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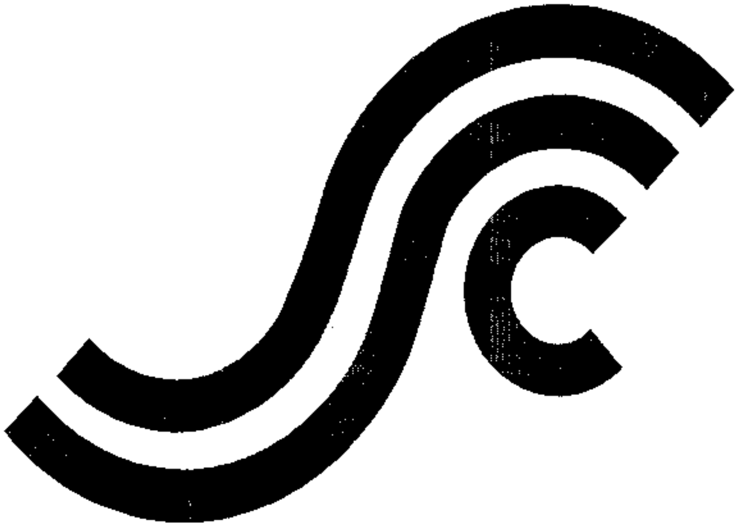
# SSC-417

# RISK-BASED LIFE CYCLE MANAGEMENT OF SHIP STRUCTURES



SHIP STRUCTURE COMMITTEE
2000

# SHIP STRUCTURE COMMITTEE

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# PREDICTION OF STRUCTURAL RESPONSE IN GROUNDING: APPLICATION TO STRUCTURAL DESIGN

Past regulatory actions to mitigate oil pollution in the case of a collision or grounding have been focusing on subdivision of tankers, but it is generally recognized that the ship structural design is also important as it affects the extent of damage in an accident. The work presented in this report evaluated the applicability of a selected simplified method to structural design and regulatory development. The method was selected based on a review of past research work. A sensitivity analysis was carried out to study the effect of changes in input parameters on the damage results. Then, a number of structural modifications were analyzed in four grounding scenarios using the selected method. The final step was to analyze structural damage and resulting outflow in 10,000 hypothetical grounding scenarios in US waters. The approach was used to compare the performance of single- and double-hull tankers and to study the effect of simple structural modifications on outflow results. Conclusions were made on the state-of-the art of the development of simplified methods, as well as on the applicability of the selected method for design and regulatory work.

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**16. Abstract**

Past regulatory actions to mitigate oil pollution in the case of a collision or grounding by design have been focusing on subdivision of tankers, but it is generally recognized that the ship structural design is also important as it affects the extent of damage in an accident. The work presented in this report evaluated the applicability of a selected simplified method to structural design and regulatory development. The method was selected based on a review of past research work. A sensitivity analysis was carried out to study the effect of changes in input parameters on the damage results. Then a number of structural modifications were analyzed in four grounding scenarios using the selected method. The final step was to analyze structural damage and resulting outflow in 10,000 hypothetical grounding scenarios in US waters. The approach was used to compare the performance of single- and double-hull tankers and to study the effect of simple structural modifications on outflow results. Conclusions were made on the state-of-the art of the development of simplified methods as well as on the applicability of the selected method for design and regulatory work.

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# CONVERSION FACTORS
## (Approximate conversions to metric measures)

| To convert from | to | Function | Value |
|---|---|---|---|
| **LENGTH** | | | |
| Inches | meters | divide | 39.3701 |
| inches | millimeters | multiply by | 25.4000 |
| feet | meters | divide by | 3.2808 |
| **VOLUME** | | | |
| cubic feet | cubic meters | divide by | 35.3149 |
| cubic inches | cubic meters | divide by | 61,024 |
| **SECTION MODULUS** | | | |
| inches $^2$ feet $^2$ | centimeters $^2$ meters $^2$ | multiply by | 1.9665 |
| inches $^2$ feet $^2$ | centimeters $^3$ | multiply by | 196.6448 |
| inches $^4$ | centimeters $^3$ | multiply by | 16.3871 |
| **MOMENT OF INERTIA** | | | |
| inches $^2$ feet $^2$ | centimeters $^2$ meters | divide by | 1.6684 |
| inches $^2$ feet $^2$ | centimeters $^4$ | multiply by | 5993.73 |
| inches $^4$ | centimeters $^4$ | multiply by | 41.623 |
| **FORCE OR MASS** | | | |
| long tons | tonne | multiply by | 1.016 |
| long tons | kilograms | multiply by | 1016.047 |
| pounds | tonnes | divide by | 2204.62 |
| pounds | kilograms | divide by | 2.2046 |
| pounds | Newtons | multiply by | 4.4482 |
| **PRESSURE OR STRESS** | | | |
| pounds/inch $^2$ | Newtons/meter $^2$ (Pascals) | multiply by | 6894.757 |
| kilo pounds/inch $^2$ | mega Newtons/meter $^2$ (mega Pascals) | multiply by | 6.8947 |
| **BENDING OR TORQUE** | | | |
| foot tons | meter tons | divide by | 3.2291 |
| foot pounds | kilogram meters | divide by | 7.23285 |
| foot pounds | Newton meters | multiply by | 1.35582 |
| **ENERGY** | | | |
| foot pounds | Joules | multiply by | 1.355826 |
| **STRESS INTENSITY** | | | |
| kilo pound/inch $^2$ inch $^{1/2}$ (ksi.... in) | mega Newton MNm $^{3/2}$ | multiply by | 1.0998 |
| **J-INTEGRAL** | | | |
| kilo pound/inch | Joules/mm $^2$ | multiply by | 0.1753 |
| kilo pound/inch | kilo Joules/m $^2$ | multiply by | 175.3 |

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# 1. INTRODUCTION

Fortunately groundings of tankers are infrequent, but the economic and environmental consequences of even a single event can be significant. The most effective way to minimize these consequences is to prevent grounding accidents. Since the Exxon Valdez grounding in 1989, preventive measures such as improved navigational aids and traffic control, use of escort tugs, increased crew training and improved working conditions have been investigated, and regulatory measures have been put in place requiring implementation of such measures. Despite these actions, not all grounding accidents can be prevented, and procedures that mitigate the consequences of spills must be considered (e.g., crew actions, vessel design, and effective spill response).

Past regulatory actions to mitigate oil pollution in the case of a collision or grounding by design have been focusing on subdivision of tankers, but it is generally recognized that the ship structural design is also important as it affects the extent of damage in an accident. However, the technology to account for accidental loads in structural design has not been available for designers or regulators, although a significant amount of work has been done in this area in the past ten years.

After the Exxon Valdez incident, the focus of the grounding research has been first to understand the mechanics of grounding and then to develop methods that could be used in design and regulatory development. The research has resulted in 1.computational tools, which use finite element analysis coupled with ship motion analysis, and 2.simplified approaches, which are based on analytical or empirical formulations describing the global and local structural behavior as well as the global behavior of the vessel relative to the obstruction. Few applications to evaluate structural designs using these methods have been published so far.

