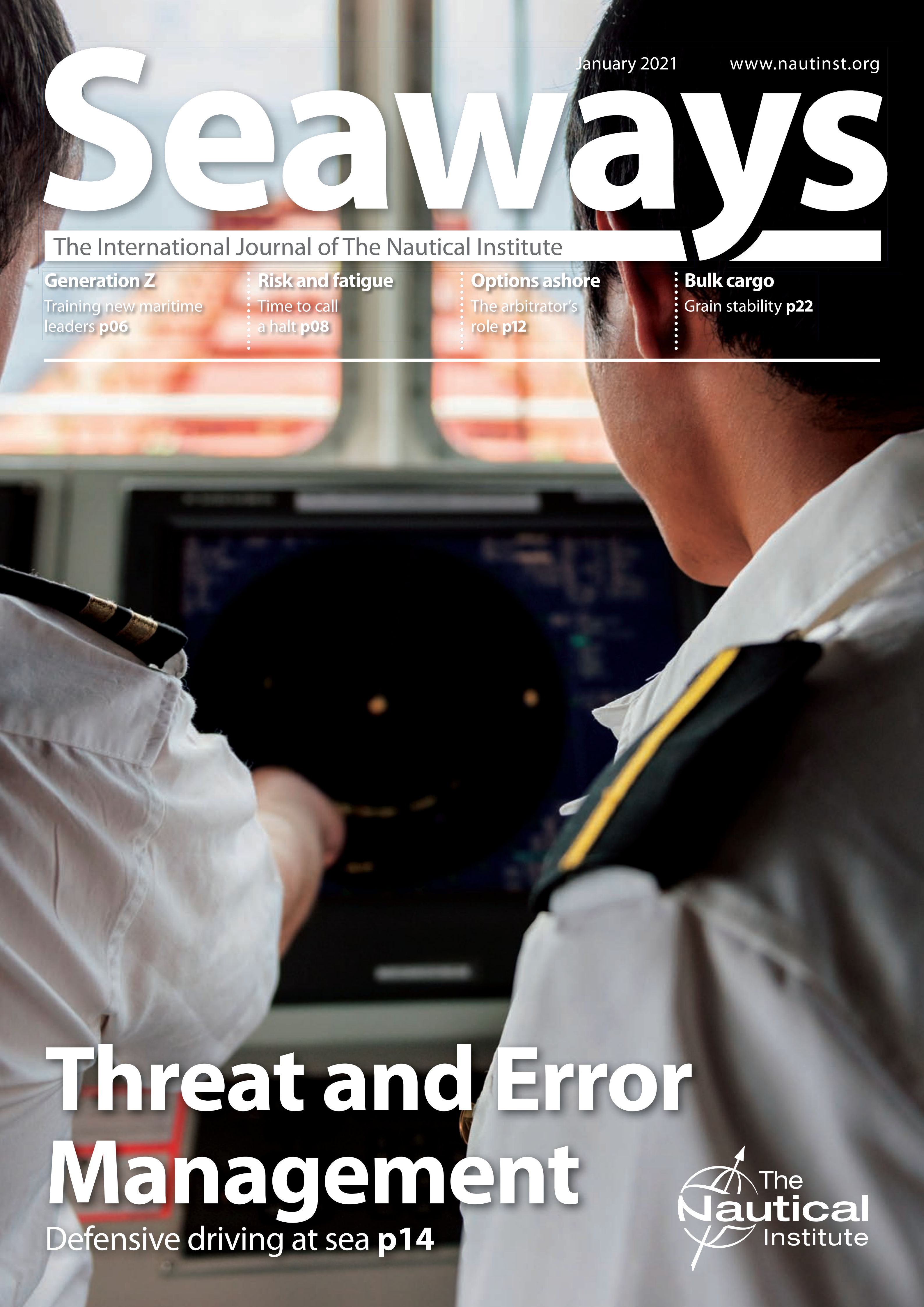

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Seaways

The International Journal of The Nautical Institute

Threat and Error Management

Defensive driving at sea **p14**

The Nautical Institute

Understanding grain stability

Slack holds, heeling moments and stability

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In the summer of 2020, the Master of a vessel chartered for a trip from Europe to Africa with grain products received a message from the harbour master at the loading port with a number of requirements. Among them:
'It is highly recommended to make loading with slack holds qnty which isn't exceed noted in grain booklet. Usually for 5 holds vessel 2 slack holds are permitted. If more it must be confirmed by same case in a grain loading booklet.'

