Dynamic numerical assessment of cargo liquefaction under the swell effect

Evaluation de la liquéfaction des cargaisons sous l'effet de la houle par modélisation dynamique

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ABSTRACT: 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 cargo. To do so, first a calibration of experimental 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 model is conducted. This dynamic simulation allows analyzing the stress distributions in the cargo as well as spotting the triggering of liquefaction due to pore water pressure build-up. The numerical calibration results of experimental tests proved that the chosen constitutive model is suitable for the transported ore. Besides, the dynamic model results allowed concluding that the denser a loaded cargo is, the more resistant to liquefaction it is. Finally, the numerical simulations also proved that a fully trimmed ore pile is more prone to liquefaction and therefore to cargo shift.

RÉSUMÉ : De nombreuses solutions, expérimentale et numérique, ont été adoptées par les chercheurs et les marins pour réduire le risque de liquéfaction de la cargaison au cours du transport maritime et par ailleurs le naufrage des minéraliers. Le but de cette étude est de développer un modèle numérique dynamique afin d'évaluer le potentiel de liquéfaction d'une cargaison au cours de son transport maritime. Pour ce faire, on procède d'abord à un calage des essais de cisaillement expérimentaux moyennant un modèle non-linéaire constitutif "UBCSAND", afin d'en déduire les paramètres exacts du sol. Ensuite, on effectue une reproduction des mouvements du minéralier sous l'effet de la houle à l'aide d'une modélisation numérique. Cette simulation dynamique permet d'analyser les distributions de contraintes dans la cargaison ainsi que de repérer le déclenchement de la liquéfaction due à l'accumulation de surpressions. Les résultats du calage numérique des essais expérimentaux ont prouvé que le modèle constitutif choisi convient au minerai transporté. En outre, les résultats du modèle dynamique ont permis de conclure que plus la cargaison est dense, plus elle est résistante à la liquéfaction. Les modélisations numériques ont montré que les tas de minerai arrimé à plat sont plus susceptibles à la liquéfaction et peuvent ainsi provoquer le ripage de la cargaison.

KEYWORDS: liquefaction, numerical modeling, dynamic motion, maritime transport.

1 INTRODUCTION

When some solid bulk cargoes such as nickel ores are shipped with high moisture and under excessive dynamic loading induced by rough seas, ore liquefaction may occur. This has been known to result in major cargo displacement/shift, causing the ship to capsize.

In order to reduce this risk, many experimental and numerical methods have been developed. For instance, a number of researchers have attempted to simulate a ship's motions within laboratory scale test-work or scale modeling to assess a cargo's liquefaction potential (Atkinson and Taylor, 1994; Koromila et al., 2013). These researches have varied significantly in terms of their approach, cargo type assessed and assumptions of motions. Unfortunately, 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, it is likely that these would only ever 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 assessing the liquefaction potential of an overall cargo behavior, in a real scale hold, subject to certain conditions and accelerations observed on typical voyages.

In the first part of this paper, a numerical calibration of cyclic shear tests is carried out in order to deduce the UBCSAND constitutive model input parameters. Later, a simulation of a cargo hold under the swell effect is conducted to elucidate the processes that could occur within the ore pile, subject to the initial conditions of the cargo and accelerations experienced on voyages. Various scenarios to determine the cargo behavior during shipment under swell motions are modeled.

2 VALIDATION OF UBCSAND CONSTITUTIVE MODEL

An attempt to calibrate a constitutive numerical model on the basis of experimental cyclic triaxial tests results obtained by CERMES laboratories is conducted. This latter is undertaken to prove the effectiveness of the UBCSAND model (Beaty and Byrne, 1998) to reproduce the liquefaction behavior of an ore sample under cyclic loading.

Figures 1and 2 illustrate the experimental and numerical results obtained after calibration. It is concluded that the UBCSAND model can reproduce properly the variations of excess pore water pressure as well as the axial deformation. The outcome of this calibration made us deduce the adequate model input parameters to reproduce the soil behavior. The generic correlations used to determine these constitutive soil model parameters proposed by Beaty and Byrne (2011) are presented in Table 1 as well as the adopted numerical model parameters.

Table 1. Different tested soil states.

