Coupled Granular Material and Vessel Motion in Regular Beam Seas

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ABSTRACT

The behaviour of granular cargos under the effect of ship motions has not been sufficiently studied and international regulations on bulky cargos' loading and stowage, despite their updating and improvement, remain empirical. In the current work we investigate the interplay of granular material flow with a vessel's motion. The method of molecular dynamics is employed for modelling granular material dynamics, combined with a standard model of ship rolling for regular beam seas. Dry granular materials, spherical particle approximation and non-linear frictional forces are the key assumptions in modelling the cargo's movement. Characteristic simulation results including comparisons against cases of rigid cargo are presented.

Keywords: *granular material, molecular dynamics, ship cargo shift, ship motion*

1. INTRODUCTION

The problem of cargo shift is one of the most important ship safety issues. The recent upgrading of international regulations concerning the loading and stowage of ship cargos in bulky form is based, almost entirely, on empirical considerations (IMO, 2012). Approaches with potential to establish a solid scientific basis for this problem, using micro-scale modelling of cargo particles' motion and their interaction with the moving ship under wind/wave excitations, are still lacking. A possible reason is because such modelling is very demanding and it calls for an interdisciplinary approach, overcoming the often fragmented nature of scientific efforts. As type of problem, cargo shift could be classified along with sloshing; with clear methodological analogies prevalent in particular when, for the latter, a smooth particles hydrodynamics (SPH) modelling approach is applied. As well known, coupled ship motions affected by liquid sloshing have been extensively studied in the past, since high impacting pressures on tank walls constitute a perennial operation hazard. Faltinsen & Timokha (2009) provided an in depth presentation of analytical and numerical models for the coupled fluid motion in a tank. Moreover, in Monaghan (2005) was included a review of commonly applied SPH techniques. When it comes to granular cargos however, the authors could not identify any research effort of similar standing. A category of interesting works have dealt, for example, with the dynamics of sloshing cargos in silo vehicles (e.g. Fleissner et al 2009). But they have not presumed any link to the ship motion problem.

A key element in the coupled roll-granular cargo problem formulation is the feedback from ensemble of discontinuously moving particles to the ship's body. Such abrupt particle movement is a characteristic of container-body motions receiving external excitations predominantly of low frequency, with some higher frequencies appearing in the excitation from time to time. Such sudden motion of the cargo constitutes the main contributing factor for a ship to acquire large roll bias, a state wherefrom capsize becomes imminent. In general, in terms of dynamics, the particles behave like oscillating masses interacting with each other and also, in unison, with the hold they are transported wherein. As a matter of fact, significant quantities of energy can be exchanged between the particles and the carrying body in a rather intermittent manner. These effects of interaction take the problem out of the convenient field of rigid body dynamics where ship stability studies are customarily performed.

In a line of research initiated at NTUA since 2011 to fill this gap, we have investigated already the excited motion of granular materials when the hold is subjected to series of prescribed oscillations. It was studied in particular the mechanism of formation of the cargo's angle of repose and associated phenomena (Spandonidis & Spyrou 2012 & 2013). In the current paper we take a step further, to study how the ship and the granular material behave, as a system, under the effect of wave excitation on the hull. Our intention is to understand how the coupling between material and ship works, in order to create a suitable tool for assessing the severity of such coupling effect. Although it is aimed to develop, in the longer run, a full ship motion model, at present we have restricted our study to regular beam sea waves in deep water, applied on a prism with rectangular cross section restrained to move only in roll.