This was not the first time that such a requirement has been heard of. In the past, agencies in charge of verifying compliance with stability criteria have demanded that loading conditions be proved against the stability or grain book.

Fortunately, the loading plan only had two slack (partially filled) holds, but the message raised a valid question. What if the plan called for more than two slack holds, and what if this was not reflected in the grain loading book?

The International Grain Code

To answer these questions, let's first look at the rules governing the carriage of grain:

Part A, reg 7 of the International Grain Code lists the minimum stability requirements for the carriage of grain as follows:

1 The angle of heel after the shifting of the grain not to exceed 12°.
2 The area of residual stability in the static diagram not to be less than 0.075.
3 The initial GM not to be less than 30cm.

The graph below represents the minimum stability requirement:

The area of the curve results from integrating the values of ordinate Y = GZ – λ, for a known interval of angle of heel between 12° and 40°.

GZ (righting arm) = KN – KG sin θ

and

$$\lambda \text{ (upsetting arm)} = \frac{\text{Transversal heeling moment}}{\text{Displacement}}$$

The value of angle of heel results from:

$$\text{Tan } \theta \text{ (angle of heel)} = \frac{\text{Transversal heeling moment}}{\text{Displacement} \times \text{GM}} \, x \; 57.3$$

GM (hydrostatic curves) and KN (cross curves) are a function of the displacement.

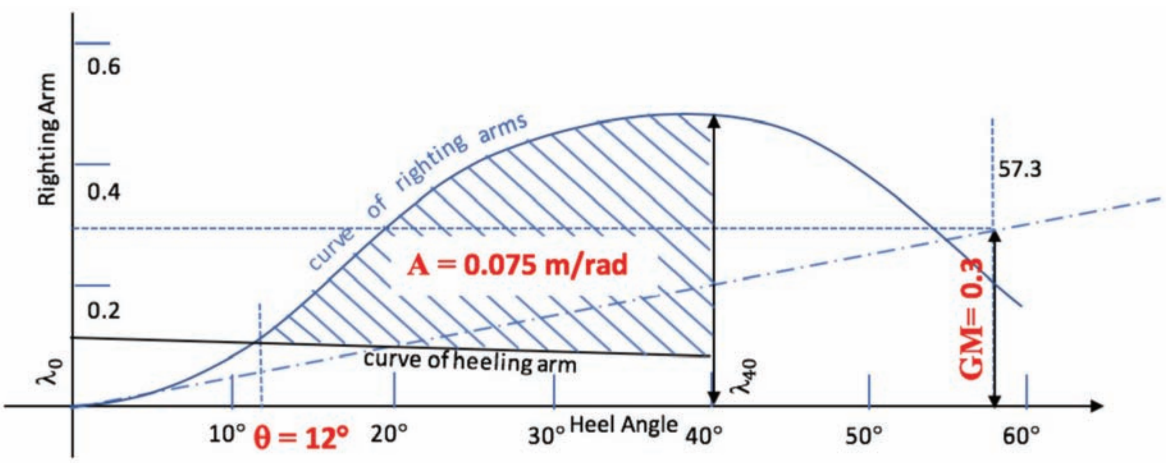
A value of transversal heeling moment that satisfies the minimum criteria is called the allowable heeling moment. This is tabulated for pre-set values of displacement (or mean draught) and KG. In practical terms, the grain stability survey comes down to comparing the actual transversal heeling moment resulting from the shifting of the grain with the allowable heeling moment – as can be seen in the ship's allowable heeling moments table.

It is well understood that the amount of slack holds should be reduced to a minimum, but nowhere in the Code is the amount of slack holds stated as a criterion.