Parameter	Determination Formula	Values
$(N1)_{60}$	$(D_R/15)^2$	16
K_G^e	$21.7 \times 20 \times (N1)_{60}^{0.333}$	1083
K_B^e	$K_G^e \times 0.7$	758
K_G^p	$K_G^e \times (N1)_{60}^2 \times 0.003 + 10$	932
φ_p	$\varphi_{cv} + (N1)_{60}^2/10$	36.6
R_f	$1.1 \times (N1)_{60}^{(-0.15)}$	0.73

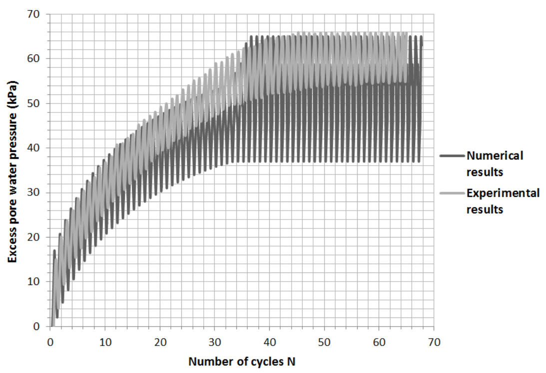

Figure 1. Excess pore water pressure evolution of an ore sample

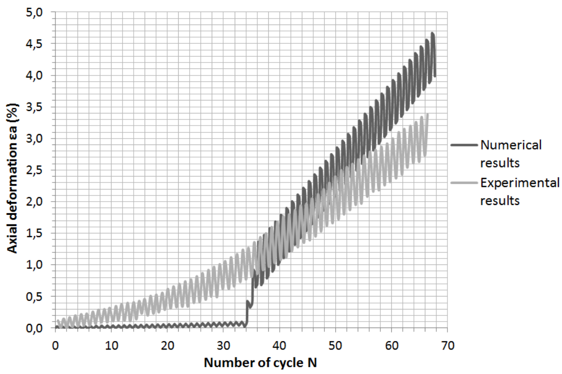

Figure 2. Axial deformation evolution of an ore sample

3 NUMERICAL MODEL DEFINITION

Understanding the cargo behavior during maritime transportation requires knowledge of the actual forces to which the bulk carrier is subjected during a voyage. In order to fully characterize the cargo behavior while shipping, much information such as bulk carrier motion characterization and wave motions are required. The numerical modeling is conducted using FLAC 2D Code.

3 .1 *Model geometry*

In this study, initial static stresses are computed from simple gravity. It is assumed that the hold is in the Full Load condition as defined in the IACS (1997).The waterline of the ship is approximately at the peak of the loaded cargo. The cargo shape and properties used for the numerical modeling are based on actual measurements and governed by 3 factors:

- The shape of the ship's hull.
- The ore volume in the hold.
- The ore natural angle of repose.

The numerical calculations are performed on a 2D cross-section of a cargo hold. A cargo geometry having a 25 m width, a 5 m height at side and a 10 m height in middle is used to approximate the Nickel ore pile after loading.

Figure 3 shows the numerical grid modeled on FLAC. In this analysis, the hold was modeled by a structural element, the slope surfaces were assumed to be seepage boundaries, and the bottom of the heap was assumed to be impervious boundaries. Interface elements, allowing slip and separation were placed between the ore and the cargo hold.

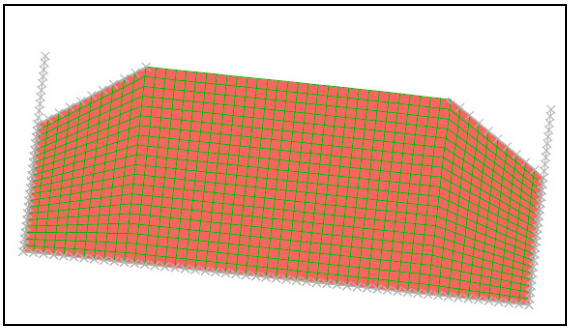

Figure 3. The numerical grid modeled on FLAC

3 .2 *Applied motion*

Understanding and describing the motion and vibrations experienced by the ship, across the possible range of sea conditions encountered, constitutes critical input for establishing the boundary conditions in the numerical modeling.

