"LIQUEFACTION" AND "DYNAMIC SEPARATION" DIFFERENT ASPECTS OF THE SAME PROBLEM

(DOI No: 10.3940/rina.ijme.2019.a4.551)

S Ferauge, **W Jacobs** and **K De Baere**, Antwerp Maritime Academy, Belgium

SUMMARY

In 2015 the Bulk Jupiter sank during bad weather loaded with bauxite. Nearly automatically everybody considered "liquefaction" to be the prime cause of this accident. Liquefaction is a phenomenon where solid bulk cargo, triggered by the ship movements, starts to behave has a high density viscous liquid in the holds. The stability is negatively influenced by the free surface effect and further research, especially by the Global Bauxite Working Group or GBWG showed that bauxite ore simply will not liquefy even under the worst case shipping conditions. Evidence from real world shipments of bauxites shows that instabilities due to moisture cannot be explained by liquefaction phenomena, but can be under a "dynamic separation" mechanism of instability. Both liquefaction and dynamic separation are caused by an excessive moisture of the bauxite cargo. However, the influence on the stability of the ship is fundamentally different.

Dynamic Separation (GBWG, 2017)

NOMENCLATURE

B	Breath of the Free Surface (m)
GvZv	Righting arm of stability moment after free surface correction (m)
GZ	Righting arm of stability moment (m)
L	Length of the Free Surface (m)
A	Surface angle of repose (deg)
Θ	Angle of heel (deg)
AA1	Original liquid surface
AOR	Angle Of Repose
B	Centre of buoyancy
BCC	Bulk Carrier Code
BIMCO	Baltic and International Maritime Council
DNV-GL	Det Norske Veritas (DNV) - Germanischer Lloyd (GL)
FMP	Flow Moisture Point
FS	Free Surface Effect
G	Centre of gravity of the cargo
G	Centre of gravity of the ship
GBWG	Global Bauxite Working Group
Gv	Virtual centre of gravity of the ship
IMSBC	International maritime Solid Bulk Code
K	Keel
M	Metacentre
MC	Moisture Content
SOLAS	Safety Of Life At Sea
TML	Transportable Moisture Limit
TT1	Liquid surface after cargo shift
UK P&I	United Kingdom Protection & Indemnity Club
WL	Water Line

1. INTRODUCTION

1.1. THE NEW INTERNATIONAL MARITIME SOLID BULK CODE (2011)

On 1 January 2011, the Bulk Carrier code (BCC), governing the carriage of solid bulk cargoes by sea, was replaced by a new version, called the International Maritime Solid Bulk Code (IMSBC). This Code provides recommendations and rules for the loading, transport and unloading of dry bulk cargoes. IMSBC is updated every 2 years. The present IMSBC (2018), with important amendments regarding the liquefaction of coal, entered into force on the 1st of January 2019 and contains 14 sections giving general information, and 5 appendices, including one (Appendix 1) giving specific information related to the carriage of certain dry bulk cargoes(IMO, 2018).

Amongst many other amendments, the changes to Section 7, the liquefaction of bulk cargoes were awarded most attention. More specifically, the IMSBC code distinguishes 3 cargo groups. There are Group A cargoes, which present liquefaction hazards, Group B shipments, presenting chemical hazards (toxicity or flammability), and, finally, Group C cargoes, which pose no risk of liquefaction or any chemical hazards (IMO, 2018).

1.2. LIQUEFACTION

Physically, liquefaction is a phenomenon in which a soil-like material is abruptly transformed from a solid dry state to an almost fluid state when the moisture content surpasses the Transportable Moisture Limit or TML. TML is the maximum moisture content of a cargo that is considered safe for transportation in ships. It is calculated as 90% of the Flow Moisture Point (FMP) (Bureau Veritas, 2018).

Under the influence of the ship's movement, motions and vibrations, the cargo compacts and the space volume between the particles reduces, which causes the pore water pressure to rise, reducing the shear strength of the particles(Gouvernec, 2018). The total quantity of cargo in one or all of the holds starts to behave as a dense liquid and reduces the ship's stability by the free surface effect (see Figure 1). In the worst case the ship might even capsize (Lee, 2017).

