Uncertainty in ship stability

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Recent high-profile incidents have unfortunately brought uncertainty regarding ship safety in terms of ship initial stability into the public eye.

One of the most tragic recent incidents due to insufficient initial stability, namely transverse metacentric height (GM_T), involved the 1994 built, 145.6m, 6,835GT, ferry *MS Sewol*. On the morning of 16 April 2014, whilst approaching her destination of Jeju, South Korea, with 476 passengers onboard, she rapidly developed a 22deg port list after executing a starboard turn. As a result, cargo shifted and she began to down-flood through the side cargo and stern vehicle doors. Within approximately 10 minutes she was heeling to 30deg and sank 3 hours later. Even though she was within a mile of land, 304 passengers and crew perished, many of them school children. It was subsequently estimated that the ship was loaded with approximately twice the legal amount of cargo and hence without sufficient water ballast to counteract the resultant increase in deadweight vertical centre of gravity (fluid, KG_f), which exacerbated the increases in lightship weight and KG_f due to modifications undertaken since build.

MS Sewol capsized and sinking, April 2014, with the loss of 304 passengers and crew

The implications of inadequate initial stability can be catastrophic; for example the loss of the 2006 built, 75.2m, 2,985gt, Anchor Handling Tug Supply (AHTS) ship *MV Bourbon Dolphin* on 12 April 2007. Whilst anchoring the semi-submersible drilling platform *Transocean Rather* in deep water off the west coast of Shetland, a heavy anchor chain that it was handling suddenly slid across the side of the deck and began to drag the ship over. She capsized within seconds, with the loss of eight of the 15 crew onboard. The capsized ship sank three days later and the subsequent Commission of Inquiry set up by the Norwegian government questioned the ship's ability to handle large anchors in such deep water.

With stringent and well established international and national regulations in place covering initial and large angle ship intact and damage stability, one might be forgiven for questioning how such events can happen. One possible cause, suggested by the authors, is uncertainty in a ship's level of initial stability, GM_T, which as discussed later could possibly be viewed as an 'experimental estimate'. It should be noted that obviously initial GM_T is not on its own a comprehensive measure of stability as many other factors, such as freeboard / reserve of buoyancy, unprotected / protected openings, subdivision etc., play a significant role in a ship's overall intact and damage stability performance. As an illustration that ship design is an often conflicting multiple criteria problem, typically it is not desirable to have ocean-going trading ships which are too 'stiff', i.e. with too large a GM_T, because this may result in unacceptable motion characteristics, specifically roll acceleration. This situation is detrimental with regard to crew / equipment operability, passenger comfort, cargo integrity (such as shifting of cargo, damage / collapse of containers) and consequently overall ship safety. Conversely, too low a GM_T is not just detrimental regarding initial stability, but can obviously also be regarding roll angle in a seaway (in addition to roll due to turning, crowding etc.). It should be noted that whilst passive (e.g. bilge keels) and active (e.g. free-surface or forced roll damping tanks) solutions are available to mitigate roll, the selection of robust dimensions, and to a lesser degree distribution of weights (hence subsequent mass inertia as well as GM_T), in order to 'de-tune' a design is a significantly more elegant and operationally efficient solution.

Research conducted by the authors has found that the determined position of the lightship KG_f (fluid, with systems at operational levels), stated in a ship's trim and stability book / loading instrument and obtained from an inclining experiment, could possibly have a significant level of uncertainty associated with it. With regard to this, the authors have recently published a paper [1] detailing an uncertainty analysis procedure for the inclining experiment; making it freely available through open access in the hope that the discussion and uptake of the method will help to protect life, assets and the environment.

Error or uncertainty?

So, what is uncertainty? It is important here to make it clear that 'uncertainty' is not 'error'.