In reality, a ship (and therefore the cargo in the hold) experiences six degrees of motion during a sea voyage: roll, pitch, yaw, surge, sway and heave. According to the marine studies work (TWG Marine Report, 2013), it was concluded that the roll is the most dangerous motion that a cargo can undergo. It is also assumed that contributions from engine vibrations are negligible.

Taking these findings into consideration, a simple numerical model is designed to apply a roll movement at the hold center of rotation. The swell motion simulated by a sinusoidal velocity is applied along the nodes of the structural element in order to rotate the cargo hold as indicated in Figure 4. The algorithm developed to simulate this motion is based on rotation equations with respect to the rolling center O (x_O, y_O) of the hold with a given roll α. The new coordinates M'(x',y') of a given point M (x,y) are determined by the following equations:

$$\begin{cases} x' - x_O = (x - x_O)\cos(\alpha) - (y - y_O)\sin(\alpha) \\ y' - y_O = (x - x_O)\sin(\alpha) + (y - y_O)\cos(\alpha) \end{cases} \quad (1)$$

Roll degree and period are deduced from real world observations. In fact, previous ore carriers instrumentations reported that the ship roll occur typically at frequencies in the order of magnitude of 0.14 Hz (i.e. 7s period) (TWG Marine Report, 2013).

3 .3 *Calculation phases*

The calculation phases simulated in the FLAC algorithm are detailed in this paragraph. Firstly, a static analysis considering the effect of gravity with the Mohr-Coulomb elastic perfectly plastic constitutive soil model is performed to reproduce the in-situ stresses before applying the dynamic loading. Afterwards, the water flow is activated. Once initial stress state is established, the soil model is changed to a pore pressure generation constitutive model (UBCSAND model) and the effective stress dynamic analysis is started. During these computations excess pore water pressures are allowed to be generated and their dissipation is modeled. The dynamic calculations are performed in large strain mode.

The model simulations are undertaken based upon material parameters derived from the results of fully saturated and undrained cyclic triaxial tests, prior to the calibration of the FEM as mentioned above.

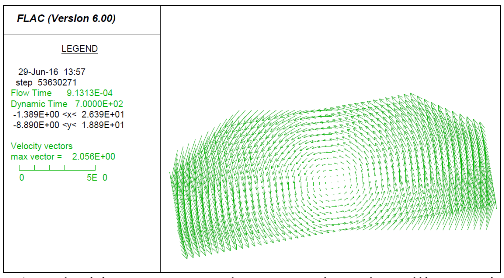

Figure 4. Velocities at cargo node to reproduce the rolling motion

3 .4 *Liquefaction assessment*

To distinguish between liquefiable and non-liquefiable areas, the parameter r_u is defined to the software by a Fish function. The pore water pressure ratio r_u, presented by the equation (2) below, is equal to the pore water pressure *u* divided by the initial effective stress in soil σ'_{ini}:

$$r_u = u / \sigma'_{ini} \quad (2)$$

This parameter allows identifying the liquefied areas when it exceeds or equals 1.

3 .5 *Parametric study*

A sensitivity study is carried out to investigate the variation effect of some key parameters on the soil behavior towards liquefaction (i.e. r_u variation) to develop useful insights.
The first studied parameter is the relative density (D_R) of the loaded ore where two conditions are investigated (loose cargo, D_R=30% and medium dense cargo D_R=60%)
Then, the slope effect is examined by comparing the results of a fully trimmed ore pile to the actual used geometry (with the natural angle of repose).

4 RESULTS

To examine the modeling exactness, several time histories and iso-values are defined in various points of the model mesh to score variations of soil parameters during swell motion. The results of these simulations are presented and discussed below.

4 .1 *Density effect*

On one hand, according to the obtained deformed meshes it is observed that generally local slip failures occur during transport at the pile slopes precisely at the corners of the hold, where there is no confinement from the ship bulkheads or side plates.
Indeed, comparing the deformed mesh after 300 cycles, as shown in Figure 5 and 6, to the initial cargo geometry in Figure 3, it is noted that the pile slopes which were initially at the ore angle of repose (35 °) gradually flatten. Furthermore, the pile surface settles along the journey under the solicitations generated by the swell on the hold.