1.3 TRANSPORTABLE MOISTURE LIMIT (TML)

Cargoes that have been identified as those 'which may liquefy' according the IMSBC code must have a signed certificate of moisture content provided by the shipper to the ship's master or his representative, including a signed certificate of the transportable moisture limit (TML) as required by Section 4, regulation 4.3.2 of the IMSBC Code.

The TML should be tested and certified according to one of three methods prescribed in the regulatory guidelines by a recognized laboratory.

Following SOLAS Chapter VI, Part A, Regulation 2(1) "The shipper shall provide the master or his representative with appropriate information on the cargo sufficiently in advance of loading…" and "Such information shall be in writing…".

The IMSBC Code, Section 4, Regulation 4.1.4: stipulates that "The various properties of a solid bulk cargo… shall be determined… in accordance with the test procedures approved by a competent authority in the country of origin…"

As required by the IMSBC Code, a certificate of moisture content must be provided by the shipper to the master stating the current moisture content with the interval between testing and loading being not more than seven days.

The master must satisfy himself that the moisture content of the cargo is not more than the transportable moisture limit. If the moisture content or MC of the cargo is smaller than the TML, loading may proceed.

The liquefaction of certain types of bulk cargo gave rise to concern with the shipping industry. BIMCO or the Baltic and International Maritime Council, representing the ship owners interest, developed on 25 July 2012 some new charter party clauses for use in time- and voyage charter parties which may involve the carriage of bulk cargoes such as nickel ore and iron ore fines which are at risk of liquefying (BIMCO, 2012).

2. LIQUEFYING CARGO AND THE STABILITY OF BULK CARRIERS

Some more details regarding the stability of bulk carriers carrying liquefying cargo are provided below.

WL: Water Line
M: Metacentre
G: Centre of gravity of the ship
Gv: Virtual centre of gravity of the ship
K: Keel
g: centre of gravity cargo
GZ: righting arm of stability moment
G_vZ_v: righting arm of stability moment after free surface correction
B: Centre of buoyancy
AA_1: Original liquid surface
TT_1: Liquid surface after cargo shift

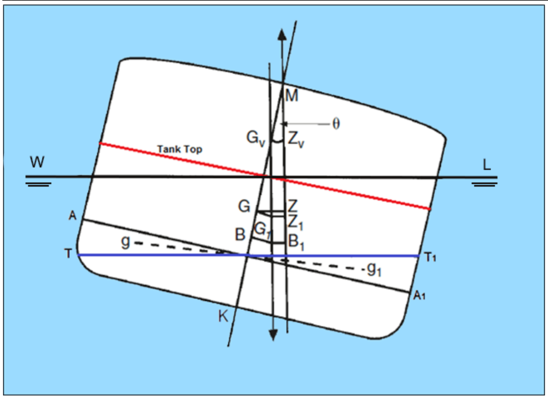

Figure 1. The free surface effect

GZ is the righting arm of the stability moment that brings a ship back to its original position when inclined by an external force. The GZ is reduced to G_vZ_v due to the presence of free moving masses on board. This effect is called the free surface effect (FS) (Figure 1).

The magnitude of this free surface effect on the GZ curve can be formulated as follows:

$$\delta\, G_v = \frac{\rho\, \Sigma LB^3}{12\Delta} \tan\alpha \tag{1}$$

G_v is the virtual center of gravity, ρ is the cargo bulk density (t/m³), Δ is the ship's loaded displacement (t), L is the length of the free surface (m), B breath of the free surface (m) and $\Sigma LB^3/12$ = total volumetric heeling moment of the cargo free surface (m⁴). α is the surface angle of repose, or for cargo that is transported above the safe TML α = 20° (Clarck, 2008).

The result is a serious reduction of the righting arm of the stability moment,

$$GZ = G_0Z - \delta G_v \sin\theta \tag{2}$$

Where G_0Z is the initial GZ, and θ is the angle of heel.

