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Numerical analysis of cargo liquefaction mechanism under the swell motion

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A B S T R A C T

Cargo liquefaction has been an arising issue since it is the major reason for numerous bulk carriers' capsizes. Many solutions have been adopted by researchers and seafarers to avoid these incidents which can be divided into experimental tests and numerical simulations. The aim of this research is to develop a dynamic numerical model in order to assess the liquefaction potential of a shipped ore. To do so, first, a calibration of experimental cyclic shear test results by means of a non-linear constitutive "UBCSAND" model is elaborated in order to deduce the exact soil parameters. Afterwards, a reproduction of the bulk carrier motions under the swell effect by means of a numerical simulation is conducted. This dynamic model allows analysing the stress distributions in the ore pile as well as spotting the triggering of liquefaction due to pore water pressure build-up. Finally, a parametric study is carried out to determine the variation effect of some key parameters on the cargo liquefaction potential.
The numerical calibration results of experimental tests proved that the chosen constitutive model is suitable for the transported ore. Besides, the dynamic model results compared to previous studies and real case observations showed the reliability of this simulation to predict the stress and pore-pressure variation as well as the liquefaction potential under the swell motion.

1. Introduction

Whilst at sea, cargoes are subject to agitation due to the swell impact (Fig. 1). The oscillatory ship movement leads to resettling of the cargo particles and compaction of the inter-granular spaces. This compaction sharply raises the water pressure, forcing the particles apart, potentially leading them to lose direct contact. The cargo loses its shear strength and thus conditions are created for the material to behave like a liquid, i.e. to liquefy [1]. Although in some cases there is no obvious water, the cargoes become soft and loose, even leading to moving. Thus, the ore carrier's stability is greatly reduced, causing a shipwreck.

According to [18], from 1988 to 2015, 24 suspected liquefaction incidents were reported. These latters resulted in 164 casualties and the loss of 18 vessels. Conferring to investigations carried out on several case histories, five main potential

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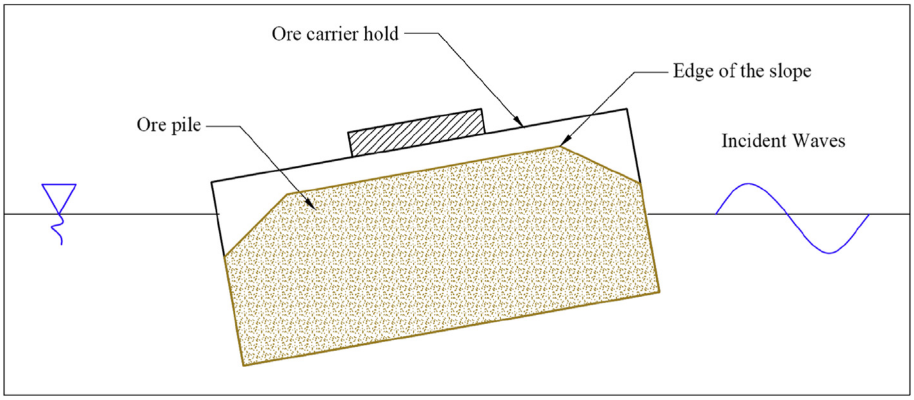

Fig. 1. Simplified mid-ship section of an ore carrier hold subject to swell motion.

causes have been identified for leading or contributing to cargo liquefaction. The first cause is related to unsafe storage conditions since cargoes are usually stockpiled uncovered and subject to all weather conditions [2]. Second, conforming to the International Association of Classification Societies [3], researches show that insufficient loading plan and improper handling of heavy and high density cargo during loading and unloading cause dangerous situations for ship structure and create excessive stress. The third reason of cargo liquefaction is attributed to poor compliance of some shippers with the testing and certification requirements about moisture test of cargo required by the IMSBC Code, pitiable ships to shore communication, ignorance and deviation from loading plans. The fourth cause was deduced after [4] investigation of a number of ore carriers to understand how cargo liquefaction leads to the loss of stability. They noted that all ore carriers' incidents, including sunken ones, were in good working condition, but experienced extreme voyage conditions. The final identified cause is related to the cargo nature since most casualties commonly involved unprocessed or minimally processed ore cargoes; such as nickel ore, iron ore fines and iron sand. Those cargoes are fine grained soils containing high moisture, although they do not visibly appear wet.

In order to reduce the liquefaction risk, many experimental and numerical methods have been developed. For instance, the IMSBC code recommends for materials prone to liquefaction several laboratory tests namely the Flow Table, the Penetration test and the Proctor/Fagerberg test. These tests allow determining the upper bound of the cargo moisture content, which is defined by the Flow Moisture Point (FMP). It is the moisture content permitting the material for passing from solid to liquid state. The IMSBC Code provisions stipulate that cargo must be shipped at moisture content significantly less than the FMP. [5] also suggested a new experimental test procedure for evaluating the shear strength of nickel ore and thus the suitability for carriage of the cargo. The test procedure uses a ‘cone Penetrometer’ to measure the shear strength of a graded sample of nickel ore suitably compacted in a standard container.

Unfortunately, no experimental test appears to have accurately captured the cargo behavior due to the scale effect. Therefore, other researchers have resorted to numerical simulations in order to elaborate a more reliable methodology to assess the cargo liquefaction potential.

For example [4], used the Level Set Method for the sloshing motion of fluid in a rectangular tank. The simulations have shown that fluid with viscosity can have a negative effect on the stability of ships under the circumstances of beam waves and winds. Warren Springs [1] have also modeled three dimensional flow numerical models to test Canadian Carol Lake Concentrate and some other iron concentrates. These numerical simulations indicated that these cargo types exhibited fast drainage characteristics and a wet base formed within a 35 h voyage. These models of flow were also validated by centrifuge tests at City University, and on-board measurements. Moreover, finite element analysis to model three dimensional flows through voyage was elaborated by the Technical Working Group [6] on Brazilian and Australian Iron Ore Fines. Indeed, scale models of various sizes of holds showed that Australian iron ore fines exhibited some slow drainage behavior and thus the formation of a wet base was not observed. However, a wet base and ‘pooling’ was observed for Brazilian ores.

On the other hand [7], and [8] have attempted to simulate a ship's motions within laboratory scale test-work or scale modeling to assess the cargo's liquefaction potential. [9] has also carried out a micro-scale modeling approach to simulate the dynamic behavior of granular materials having physical properties conforming to bulky ship cargos. The researches have varied significantly in terms of the used approach, assessed cargo type and assumptions of motions. Unfortunately, most of these investigators have encountered difficulties when scaling the ships motions (in six degrees of freedom) to a small sample of material. Others have neglected to consider scaling completely. In fact, no scale test-work appears to have accurately captured cargo behavior. In most cases, the scaling issue appears to be due to the difficulties associated with applying scaling laws to the problem (including scaling of accelerations, particle size, relative densities, moisture migration and confining pressures).

Given the previously cited issues, previous studies would only give a gross approximation of the ship's motions and their impact on a cargo sample. Taking into account all these features, this paper aims to advance a reliable numerical model