Since the computational tools using nonlinear finite element analysis are time consuming, their application to analyze a large number of grounding cases is not practical. A simplified methodology to predict structural response in grounding is needed for regulatory and design work. The objective of the work presented in this report was to evaluate the applicability of existing simplified methods to structural design and regulatory development.

First past research work was reviewed and summarized. A simplified method was then selected for further evaluation. The program DAMAGE developed by Joint MIT-Industry Project on Tanker Safety under the direction of Professor Wierzbicki was selected for this study. The use of other simplified approaches was considered, but DAMAGE is the only one available as software, and it has the widest range of applicability of published simplified methods. The performance of DAMAGE in predicting structural response in three validation cases was investigated. A sensitivity analysis was carried out to study the effect of changes in input parameters on the damage results. Then a number of structural modifications were analyzed in four grounding scenarios using the selected method. The final step was to analyze structural damage and resulting outflow in 10,000 hypothetical grounding scenarios in US waters. The approach was used to compare the performance of single- and double-hull tankers and to study the effect of simple structural modifications on outflow results.

Conclusions were made on the state-of-the art of the development of simplified methods as well as on the applicability of the selected method for design and regulatory work. Finally recommendations were made for future work.

## 2. REVIEW OF PAST WORK

Structural response in grounding involves the global behavior of the vessel relative to the obstruction as well as the global and local structural behavior. The past research summarized below has provided insight into the significance of the various factors and has advanced the development of simplified methods applicable to structural design and regulatory use.

The research on structural behavior in grounding started with the empirical work of Card in the 1970's [Card 1975], and has since then evolved into large numerical simulations and experiments, and finally to development of simplified methods applicable to structural design.

Card's empirical work was based on a survey of 30 grounding incidents in the U.S. waters from January 1969 to April 1973. In each of these cases, the extent of damage was analyzed to determine the effectiveness of a double bottom in reducing pollution. He concluded that fitting tankers with a B/15 high double bottom would have prevented 27 of the 30 oil spills.

A few years later, Vaughan [1978] proposed a simplified method to predict energy absorption in a grounding damage. Similar to a well-known method developed by Minorsky for collision [Minorsky 1959], the Vaughan method is based on the assumption that the energy absorption can be characterized by the volume of distortion and by the area of torn plate.

It wasn't until a decade later following the Exxon Valdez accident that ship structural response in grounding became an active area of research. The focus of the research has been to improve tanker designs to prevent and mitigate oil outflow in grounding.

In 1991, the Japanese Association for the Structural Improvement of the Shipbuilding Industry (ASIS) started a seven-year research project on "Protection of Oil Spills from Crude Oil Tankers." This research project has supported large-scale grounding experiments [Ludolphy, Wevers and Vredeveldt 1995], model grounding experiments [Kuroiwa, et. al., 1992], and numerical simulations [Kuroiwa 1996]. The project developed the finite element method coupled with ship motion analysis to a level where a fairly accurate simulation of a real grounding accident is possible. However, the application of the finite element method to study design alternatives is not practical, except in research and development environment, because the analysis is time consuming and it requires a high level of expertise.

Wang, Ohtsubo and Liu [1997] proposed a simplified method for calculating the grounding strength of bottom structures. Their method considers four primary failure modes: stretching failure of transverse structures, denting, tearing and concertina tearing failure of bottom plates. A relatively simple mathematical formulation is given for each failure mode and the grounding damage is calculated by combining the failure modes. Global dynamics of the ship are simplified: only horizontal motions are considered. Resistance during grounding is considered to be periodic following the periodicity of the structure: a period lasts from one transverse structure to the next. The method is elegant in its simplicity, but the assumptions in the method limit its direct application to raking type damage only.

In the United States, the Carderock Division of the Naval Surface Warfare Center (NSWCCD) has conducted grounding experiments, and the MIT-Joint Industry Project on Tanker Safety has developed computationally efficient models of tanker bottom structural members.

The NSWCCD tests were carried out on a conventionally framed double-hull design and on the Advanced Double Hull (ADH) design (ADH is a uni-directional design) [Rodd 1996]. The results from the experiments can be used for validation of simplified methods.

The Joint MIT-Industry Project on Tanker Safety (1992–2000) carried out research on plastic energy dissipation by the ship's structure, fracture and tearing processes of steel plates, and the contact and friction phenomena between the obstruction and stiffened panels. Results from these studies were used to develop and provide validation for the computational models used in the program DAMAGE (Damage Assessment of Grounding Events) [Little, et. al., 1996].

The theory of grounding on a conical rock (pinnacle) adopted by DAMAGE is largely based on the doctoral dissertation of Simonsen at the Technical University of Denmark

[Simonsen 1997]. Simonsen's work presents mathematical models for grounding response on soft seabed and on a rock pinnacle. An earlier work at the same university by Pedersen [1994] studied a vessel grounding on sand, clay and rock sea bottoms.

In 1996, International Conference on Design and Methodologies for Collision and Grounding Protection of Ships was held in San Francisco. In this conference much of the research described above was reported and discussed by the experts in the field. The 2nd International Conference on Collision and Grounding of ships was held in July 2001 in Copenhagen, Denmark. New research since 1996 was presented in this conference. While the focus of the first conference had been on prediction of structural mechanics in ship grounding and collision, the second conference had a number of papers on accident scenarios and their probability of occurrence, as well as on risk analysis and rule development. Software for grounding and collision risk analysis, GRACAT, developed at the Technical University of Denmark was introduced. This software is available for research purposes and can be downloaded from web-site www.ish.dtu.dk/GRACAT. The European Union funded research on collision and grounding, which is based on more general principles of risk-based design, was also discussed at the conference [Vassalos 2001], [Otto et. al., 2001], [Vredeveldt 2001].

Most of the papers on structural mechanics presented work on collision rather than grounding. Two papers on grounding mechanics dealt with new types of structures and materials. Naar, Kujala, Simonsen and Ludolphy compared crashworthiness of four different double-bottom structures indented by a rigid cone [Naar et. al., 2001]. The finite element analysis was done by computer program LS-DYNA. The structures included a conventional double-bottom structure, a structure with hat-profiles and T-profiles, a structure with a sandwich panel as the bottom plating, and a structure with hat profiles on the outer and inner bottom. The study found that the use of hat-profiles increased the energy absorption capability of the structure without a large increase in steel weight. Amdahl and Stornes studied energy dissipation in welded structures subjected to axial crushing by experiments and simulations using LS-DYNA [Amdahl et. al., 2001].

Lax and Kujala reported on innovative model test technique to investigate the impact of global ship motion in grounding accidents [Lax and Kujala, 2001]. In the tests the bottom of a wooden ship model was replaced by urethane to simulate the behavior of a typical double bottom with respect to the average grounding force and damage extent.

Louka and Samuelides presented a methodology to provide a relationship between possible damage cases and their consequences using simple analytical approaches [Louka and Samuelides, 2001].

A paper by Wang, Spencer and Chen reviewed the state-of-the art of the research on both collision and grounding [Wang et. al., 2001]. This paper provides a comprehensive bibliography on standards for design against collision and grounding, definition of accident scenarios, evaluation approaches, and acceptance criteria.