An error, for example, may be made when conducting an inclining experiment, resulting in an incorrect lightship - weight, longitudinal (LCG) and transverse (TCG) centres of gravity as well as KG_f. Such mistakes are always possible. However, appropriate and thorough preparations and conduct of an inclining experiment together with robust quality systems can, and do, reduce the risks to levels that are more than acceptable. Hence, the use of qualified and most importantly experienced personnel, (especially the conducting officer) a robust and comprehensive inclining procedure, internal company procedures, and the appropriate level of oversight and governance by the flag authority (or classification society if empowered to so act) must be viewed as a pre-requisite.

Uncertainty, on the other hand, describes the level of precision with which we can make a measurement. Let's say we wanted to know the length of an engine component to within a millimetre. In this case we might reasonably use a tape measure calibrated in millimetres, and obtain satisfactory results. If, however, we needed to know the measurement to within microns we would need to use a measuring device i.e. a micrometre with a greater degree of precision.

Actually, we would need more information too: we would need to know at what temperature the measurement was made; and, we may also need to tightly define how to support the device whilst taking the measurement. Nevertheless, whatever instrument or method we use, we will only ever have an estimate of the measurement to within some defined level of precision.

For the inclining experiment, the precision with which we take various contributing measurements and how these values propagate through the data reduction equations dictate the precision in our derivation of the as-inclined GM_T and subsequent calculation of the lightship KG_f. This precision limit is what we call 'uncertainty' and, generally speaking, may be thought of as the standard deviation of the mean value in the derived 'experimental estimate' of lightship – weight and, specifically in this case, the KG_f.

Establishing uncertainty

Though thoroughly established in scientific circles, the use of uncertainty analysis seems to be experiencing some difficulty in gaining traction within engineering disciplines, and therefore in applications relating to qualifying and understanding any uncertainty associated with engineering calculations. No reputable scientist would attempt to claim the existence of a new discovery, say a new particle, without first methodically establishing the uncertainty in the experimental data sets supporting the thesis.

Whereas the precision with which a ship's lightship KG_f is established, which is arguably the single most critical value relating to the safe operation of that ship, seems to pass without critical questioning regarding potential uncertainty. It is possible that the perceived or actual reluctance to embrace uncertainty analysis may simply be a lack of familiarity of the subject; 'ironically' a fear of the unknown!

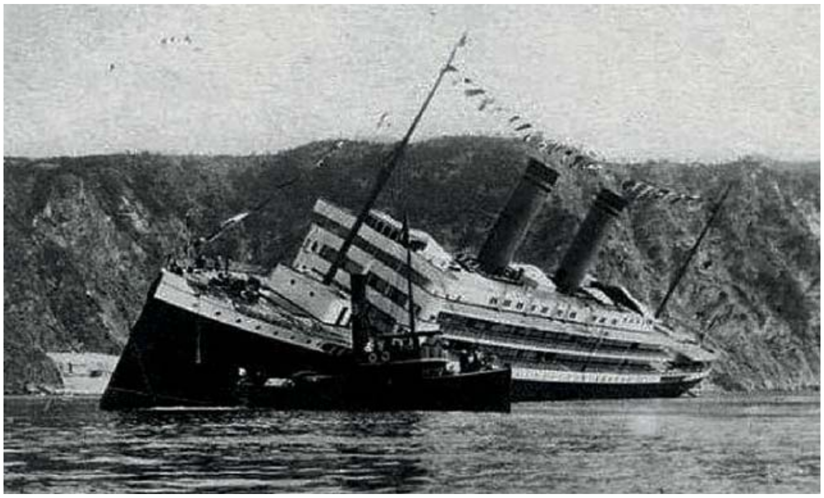
This should not be an issue as the mathematical theory and tools used in uncertainty analysis are surprisingly simple and well within the understanding of any trained and qualified professional engineer or scientist, such as a naval architect. In the most general sense, the uncertainty in an estimated or scientifically calculated value is simply the root-sum-square of the uncertainty in each input variable multiplied by the sensitivity of the result to a change in that variable.

Consider first the uncertainty in the variable. This can typically take one of two forms:

1. If the variable is measured as a function of time, then we would most likely have a sufficiently large sample size to undertake a simple statistical analysis.