It is also worth mentioning that the deformations of the slopes depend on the ore state. It is noticed that the ore pile geometry deforms gradually and in a remarkable way when the loaded cargo is looser. It is deduced that the denser the material is, the less likely to deform it is and thus the less prone to liquefaction it is.

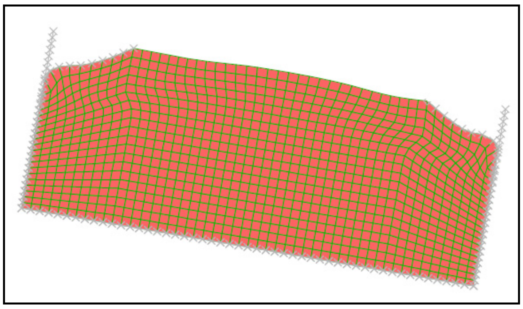

Figure 5. Deformed mesh for a loose ore (after 300cycles)

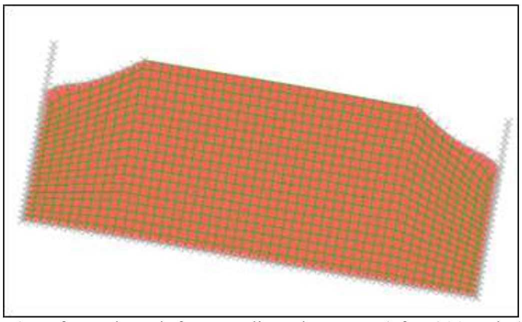

Figure 6. Deformed mesh for a medium dense ore (after 300cycles)

On the other hand, when analyzing the distributions of pore pressure given, it is noted that the formation of liquefied areas occurs after a large number of cycles and the extent of these areas is more important as the cargo is looser.

According to figures 7 and 8, it should be mentioned that the liquefied zones (r_u>1, non colored areas) remain located under the slopes and at the bottom of the heap. Thus, it is deduced that the ore liquefaction remains localized and does not affect the whole cargo. Correspondingly to the pore water pressure evolution, this ratio reaches a certain stable state after a number of cycles.

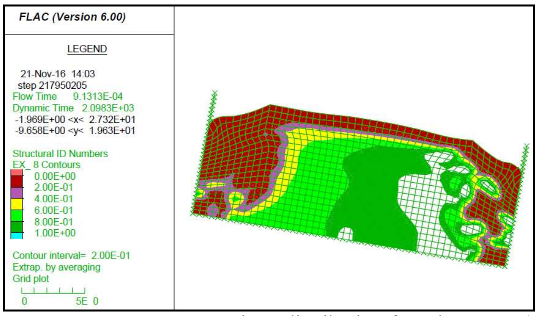

Figure 7. Pore-water pressure ratio r_u distribution for a loose ore (~300 cycles)

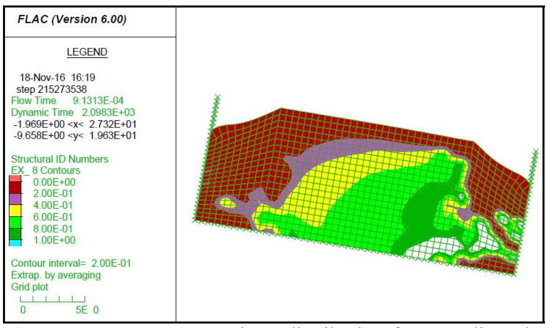

Figure 8. Pore-water pressure ratio r_u distribution for a medium dense ore (~300 cycles)

4 .2 *Slope effect*

The same simulations are conducted on a fully trimmed ore pile to assess the slope effect. The ore surface in this case tends to slightly settle but the geometry remains almost unchanged. This observation is confirmed by the distribution of plastic points illustrated in Figure 9 compared to those in Figure 10. However, when the cargo is horizontally trimmed, the liquefied areas (r_u >1, non colored areas) spread to reach the surface and the pile sides as shown in Figure 11.

The effect of limiting trimming to the ore natural angle of repose can therefore reduce the expansion of liquefaction since the liquefied areas remains localized and confined at the center of the cargo as presented in Figure 8.