2. ASPECTS OF THE BEHAVIOUR OF VIBRATED GRANULAR MATERIAL

As it is intended to combine a ship roll model with a suitable granular material flow model, in this part are reviewed briefly some aspects of their modelling and behaviour. General interest for the study of granular flows is inspired by their several industrial applications as well as by their complex rheological character. A granular material flow typically is comprised of a particulate solid in an interstitial fluid (usually air) subjected to a shearing force. In the most common granular material vibration experiments the considered materials are sand, grain or glass spheres (usually 0.5 – 3 mm diameter with standard deviation 5%). They are placed in a rectangular or cylindrical container mounted on a rigid base which is subjected to multi axial, sinusoidal oscillations. Even these simple systems can exhibit surprisingly complex behaviour that has yet to be fully explained. For example, the particle bed can behave as a "cloud" of particles with little or no structure; and in other cases the particle bed moves as a coherent mass. Depending on the frequency and amplitude of acceleration, vibrated granular materials can give rise to various phenomena such as compaction, convective flow, size segregation and “arching”. Particle rearrangements induced by vibrations lead to lower shear strength and higher ability to flow. In the full fluidization regime, there are no permanent contacts between particles and the system behaves as a dissipative gas. When particle accelerations remain below the gravitational acceleration, the system keeps its static nature and the vibrational energy propagates through a rather compact network of inter-particle contacts. On the other hand, vibrations at high frequency and low amplitude lead to slow (logarithmic) decay of the pore space as a function of time. Several theories trying to explain this behaviour have been proposed (e.g. Laroche et al. 1989; Gallas et al. 1992; Corwin et al. 2005); yet none seem to be universally accepted. Another phenomenon that is observed for deep beds is the formation of surface waves. The waves travel from the lowest point of the heap up the slope to the peak but do not interfere with the continuous avalanche of particles associated with the convection pattern. The waves increase in length and decrease in height as they travel up the slope and eventually disappear at the peak. The onset of the travelling surface waves depends on the vibration- amplitude-to-particle-diameter ratio. Standing surface waves form at half the excitation frequency for certain ranges of the excitation amplitude and frequency, following a mechanism similar to the Faraday instability (Douady & Fauve 1988; Miles & Henderson 1990).

3. EQUATION OF MOTION

The analysis is performed in model scale and a small rectangular hold is considered. It is placed inside a box barge that is allowed to be rotated in roll only, around a specific axis (1-DOF approach). That is, the roll centre is considered fixed (point *P* in Figure 1). Each particle's motion is monitored from another coordinate system, whose origin is placed at the hold's bottom left corner (*ZOY*). This coordinate system remains always horizontal (i.e. it does not follow vessel's rotation). System *yKz* is also placed at the bottom left corner; but it follows the motion of the hold in such a manner that its *z*-axis is always perpendicular to the bottom. The reference system *aPb* is assumed to be at the centre of rotation of the vessel (which in the current study coincides with the middle point of the ideal flat free surface). This coordinate system follows vessel's rotation.

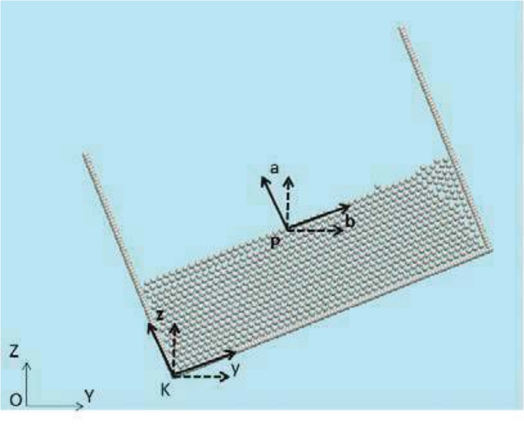


Figure 1 The three different coordinate systems (solid lines) and their irrotational equivalents (dashed lines) are being depicted.

In Figure 1 systems *yKz* and *aPb* are depicted with solid lines. In what follows, only the dynamics on the xy plane is under investigation due to the 2D nature of the developed granular material algorithm. Thus, the barge is assumed to be long enough (2 m) compared to her height (0.3 m) and beam (0.34 m). These dimensions should facilitate direct comparison with the results of experiments in the future.

Two different problems need to be tackled simultaneously: The wave induced ship motion and the motion of the granules inside the hold. On the basis of the so called "molecular dynamics" method we predict the trajectory of each individual particle, assumed to interact with all its neighbouring particles through non-linear elastic and frictional forces. "Molecular dynamics" is the most important among the simulation methods that have been used for granular flows. It involves solution of Newton's equation of motion for every particle. Normally to the line of contact of particle collisions we have considered nonlinear elastic and frictional forces; while transversely we have assumed acting a purely frictional force:

$$
\begin{aligned}
F_{nor} &= -k_n \xi^{3/2} - \gamma_n \xi^{1/2} \dot{\xi} \\
F_{\tan} &= -\min\left(\left|\gamma_s u_s\right|, \left|\mu F_n\right|\right) \cdot sign\left(u_s\right)
\end{aligned}
\qquad (1)
$$

γ_n and γ_s are normal and shear damping constants respectively; k_n is non-linear stiffness coefficient, u_s is the shear velocity component and μ stands for the dynamic friction coefficient (see Spandonidis & Spyrou 2012 for details). Collision forces are computed for each couple and at every time step. From them, the forces that act on the side plates of the hold are obtained.

