

Techno-Economic Assessment of Hull-mounted Sonar for Oil-spill Risk Control

Ernestos Tzannatos and Alexandros Xirouchakis

(Dept. of Maritime Studies – University of Piraeus)

(E-mail: et@unipi.gr)

Despite continuous efforts to improve shipping safety, groundings are still the prime cause of large scale oil pollution of the marine environment. As the bridge operator remains the most important part of navigation, the provision of tools which promote his understanding of the threats which lie ahead of the ship has become a permanent challenge. In this work, the use of a hull-mounted forward-looking sonar as a navigational aid for grounding avoidance and ultimately as an associated oil-spill risk control option for oil tankers is examined according to the Formal Safety Assessment (FSA) approach. In this context, the sonar's oil-spill risk reduction potential and its overall cost were estimated and assessed against the Cost of Averting a Ton of oil Spilled (CATS) criterion. It was found that the currently available sonar technology has a maximum detection range which is adequate for the avoidance of powered groundings in the case of small-sized oil tankers only. However, for this ship size category, the attained oil-spill risk reduction was found to be low and sonar use was proved to be cost ineffective. However, it was found that sonar technology will offer sizable oil-spill risk reduction in large-sized oil tankers and their requirement for longer sonar detection range can be easily met cost-effectively as an oil-spill risk control option for ships of this size.

KEY WORDS

1. Shipping risk.
2. FSA.
3. Sonar.
4. Oil spills.

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1. INTRODUCTION. The widely acknowledged dependency of shipping accidents on the human factor has been instrumental in shaping IMO policy for shipping safety and pollution prevention over the last two decades. The ISM Code (2008) was introduced to ensure adherence to rules and regulations with the aim of reducing human errors and improving the safety record in shipping (Schröder-Hinrichs, 2010; Tzannatos, 2010), while ICT progress led to the development and eventual installation of navigational aids, such as the Global Maritime Distress and Safety System (GMDSS), Electronic Chart Display and Information Systems (ECDIS), Automatic Information System (AIS) etc, in order to provide valuable support in various and often critical ship bridge operations (Nash, 2008; Norris, 2007).

The recent grounding accidents of the cruise ship *M/S Costa Concordia* in the Tyrrhenian Sea and the container ship *M/V Rena* off the coast of New Zealand have brought to the fore the importance of powered groundings (i.e. without the loss of propulsion) in the causation of shipping disasters and the need to seek further measures for safety improvement.

While the release of the official investigation report into the *Costa Concordia* accident of 13 January 2012 is still pending, preliminary evidence points towards human error – or even recklessness, possibly compounded by ECDIS warning failure for the ship's deviation from the safe course.

With regard to the grounding of *Rena* on the 5 of October 2011, according to the interim report by the Transport Accident Investigation Commission (TAIC) released in March 2012 (TAIC, 2012), “*passage plans were repeatedly changed in order to reach the harbour before ebbing tides made it unsafe*” and “*as the ship headed straight for the reef at 17 knots, a radar signal alert was activated but the master failed to see anything after looking through binoculars from the windows of the bridge. As the master began to walk through the wheelhouse to the chartroom, the ship hit the reef.*” The *Rena* accident together with some of the most notable of the past (e.g. *Torrey Canyon* and *Exxon Valdez*) reinforces the strong connection between human errors and the oil pollution from tankers (Arsenie & Hanzu-Pazara, 2008).

With particular reference to powered groundings, the provision of a system dedicated to grounding avoidance, such as sonar, would have increased the active redundancy in navigation systems by virtue of the additional monitoring and warning facility offered by the system. However, within the policy framework of sustainable shipping, it is necessary to adopt the approach that every Risk Control Option (RCO) in shipping has to demonstrate its cost-effectiveness in averting any specific type of damage, following the initial guidelines for Formal Safety Assessment (FSA) introduced in 2002 and their amendments (MSC/Circ.1023/MEPC/Circ.392, MSC/Circ.1180-MEPC/Circ.474 and MSC-MEPC.2/Circ.5.). According to IMO (<http://www.imo.org/OurWork/Safety/SafetyTopics/FormalSafetyAssessment.aspx>), FSA has been described as “*a rational and systematic process for assessing the risks associated with shipping activity and for evaluating the costs and benefits of IMO's options for reducing these risks*”. It is also stated that “*It can be used as a tool to help evaluate new regulations or to compare proposed changes with existing standards. It enables a balance to be drawn between the various technical and operational issues, including the human element and between safety and costs.*”

In general, an expert review of all aspects of maritime risk and the tools available for improving the industry's safety record has been written by Kristiansen (2004), whereas comprehensive guidelines for risk-based decision making in marine safety management are presented by the USCG (<http://www.uscg.mil/hq/cg5/cg5211/E-Guidelines.asp>).