   For example, imagine that we have tainted a ship model along a towing tank and measured some resultant generated force. The measured force will obviously fluctuate about some mean value and we would typically take this mean value as our measured result to be used in subsequent calculations. In this case we could reasonably take the uncertainty to be the standard deviation of the mean value.
2. If, on the other hand, we only have a static measurement, then we have to rely on alternative methods.

   This might include information from calibration certificates, past experience or simply based on sound engineering judgement. As an example we could take the uncertainty in an inclining weight group as the value given on the calibration certificate for the load cell used to weigh each of the weight groups – typically, this is undertaken in the presence of the flag / classification society surveyor, during the final preparations for the inclining experiment. That is, the calibration certificate might say that the load cell is accurate to plus or minus some value;



SS Principessa Jolandia capsizing directly following launch, September 1907 and we would take that value to be our uncertainty.

As a second example, for an inclining experiment being conducted using solid weights, rather than water shifts via pumping, we might think about the distance we have moved an inclining weight group across the deck of the ship. Though we may be measuring the distance with a tape-measure calibrated in millimetres, it would perhaps be unrealistic to expect an uncertainty of millimetres.

Considering that in order to afford movement using a quayside crane or fork-lift truck, the inclining weight group may be on a wooden pallet and the deck marks that the pallet must be aligned with will more than likely be made with chalk or masking tape, an accuracy of centimetres may be more realistic! In this case it is appropriate that the conducting officer assigns an uncertainty of possibly a centimetre - without the additional consideration of the beam of the ship in question and hence the uncertainty associated with the measurement of the distance over which the inclining weight groups are being transferred.

Establishing sensitivity

Considering next the sensitivity of the result to a change in each variable, though more sophisticated methods exist, this can actually be readily achieved by simply assigning varying realistic values in to the equations and seeing what happens when small changes are made to the values in question.

If for example, as is typical, we have a spreadsheet containing the calculations required for the analysis of an inclining experiment, then the input variables will include a range of parameters such as: the mass and centres of each group of inclining weights (or water ballast, if being utilised); transfer distances for each shift; draught measurements / water densities / temperatures at various positions and depths both before and after (and possibly during) the experiment; pendulum lengths; deflections for each shift at each pendulum; and so on.

The output would be the derivation (our 'experimental estimate') of the as-inclined displacement, LCG, TCG and GM_T of the ship. Following subsequent quantification of deadweight items to be removed ('offs' such as fluids in tanks, stores, yard dunnage, personnel, etc.) and lightship items yet to be fitted ('ons') undertaken prior to the experiment, the ship's lightship weight, LCG, TCG and KG_f can be established.

***USS Lafayette*, ex *SS Normandie*, capsized in New York harbour following fire, February 1942**

Taking each of the input variables in turn, we can make a small change in that input variable and record the change in the overall result. Then, dividing the change in the result by the change in the input variable gives us the sensitivity coefficient. This coefficient informs us how sensitive the result is to a small change in the input variable in question.

Combining uncertainty

Once we have estimated the uncertainty for each input variable and calculated the associated sensitivity, we are in a position to establish the estimate of the combined uncertainty.

The first step is simply to take the squared value for each individual uncertainty and multiply it by the squared value for the corresponding sensitivity coefficient. The second step is to sum them and take the square-root of the result.

In its simplest form this is combined uncertainty. In essence, that is all there is to it! Of course many more subtleties can be included for those specialising in uncertainty analysis. Nevertheless, undertaken in this way, the resulting uncertainty can, for all intents and purposes, be thought of as the standard deviation of the 'calculated estimate' of the lightship KG_f obtained from the inclining experiment. Considered as a standard deviation, we can then apply typical statistical methods for exploring the confidence interval of the 'experimentally estimated' KG_f.

Inclining experiment uncertainty

The paper under discussion here [1] explores, through case studies, typical values of the uncertainty in the 'experimental estimate' of the lightship KG_f obtained from the inclining experiment, see Annex 1 of the International Maritime Organization's (IMO) 2008 Intact Stability (IS) Code regarding merchant ships and, for example, for naval ships and auxiliaries Section 5 of the United Kingdom's Ministry of Defence (MoD) Marine Acquisition Publication (MAP) 01-024. The study found that two out of the five ships investigated had an associated uncertainty in lightship KG_f in the order of 0.15m.