Newton's equation for ship roll motion is also solved at each time step, with loads considered due to added moment of inertia, hydrodynamic damping, restoring, "Froude-Krylov" moment and the impacting moment due to possible particles' impact with hold's side walls. Vessel's roll motion can be described then by Eq. (2) which is solved in time, coupled with the nonlinear molecular dynamics model of the granular material:

$$\begin{aligned}(I+\delta I)\ddot{\varphi}+B_1\dot{\varphi}+B_2\dot{\varphi}\left|\dot{\varphi}\right|+M_R &= \\ = mg\,GM\,r\,Ak\cos\left(\omega t\right)+M_I\end{aligned} \qquad (2)$$

φ is the roll angle, I and δI are respectively the roll moment of inertial and the added moment of inertia, B_1 and B_2 are the linear and the quadratric roll damping coefficients. δI and B_1 were calculated with a linear BEM code while B_2 was taken as frequency independent. M_R is the restoring moment calculated as the sum of three moments (M_B due to buoyancy, M_S due to ship's weight and M_C due to cargo's weight) calculated around the fixed axis of rotation:

$$M_R = M_B + M_S + M_C \qquad (3)$$

Moreover, the impact moment M_I generated by the particles' contact with nonzero relative velocity with hold's walls is calculated.

In order to verify our results we performed reliability tests as proposed by Haile (1997). Different operating systems (Windows 8, Windows XP, Linux RedHat 5.1), hardware configuration and computational software (Microsoft Visual C++, Mathematica, Matlab) were used, in order to calculate the systemic error. Also, several repetitions were performed for each numerical experiment in order to check conservation principles and monitor the statistical error. The algorithm can provide accurate calculations with a statistical and systemic error whose deviation does not exceed 2%. Validation of the coupled motion results could not be done at this stage due to lack of suitable experimental measurements and we relied on separate validation of the two sub-algorithms. For the validation of the molecular dynamics algorithm see Spandonidis & Spyrou (2013). Concerning the ship motion equation, results for "empty hold" and for "hold with solid (frozen) cargo" were compared against similar experimental results obtained by Rogenbake & Faltinsen (2003) and by Murashige & Aihara (1998), indicating that the algorithm performs very well with a standard deviation less than 1%.

4. CASE STUDY

We assumed the hold filled with cellulose acetate particles of diameter 0.3 cm such that the particle parameters (friction, stiffness etc) coincide with these experimentally measured by Forester et al (1994). The draft with the material inside is (in initial position) 0.11 m. The material height-to- width-ratio is 0.36 which corresponds certainly to a "finite" material depth case. The vessel was free to move only in roll, with an external excitation owed to waves that were fixed in amplitude and frequency. Granules were considered as smooth spheres with diameters that could be either fixed or varied in some range and they could be translated (horizontally-vertically) or rotated. At this specific stage we assumed dry granules and the weight of the cargo equalled that of the vessel itself (even though this would not be the real case e.g. for a bulk-carrier). Several tests were performed before beginning the actual numerical experiments, in order to identify the critical parameters. At first step, the material was left to balance in calm water. In this way the draught of the barge and its initial roll angle were calculated for several slightly different initial free surface configurations. The eigenperiod of the barge lies within acceptable, for real case scenario, limits. In addition, following the tilting table method described in the International Maritime Solid Bulk Cargoes code -IMSBC (IMO 2012), we determined the critical angles leading to cargo shift. In Figure 2 is depicted the horizontal displacement of the centre of mass versus the tilting angle, for different tilting rates. As indicated, when relatively slow rates are applied (smaller than 1 rad/s) two angles with values close to 25 and 42 deg are identified.

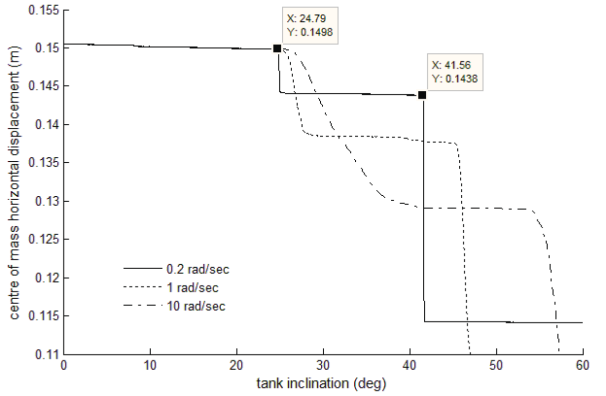


Figure 2 Center of mass displacements versus vessel inclination (the illustration is based on the zKy coordinate system).

