Evaluation of Frictional Force Effects on Internal Loads due to Dry Bulk Cargo during Transverse Ship Motion Using Discrete Element Method

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ABSTRACT

To evaluate the loads due to dry bulk cargoes on the inner hull of bulk carriers, this study investigates effects of the inter-particle and particle-wall frictional properties on internal pressure using Discrete Element Method (DEM) in a vessel that simulates a cargo hold with transverse acceleration. The DEM results indicate that frictional force on the bottom and the side wall reduces the inertia force on the side plate and the dominant factor in the dynamic internal load due to dry bulk is the particle-wall one, not the inter-particle one.

KEY WORDS: Discrete Element Method; Friction Coefficient; Dry bulk cargo; Design load.

NOMENCLATURE

- \( \mu_{s-p} \): Coefficient of static inter-particle friction in sliding direction [-]
- \( \mu_{s-w} \): Coefficient of static particle-wall friction in sliding direction [-]
- \( g \): Gravitational acceleration, taken equal to 9.806 [m/s²]

INTRODUCTION

Dry bulk cargoes, e.g. iron ore, are aggregates of granular materials transported by bulk carriers. They have soil-like characteristics and have complex load distributions since the load are transmitted from the points of contact of the particles. A precise evaluation method can contribute to more rational design of bulk carriers. Currently, the prevailing formulae estimate the internal load undergoing transverse acceleration as the total of the static pressure, dynamic pressure caused by inertial force due to acceleration, static shear force, and dynamic shear force. The dynamic pressure due to transverse acceleration is supposed to be reduced by frictional forces between the cargo and the inner hull surface.

There have been some experimental studies on pressure due to transverse acceleration. Nagamoto et al. (1974) measured the ore pressure using earth pressure cells in model tests and discovered that the side shell pressure increases proportionally to the 1.1 power of the transverse acceleration. Tanaka et al. (1999, 2002) noted that the dynamic pressure measured by strain gauges were smaller than the pressure estimated as liquid cargoes. Those experiments imply that the frictional force reduces the pressure, but the mechanism has remained unclear.

Although the experimental measurement has difficulties to accurately measure the ore pressure and the frictional force, numerical calculations enable frictional forces to be simulated. In particular, Discrete Element Method (DEM) has been employed in several studies to evaluate the pressure during ship motion (Toh et al., 2018; Yanagimoto et al., 2022). Toh et al. evaluated the static and dynamic ore pressure in the rolling ship using by experiments and DEM. The DE analysis results are in good agreement with the experimental results. However, there are few investigations focusing on the frictional parameters of the cargoes and the loads during transverse ship motion.

The transverse pressure due to dry bulk cargo is less than the vertical one because of its shear resistance. The prevailing formulae for the static pressure are based on earth pressure theory involving the coefficient of earth pressure at rest \( K_e \) which is the empirical equation proposed by Jaky (1944). The inter-particle friction may influence the value of the coefficient \( K_e \). Meanwhile, the formula for the dynamic transverse pressure is corrected using a constant factor, while the reduction is not sufficiently explained.

Therefore, in order to further rationalize bulk carriers design with more accurate estimation formulae, the focus is on the inter-particle and particle-wall friction coefficients and the comprehensive effect of the coefficients on the internal loads due to dry bulk cargoes accelerated transversely. Following above previous studies, the authors employ DEM simulation. This paper first describes the method of DEM and the relation between physical properties of dry bulk cargo and friction coefficients are described. Then, the internal loads consisting of normal pressure and shear stress on the hull and the effect of the friction coefficient on these loads are evaluated using numerical analyses of transverse accelerated rectangular tank.

METHOD

DEM, developed by Cundall and Strack (1979), computes the motion and deformation of a material as discrete elements such as spheres or discs. The behavior of particles is obtained by describing the contact forces between the particle and other elements with springs and dampers and solving the equations of motion in the translational and rotational directions. Hence, DEM is suited for the analysis of granular