The implication is that if one of these ships were loaded in such a manner to give a loading condition with the minimum allowable GM_T of 0.15m there would be a 50% chance of the actual GM_T being smaller than 0.15m and approximately a 16% chance of the ship having zero or negative initial stability, GM_T, resulting in the ship taking up an angle of loll or worse, capsize!

Even before an inclining experiment is conducted to 'experimentally' establish a ship's lightship, it is imperative that the 'calculated estimate' of lightship is as accurate as possible. As every shipyard naval architect knows, the production and maintenance throughout the various stages of design and construction of an accurate and robust lightship 'estimate' is of paramount importance as failure to do so can have extremely serious consequences.

An example illustrating this, from over a century ago, concerns the launching of the 141m, 9,210GRT *SS Principessa Jolandia*. This transatlantic ocean liner was built in Genoa for Navigazone Generale Italiana (NGI) for operation on their South American service. Upon launch on 22 September 1907 she was almost fully completed, even with all fittings and furniture installed! Due to this, and possibly other contributing factors, her launch condition had insufficient stability. Hence, she heeled sharply to port immediately upon lifting off the launch ways. Despite the efforts of attending tugs to right her, movable fittings shifted, increasing her list further, and she began to down-flood within 20 minutes and shortly after capsized, resting on her port side – fortunately without loss of life.

It is standard practice for a deadweight survey to be undertaken on a new ship following launch / float-out from the building dock. An inclining experiment may possibly then only be conducted upon mechanical completion and commissioning of all systems prior to delivery. However, it is worth noting that inclining experiments may also be conducted at various stages throughout the life of a ship, not just at intervals required by IMO SOLAS Chapter II-1 Part B-1 Regulation 5.

For complex new-builds, it is not uncommon for a shipyard to conduct, at the earliest opportunity, its own 'internal' post-launch / float-out inclining experiment. This may be undertaken for a number of reasons: confirming the as-launched loading condition and hence as-launched lightship; updating the final (as-built) lightship 'estimate' and associated stability calculations; updating stability calculations covering the outfitting phases with respect to water ballast requirements, the maximum amount of firefighting water that can be added to each deck to maintain a suitable margin on GMT and freeboard. There have been a number of examples of ships capsizing during outfit or conversion whilst berthed in a river or basin.

One notable one was the loss of the former SS Normandie, the famous 313.6m 83,423gt transatlantic ocean liner built in 1935 for Compagnie Generale Transatlantique (CGT), whilst undergoing conversion to the troopship USS Lafayette (AP-53) at Manhattan's Pier 88 in New York harbour. Following the outbreak of fire during the afternoon 9 February 1942, which spread rapidly due to the ship's woodwork still being in situ and the fire system being non-operational, fireboats and shore appliances poured water on the blazing ship. As a result of the build-up of firefighting water onboard it began to heel to port and consequently down-flood. Efforts to counter-flood were unsuccessful and shortly after midnight she was abandoned and eventually capsized a couple of hours later, settling on the bottom at approximately 80degs with the death of one dockyard employee. She was finally re-floated in August 1943 and subsequently dry-docked but, due to substantial hull damage and machinery deterioration, she was not repaired and was finally broken up between 1946 and 1948.

Builder's inclining experiments may also be undertaken at other points during the build process such as prior to sea trials and at any juncture that a draught / deadweight survey identifies an unexpected or major change to displacement and hence potentially KG_f.

For ships about to undergo conversion, it is common, especially for older tonnage, for the dockyard or design consultants to conduct an 'internal' pre-docking inclining experiment. This is typically to identify any 'unaccountable' weight growth which has occurred over its trading life. This therefore facilitates confirmation of the 'baseline' lightship on which the conversion 'on's' and 'off's' are applied, and hence the updating of the as-converted lightship 'estimate' and associated stability calculations etc. prior to completion and conduct of the as-converted inclining experiment.