Regulation 6.3.6 of the International Grain Code states that the information which shall be approved by the Administration shall include:

6.3.6 – *Typical loaded service departure and arrival conditions and where necessary intermediate worst service condition (recommended that such conditions be provided for three stowage factors).*

That does not mean that the manual should include every possible load condition – the list would be endless. Nor does it mean that a plan has to be reflected in the typical conditions included in the manual in order to be valid.



The documentation on board should be complete enough to show that the vessel meets all the intact and grain stability criteria for a specific loading plan (as well as longitudinal strength and hold mass criteria), including:

- Tables or curves of volumetric heeling moments for holds
- Tables of allowable heeling moments
- Tables of curves of minimum and maximum hold mass for single and adjacent holds
- The class-approved loading instrument.

Technicalities aside, the message quoted at the beginning of the article reflects a lack of understanding of the assessment of grain stability and how the results of the calculations should be construed.

Understanding grain carriage and stability

It is important for shipmasters and officers to understand the information contained in the grain booklet and the physical meaning of the grain calculation results.

Holds loaded with grain can be slack, full untrimmed, full trimmed (manually or mechanically) and full self-trimmed (vessels with fore and aft upper stools). The empty volume of a slack hold allows the grain to flow freely and shift from one side to the other.

However, regardless of how the hold is loaded, all methods have the potential for grain to shift. Full untrimmed holds will become slack while in passage as the motion and vibration of the sea and the engine cause the grain to settle into void spaces fore and aft behind the hatch coaming vertical strakes. Even trimmed or self-trimmed full holds will have small cavities and intricate spaces into which the grain can shift.

Because grain is non-cohesive, if the angle of the roll exceeds the angle of repose of the grain, or if the rolling carries enough energy to overcome the internal friction of the grain even at smaller angles (Biran, 2003), the grain may start flowing freely from one side to the other.

I have carried out experimental tests with a model cargo hold filled with grain and suspended on an oscillating mechanism. The results showed that oscillations close to the angle of repose at small frequencies of balance or rolling periods can cause the grain to shift slightly to both sides without resulting in a permanent list. Oscillations with longer frequencies can cause global shifting to one side.

When global shifting occurs, the centre of gravity of the mass of grain will displace transversally, creating a heeling moment. That moment, like any moment in physics, is proportional to the distance or arm and the physical quantity (volume, weight etc). The volumetric moment is calculated by multiplying that moment by the length of the compartment. The International Grain Code has specific rules and tables for calculating the depth of the void in filled compartments (the depth in partially filled compartments is the ullage) and the heeling moments based on 25° slope and 15° slope for trunks and spaces of limited void transverse area.

The amount of heeling moment depends on the volume of grain and the breadth of the space available for it to shift in – so the geometry of the cargo hold is a defining factor. This suggests that not every slack hold will have the same heeling moments. Smaller holds or tapered holds of smaller breadth compared with square holds will have smaller heeling moments.

A hold that is almost empty will contain less volume of grain and thus have less heeling moment than the same hold loaded to about half its capacity. The same applies to a hold loaded almost to full capacity. Here, the volume is greater, but as the surface of the grain is constrained by the narrow hatch coaming, there is less breadth, so the heeling moment will be smaller than in the same hold loaded to half capacity. In short, two almost empty holds may produce less heeling moment than one half-full hold.

Accordingly, the five-hold vessel quoted in the statement may be loaded with holds 1 and 5 (tapered holds with less breadth) and No 3 almost empty (less volume of grain), giving a total of three slack holds, and be in a better stability condition than if loaded with holds 2 and 4 filled at 50%, giving a total of two slack holds. If properly loaded, even a vessel with more than three slack holds can pass grain stability requirements.

Overall grain stability is calculated by comparing the amount of heeling moments for all holds loaded with grain, assuming the grain has shifted, with the maximum allowable heeling moment.

If the maximum allowable heeling moment is greater than total amount of heeling moments once the grain has shifted, the vessel will still meet the stability criteria even with shifted cargo – that is, it will have a permanent angle of heel not greater than 12°, and fluid GM not lesser than 0.3 metres and an area of residual stability under the curve, not less than 0.075 m/rad.

With this in mind, we can answer some questions:

Is the number of slack holds the most important factor to consider when loading grain and assessing the stability?