3. DYNAMIC SEPARATION

3.1 THE ACCIDENT OF THE BULK JUPITER

Recently, some very serious bulk carrier accidents revealed that there is more at hand than the "liquefaction" of dry bulk cargoes.

On 2 January 2015, the Bulk Jupiter encountered very bad weather and sank off the coast of Vũng Tàu, Vietnam. She had departed from Kuantan, Malaysia on 30 December 2014 with a cargo of 46,400 tons, evenly distributed on board within all five hold.

Figure 2. The Bulk Jupiter (shipspotting, 2018)

The "Bulk Jupiter" was loaded with bauxite, a sedimentary rock with a relatively high aluminum content. (Bahamas Maritime Authorities, 2015) Bauxite is the world's main source of aluminum. Like iron ore fines and nickel laterite, it is a mineral ore which is simply mined and shipped with little or no processing. As a consequence, the material contains a broad range of particle sizes ranging from very fine powder all the way up to quite large rocks, although the proportion of fine material and coarse lumps varies depending on the source (Miller, Crouch, & Bell, 2015).

3.2 DYNAMIC SEPARATION

Since the water tightness of the bulk carrier was not affected the most obvious explanation for the foundering of the ship would be liquefaction of the cargo. However, this turns out to be impossible for two reasons.

Firstly, stability calculations tell us that even if the cargo in all of the holds had liquefied, the final stability condition of the ship would still have been sufficient to withstand the bad weather conditions during the accident. The sinking of m/v Bulk Jupiter was also associated with certain phenomena that could not be explained by a "simple" reduction of GZ, the righting lever. The crew noticed an atypical rolling behavior of the ship, soon followed by a permanent list increasing in time. When the list reached 15° or more the ship capsized in a matter of minutes. (ClassNK, 2018).

Secondly, as proven by Menkiti and Evans (2017), bauxite ore simply will not liquefy even under the worst case shipping conditions.

Figure 3 has on the vertical axis the CSR or Cyclic Stress Ratio, which is the ratio of the axial deviator stress to the sample confining stress in cyclic tri-axial testing and on the horizontal axis the number of cycles. CSR has been simulated for a Handymax Bulk carrier on 4 typical bulk carrier voyages.