The former is the angle where heap formation occurs; while the latter should be considered as the true angle of repose (Spandonidis & Spyrou, 2013). Moreover, it is shown that when a large enough tilting ratio is used, the cargo behaves in a slightly different way. In that case, the flow of the cargo is larger after the first critical value is reached.

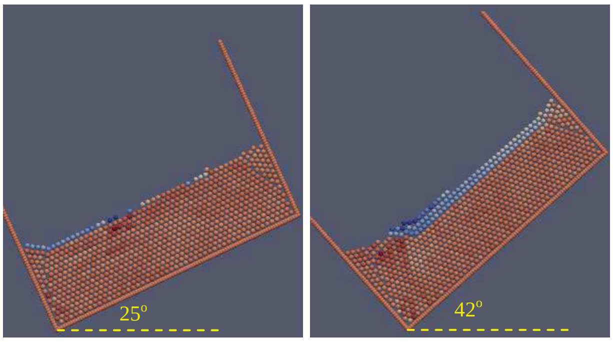
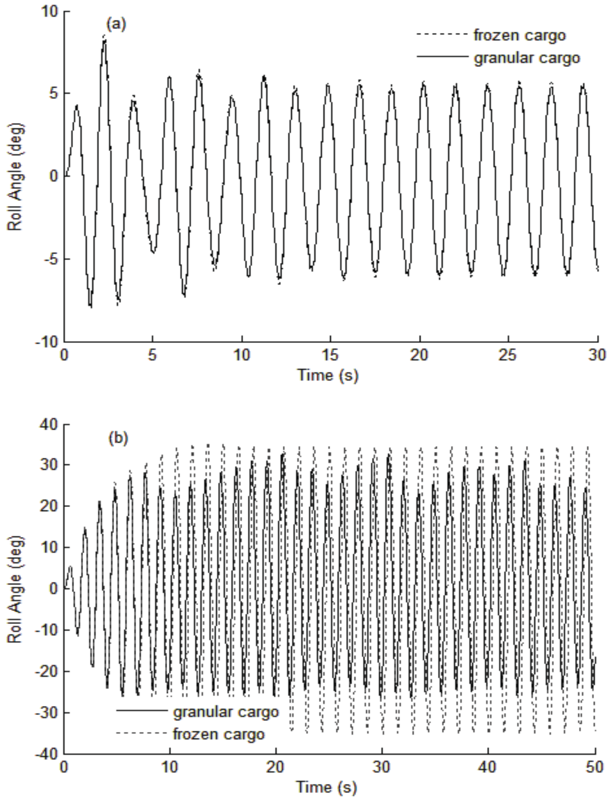


Figure 3 Time shots of inclined vessel when roll angle has a value of 25° (left) and 42° (right).

In Figure 3 is shown cargo's state inside the hold at specific time instants when critical angles are reached. Red colour is used when the particle has kinetic energy close to 0 and blue when it has clearly nonzero kinetic energy. In this way the percentage of material involved in cargo shift can be illustrated. Our main goal was the identification of critical parameters affecting system's dynamic response.

Two kinds of numerical experiments were performed. The first was basically a reference case and the vessel was loaded with *solid cargo*; that is cargo with the same weight and mass centre with the granular but without the ability to move. It was tested in several wave frequencies and amplitudes. Analysis of these results provided a good feeling of the most significant frequency region for further investigation. The second series involved tests with actual granular cargo. The wave frequency and amplitude region of interest were 2.3-6.5 rad/s and 0.005-0.025 m, respectively.