From the above it can be seen that it is imperative that a robust weight control procedure is put in place by the shipyard during both construction and outfitting of a ship and by the dockyard during a conversion or upgrade. Not only must it be in place but most importantly rigorously put into practice with all 'on's' and 'off's, both permanent and temporary, noted and the loading condition weight and KG_f updated on a regular basis. In addition, when afloat, regular draught mark surveys must be undertaken as a cross check. Regarding the preparation for and conduct of an inclining experiment, such accurate information gives the conducting officer a very good indication of what to expect and, most importantly, also to assess in 'real time' the validity of the inclining experiment with certainty.

MV Deneb capsized alongside the quay in Algeciras, June 2011

Car Carrier *MV Hoegh Osaka* grounded in the Solent, January 2015

Loading condition uncertainty

It should be pointed out that the above is purely based on the uncertainty in the lightship alone. It is quite possible that the uncertainty in the loading conditions, as compared to those presented in a ship's approved trim and stability book / loading instrument, may be of greater significance. This is due to the uncertainty associated with accurately establishing the cargo deadweight embarked, either solid or fluid (from radar / pneumatic / manual soundings and / or ullages together with stated densities), the state and variation in the various solid and fluid consumables throughout a voyage, together with any water ballast present at the beginning or added during a voyage.

In the recent past, a potentially disastrous issue was identified in the establishment of the actual deterministic damage stability performance of tankers, in particular product tankers, due to the effect of 'drop-out' of liquid deadweight i.e. that is available for loss due to damage.

This has now been addressed through the introduction of the requirement that a suitable stability loading instrument be fitted to all oil and chemical tankers built after 1 January this year (gas tankers from 1 July) and installed on existing tonnage before 1 January 2021 (gas tankers by 1 July 2021) depending on the date of the next renewal survey. However, due to the amount and distribution of cargo onboard having to be established from soundings / ullages and fluid densities, there is obviously still uncertainty relating to the cargo weight and KGf, and hence the 'simple' compliance with the intact and damaged stability criteria (critical KG_f/ GM_T envelope values) due to the resultant uncertainty in GM_T.

Passenger ship stability is indisputably an extremely important topic, for both national and international regulators, and hence is under constant review. As discussed in May at RINA's international conference on the Design and Construction of Ferries and Ro-Pax Vessels held in London, major changes relating to the SOLAS probabilistic damage stability requirements for passenger ships have just been discussed by the 96th session of the Maritime Safety Committee (MSC 96).

Specifically these concerned changes to the survival $s_{final,\,i}$ factor for the final equilibrium stage of flooding and significant enhancement of the required subdivision index *R*, which will hopefully enter into force for new ships constructed on or after 1 January 2020. Although probabilistic calculations are not performed on actual loading conditions, as is done for most deterministic assessments, the KG_f for each loading condition must be within the 'safe seagoing' boundaries of the combined critical intact and damage KG_f / GM_T envelope values. The critical intact values also provide the KG_fs initially applied for the calculation of the damage case 'bare boat' intermediate and final survival si factors and hence the attained subdivision index *A* for the associated representative range of three draughts considered.

Similar to the loss of the former *SS Normandie* discussed above, a more recent example of the effect of water within the hull was the loss of the passenger ship *MS al-Salam Boccaccio 98*. She was a 131m, 11,799gt, roll-on/roll-off (ro-ro) car and passenger ferry built in 1970. On 3 February 2006 whilst crossing the Red Sea from Duba, Saudi Arabia, to Safaga, Egypt, with 1,418 passengers and crew onboard, an uncontrollable fire broke out. As a consequence, exacerbated by the scuppers not functioning correctly, firefighting water accumulated resulting in the ship becoming unstable. Due to this, and possibly also the weather conditions, the ship began to list excessively and began to down-flood and subsequently sank with the loss of 1,031 lives.