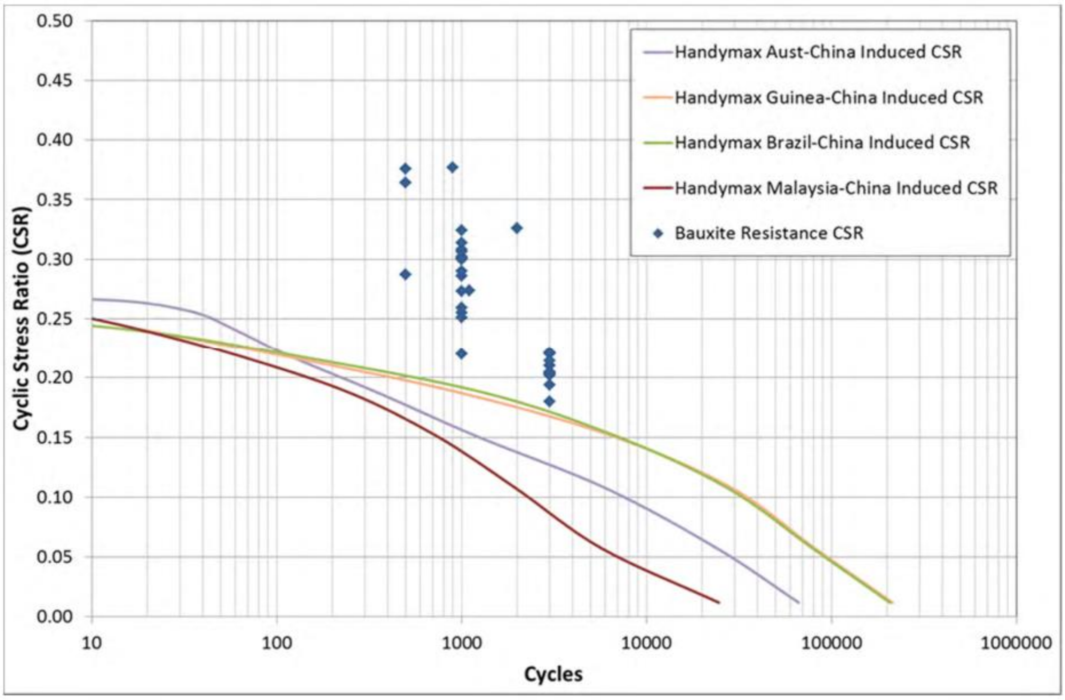

Figure 3. Bauxite Resistance to Liquefaction (Menkiti & Evans, 2017)

Previous tests by Menkiti & Evans indicated that Handymax vessels induce the largest forces in the cargo as they roll and pitch more when compared to other bulk carrier types.

To evaluate the risk of liquefaction, the load induced by the cyclic motions of the ship such as rolling, pitching and slamming is expressed in terms of induced cyclic shear stress (colored full lines on the graph) and this is compared with the liquefaction resistance (Resistance Cyclic Stress Ratio) of the bauxite cargo (blue diamonds). For all the test conducted the Induced Cyclic resistance Ratio is smaller than the Resistance Cyclic Stress Ratio and liquefaction will never occur.

Evidence from real world shipments of bauxites shows that instabilities due to moisture cannot be explained by liquefaction phenomena, but can be under a "dynamic separation" mechanism of instability.

An in-depth study was carried out by a group of experts called Global Bauxite Working Group or GBWG. This study showed that certain types of bauxite cargoes with a large proportion of smaller particles could be subject to a newly-identified phenomenon, known as "dynamic separation", when there is excess moisture in the cargo.

In response to this study, the IMO published (on September 20, 2017) its circular CCC.1/Circ.2/Rev.1, stating that certain bauxite cargoes should be treated as Group A cargoes (cargoes which may liquefy).

This new group of bauxite cargo will be known under the name of "Bauxite Fines". In the same circular a new test procedure for determining the TML for bauxite and amendments to the individual schedule for Bauxite of Group C were established. IMSBC will be adapted and the date for entry into force of these draft amendments to the IMBSC Code is expected to be 1 January 2021.
Ships carrying bauxite (or other mineral ores) have an important initial static stability. An excessive GM value results in shorter rolling periods and high accelerations which may trigger liquefaction (DNV-GL, 2015). The moisture is likely to migrate downwards, resulting in an increasing moisture level towards the bottom of the hold. During the voyage, the vibrations and movements of the ship will also trigger the migration of fine particles to the bottom of the hold, leading at the same time to a compaction of the cargo and an increase of the cohesive forces. This compaction will hamper the drainage of the humidity by the ship's bilge system. (Australian Governement, 2018)

This stratification will result is an unstable lower part of the cargo. The increased portion of fines and the high humidity will increase the risk of sliding of the cargo.

The behavior of this lower part is governed by the angle of repose (AOR). The angle (see Figure 4) of repose is the steepest slope of the unconfined material, measured from the horizontal plane on which the material can be heaped without collapsing.

If the stratification occurs parallel to the hold bottom, this lower part of the cargo will shift to one side when the rolling angle of the ship to port or starboard is greater than the angle of repose as shown in the upper part of Figure 5 (dynamic separation). When this happens, a permanent list is created and this may eventually lead to the capsizing of the ship.

Figure 4. Angle of repose

The AOR is a characteristic related to interparticular friction or resistance to movement between particles.

However, the AOR is a complex function of many parameters. Particle size and shape, granulation, density, pressure, surface area, cohesion, moisture content and the material's coefficient of friction all play a role when determining its value. DNV-GL points out that the same cargo might be unstable when the humidity is high or low but is stable at average moisture levels (DNV-GL, 2015). Literature study shows that the AOR of bauxite varies between 20 and 44° (RKM, 2016). The Bulk Jupiter, at the time of the accident, was sailing the leftover of a tropical storm. Wave heights of 6 meters and wind speeds up to 35 knots were reported. The chief cook, the only survivor, mentioned heavy rolling and pitching.