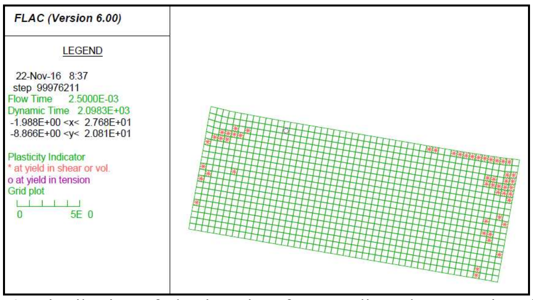

Figure 9. Distribution of plastic points for a medium dense ore in a fully trimmed ore pile (~300 cycles)

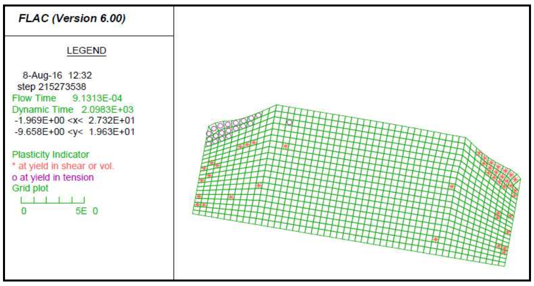

Figure 10. Distribution of plastic points for a medium dense ore (~300 cycles)

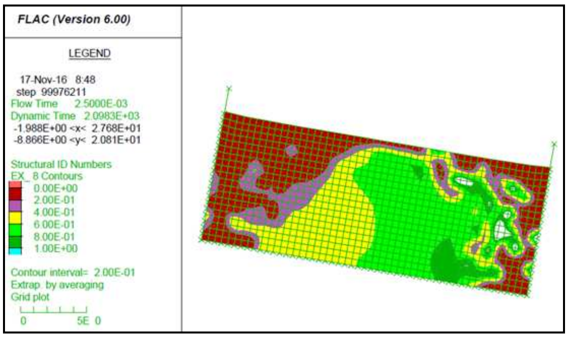

Figure 11. Pore-water pressure ratio r_u distribution for a medium dense ore in a fully trimmed ore pile (~300 cycles)

5 CONCLUSION

The present paper studied numerically the assessment of cargo liquefaction potential that can result from the swell effect. First, the calibration results show that the UBCSAND model can fairly predict the experimental results of a cyclic triaxial shear test. The major limitation of this model is the irregular evolution of excess pore water pressure or axial strain when the soil approaches the liquefied state.

Second, the conducted numerical simulations suggest that the slopes of the ore pile would incrementally flatten during the journey under the swell motions. In fact, there is a tendency to slide, in particular at the periphery and slopes that remained at the cargo surface after loading where the confining pressures are low. Whilst these incremental movements, which traduce a cyclic mobility phenomenon, may cause some instability to the cargo surface, it does not lead to large scale cargo shift required to cause ship instability. The central part of the cargo decreases slightly in height but doesn't experience any significant horizontal movement. The settlement of the ore pile depends on the number of cycles as well as the amplitude of the loads. These same observations were witnessed in the case of the maritime transport of iron ore fines (TWG marine report, 2013). Moreover, the pore water pressure ratio iso-values indicate that the ore is temporarily liquefied and/or dilates cyclically associated with the rolling. This is called cyclic mobility / softening and means the ore loses strength but recovers cyclically associated with the rolling of the ship. Since the liquefied areas are localized and concentrated, it is estimated that the ore carrier remains stable even after cargo liquefaction.

The evaluation of the relative density effect on the liquefaction potential of the shipped cargo proved that the denser a cargo is, the less prone to liquefaction it is. In fact, for dense ores, their tendency to dilate during cyclic shearing, generates negative pore water pressures and increases their resistance to shear stress.

Computations elaborated to assess the slope effect attest that an ore pile trimmed to his natural angle of repose is more resistant to liquefaction than a fully trimmed one. This may be due to the extent of drainage surface since it is more important along the slopes and also related to the existence of an initial cyclic ratio near the slopes (the anisotropic state of consolidation stabilizes the material with respect to the cyclic mobility phenomenon).

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