## 3. DAMAGE

The program DAMAGE was selected for further testing and analysis, because it has the widest range of applicability of the published simplified methods. It is available as a user-friendly program that allows prediction of structural damage for a large range of structural arrangements and grounding scenarios. It is limited in terms of the type of the obstruction (pinnacle only) and the type of grounding (powered, head-on grounding only), and the structural model includes the cargo block only.

The theory behind the models in DAMAGE can be found in [Simonsen and Wierzbicki 1996] and in [Simonsen and Wierzbicki 1997]. Simonsen presented verification of the theory by comparing calculated results with the US Navy 1/5-scale grounding experiments and with an actual grounding of a VLCC [Simonsen 1998]. The predicted energy absorption and the penetration of fracture were compared with the experimental measurements. The difference was in the order of 5 percent for the energy absorption and 15 percent for the fracture penetration. A fairly good agreement was found between predicted and actual observed damage extents. The importance of taking into account ship motions was illustrated.

The software DAMAGE contains closed form solutions for the resistance of each structural element. It is a PC-based program operating in the Windows environment. The ship's structure is modeled by selecting typical ship structural members from a menu. The model includes the complete cargo block without the bow and the stern of the ship. The computation is carried out in a stepwise manner by moving the ship forward and, at each time step, finding the rock penetration and static equilibrium of the ship. The program can be run in a coupled or uncoupled mode. The coupled mode takes into account ship motions. The uncoupled mode ignores the effect of ship motions. In the coupled mode, sway and yaw motions are neglected. Heave, roll and pitch motions are calculated based on static equilibrium using a simplified model. Surge motion is calculated based on energy balance. The motions, rock penetration, structural reaction force and plating status (ruptured or not) are output for each time step.

The ground is characterized by the rock tip radius and semi-apex angle, which define the conical shape of the rock. The ship-ground interaction is defined by the rock eccentricity (i.e. the distance from centerline), rock elevation, ship velocity, trim angle and friction coefficient. Global ship parameters include displacement, breadth of flat bottom, transverse and longitudinal metacentric height, longitudinal center of floatation, and waterplane area coefficient. Structural design is defined in detail on the bottom structure, and material characteristics are defined by a stress-strain curve and rupture strain.

Brown and his students at MIT used DAMAGE to simulate grounding damage data for a MARPOL tanker [Sirkar, et. al., 1997]. They developed probability density functions for damage extents based on the generated data and compared them with the probability density functions used in "Interim Guidelines for the Approval of Alternative Tanker Designs under Regulation 13F of Annex I of MARPOL 73/78" (*IMO Guidelines*) [IMO 1996]. The agreement between the points generated by DAMAGE and the functions in *IMO Guidelines* was good with some exceptions (for example the damage width prediction was not satisfactory). In a 1998 paper [Rawson, et. al. 1998] they presented a similar analysis for a double-hull tanker and a mid-deck tanker and demonstrated the use of the program in a methodology to compare tanker designs.

Brown's work illustrated the potential that the program DAMAGE has for use in a design and regulatory environment. This report presents further validation work for the program as well as an evaluation of its performance in comparing structural alternatives.

### 3.1. Validation of Damage

It has not been possible to fully validate DAMAGE since sufficient data on actual grounding cases is not available. Validation cases were limited to the ones used in the past by Simonsen to verify his theory. The cases include a grounding of a VLCC off the coast of Singapore, large-scale tests in the Netherlands, and model tests at Carderock. It is recognized that more validation cases are needed to properly evaluate the applicability of DAMGE to predict structural response in various grounding scenarios.

The following sections describe the results of the validation studies and present conclusions on the applicability of DAMAGE to evaluate structural designs.

## VLCC Grounding

A VLCC grounded on the *Buffalo Reef* off the coast of Singapore on January 6, 1975. The speed of the vessel at the time of grounding was approximately 12 knots and the bottom rupture extended approximately 180 meters aft of the bow along the centerline. The width of the rupture varied from 3 to 5 meters. The depth of the indentation was 2 to 3 meters. The input for DAMAGE is shown in Table 3.1, and the output is shown in Table 3.2.

DAMAGE predicted the damage length quite accurately: the difference between the calculated damaged hull length of 177 meters and the observed damage length of about 180 meters is only 1.7%. However, since the actual transverse location of the rock is unknown, the effect of the changes in the rock eccentricity (e) was studied, and the results are shown in Figure 3.1.

Table 3.1: Principal Input for VLCC

| | | | |
|---|---|---|---|
| **LBP (m)** | 304 | **Beam (m)** | 53.4 |
| **Displacement (ton)** | 273,000 | **Draft (m)** | 19.8 |
| **Impact Velocity (knot)** | 12.0 | **Depth (m)** | 25.7 |
| **Rock Elevation (m)** | 4.40 | **Rock Tip Radius (m)** | 1.0 |
| **Rock Eccentricity (m)** | 5.0 | **Rock Semi-Angle (deg)** | 50 |

Table 3.2: Principal Output for VLCC

| | |
|---|---|
| **Run Mode** | Coupled |
| **Total Energy Dissipation ($10^9$ J)** | 5.475 |
| **Total Damaged Hull Length (m)** | 176.9 |
| **Damaged Width (m)** | 3.4-4.0 |
| **Maximum Penetration (m)** | 4.0 |

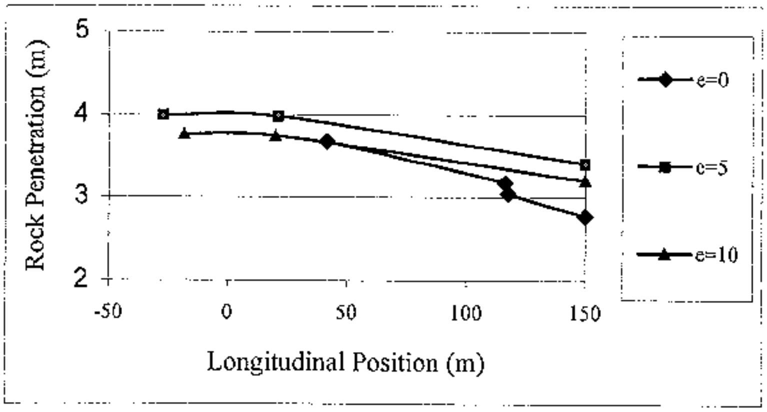

Figure 3.1: Rock Penetration as a Function of Rock Eccentricity

As the rock moves away from centerline the effect of ship motions increases. At e= 0 the damage length is 108 meters, and at e=10 meters the damage length is 168 meters.

Kuroiwa applied the finite element method to simulate the same grounding accident [Kuroiwa 1996]. He simulated about 15 seconds of the grounding. The simulated damage extent was reported to compare well with the observed damage extents. The simulation results (duplicated from Kuroiwa's paper) are used here in lieu of actual observations to compare with forces predicted by DAMAGE. Figures 3.2-3.4 present the comparison of DAMAGE results with the simulation results.