In a more specific context, various research studies have analysed the causation chain of ship groundings and collisions through the use of risk assessment techniques, such as Fault Tree Analysis (FTA) and Event Tree Analysis (ETA), forming the basis for the prediction of risk associated with these accidents (Celik et al., 2010; Antao and Guedes Soares, 2006; Brown and Haugene, 1998; Amrozowicz et al., 1997; Amrozowicz, 1996). FSA studies have been concentrated on the cost-effectiveness of RCOs, e.g. ECDIS/ENC (DNV, 2006), helicopter landing areas (Guassardo and Demaria, 1998; Skjong et al., 1997) and quick evacuation systems and aids

(Skjong and Wentworth, 2001; Vanem and Ellis, 2010). Another side of FSA research has been aimed at the refinement of the RCO acceptance criteria, i.e. the Cost of Averting a Fatality (CAF) and particularly the Cost of Averting a Ton of oil Spilled (CATS) (Psarros et al., 2011; Kontovas et al., 2010; Kontovas and Psaraftis, 2009; Psaraftis, 2008; Vanem et al., 2008; Skjong et al., 2007). Most of the aforementioned FSA research has been conducted in support of IMO deliberations for relevant policy making.

With regard to sonar research for anti-collision purposes, the use of forward-looking sonar (FLS) has been mainly focussed on autonomous underwater vehicles (AUV) employed in ocean research or naval operations, for which a review on obstacle detection and avoidance is presented by Tan et al. (2004a; 2004b). For surface vessels, sonar research initiated by Zimmerman and Miller (2002) led to the development of 3-D FLS technology which entered into commercial production in 2004 (Maritime Global net – January 8, 2004 – “US firm launches anti-collision sonar”, Newswise – January 6, 2004 – “First Sonar for Marine Navigation, Obstacle Avoidance”) (Zimmerman and Miller, 2008). As would be expected from an industry that is known for its “resistance-to-change”, the ship owners’ response to sonar installation for the avoidance of underwater obstacles has been hesitant so far, as they await demonstrable evidence that the system is cost-effective.

In this work, the attempt to estimate the cost-effectiveness of hull mounted FLS on merchant ships makes a unique contribution to risk control in shipping and generally enriches the ongoing research on shipping safety through the application of the FSA methodology. The case of oil tankers is considered to be particularly important, because the frequency of their powered groundings and the resulting oil pollution define a risk which has to be analysed and the sonar installation as a potential RCO needs to be assessed. Furthermore, the current analysis lays down the foundations for conducting a similar exercise for other ship types which also deserve attention for alleviating the risk of groundings particularly with regard to other dire consequences, such as the loss of life and/or property.

2. METHODOLOGY

2.1 *Sonar technical effectiveness.* Taking into account that sonar specifications not only differ but are also limited, the technical effectiveness of the sonar system (i.e. equipment and operator) towards avoiding underwater obstacles depends primarily upon the sonar detection range. In conditions of propulsion system availability, the ship circle manoeuvre as shown in Figure 1 is considered to be more effective for grounding avoidance than the full astern – crash stop (Cockcroft and Lameijer, 2012; ABS, 2006).

In order to successfully avoid the obstacle ahead, a ship sailing with a speed, V_S , should be capable of accommodating within the time made available by the sonar detection range, R_N :

- a) the obstacle avoidance manoeuvre,
- b) the response of the bridge crew to the verified obstacle detection and
- c) the obstacle detection verification, according to:

$$R_N = (T_M + T_H + T_N) \times V_S \quad (1)$$

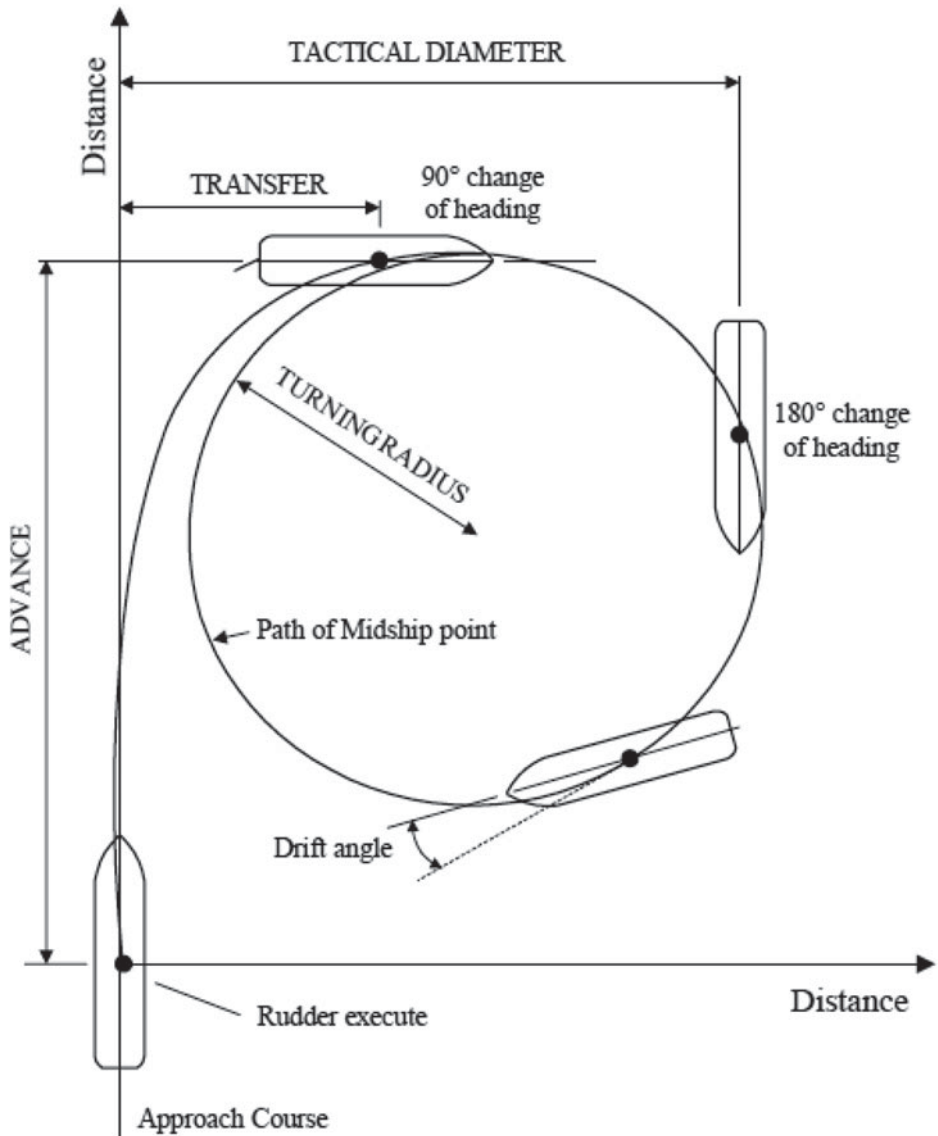


Figure 1. Circle manoeuvre (ABS, 2006).

where,

R_N = sonar detection range (m)

T_M = time for obstacle avoidance manoeuvre (s)

V_S = ship speed (m/s)

T_H = time for bridge crew response (s)

T_N = time for obstacle detection verification (s)

After the initiation of the manoeuvre, the time, T_M , required to sail the “advance” distance of the circle manoeuvre (Figure 1) is given by the expression:

$$T_M = k \times (L_S/V_S) \quad (2)$$

where,

k = circle manoeuvre coefficient

L_S = ship length (m)

Taking also into account that IMO requires that the “advance” distance is to be less than 4.5 ship lengths (IMO, 2002), an average value of ‘ k ’ equal to four is assumed to be appropriate. Combining expressions 1 and 2, the maximum ship size (length), L_S , which can successfully perform the obstacle avoidance circle manoeuvre within a sonar detection range, R_N , is:

$$L_S = 1/4 \times [R_N - (T_H \times V_S) - (T_H \times V_S)] \quad (3)$$

2.2 Sonar cost-effectiveness. According to the basic structure of the FSA methodology, the first step towards assessing the cost-effectiveness of the sonar system is the estimation of the existing oil-spill risk. Expressed in terms of spilled tons per ship-year, the figures of existing oil-spill risk are based upon the historical record of accidents (all powered groundings and contacts) suffered by the oil tanker fleet and the associated oil spillages, during 2004–2007, as obtained through the International Tanker Ownership Federation Limited database, Lloyd’s Casualty Database and Intertanko’s Casualty reports database. The existing oil-spill risk is estimated for specific categories of ship size in order to separately assess the need for their risk control, as well as to separately estimate the oil-spill risk reduction potential and the cost-effectiveness offered by sonar systems suitable for the different ship size categories on the basis of their different detection ranges and costs.

In the presence of navigating conditions which inevitably lead to powered groundings (and contacts), the Fault Tree Analysis (FTA) diagram of Figure 2 presents the probability of powered groundings (and contacts) due to the failure probability of the sonar system with reference to the reliability of its technical and human components, as well as the probability that the underwater obstacle despite being successfully detected may be unavoidable through the circle manoeuvre due to its particular morphology (e.g. semi-closed shape tighter than the “tactical” diameter that can be attained by the ship).

Probabilities of basic causes leading to sonar system failure are derived from historical failure data such as Mean Time Between Failure (MTBF) of components, units, subsystems or functions, as well as error rates associated with the execution of human tasks.

Applying top-down deductive failure analysis and using Boolean logic, the estimated probability for unavoidable grounding (and conversely the probability of successful obstacle avoidance) is utilised in conjunction with the existing oil-spill risk in order to determine the oil-spill reduction potential offered by the sonar system in terms of spilled tons per ship-year.