In Figure 4 are shown some examples of comparison of behaviour, for four different frequency values and wave amplitude fixed at 0.01m. The key findings are as follows:



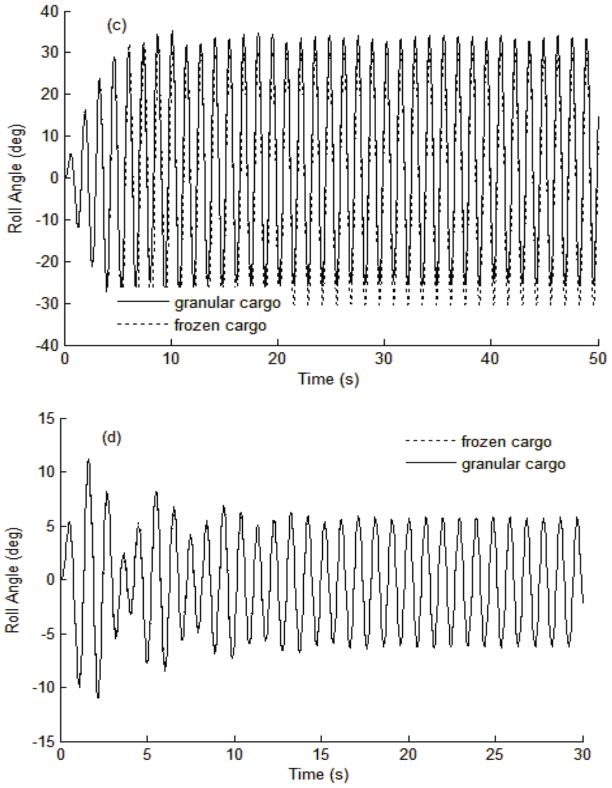


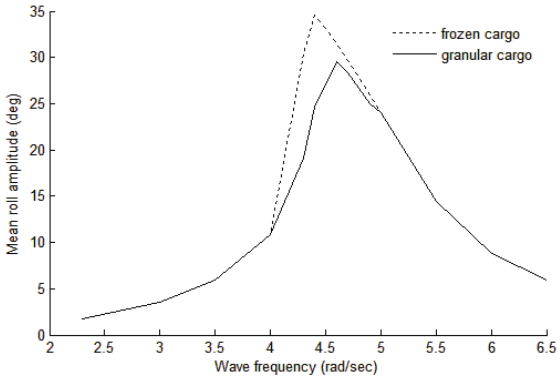
Figure 4 Comparison of response of frozen and granular cargo. The excitation amplitude s fixed at 0.01m and the frequency varies: a) 3.5 rad/s, b) 4.4 rad/s, c) 4.7 rad/s and d) 6.5rad/s.

a) For wave frequency values below 3.5 or above 6 rad/s, barge's response is limited (Fig. 4 (a) and (d)). After a short transient, she reaches a max roll angle less than 5 deg. The behaviour of the barge does not depend on whether she is frozen or with movable cargo (i.e. the granular material does not perform any substantial motion).

b) For wave frequency between 3.5 and 6 rad/s, the barge, in either condition, enters a resonant region. As shown in Figure 4b, the peak response amplitude for the case of frozen cargo appears at frequency 4.4 rad/s and a maximum roll angle about 36 deg is reached. The "unfrozen" system shows smaller response, mainly apparent after a frequency about 4 rad/s. The peak roll angle reached is less than 30 deg. The lower response is because the granular material reaches the first critical angle of heap formation which sets it in motion. As the phase of cargo's movement opposes that of the vessel, the overall motion becomes smaller. Calculation of moments indicates that, the moment due to cargo's mass centre, and not the impact moment, is the primary cause of this effect.

c) Further observation of Figure 4b produces two more, secondary, findings. Firstly, the motion of the vessel with the granular cargo has become asymmetrical. Local movement of cargo occurring around the one corner of the free surface, leads to lower absolute roll peak when the hold rotates clockwise. Secondly, for certain values of wave frequency, the steady-state is characterized by more than one frequency. As confirmed from Figs. 4b and 4d where the simulation was run for 50 s, this phenomenon is not transient but it is true long-term response.

d) Inside the resonant region and after a critical value of 4.7 rad/s the two systems present almost identical mean responses. Despite though their similar behaviour, the initial movement of the granular cargo during the transient stage leads to larger absolute roll amplitude. For the case of 4.7 rad/s (Fig. 4c) both systems oscillate with mean roll amplitude of 30 deg. But for the granular cargo, an almost 2 degree dynamic roll bias is incurred, generating a higher absolute roll peak. These findings are summarized in Fig.5.