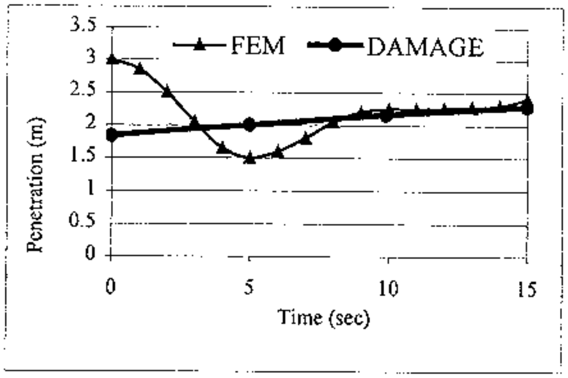

Figure 3.2: Vertical Penetration for DAMAGE and Simulation

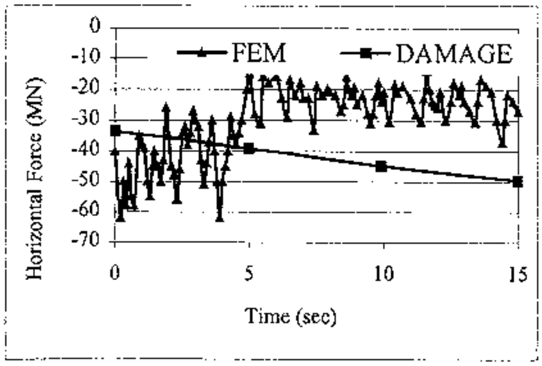

Figure 3.3: Horizontal Contact Force During Grounding

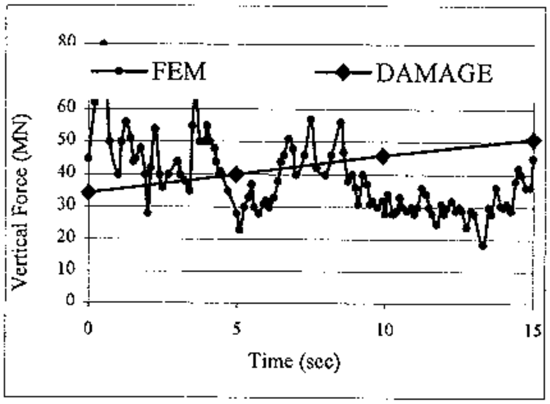

Figure 3.4: Vertical Contact Force During Grounding

It can be seen from the figures that DAMAGE neither predicts the minima and maxima of the forces nor the initial penetration predicted by simulations, but the average forces and penetration are in reasonable agreement with simulation results. The trend in the horizontal force predicted by DAMAGE is different from the one predicted by the finite element analysis

## *NSWCCD* Tests

The Carderock Division of the Naval Surface Warfare Center (NSWCCD) conducted a series of 1:5 scale grounding experiments on a conventional double-hull design and on a uni-direcitionally framed design [Rodd 1996]. The models, which consisted of two compartments, were attached to railcars. They were released down a ramp to strike an artificial rock. One of the models had a conventional double-hull design and the others had a uni-directional design with differences in stiffener spacing and plating thickness.

The test vehicle was trimmed to an angle so that the rock would enter the structure approximately 50mm below the inner bottom, and at the aft bulkhead the penetration would be equal to twice the double bottom height.

Results of the conventional double-hull test were compared with the results of the computer program DAMAGE. The DAMAGE input is shown in Table 3.3. Thickness of the transverse bulkheads is increased to account for the effect of stiffeners. Since the models were fixed to railcars, DAMAGE calculations were done in an uncoupled mode[1].

Figure 3.5 shows the comparison of the measured and the predicted horizontal force and Figure 3.6 shows the same comparison for the vertical force. DAMAGE prediction agrees remarkably well with the measured values, which were obtained from [Simonsen 1998].

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[1] In DAMAGE, the "coupled" calculation mode considers global motions (surge, heave, pitch, and roll), and the "uncoupled" mode ignores all ship motions except surge.

Table 3.3: Principal Data Used in DAMAGE for the Four Tests

| **Parameter** | NSWCCD |
|---|---|
| **Length Between Perpendiculars (m)** | 7.32 |
| **Breadth (m)** | 2.54 |
| **Displacement (tons)** | 223 |
| **Ship Velocity (knots)** | 14 |
| **Trim Angle (degree)** | 3.38 |
| **Rock Elevation (m)** | 0.375 |
| **Rock Tip Radius (m)** | 0.17 |
| **Rock Semi-Apex Angle (degree)** | 45 |
| **Double Bottom Height (m)** | 0.38 |
| **Inner Bottom Thickness (mm)** | 3.0 |
| **Shell Thickness (mm)** | 3.0 |
| **Plate Thickness of Girders (mm)** | 2.3 |
| **Plate Thickness of Floors (mm)** | 2.3 |
| **Transverse Bulkhead Thickness (mm)** | 6.0 |
| **Material Yield Strength (MPa)** | 283 |
| **Material Ultimate Strength (MPa)** | 345 |
| **Fracture Strain** | 0.22 |

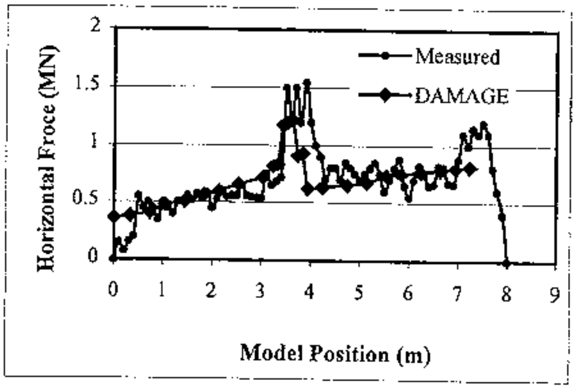


Figure 3.5: Horizontal Contact Force During Grounding

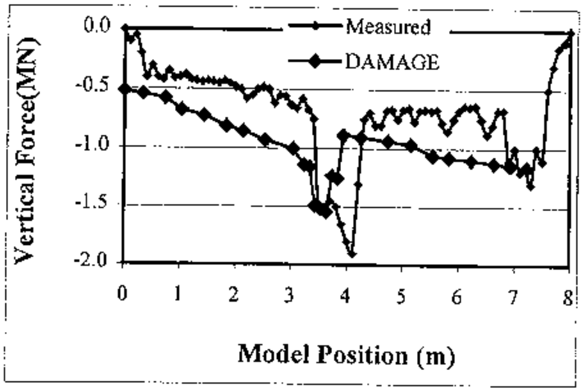


Figure 3.6: Vertical Contact Force During Grounding

## *ASIS* Tests

The Association for Structural Improvement of Shipbuilding Industry (ASIS) conducted large-scale grounding tests with an inland waterway tanker in the Netherlands in 1994 and 1995. A test section was attached to the tanker and run aground on an artificial rock. Input for DAMAGE is shown in Tables 3.4 and 3.5.