The granulation and humidity of each shipment of bauxite is different and unknown. The Australian Maritime Safety Authority (Australian Governement, 2018), Miller et al. (2015) and Lie et al. (2017) suggest that during handling, loading and the carriage of the bauxite ore a vertical and horizontal stratification occurs in function of the lump size. As such, the angle of repose is not a uniform value but will vary throughout the cargo in function of the height, time after loading and the movements of the ship at sea. Prediction of the behavior of each layer becomes difficult if not impossible.

3.3 DYNAMIC SEPARATION AND LIQUEFACTION COMPARED

Both "Liquefaction" and "Dynamic Separation" are thus caused by excess humidity in the cargo, beyond the TML. However, the further physical manifestation differs markedly (Figure 5).

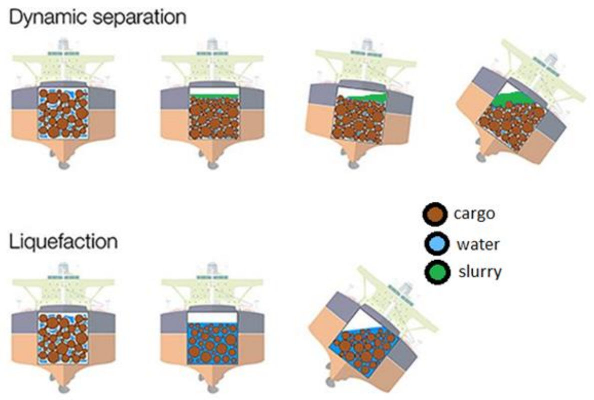

Figure 5. Liquefaction versus dynamic separation (Australian Governement, 2018) (Australian Maritime Safety Authority, 2017)

The liquefaction part shows that the complete cargo quantity starts to behave as a high-density liquid, moving in synchrony with the rolling movement of the ship and compromising the stability due to the free surface effect.

If, however, the cargo is composed of different grain sizes (more than 30% of fine particles less than 1 mm and more than 40% of particles less than 2.5mm (both)) (IMO, 2017), the smaller sizes will migrate during loading and carriage to the bottom and impede normal drainage of the cargo. The increased moisture content in the lower parts will reduce the angle of repose.

At the surface of the cargo a slurry (green in the top part of Figure 5) will start to form. Free water will be pushed upwards due to moisture migration, particle rearrangement and compactation (Rose, 2014) and mix with cargo particles. This slurry will behave as a high viscosity mixture such as wet concrete. The bulk of the cargo underneath the slurry layer remains undisturbed.

As a consequence of the rolling and pitching movements of the ship the slurry accumulates on the low side and the free slurry surface causes vessel to develop list or heel. This list will gradually increase as the slurry increases in mass and density as more particles are entrained in the liquid and are deposited to the lower end of the hold.

The sloshing of the slurry will erode the solid cargo beneath, further increasing the list. When the list becomes bigger than the angle of repose (AOR), the lower part of the cargo will suddenly shift to one side and eventually cause the ship to capsize.

The scenario above fully corresponds with the atypical ship motion observed by the crew (ClassNK, 2018). This wobbling is caused by the movement of a free surface slurry over the top of the cargo which is out of phase with the roll period of the ship.

To gain further insight into the stability behavior of a ship loaded with bauxite, we set up a simulation, using equation 2. The ship used is a bulk carrier similar to the Bulk Jupiter, loaded in the same way.

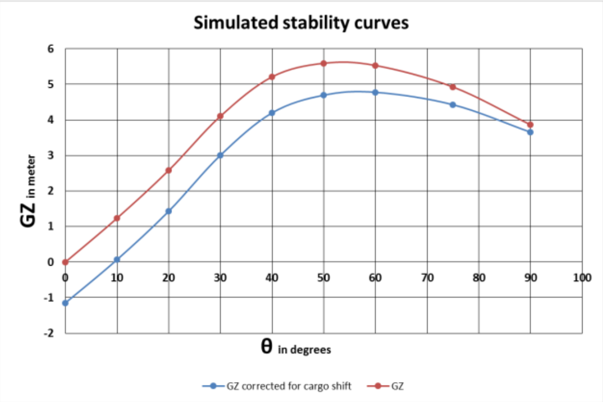

Figure 6. The virtual rise and horizontal shift of G and the consequently decrease of the righting arm GZ, as a result of cargo shift. GZ in m & θ in degrees