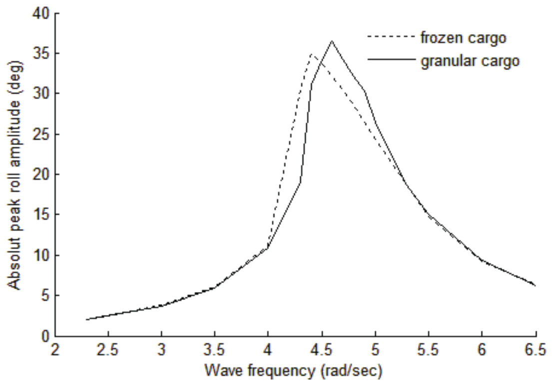
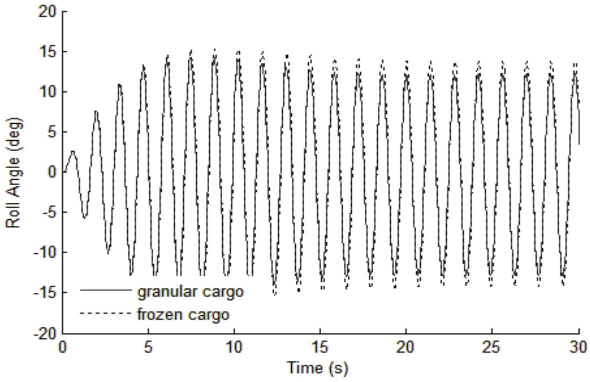


Figure 5 Mean roll amplitude (up) and absolute roll peak (down), for 0.01m excitation.

For wave amplitudes between 0.005 and 0.15 m, our simulations yielded that the behaviour remains qualitatively similar to that obtained for 0.01 m excitation.

In Figure 6 appear comparisons at the two ends of the investigated region of wave amplitude [0.005 m (up) and 0.015 m (down) - wave frequency, respectively, 4.5 and 4.3 rad/s]. Notably, for wave amplitude 0.015 m, the granular cargo case is associated with smaller response but with a “clear” second frequency existing in the steady state due to material’s displacement.



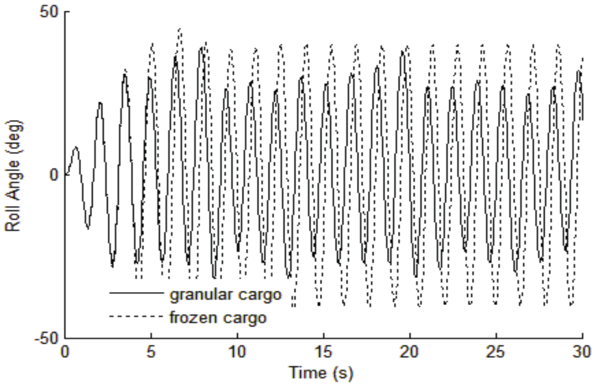


Figure 6 Comparison of response of solid and granular cargo: (up) excitation amplitude 0.005m and frequency 4.5 rad/s; (down) excitation 0.015m and frequency 4.3 rad/s.

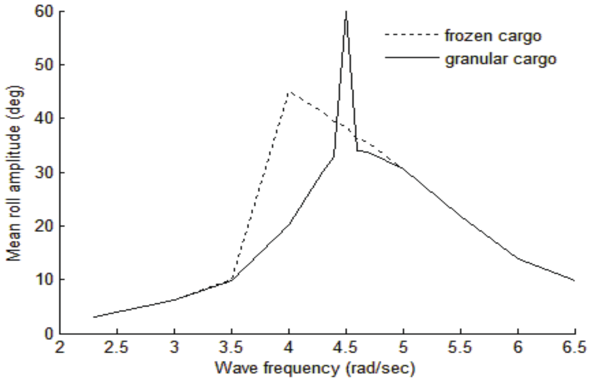


Figure 7 Mean roll amplitude for wave amplitude 0.017 m and frequency 4.3 rad/s

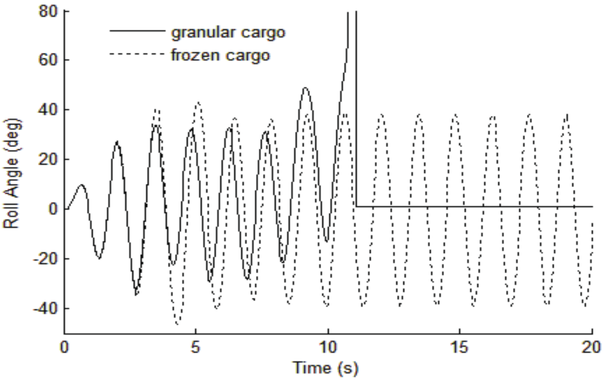


Figure 8 Comparison between frozen and granular cargo for wave amplitude 0.0017m and frequency 4.5 rad/s.