Finally, the Cost of Averting a Ton Spilled (CATS) constitutes the basic criterion for the economic assessment of the sonar system. The value of CATS represents the current overall unit cost of an oil-spill based on the record of the world-wide averaged sum of clean-up and compensation costs, multiplied by an assurance factor which reflects the society’s willingness-to-pay (WTP) for the prevention of the disaster rather than its cure. According to recent research work in this area, the value of CATS has

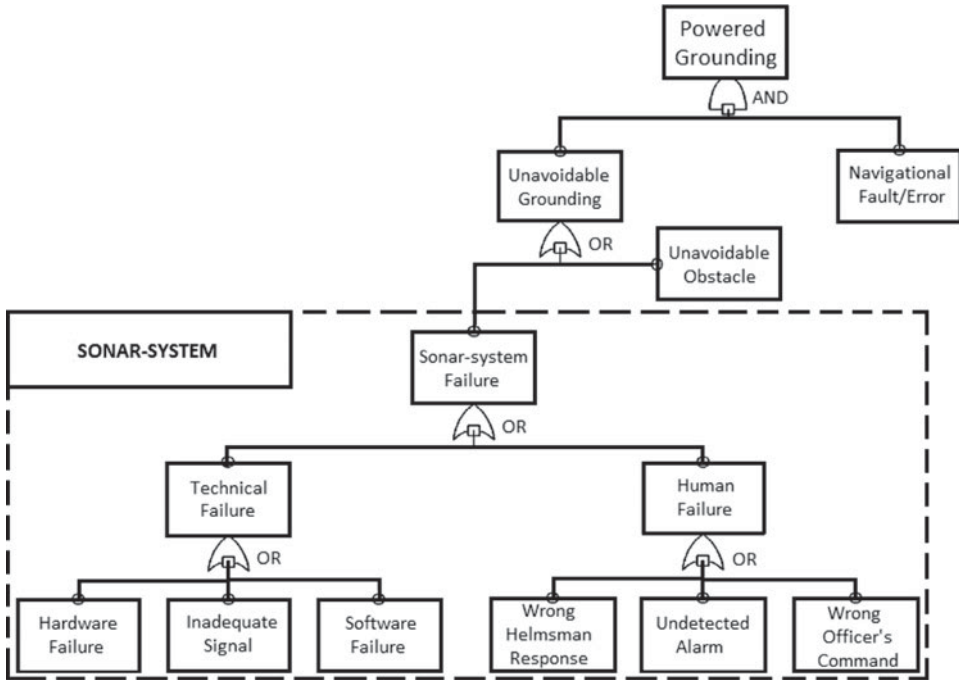


Figure 2. Basic FTA diagram for powered grounding in the presence of a sonar-system.

been estimated at 80,000 USD/ton (Psarros et al., 2011) and the cost-effectiveness of any oil-spill RCO depends on its ability to fulfill the following expression:

$$CATS \geq (\Delta C/\Delta R)_{RCO} \tag{4}$$

where,

CATS = 80,000 USD/ton

ΔC = the overall cost of the RCO (USD/ship) expressed in Net Present Value (NPV terms)

ΔR = the oil-spill risk reduction (tons/ship) offered by the RCO for the duration of the remaining useful life of the ship, assumed to be 25 years for a new build.

3. RESULTS AND DISCUSSION

3.1 *Sonar technical effectiveness.* The longest detection range of any commercially available hull-mounted forward-looking sonar employing the echolocation (active) principle is currently equal to 900 m under normal (usual) seawater physical conditions. Therefore, assuming that obstacle detection is ensured through three successive pings emitted at an interval of 1.7 s, the overall duration (T_N) for the verification of the obstacle detection was set at 5.1 s. Following this, the minimum time required for the effective operator’s response (T_H), i.e. for the initiation of the circle manoeuvre by the bridge crew, was assumed to be on average equal to 10 s. Finally, although the service speed of oil tankers differs according to their size and freight demand, for the purposes of the current analysis, an average sailing speed (V_S) of 14 knots (7.2 m/s) was assumed to be appropriate for all ship size categories under the normally prevailing market conditions.

Table 1. Oil-spill risk due to all powered groundings & contacts during 2004–2007.

Risk Parameter	Ship Category				
	Handy (≤ Handymax)	Panamax	Aframax	Suezmax	VLCC
No. of Ships	2500	299	712	250	478
No. of Years	4	4	4	4	4
Ship-years	10000	1196	2848	1000	1912
No. of accidents	(37 + 18) = 52	(11 + 5) = 16	(4 + 1) = 5	(8 + 1) = 9	(0 + 3) = 3
No. of accidents per ship-year	0.0052	0.0134	0.0017	0.0090	0.0016
Total oil-spill (tons)	(2006 + 25) = 2031	(0 + 70) = 70	0	(1055 + 0) = 1055	(0 + 9000) = 9000
Total oil-spill per accident (tons/ accident)	39.06	4.37	0	117.2	3000
Oil-spill Risk (tons/ ship-year)	0.203	0.058	0	1.055	4.800

Note: Accidents = All groundings and contacts.