Table 3.4: ASIS Test Setup

| | | | |
|---|---|---|---|
| **Ship Length, L (m)** | 68.3 | **Test Section Double Bottom Height (mm)** | 750 |
| **Ship Beam, B (m)** | 9.4 | **Test Section Bottom Thickness (mm)** | 5 |
| **Rock Apex Angle (deg)** | 49 | **Test Section Inner Bottom Thickness (mm)** | 5 |
| **Rock Height (m)** | 1.5 | **Test Section Floor Spacing (mm)** | 1250 |
| **Rock Tip Radius (m)** | 0.60 | **Test Section Girder Spacing (mm)** | 3500 |
| **Test Section Length (m)** | 7.15 | **Test Section Stiffener Spacing (mm)** | 250 |
| **Test Section Beam (m)** | 5.5 | **Test Section Stiffener Depth (mm)** | 150 |

Table 3.5: ASIS Test 2 Grounding Scenario

| | |
|---|---|
| **Rock Elevation (m)** | 1.31 |
| **Impact Velocity (m/s)** | 4.06 |
| **Mass (ton)** | 678.8 |
| **Trim (deg)** | 1.208 |
| **Rock Eccentricity (m)** | 1.75 |

The results calculated by the program DAMAGE were compared with experimental results. Figures 3.7-3.9 show the comparison of the results for ASIS test 2. Global ship motion effects are included in the calculations.

DAMAGE does not predict minima or maxima for either the penetration or the forces, but it seems to predict the average values satisfactorily. The same observation was made when DAMAGE results were compared with simulations for the VLCC grounding.

Large differences in the penetration at the initial stages of grounding are due to simplifications in the global motion calculations.

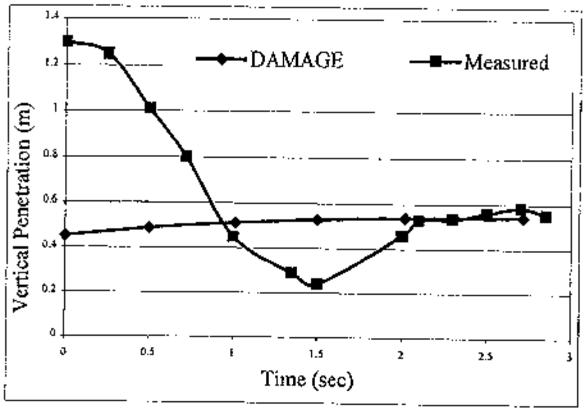


Figure 3.7: Comparison of Vertical Penetration (ASIS Test No.2)

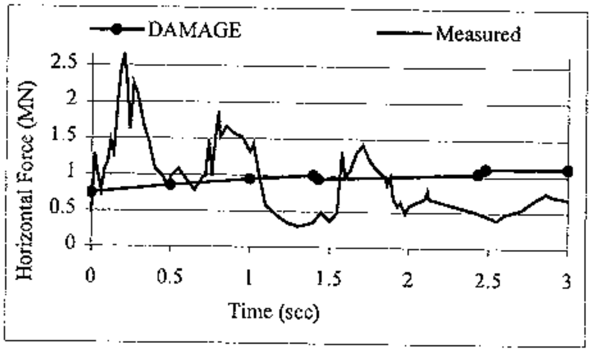


Figure 3.8: Comparison of Horizontal Forces (ASIS Test No.2)

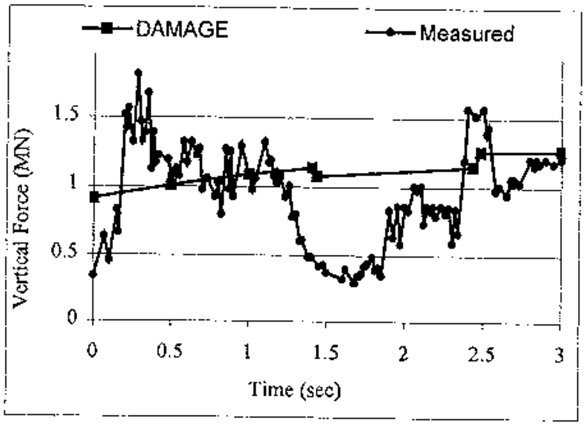


Figure 3.9: Comparison of Vertical Forces (ASIS Test No.2)

## Applicability of DAMAGE

The software DAMAGE has the widest applicability of published simplified methods. It is easy to use and the computation is fast. DAMAGE provides a good tool for probabilistic analysis involving large amounts of input and output data. The main limitations of DAMAGE are the type of the obstruction (pinnacle only), the omission of the bow structure in the model, the limitation to the use of conventional structural arrangements, and the limitation of grounding types to head-on powered groundings.

The test cases indicate that the internal mechanics without the effect of ship motions is captured well by DAMAGE, and DAMAGE predictions on the average values of penetration and internal forces are good. DAMAGE predicted longitudinal damage extent well in the studied cases. However, it must be noted that the analytical formulas for the failure modes are limited to local behavior of the structure. For example, DAMAGE cannot predict possible inner bottom rupture caused by the internal double-bottom structure pushing the inner bottom. Further review is recommended on the prediction of structural component response to confirm that DAMAGE is an accurate tool for structural design evaluation. This will require additional data from either actual groundings or large-scale model tests.

## 3.2 Sensitivity of DAMAGE Results to Grounding Scenarios

The sensitivity of DAMAGE results to changes in grounding parameters, including global ship characteristics, ground characteristics and their interaction, was studied. The grounding parameters and their initial values are shown in Table 3.6.

Table 3.6: Sensitivity Analysis Input Data

| | | | |
|---|---|---|---|
| **Young 's Modulus (MN/m$^2$)** | 200,000 | **Poisson Ratio** | 0.3 |
| **0.2% Yield Stress (MN/m$^2$)** | 262.83 | **Specific Work of Fracture (KJ/m$^2$)** | 200 |
| **LBP (m)** | 304 | **Breadth (m)** | 53.4 |
| **LCF (- aft of MS) (m)** | -4.4 | **Depth (m)** | 25.7 |
| **Breadth of Flat Bottom (m)** | 48.4 | **Draft (m)** | 19.8 |
| **Number of Tanks** | 3 x 5 | **Cargo block length (m)** | 220 |
| **Displacement (tons)** | 273,000 | **Waterplane Area (m$^2$)** | 12,600 |
| **$GM_T$ (m)** | 5.3 | **$GM_L$ (m)** | 330 |
| **Ship Velocity (knots)** | 12 | **Trim Angle (deg)** | 0 |
| **Rock Type** | Pinnacle | **Rock Tip Radius (m)** | 1.0 |
| **Rock Semi-Apex Angle (deg)** | 45 | **Friction Coefficient** | 0.4 |
| **Rock Eccentricity (m-CL)** | 5.0 | **Rock Elevation (m-BL)** | 4.4 |
| **Bulkhead Position (- aft of MS) (m)** | [132] ~ [77] ~ [49.5] ~ [22] ~ [-33] ~ [-88] | | |
| **Bottom Type** | Single Bottom | | |
| **Bulkhead Thickness (mm)** | 20 | **Bottom Plate (mm)** | 35 |
| **Transverse Frame Spacing (mm)** | 5000 | **Long. Stiffener Spacing (mm)** | 1000 |

The analysis was based on the following principles:

1. Only one parameter is changed at a time. Other parameters are kept at their initial values.
2. The results are characterized by three parameters: total energy dissipation, total damaged hull length, and the maximum penetration during grounding.
3. DAMAGE run mode is "coupled", i.e., the global motions are included.