Further increase of the excitation leads however to a substantially different behaviour (Figure 7): for wave amplitude 0.017 m and frequency 4.5 deg/s, the material inside the hold moves in such a way that the barge cannot return towards the upright position and capsize is finally realized.

To investigate deeper this behaviour we considered the first seconds of motion. Figure 8 depicts in a comparative manner the 20 first seconds for the two systems. At about the 10th second, the barge with the granular cargo capsized. Whilst she initially behaved in a similar to the 0.01m wave amplitude case (that is, smaller mean roll angle and quasi-steady state response), suddenly a large peak value appeared (almost 45 deg). This is above the material's second critical angle associated with its angle of repose. In the ensuing cycle the roll angle grows further and capsize finally occurs. Visual inspection of the cargo inside the hold indicates that, that due to high acceleration, significant amount of material is displaced during the two roll cycles before capsize (Figure 9). Wave amplitudes larger than 0.02m generate qualitatively similar results for material's behaviour.

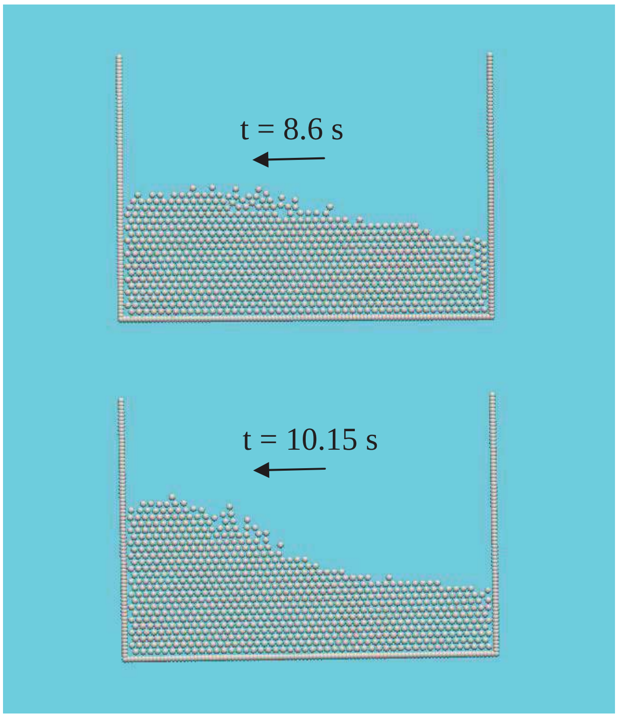


Figure 9 State of cargo inside the hold at two successive passages of the barge from the upright position: (up) seventh roll cycle; (down) 8th roll cycle in which capsize occurs. The arrow indicates the direction of motion (anti-clockwise).

5. CONCLUDING REMARKS

A step towards a systematic investigation of the coupled granular material-and-vessel-motion in regular beam seas, based on numerical procedures, was presented. The vessel was allowed to move only in roll direction performing thus a restricted 1 DOF motion. Several values of wave amplitude and frequency were applied on a scaled container containing spherically shaped particles of granular material in order to capture the response of the system. Special attention was given in the comparison of the results against corresponding cases where the cargo was treated as solid ("frozen").

These results indicated that, although the same resonant region occurs for both systems, in the case of granular cargo and for wave amplitudes below a certain limit, the motion of the system is smaller. This leads to a system that is even more stable that its frozen counterpart, even though it appears to have some difficulty in reaching steady state. For higher wave amplitudes a new region appears where the vessel due to her cargo's movement, shows larger response and in some cases it capsizes. An effort to analyse this behaviour revealed that, this is related with a shift of the roll resonance peak value.

A logical next step in our research would be the experimental examination of these results. In the meantime, several different numerical experiments are executed in a systematic way. Specifically, different material-height-to-hold-width ratios, constant wave steepness, more than one frequency wave packets, different material parameters and different vessel shapes are under study. Furthermore, dynamical analysis tools are being considered for capturing more rigorously vessel dynamics as influenced by the granular material's movement. It is remarked that, a further investigation based on a 3 DOF coupled motion is currently under verification /validation. Early results indicate some significant effects for higher frequencies.

6. ACKNOWLEDGMENTS

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