Another major issue which has come to the fore over recent years relates to the actual weight and centres of containers loaded on ships. One such non-fatal example of the consequence of this involved the 1992 built, 101.1m, 3,992GT, feeder containership *MV Deneb,* which capsized whilst loading cargo in Algeciras, Spain, on the afternoon of 11 June 2011. Upon loading a 40' container at height, the ship began to list to starboard. The ship initially heeled slowly, but progressively more rapidly, until at approximately 45degs the containers contacted with the quayside. Harbour tugs were employed to push the ship in to the quay in order to prevent total capsize. The bow and then engine room began to down-flood and within hours the ship was resting on the bottom at approximately 54degs. During the night she finally settled at a heel of 75degs following the collapse of some of the ship's structure in contact with the quay. A subsequent investigation established that approximately 10% of the 168 containers loaded were significantly in excess of the declared weights. For the 16 containers in question, this excess ranged between 1.9 and 6.7 times, equating to them being 278tonnes in excess of their declared 93tonnes– approximately 200% overloaded.

It has been accepted by the international maritime community that miss-declared container weights have very serious implications for the uncertainty of the initial stability of the loading conditions of containerships and hence compliance with both intact and damage stability criteria. As a result the mandatory weighing of containers recently entered into force on 1 July this year.

Considering the above, it is surprising that, in 2015, the United Kingdom revoked its Merchant Shipping regulations regarding the weighing of goods vehicles and cargo transported on ships on which passengers are also embarked. These were introduced in 1988 and 1989 as a consequence of the loss of *MS Herald of Free Enterprise*, a 131.9m, 13,601gt, ro-ro car and passenger ferry built in 1980. Just after leaving the harbour at Zeebrugge, Belgium, enroute to Dover, United Kingdom, on the night of 6 March 1987 with 539 passengers and crew onboard, water began to enter the car deck due to her bow door still being open. As a consequence of this Water-on-Deck (WoD) and resultant free surface, her GM_T was diminished and she capsized within minutes with the loss of 193 passengers and crew. Astonishingly, no equivalent regulations for the weighing of vehicles or cargo, in order to accurately ascertain deadweight and KG and hence a ship's sailing loading condition and, therefore, establish both stability and longitudinal strength, were introduced by any other countries, either within the European Union or the wider world. As alluded to above, in the decades since significant enhancements have been made to passenger ship stability standards. Much of these were also driven by the loss of *MS Estonia*, a 157m, 15,566gt, ro-ro car and passenger ferry built in 1980, which sank in the Baltic Sea on the night of 28 September 1994 enroute from Tallinn, Estonia, to Stockholm, Sweden, with the loss of all 989 passengers and crew.

A recent incident due to the inappropriate loading of vehicles involved the 2000 built, 179.9m, 51,770gt, pure car and truck carrier (PCTC) *MV Hoegh Osaka*. On the evening of 3 January 2015, shortly after departing Southampton, she developed a severe list after executing a turn to port at 12knots due to her GM_T being inadequate. The upper vehicle decks were full whilst the lower decks were lightly loaded which, together with the state of the bunker oil low down in the ship being light, resulted in a high KG_f. However, for a number of reasons her inadequate stability was not identified prior to departure and whilst she had a positive GM_T upon departure this was less than the IMO statutory requirements. She lost steerage and propulsion as her heel increased to in excess of 40degs and grounded on Bramble Bank in the Solent, which prevented her from capsizing, as due to the heel cargo shifted and breached the hull causing down-flooding. She finally settled at 52degs to starboard and all the crew were able to be safely evacuated from the ship and surrounding waters, and she was subsequently salvaged without pollution to the environment.

SS Flying Enterprise **sinking in western approaches, January 1952**

What of other ship and cargo types?

There are numerous IMO instruments in force covering the various ship types. These are obviously under constant scrutiny, investigation and revision by the international maritime community – proposed and adopted updates to the intact and stability regulations from 2010 to date for all ship types have been discussed at recent RINA international conferences addressing ship stability.