The analysis studied the sensitivity of the results to:

- The ground characteristics
- The parameters defining the ship-ground interaction
- The global ship parameters
- The bottom structural design

- The material characteristics.

In DAMAGE the ground is characterized by the rock tip radius and semi-apex angle, which define the shape of the rock. The ship-ground interaction is defined by the rock eccentricity (i.e. the distance from centerline), rock elevation, ship velocity, trim angle and friction coefficient. Global ship parameters include displacement, breadth of flat bottom, transverse and longitudinal metacentric height, longitudinal center of floatation, and waterplane area coefficient.

At the local level the following structural details were investigated: longitudinal stiffener spacing, thickness of outer bottom, spacing of longitudinal girders and transverse floors, and characteristics of longitudinal girders and transverse floors. The material characteristics were defined by 0.2% yield stress and specific work of fracture.

As can be expected the results are very sensitive to the rock elevation, rock shape and transverse location, ship velocity and displacement. The results were found sensitive also to the value of the friction coefficient[2], and the trim angle.

Surprisingly, the tank spacing as well as the characteristics of both the transverse bulkhead and the longitudinal bulkhead had very little effect on damage results. The results were not very sensitive to small changes in material characteristics.

The longitudinal center of floatation and both the longitudinal and the transverse metacentric height had little effect on damage results.

Damage results were sensitive to the thickness of the outer bottom. Reducing the spacing and increasing the scantlings of longitudinal girders and transverse floors also affected damage results, but not as effectively. The same conclusion applies to longitudinal stiffeners. Table 3.7 summarizes the analysis.

---

[2] Friction coefficient values 0.3-0.4 are typically used in grounding analysis [Simonsen 1998].

Table 3.7: Summary of Damage Results Sensitivity Analysis

| **Increasing the Value of the Parameter** | **Changing of Damage Results (m)** | | **Sensitivity** |
|---|---|---|---|
| | **Damaged Length** | **Max. Penetration** | **Sensitive=S**<br>**Insensitive=I** |
| **Rock Eccentricity** | Increase | Decrease | S |
| **Ship Velocity** | Increase | Increase | S |
| **Rock Elevation** | Decrease | Increase | S |
| **Longitudinal Metacentric Height** | Decrease | Increase | I |
| **Transverse Metacentric Height** | Decrease | Increase | I |
| **LCF moves aft** | Increase | Decrease | I |
| **Waterplane Area Coefficient** | Decrease | Increase | I |
| **Friction Coefficient** | Decrease | Decrease | S |
| **Stiffener Size** | Decrease | Decrease | I |
| **Rock Tip Radius** | Increase | Increase | S |
| **Rock Semi-apex angle** | Decrease, then increase | Increase, then decrease | S |
| **Thickness of Outer Bottom** | Decrease | Decrease | S |
| **Displacement** | Increase | Increase | S |
| **Spacing (longitudinal and transverse)** | Increase | Increase | I |
| **Longitudinal Girders** | Decrease | Decrease | I |
| **Transverse Floors** | Decrease | Decrease | I |
| **Number of Transverse Bulkheads** | Decrease | Insensitive | I |
| **Number and Location of Longitudinal Bulkheads** | Insensitive | Insensitive | I |
| **Trim Angle** | Increase | Decrease | S |

## 3.3 Structural Modifications

Based on the analyses presented in Sections 3.1 and 3.2 DAMAGE was found to provide a good tool for comparative studies, and it was used to investigate the effect of a number of structural modifications in 8 selected grounding scenarios. A 150,000DWT double-hull tanker was used as the base ship. Data for the base ship are shown in Table 3.8.

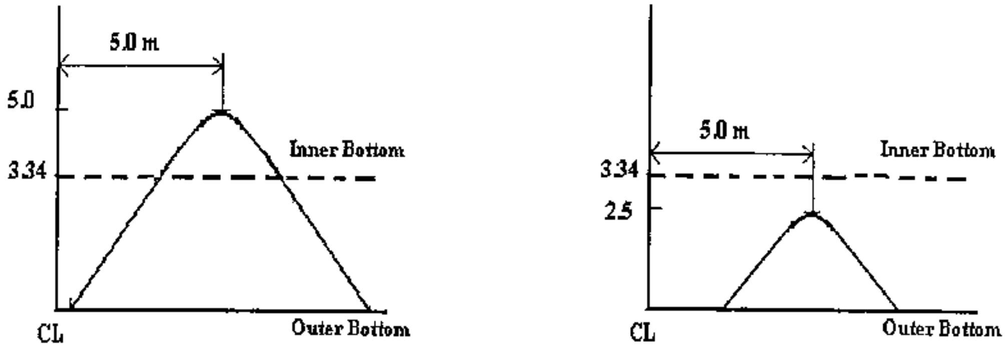
Table 3.8: Baseship Data

| | |
|---|---|
| **Length Overall (m)** | 274.50 |
| **Length Between Perpendiculars (m)** | 261.00 |
| **Breadth (m)** | 50.00 |
| **Depth (m)** | 25.10 |
| **Double Bottom Height (m)** | 3.34 |
| **Lightship Weight (ton)** | 24,116 |
| **Number of Tanks Longitudinally** | 7 |
| **Length of Cargo Block (m)** | 202 |
| **Thickness of Longitudinal Bulkheads (mm)** | 15.5 |
| **Thickness of Transverse Bulkheads (mm)** | 16.5 |
| **Stiffeners - Longitudinal Bulkheads [N=25]** | 450x100x12.5/19 |
| **Stiffeners - Transverse Bulkheads [N=50]** | 700x200x13/22 |
| **Keel Plate Thickness (mm)** | 18.5 |
| **Transverse Floor Spacing (mm)** | 5200 |
| **Transverse Floor Thickness (mm)** | 17.5 |
| **Longitudinal Web Spacing (mm)** | 17850 |
| **Longitudinal Web Thickness (mm)** | 47.00 |
| **Outer Bottom Thickness (mm)** | 17.00 |
| **Inner Bottom Thickness (mm)** | 17.00 |
| **Outer Bottom Stiffeners, Longitudinal [N=50]** | 600x150x12.5/23 |
| **Inner Bottom Stiffeners, Longitudinal [N=40]** | 600x125x12.5/22 |
| **Center Vertical Keel Thickness (mm)** | 46.0 |

Four different rock configurations were selected: one with a high rock elevation (HE), one with a mediate rock elevation (ME), one with a low rock elevation (LE), and one with a sharp tip (ST). The rock eccentricity was set to be 5 meters. The definition of these four rock configurations is shown in Table 3.9 and Figure 3.10.