Figure 6 shows the red original GZ-curve of our model ship with an initial GM of 7.04m. Given the remarks formulated by Menkiti & Evans, the free surface effect is negligible. Due to a sliding of the bauxite cargo in all five of the cargo holds, the GZ value is reduced to the blue curve, which shows the simulated GZ value after a cargo shift of in total 4400 tons. This correction is calculated on the dimensions of the holds (approx. 28x24m) of our model ship, with a cargo density of 1.5 ton/m and a displacement of 59718 t.

A permanent list of 10° (intersection with the horizontal axis) developed. This is an unsafe situation because after the next wave this permanent list will increase. For ships with a sufficient stability, this build up in list will gradually decrease since the righting lever GZ increases with angle of heel θ. The shifting of the cargo will not necessarily cause capsizing. On the contrary, when the stability of the ship is insufficient, the ship will heel further than the maximum GZ value, the heeling moment caused by the shift of cargo will become greater than the righting moment and in a short period of time the ship will founder.

The dynamic stability (work done by the righting moment) of the ship is represented by the area under the GZ curves. In heeled condition (blue curve), the dynamic stability is drastically decreased. In bad weather, where rolling angles are already significant, this reduced dynamical stability will result in even larger angles causing further sliding of the cargo. Hence, whenever confronted with liquefaction/sliding on board, it is of the utmost importance to avoid regions with bad weather.

4. CONCLUSION: HOW TO AVOID?

The captain and crew can avoid this awkward situation by careful monitoring of the cargo when loading. If in doubt, a simple "can test" can give an indication of the real humidity content of the cargo. This so called 'can test' is exactly what it says: put some cargo in a can, bang it on the ground for a minute and see if the contents start to flow.

Figure 7. A « negative » can test with moisture at the surface (Spencer & Tilsley, 2011)

If the result of the "can test" shows a high moisture content, loading should be stopped, a Letter of Protest issued, P&I club advised and a more thorough lab test requested.

The process of liquefaction and dynamic separation can be prevented by ensuring that the bauxite has a limited content of fines and moisture content, as both particle size distribution and moisture content are the main parameters for the occurrence of this phenomenon (Russell, 2017).

The effects of dynamic separation cannot be ignored in the field, especially because the physical characteristics of bauxite ore have lately been changing for the worse. For technical reasons, the end receivers of the bauxite ore require to receive a product that consists of smaller lumps. This has resulted in some mines sieving the ore to remove the >100 mm fraction, an operation which can involve washing the ore with high power water jets through a rotary sieve to produce both bauxite fines and coarser material. Inevitably the moisture content of the cargo is increased (Miller, Crouch, & Bell, 2015).

The crew should keep a close watch for the presence of cargo splatter marks on the bulkheads, shell plating and hatch coamings as these can only arise because of transient liquefaction of the cargo as it is being dropped onto the developing cargo stow in the holds. The presence of such marks indicates that portions of the cargo loaded have a moisture content in excess of TML. In addition, the crew should check for accumulation or pooling of water around the periphery of the stow as this may indicate that the cargo is saturated.

At sea, if one feels that the rolling movement of the ship is not regular but "wobbling", this should be considered as the first indication that there is something wrong with the cargo (Russell, 2017; IMO, 2017).

The movements of the ship can be softened by adjusting speed and heading. The stability and consequently the ship reaction to an external force can be adjusted by changing the ballast condition of the ship.

Liquefaction and dynamic separation are two sicknesses with one cure. The effective moisture content of the cargo to be loaded should be below the TML. Captain and crew must maximize their effort to verify this. Very often being attentive during loading in addition to a simple test in case of doubt can avoid serious and potentially life threatening danger."

Due diligence" – two small words –should, of course, never be neglected.

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