As illustrated above, the shifting of cargo can induce heel as well as causing breaches in the hull. There have been many examples of the consequences of cargo shifting, but one of the most dramatic involved *SS Flying Enterprise*, whose cargo manifest has been a point of speculation. She was a World War II type C1-B, 120.8m, 6,711gt, general cargo ship built in 1944. On the night of 25 December 1951 whilst in the Western Approaches to the English Channel bound for the United States from Hamburg, West Germany, she encountered a storm. This caused the cargo to shift and on 28 December she issued a SOS by which time she had a list of 45deg to port. Mid-afternoon on 29 December all the passengers and crew, bar the captain, were evacuated, with the loss of one life. By 4 January 1952 when a crewmember of a tug was transferred to the ship she was listing at 60deg. A tow line was finally attached on 5 January from the tug *Turmoil* and a tow to Falmouth, 300nautical miles away, commenced. However, early in the morning of 10 January the line parted, with the list increasing, her captain and tug crewman abandoned ship mid-afternoon and she finally sank an hour later only 41 nautical miles from Falmouth.

The aim of this article has been to highlight and discuss potential uncertainty in the initial stability and hence the safety of a ship. A final example, concerning this time a small and simple ship, is the loss of the *MV Lairdsfield*, a 53.2m, 522gt single hold coaster built in 1953. She had loaded 373tonnes of hollow hexagonal steel columns, tiered between dunnage, and 354tonnes of steel plates on top, at Middlesbrough on the North East Coast of the United Kingdom. As a result of these loading arrangements the deadweight KG_f was higher than the ship was designed for and hence, whilst she did have a positive GM_T, her stability was inadequate for sailing in open water. Hence, when leaving the River Tees fully loaded on 6 February 1970 in moderate weather, possibly whilst undertaking a turn, she suddenly capsized without any distress signal resulting in loss of all 10 crew onboard.

Though the inclining experiment paper [1] does not itself explore the uncertainty in the stability of a loaded ship, it provides a complete and robust tool set sufficient to do so. The implication for various different ship-types could very well be substantial.

Practitioners may be well advised to investigate the uncertainty in the estimate of the loaded seagoing GM_T to identify probable safe working limits.

Similarly, legislators may be well informed by such studies when considering changes to loading rules etc.

Those seeking to update the existing stability standards should also ensure they consider such uncertainty regarding KG_f. This variation in G may be substantially more influential than, for example, any possible precision improvement gained from reforming the underlying assumption in wall-sided theory regarding the stationarity of the transverse metacentre (M_T) as traditionally applied in the derivation of the as-inclined GM_T.

Summary

What can uncertainty analysis actually do to aid our engineering comprehension and hence our effectiveness as ship designers / builders and practicing naval architects? Well, the important thing to appreciate is that a wide uncertainty band does not 'necessarily' mean a poor measurement; it is all about information.

We might for example arrive at some 'estimated' value, calculated as a function of multiple parameters that we have measured directly. Taking into account the precision associated with each of the values we measure, and accepting how these uncertainties propagate as we calculate the value of interest, we establish the related uncertainty.

If, however, instead of calculating the uncertainty, we choose to repeat the measurement a great many times, we might, if we are fortunate, get sufficiently close to the same value each time. We could then take the uncertainty to be simply the standard deviation of the mean value. We would therefore have a smaller uncertainty and consequently more confidence in our result, but with the associated additional cost in both time and resources, and subsequently money.

Conclusion

So what's the bottom line? Uncertainty analysis can assist us, as naval architects, to effectively decide how to best utilise our time and resources in the most efficient manner in order to improve confidence in the parameters that are of most significance and importance to us, our clients and on the projects which we are undertaking. The parameters that warrant the most attention are those that present the greatest risk; that is risk to persons, property and/or the environment.

Ship stability, as with other critical parameters relating to ship operations, is of paramount importance, and should therefore be dealt with accordingly with an appropriate uncertainty analysis. *NA*

Disclaimer:

The views expressed in this article are those of the authors and not necessarily represent those of the organisations with which they are affiliated and the professional institutions of which they are members.

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