On the basis of the aforementioned data and assumptions and using expression (3), the ship which can successfully perform the obstacle avoidance manoeuvre was found to be limited to a length of:

$$L_S = 1/4 \times [R_N - (T_H \times V_S) - (T_H \times V_S)]$$

$$= 1/4 \times [900 - (10 \times 7.2) - (5.1 \times 7.2)] = 197.8 \text{ m.}$$

This length covers all ship sizes up to and including the Handymax category (namely all the Handy ships), whereas for the Panamax, Suezmax and VLCC (and ULCC) categories there is not adequate time (or distance) available to avoid the underwater obstacle detected by the 900 m sonar. Using expression (1), it was found that the minimum sonar detection ranges adequate for avoiding underwater obstacles in the case of Aframax ($L_S = 250$ m), Panamax and Suezmax (average $L_S = 300$ m) and VLCC ($L_S = 340$ m) oil tankers are equal to 1108, 1295 and 1457 m, respectively.

3.2 *Existing oil-spill risk.* Irrespective of accident type and location, the highest (by far) oil-spill risk was found to be associated with the VLCC category, followed by that of the Suezmax, Handy and Panamax fleets in decreasing order, whereas the accidents of Aframax ships produced no oil spillage (Table 1).

The oil-spill risk plot shown in Figure 3 provides an indication of the clear need for risk control for the VLCC, Suezmax and Handy ships, as these categories lie above the As Low As Reasonably Practicable (ALARP) region, whereas the risk associated with the Panamax category appears to be tolerable as it lies within the ALARP region (although close to its upper limit). The ALARP boundaries were based and drawn according to the research work conducted by McGregor et al (2009) on the oil-spill risk of the Aframax fleet.

Furthermore, taking into account that the use of any forward-looking sonar is most suitable for detecting sharp (not sloping) changes of the seafloor, the current approach focuses on the obstacle avoidance and the oil-spill risk reduction potential of the sonar with reference to hard groundings and contacts. Concentrating on this particular accident record, the analysis shows that the existing oil-spill risk of Handy ships is

Table 2. Oil-spill risk due to hard powered groundings and contacts during 2004–2007.

Risk Parameter	Ship Category		
	Handy (\leq Handymax)	Suezmax	VLCC
No. of Ships	2500	250	478
No. of Years	4	4	4
Ship-years	10000	1000	1912
No. of accidents	30	8	3
No. of accidents per ship-year	0.003	0.008	0.0016
Total oil-spill (tons)	833	1055	9000
Total oil-spill per accident (tons/accident)	27.8	131.9	3000
Oil-spill Risk (tons/ship-year)	0.084	1.055	4.800

Note: Accidents = All hard groundings and contacts.

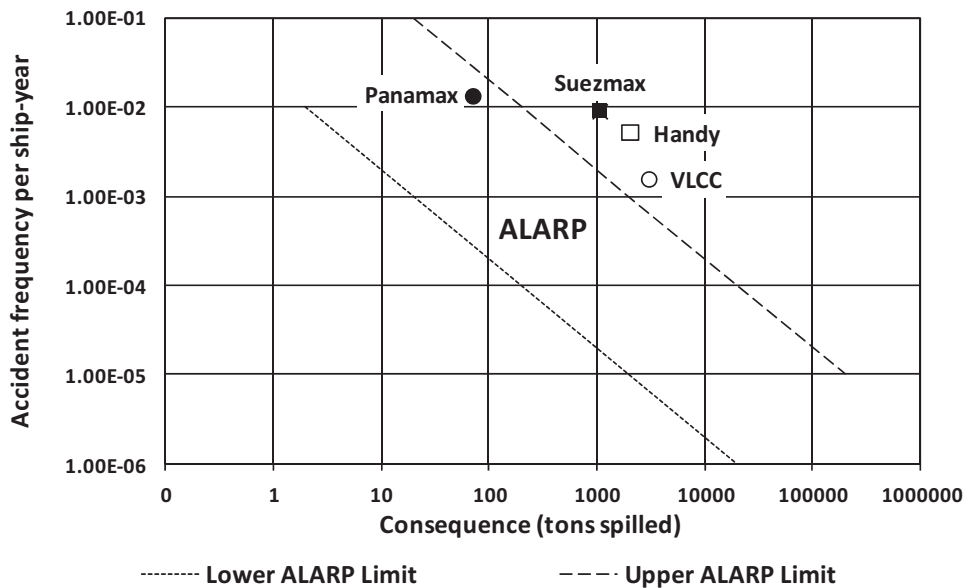


Figure 3. Oil-spill risk plot and ALARP region.

reduced by 58.6% and that of Panamax becomes negligible, whereas that of the VLCC and Suezmax categories remains unaltered (Table 2).

3.3 Oil-spill risk reduction. The technical reliability of the sonar system depends upon the operation of its hardware or software components and the quality of the detection signal. More analytically, hardware failure involves the breakdown of the “wet” or “dry” parts of the equipment during the appearance of the obstacle, the former part being associated with the hull-mounted unit (mainly the hydrophone) and the latter with the signal processing and output (e.g. alarm) unit. Through reference to available research on sonar failure rates, the Mean Time Between Failures (MTBF) for the “wet” and “dry” hardware parts was assumed to be equal to 40,000 and 6000 hours, respectively (ELAC Nautik, 2011; Li, 2011), whereas the MTBF for the sonar’s software failures was taken to be equal to 1000 hours (Hoppe, 2001).

