iron ore fines and bauxite fines) vary according to the gravimetric moisture contents; thus the behaviors of the same cargoes in cargo holds of the ship also vary according to the gravimetric moisture contents. For example, when performing rolling tests on iron ore fines from Carajás, Brazil, Tsuruta et al. (2020) observed the following: free-surface water emerged from the iron ore fines owing to the container motion when its gravimetric moisture content exceeded 7% or 9%, its pore water pressure increased during the roll motion under some conditions, and the high-moisture iron ore fines behaved as viscous fluid during the roll motion. Meanwhile, very few numerical calculations of fine solid bulk cargoes have appropriately considered pore water pressure (Nakamura et al., 2017; Shimizu et al., 2022).

The discrete element method (DEM; Cundall and Strack, 1979) traces particle motion explicitly. The method has solved problems for geomechanics with large deformations of soil, fractures of rock, and dynamics of the particle system. With the recent progress in hardware performance, the method is applied in many engineering fields, not only geoengineering but also mechanical and process engineering, earth science and technology, and so on (e.g., Shimizu and Cundall, 2001; Naito et al., 2020).

Furthermore, there are several coupling schemes with fluid under the DEM to solve problems including fluid interaction (Tsuji et al., 1993; Kawaguchi, 2003; Okura et al., 2004; Shimizu, 2006, 2011; Harada et al., 2018, 2019). The microscopic fluid coupling scheme (Shimizu, 2011), adopted in this study couples pore fluid with a particle system to consider pore water pressure. Using the scheme, Shimizu and colleagues conducted a debris flow simulation (Shimizu et al., 2009) and a simulation in which liquefaction occurs in an oscillating box under a centrifugal experiment (Shimizu and Inagawa, 2010). The scheme is verified by comparing the numerical results with experimental ones.

Shimizu et al. (2022) conducted the two-dimensional numerical simulations, which mimic the experiment by Tsuruta et al. (2020) to represent liquefaction in saturated iron ore fines using the microscopic fluid coupling scheme. The results show that pore water pressure increases while effective stress decreases during roll motion. Particle movement on the surface is similar to that observed in the experiment by Tsuruta et al. (2020).

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