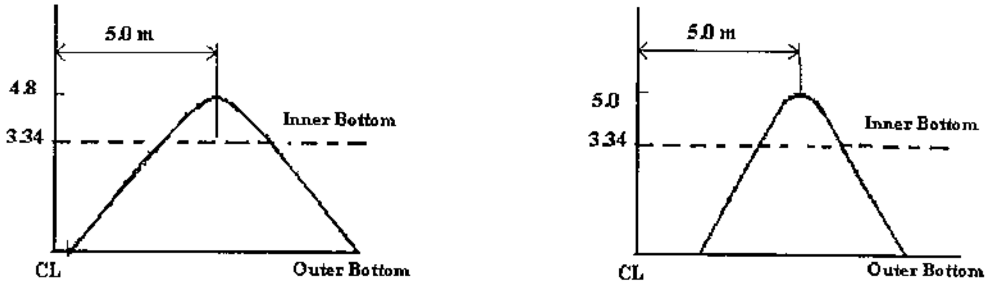
Table 3.11: Definition of Rock Configurations

| Scenario | Rock Tip Radius | Semi-Apex Angle | Elevation | Eccentricity |
|---|---|---|---|---|
| HE | 1.0 m | 45 | 5.0 m | 5.0 m |
| LE | 1.0 m | 45 | 2.5 m | 5.0 m |
| ME | 1.0 m | 45 | 4.8 m | 5.0 m |
| ST | 1.0 m | 30 | 5.0 m | 5.0 m |



Scenario: HE

Scenario: LE



Scenario: ME

Scenario: ST

Figure 3.10: Sketch of Four Grounding Scenarios

Two velocities were used in the analysis: 14 knots and 7 knots to represent a service speed and port speed of a tanker.

In order to investigate the effectiveness of different structural designs to the grounding accidents, a total of nine different structural designs were modeled, using the American Bureau of Shipping SafeHull software. The structural dimensions in these nine designs met the minimum classification requirements (SafeHull Phase A, ABS Rules 97/98), except for the modified scantling. The structural differences in the designs were either in the plate thickness or in the structural spacing (Table 3.10). The original design is Design 0.

The modifications in Designs 1-3 were:

- An increase in the outer bottom plate thickness from 17mm to 25mm (Design 1)
- An increase in the inner bottom plate thickness from 17mm to 25mm (Design 2)
- An increase in both the outer bottom and the inner bottom plate thickness from 17mm to 25mm (Design 3)

Consequently, the scantlings of stiffeners along the outer bottom and inner bottom were changed to minimize the weight increase. Comparing to the original design, these modifications increased the longitudinal structural steel weight for unit length from 17371 tons to 17837 tons, 17932 tons, and 18398 tons respectively.

The modifications in Designs 4, 5 and 6 were:

- Additional longitudinal girder (Design 4)
- Two additional longitudinal girders (Design 5)
- Additional transverse floor in cargo tanks (Design 6)

The modifications in Designs 7 and 8 are:

- Decrease in the double bottom height from 3340 mm to 3000mm (Design 7)

- Increase in double bottom height from 3340mm to 3500mm (Design 8)

The weight changes for designs 4-8 were not recorded, because their comparison would not be meaningful. The SafeHull input included longitudinal structure only, and the changes in the transverse structure were not taken into account. The subdivision changes and stability checks were not done for modifications 7 and 8.

Table 3.10: Structural Designs

| **Design** | **Double bottom height (mm)** | **Outer bottom thickness (mm)** | **Inner bottom thickness (mm)** | **Transverse frame spacing (mm)** | **Longitudinal girder spacing (mm)** | **Steel weight (ton)** | **Change in weight** |
|---|---|---|---|---|---|---|---|
| **0** | 3340 | 17 | 17 | 5200 | 17850 | 17371.8 | ----- |
| **1** | 3340 | **25** | 17 | 5200 | 17850 | 17837.0 | 2.68% |
| **2** | 3340 | 17 | **25** | 5200 | 17850 | 17933.0 | 3.23% |
| **3** | 3340 | **25** | **25** | 5200 | 17850 | 18398.2 | 5.91% |
| **4** | 3340 | 17 | 17 | 5200 | **8925** | NA | NA |
| **5** | 3340 | 17 | 17 | 5200 | **5950** | NA | NA |
| **6** | 3340 | 17 | 17 | **4457** | 17850 | NA | NA |
| **7** | **3000** | 17 | 17 | 5200 | 17850 | NA | NA |
| **8** | **3500** | 17 | 17 | 5200 | 17850 | NA | NA |

## Damage Results for Different Structural Designs

A total of 72 grounding cases, 9 different structural designs under 8 different grounding scenarios were analyzed using the program DAMAGE. The following is a summary of the results.

1. High rock elevation: At service speed, designs 1, 3, 4, 5, and 8 show better performance than the original design in preventing inner bottom plating from rupture. For design 5 (two additional longitudinal girders), design 3 (increased plating thickness) and design 8 (increased double bottom height) the inner bottom rupture is significantly reduced. At port speed, all design modifications perform better than the original except design 7 (reduced double bottom height).

2. Medium rock elevation: At service speed, no inner bottom plating rupture occurs for design 5 (additional girders) and design 8 (increased double bottom height). All design modifications perform better than the original except design 7 (reduced double bottom height) at both speeds.

3. Low rock elevation: No design had rupture of the inner bottom[3]. At service speed, all designs have a ruptured outer bottom throughout the cargo block. In this kind of raking scenario, the structural modifications had little impact on the damage extent.

4. Sharp rock tip: At service speed the rock penetrated through the entire cargo block for all designs. At port speed, designs 1, 2, 3, 5 and 6 had reduced outer bottom and inner bottom rupture. This was the only grounding scenario where the increased double bottom height did not reduce the inner bottom rupture significantly.

---

[3] DAMAGE does not predict inner bottom rupture caused by the internal double bottom structure pushing the inner bottom.

Among all the nine selected designs, the design 5 with two additional longitudinal girders showed the best performance in preventing inner bottom plate rupture and oil outflow in the selected grounding scenarios. Design 7 with the reduced double bottom height had the worst performance. In the low-obstruction raking scenario all the designs had similar performance and no oil outflow. If the tanker met a high-elevation, sharp-tip grounding scenario at service speed, serious damage occurred in all selected designs. Even if the tanker met the grounding scenario at the lower speed, all designs had serious inner bottom plate rupture.

Although adding longitudinal girders seems to be the best modification in preventing inner bottom plate from rupturing in the eight selected grounding scenarios, it may not be the most effective design, if the increase in steel weight were taken into account. If the damage extent is studied as a function of the structural steel weight, design 8 with the increased double bottom height is found to be effective in reducing the inner bottom rupture. This observation is tied to the selected grounding scenarios, particularly to the height of the obstruction relative to the ship bottom. Increasing outer bottom plating thickness was also found to be effective in reducing inner bottom rupture. Increasing the thickness of both the outer and inner bottom plating reduces the ruptured length more, but at the cost of increased weight.

It must be noted that the weight changes were based on the longitudinal structure only and the changes in transverse structure were not properly accounted for. It should be also kept in mind that the design performance in this study was measured in terms of the extent of structural damage. The changes in the damage extent may have no effect on the oil outflow since it is a function of the damage location and the tank subdivision as well.