Also, assuming the Mean Time To Repair (MTTR) for both “wet” and “dry” parts to be equal to 48 hours, the total probability that the system will be down during the appearance of an obstacle was found to be 1.1%. Furthermore, the probability that the system will not receive an adequate signal in any of the three successive pings (assuming a 50% detection probability for each ping) was estimated to be 13.6%. According to the FTA (Figure 2), the probability that the sonar system will technically fail to detect the obstacle was found to be equal to 14.6%.

With regard to the human reliability of the sonar system, the probability that the bridge crew will fail to respond effectively to a verified detection of an obstacle ahead of the ship was found to be equal to 5.0%, based upon the individual task failure data provided through the NARA and CREAM techniques (Chandler et al., 2006).

Therefore, the combined (technical and human) failure probability of the sonar system was estimated at 18.9%. Alternatively, the system presents a combined reliability of 81.1% which is the product of the reliability of its technical (85.4%) and human (95.0%) component.

Finally, the obstacle shape may be such that the ship will be unable to complete the circle manoeuvre necessary for its avoidance within the space available. Based upon the historical record of Handy ships which encountered obstacles of this type, the probability of such occurrence was estimated to be 13.3%.

The overall probability that the sonar-equipped Handy ships will suffer a powered grounding either due to sonar system failure or due to the shape of the obstacle was found to be equal to 29.7%. This represents an overall improvement of powered grounding avoidance of 70.3% and with the existing oil-spill risk being equal to 0.084 tons/ship-year (Table 2), the associated oil-spill risk reduction, ΔR, for a Handy newbuilding with a useful life of 25 years was estimated at 1.48 tons per ship.

Following the same methodology, the reduction of the grounding probability due to the installation of the extended detection range sonar systems on Suezmax and VLCC ships was found to be equal to 63.0% and 58.1%, respectively. Therefore, taking into account the existing oil-spill risk for these categories (Table 2), the oil-spill reduction potential offered by the sonar system for Suezmax and VLCC ships with a useful lifespan of 25 years (i.e. on new build ships) was found to be 15.2 and 61.8 tons per ship, respectively.

3.4 *Sonar cost-effectiveness.* The purchase cost of the commercially available and technically suitable sonar for the Handy category was quoted at 172,000 USD per ship (from a personal communication with George Papanikolaou of GP ENGINEERING, exclusive representative of FARSounder Inc. 3D Sonar Systems in Greece) and is assumed to be paid in full on completion of the sonar installation. The annual operating cost is comprised of maintenance and personnel training and is currently estimated at 2812 USD per ship (Vanem et al., 2007), whereas its Net Present Value (NPV) is based on the useful life of a new build ship (i.e. 25 years) and a constant annual depreciation rate of 5%. The consideration of these initial and running costs for the sonar system presents an overall cost, ΔC, equal to 220,539 USD per ship. Taking into account that the oil-spill risk reduction, ΔR, offered to the Handy category by this sonar system is 1.48 tons per ship, expression (4) becomes:

$$\begin{aligned} \text{CATS} &= 80,000 \text{ USD/ton} \geq \Delta C/\Delta R \\ &= 220,539/1.48 = 149,013 \text{ USD/ton} \end{aligned}$$

Table 3. Technical and cost-effectiveness of sonar-systems.

Parameter	Ship Category		
	Handy (\leq Handymax)	Suezmax	VLCC
Existing oil-spill risk (tons/ship-year)	0.084	1.055	4.800
Sonar detection range (m)	900	1295	1457
Accident reduction potential (%)	70.3	63.0	58.1
Oil-spill risk reduction (tons/ship-year)	0.059	0.609	2.472
ΔC (USD/ship)	220,539	1,328,800**	5,577,600**
Oil-spill risk reduction, ΔR , (tons/ship)*	1.48	16.61	69.72
$\Delta C/\Delta R$ (USD/ton)	149,013	80,000**	80,000**

* Based upon a ship's useful life of 25 years.

** Maximum ΔC for $\Delta C/\Delta R = \text{CATS} = 80,000$ USD/ton.

Therefore, although the commercially available 900 m range sonar system was found to be technically adequate for obstacle avoidance by Handy ships, it was not proved to be cost-effective in reducing the oil-spill risk associated with their powered groundings. For this ship category, the sonar system would have been cost-effective if the NPV of its overall cost was at least 46.3% lower, i.e. less than 118,400 USD/ship. However, this figure is significantly lower (by 31.2%) than the quoted purchase price for the sonar alone (172,000 USD/ship) and it will be very difficult to meet in the near future. Alternatively, the cost-effectiveness of the sonar would have been justified if the oil-spill reduction potential, ΔR , were to be at least 2.76 tons/ship (i.e. an improvement of 86.5%) which is also very unlikely, considering the currently observed low oil-spill risk (0.084 tons/ship-year) for this ship category and/or the already high (70.3%) reliability of the sonar system.