No. The most important factor is that the maximum heeling moment should be as low as possible. If a loading plan with more slack holds results in a smaller heeling moment, as in the example above, this is the loading plan that should be chosen. If the data show that one big central cargo hold loaded to around half its volume carries more heeling moment in case of shifting than two smaller tapered-end holds almost empty, then the risk of a shift of grain leading to a permanent list are greater with that single slack hold.

Of course, some loading plans do have unnecessary slack holds, and this should be avoided. The plan should always strive for maximum stability performance – that is, the greatest possible margin between the allowable heeling moment and the actual transversal heeling moment. That is the criterion to meet.

Does the number of slack holds affect how much or how little the grain shifts?

No. The shifting of the grain will depend on:

- The extent of any rolling (angle of heel reached)
- The frequency or period of rolling
- The properties of the grain (granulometry, humidity etc)
- To some extent the geometry of the compartment, internal longitudinal members close to the surface of the grain etc.

Any hold loaded with grain, even if full, has the potential for cargo to shift if the conditions of large frequencies and angles of roll and smaller internal friction are met.

Does meeting the grain stability criteria mean that the grain will not shift?

No. It means that if the grain does shift, the permanent angle of list will not exceed 12°, that the GM is greater than 0.30 metres and that the area of residual stability under the static curve will exceed 0.075 rad/m, and therefore the vessel meets the minimum stability requirements as set out by the International Grain Code.

Does meeting the grain stability criteria mean the vessel is safe against capsizing?

Again, no. Meeting the grain criteria, like meeting the intact stability criteria, does not prevent capsizing, which is a complex phenomenon. One Grain Code criterion is that after the whole cargo has shifted, the maximum angle of permanent list is 12°, which is still manageable. However, consider that when rolling, the permanent angle of list is now the position of equilibrium (as seen in *MV Modern Express* listing 40° in the North Atlantic in 2016). The oscillations will add to the permanent list, and there is a risk that they may reach the angle of flooding. Another criterion is that the fluid GM is not less than 0.3 metres, to prevent the vessel from being in a situation of negative equilibrium and an angle of loll adding to the permanent heel.

Curve of residual stability – some questions

The other criterion is that the area of the curve of residual stability must not be less than 0.075 m/rad. This area represents the energy the vessel has in storage for returning to the upright position after rolling. Bear in mind, however, that the grain criteria were set out before the entry into force of the Intact Stability Code. The ISC has its own criterion with respect to the area of the curve (0.055 m/rad for angle of heel up to 30° and 0.09 m/rad for angle of heel up to 40°), but there is no verification for how the vessel complies with the ISC if the grain shifts. In other words, if the vessel is subjected to a sustained beam wind while having a permanent list of 12°, would the new list exceed 16°? Or would the area under the curve of GZ to the new upsetting arm curve or lever resulting from the grain upsetting moment lA–B plus the wind upsetting lever lw2 (new area b) be larger than the area a of wind and rolling?

Or what if the vessel, already with a permanent list after the grain has shifted, encounters any of the models of failure described in the second generation of intact stability: dead ship, pure loss of stability, parametric rolling or broaching, which can cause even an upright vessel to capsize?

In normal operating conditions, Masters should exercise caution during severe weather and rolling in order to prevent capsize. In the case of the grain shifting, such caution is *essential* and should include changing course and speed as needed to mitigate the balance and ship motions.

All this will seem obvious to many readers, but some approaches to grain stability assessment suggest they may not be to everybody. Many stability plans are made giving preference to partially filling central fuller-shaped holds rather than end-tapered holds, or with holds left slack for no apparent reason. Sometimes, calculations show that that plan will result in very marginal compliance without regard to the fact that the stowage factor when loading will not exactly match the one used for calculations, and the mismatch may result in non-compliance. Sometimes, the plan ignores the many resources available to improve the grain margin, like using ballast in double-bottom tanks. Some calculations are done using untrimmed volume when not planning for trimming ends, giving false capacities.

Detailed explanations on the calculation and assessment of grain stability, can be found in *General Information for Grain Loading* from the National Cargo Bureau Inc.