Similarly, using expression (4), the extended range sonar systems for the Suezmax and VLCC categories were found to fulfill the CATS criterion for a maximum overall cost of 1,328,800 and 5,577,600 USD per ship, respectively. It should be noted at this point that cost associated with the detection range capability of the sonar is mainly included in its purchase cost, which with reference to the 900 m range sonar represents about 80% of its overall cost. Therefore, it can be assumed that the technology necessary to increase the sonar detection range by 43.9% (for Suezmax) and 61.9% (for VLCC) may be easily offered through a six-fold and 25-fold increase of purchase cost, respectively.

A summary for the technical and cost-effectiveness of the sonar systems for the Handy, Suezmax and VLCC categories is shown in Table 3.

It is important to mention that if the sonar system is not found to be cost-effective with reference to a new build ship, the assessment of its cost-effectiveness on existing ships becomes meaningless because the potential of oil-spill risk reduction, ΔR , diminishes as the remaining (useful) life of the ship is reduced.

Finally, on the basis of the aforementioned results, it became evident that the inevitable uncertainties involved in the current analysis must be very significant in order to decisively alter the results. Therefore, the conducted techno-economic assessment of the sonar system as a risk control option of oil-spills due to powered groundings of oil tankers is considered to be adequately reliable.

4. CONCLUSIONS. Ship groundings (including contacts) are the prime cause of large oil-spills in the marine environment and amongst them, those associated with oil tankers of the Handy, Suezmax and VLCC size stand at the forefront of oil-spill risk control. According to the FSA approach, the introduction of any risk control option in shipping should be examined for its cost-effectiveness in averting accidental damage and for oil-spill risk control, CATS constitutes the appropriate criterion.

In this context, the currently available hull-mounted forward-looking sonar technology offers a navigational aid which, although capable for obstacle avoidance by small-sized (Handy) ships was not proved to be a cost-effective option for reducing the oil-spill risk of these ships. More specifically, the overall cost of the sonar in averting the spillage of one ton of oil was found to be equal to around 150,000 USD, which is almost double than the acceptance limit set by the CATS figure of 80,000 USD. In contrast, longer-ranged sonar systems could be developed and offered at a much higher purchase price than current systems; despite this higher cost, they will still be cost-effective in the reduction of the high oil-spill risk associated with large-sized oil tankers.

REFERENCES

- ABS (2006). *Guide for vessel maneuverability*. American Bureau of Shipping, ABS Plaza, 16855 Northchase Drive, Houston, TX 77060 USA.
- Amrozowicz, M., Brown, A.J. and Golay, M. (1997). A Probabilistic Analysis of Tanker Groundings. *7th International Offshore and Polar Engineering Conference, ISOPE-97*, May, 25–30, Honolulu, Hawaii, USA.
- Amrozowicz, M.D. (1996). *The Quantitative Risk of Oil Tanker Groundings*. Naval Engineer and Master of Science in Ocean Systems Management Thesis, Dept. of Ocean Engineering, Massachusetts Institute of Technology, USA.
- Antao, P. and Guedes Soares, C. (2006). Fault-tree Models of Accident Scenarios of RoPax Vessels. *International Journal of Automation and Computing*, **2**, pp. 107–116.
- Arsenie, P. and Hanzu-Pazara, R. (2008). Human Errors and Oil Pollution from Tankers. *TransNav – International Journal on Marine Navigation and Safety of Sea Transportation*, **2**:4, pp. 409–413.
- Brown, A. and Haugene, B. (1998). Assessing the Impact of Management and Organizational Factors on the Risk of Tanker Grounding. *8th International Offshore and Polar Engineering Conference, ISOPE-98*, May, 24–29, Montreal, Canada.
- Celik, M., Lavasani, S.M. and Wang, J. (2010). A risk-based modelling approach to enhance shipping accident investigation. *Safety Science*, **48**:1, pp. 18–27.
- Chandler, F., Chang, J., Mosleh, A., Marble, J., Boring, R. and Gertman, D. (2006). *Human Reliability Analysis Methods Selection Guidance for NASA*, NASA/OSMA Technical Report, NASA Headquarters Office of Safety and Mission Assurance, 300 E Street SW, Washington, DC 22039, http://www.hq.nasa.gov/office/codeq/rm/docs/HRA_Report.pdf
- Cockcroft, N. and Lameijer, J.N.F. (2012). *A Guide to the Collision Avoidance Rules*. 7th edition, ISBN-10: 0080971709, Butterworth-Heinemann.
- DNV (2006). *FSA Study on ECDIS/ENCs: Details on Risk Assessments and Cost Benefit Assessments*. MSC 81/INF.“Y”. Submitted by Denmark and Norway.
- ELAC Nautik (2011). *Navigation and Detection Sonar VANGUARD Optimum Protection for Surface Vessel*, L-3 Communications ELAC Nautik GmbH, Neufeldtstrasse 10, 24118 Kiel, Germany.
- Guassardo, G. and Demaria, G. (1998). *Formal Safety Assessment Study on the Effects of Introducing Helicopter Landing Area (HLA) on Cruise Ships*. Report TR RIS 98004. Registro Italiano Navale (RINA).
- Hoppe, W. (2001). *An Industry Applicable Approach to predict Software Reliability*, *13th Workshop Testmethods and Reliability of Circuits and Systems*, February, 18–20, Miesbach, Germany.
- IMO (2002). Resolution “Standards for Ship Maneuverability”, MSC.137(76) 4 December 2002.
- IMO (2008) Resolution A.741 (18), International Management Code for the Safe Operation of Ships and for Pollution Prevention, 1993, as amended by IMO Resolution MSC.273 (85), 2008.

- Kontovas, C., Psaraftis, H. and Ventikos, N. (2010). An Empirical Analysis of IOPCF Oil Spill Cost Data. *Marine Pollution Bulletin*, **60**:9, pp. 1455–1466.
- Kontovas, C. and Psaraftis, H. (2009). Formal Safety Assessment: A Critical Review. *Marine Technology*, **46**:1, pp. 45–59.
- Kristiansen, S. (2004). *Maritime Transportation – Safety Management and Risk Analysis*. ISBN 0750659998, p. 528. Elsevier Butterworth–Heinemann, London.
- Li, Q. (2011). *Digital Sonar design in Underwater Acoustics: Principles and Applications*. ISBN 10: 3642182895, Hangzhou: Zhejiang University Press, Berlin, New York: Springer.
- McGregor, J., Moore, C., Downes, J. and Aksu, S. (2009). Evaluation of the Environmental Risk of Aframax Tankers, *3rd World Maritime Technical Conference, WMTC 2009*, Jan. 21–24, Mumbai, India.
- Nash, N. (2008). A Modern Day Cruise Ship Master’s “Captain’s Navigation Orders”, *The Journal of Navigation*, **61**:3, pp. 547–556.
- Norris, A. (2007). AIS Implementation – Success or Failure? *The Journal of Navigation*, **60**:1, pp. 1–10.
- Psaraftis, H. (2008). Environmental Risk Evaluation Criteria. *WMU Journal of Maritime Affairs*, **7**:2, pp. 409–427.
- Pсарros, G., Skjong, R. And Vanem, E. (2011). Risk acceptance criterion for tanker oil spill risk reduction measures. *Marine Pollution Bulletin*, **62**:1, pp. 116–127.
- Schröder-Hinrichs, J.U. (2010). Human factors in the maritime world: are we keeping up to speed? *WMU Journal of Maritime Affairs*, **9**:1, pp. 1–3 (Editorial).
- Skjong, R., Vanem, E., Endresen, O. (2007). *Risk Evaluation Criteria*, SAFEDOR Report., SAFEDOR-D-4.5.2-2007-10-24-DNV-RiskEvaluationCriteria-rev-3.0.
- Skjong, R. and Wentworth, B.H. (2001). *Formal Safety Assessment of Life Saving Appliances for Bulk Carriers*. FSA/LSA/BC, MSC 74/5/5. Submitted by Norway and ICFTU.
- Skjong, R., Adamcik, P., Eknes, M.L., Gran, S. and Spouge, J. (1997). *Formal Safety Assessment of Helicopter Landing Area on Passenger Ships as a Safety Measure*. DNV Report 97-2053.
- TAIC. (2012). *Interim Report Marine Inquiry 11-204: Containership MV Rena grounding on Astrolabe Reef on the 5th of October, 2011*. Report release date: 8th March, 2012. <http://www.taic.org.nz/ReportsandSafetyRecs/MarineReports/tabid/87/language/en-US/Default.aspx>
- Tan, C., Sutton, R. and Chudley, J. (2004a). Collision avoidance systems for autonomous underwater vehicles, part a: a review of obstacle detection. *Journal of Marine Science and Environment*, Part C, No C2, pp. 39–50.
- Tan, C., Sutton, R. and Chudley, J. (2004b). Collision avoidance systems for autonomous underwater vehicles, part b: a review of obstacle avoidance. *Journal of Marine Science and Environment*, Part C, No C2, pp. 51–62.
- Tzannatos, E. (2010). Human Element and Accidents in Greek shipping. *The Journal of Navigation*, **63**:1, pp. 119–127.
- Vanem, E. and Ellis, J. (2010). Evaluating the cost-effectiveness of a monitoring system for improved evacuation from passenger ships. *Safety Science*, **48**:6, pp. 788–802.
- Vanem, E., Endresen, O., Skjong, R. (2008). Cost-effectiveness criteria for marine oil spill preventive measures. *Reliability Engineering and System Safety*, **93**:9, pp. 1354–1368.
- Vanem, E., Eide, M.S., Gravir, G. and Skjong, R. (2007). Cost-Effectiveness of Preventing Grounding with ECDIS, *4th International Conference on Collision and Grounding of Ships, ICCGS 2007*, September, 9–12, Hamburg, Germany.
- Zimmerman, M.J. and Miller, J.H. (2008). 3-D forward looking sonar with fixed frame of reference for navigation. US Patent No. 7,355,924.
- Zimmerman, M.J. and Miller, J.H. (2002). *Interferometric Imaging Method Apparatus and Systems*, US Patent App. 10/177,889.