The following conclusions were made based on the study:

1. Even small changes in a traditional structural arrangement, such as the height of the double bottom or the thickness of the bottom plate, can have a significant effect on damage extent.

2. The results are highly dependent on the selected grounding scenarios, and a probabilistic study including a large number of grounding scenarios is necessary to study the effect of structural modifications.

3. Since the changes in the damage extent do not necessarily result in changes in outflow, the probabilistic analysis must include outflow calculation.

# 4. PROBABILISTIC ANALYSIS

The deterministic study of structural modifications in Chapter 3 was limited to eight grounding scenarios and the conclusions from it cannot be generalized. However, this type of deterministic investigation provides insight into the effects of the scenarios and the structural modifications, which can be lost in a probabilistic study. The objective of the work presented here was to expand on the deterministic work and to determine structural damage and resulting outflow for alternative designs in a large number of grounding scenarios.

The analysis included definition of the grounding scenarios, description of the analyzed tankers, determination of the structural damage and resulting outflow, and analysis of the results. Existing double-hull tanker designs were used as a base case, and two tanker sizes (40,000 DWT and 150,000DWT) were studied. The analysis was carried out for 10,000 grounding events. Structural damage and oil outflow was determined for the events, in which the cargo block was ruptured. Damage-extent and outflow distributions were generated, and statistical analyses were carried out to investigate the relationship between the inputs describing the grounding scenarios and the resulting damage and outflow. The tanker designs were then modified to study the effect of the design features on the results. First, the performance of the double-hull tankers was compared with the performance of single-hull tankers with the same capacity, and the effectiveness of the double-bottom height was investigated. Then simple modifications were made to the bottom structure, and their effect on the results was analyzed.

The report describes first the grounding scenarios and the analyzed vessels. Then the approach used in the analysis is discussed, and the results for the base case and the modifications are summarized. Finally, conclusions are made on the approach and the details of the analysis.

## 4.1 Grounding Scenarios

The 10,000 grounding incidents were selected to sample conditions in U.S. waters with a high density of tanker traffic. Data was collected for four locations (Galveston Bay, Delaware Bay, San Francisco Bay, Farallon Islands outside of San Francisco Bay), and the assumption was made that the vessels had an equal likelihood of being in each of the geographic locations. The accident factors, which define the grounding scenarios, include the vessel speed, tidal conditions, obstruction depth, apex angle and tip radius, obstruction location relative to centerline of the ship, inert gas pressure in cargo tanks, minimum outflow from cargo tanks adjacent to water, and capture of oil into ballast tanks. Available data were inadequate for many of the variables, and further refinement of the accident factor distributions is recommended.

Accident factors for grounding were collected from the following sources:

- Speed distribution was based on information received from pilots and operating personnel on typical speeds in Galveston lightering area, in San Francisco Bay near Carquinez Strait Bridge, and outside of San Francisco Bay. No data was available for Delaware, but speeds were assumed to be similar to San Francisco Bay speeds.

- Tidal distribution was based on information in the four locations obtained from NOAA web site (http://tidesonline.nos.noaa.gov).

- Obstruction depths were based on information on obstruction depths in Galveston, Delaware and San Francisco Bay. This information was received form Coast Guard VTS centers and NOAA charts. No data was available on the shape of the obstructions in these locations.

- The distribution for the obstruction tip radius was taken from [Rawson 1998]. The minimum and maximum apex angles were based on the limitations of the theory in DAMAGE, and a uniform distribution was assumed. Positive correlation (0.80) was assumed between tip radius and apex angle.

- Inert gas pressure[4] distribution was based on information on a typical range of inert gas pressures provided by Intertanko.

- Capture and minimum outflow[5] distributions were selected based on model test results referred to in [IMO 1992]. Moderate positive correlation (0.50) was assumed between speed and minimum outflow.

The accident-factor distributions were sampled using Monte Carlo techniques. The accident factors and their ranges are given in Table 4.1, and histograms of the generated input data are shown in Figures 4.1-4.9.

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[4] Inert gas pressure is maintained in cargo tanks to avoid explosive conditions.

[5] 'Capture' refers to the amount of oil that is captured in ballast spaces adjacent to damaged cargo tanks. Minimum outflow is assumed from tanks adjacent to seawater to account for dynamic effects.

Table 4.1: Data for Accident Factors and Their Distributions.

| VARIABLE | MINIMUM | MAXIMUM | DISTRIBUTION |
|---|---|---|---|
| **Speed in knots** | 0 | 20 | Probability that the speed is in the range<br>0 – 5 knots -- 25%<br>5 - 8 knots -- 45%<br>8 – 15 knots – 8%<br>15 – 16 knots –20%<br>16 – 20 knots – 2% |
| **Obstruction depth from MLW in meters** | 0 | 19 | Probability in depth ranges<br>0-5 m – 11%<br>5-10 m --28%<br>10-15 m – 31%<br>Larger than 15m – 36% |
| **Obstruction apex angle in degrees** | 15 | 50 | Truncated Normal distribution. Strong positive correlation with tip radius (0.80). Large apex angles correspond to large tip radii. |
| **Obstruction tip radius in meters** | 0 | 10 | Truncated Normal distribution. |
| **Non-dimensional rock eccentricity e/(B/2) from CL** | 0 | 1 | Uniform distribution |
| **Tidal variation in meters from mean low water** | 0 | 2.5 | Probability that the tide is in the range<br>0-0.7 m ---50%<br>0.7 – 1.7 m --- 35%<br>Greater than 1.7 m ---15 % |
| **Inert tank pressure in mm WG** | 400 | 1000[6] | Uniform distribution |
| **Capture in ballast tanks in % of tank volume** | 0 | 50 | Uniform distribution |
| **Minimum outflow as % of ruptured tank volume** | 0.5 | 1.5 | Uniform distribution; Moderate positive correlation with speed (0.50). Higher speeds are more likely to have higher minimum outflow. |

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[6] Pressure valves are preset at 1500 WG, but to allow the use a uniform distribution the range of 400 – 1000 WG was applied.

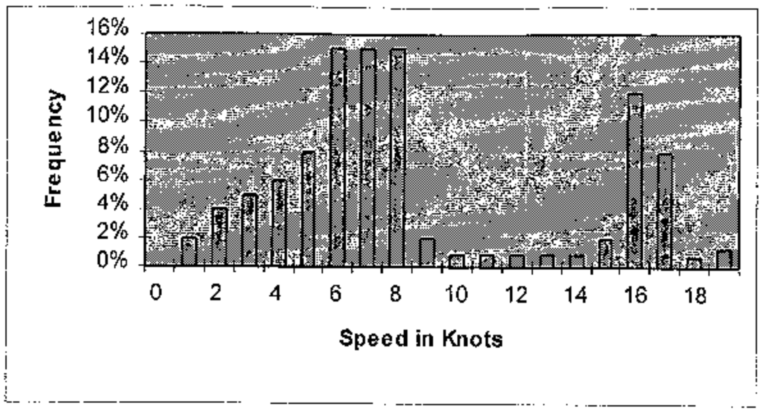

Figure 4.1: Vessel Speed Distribution

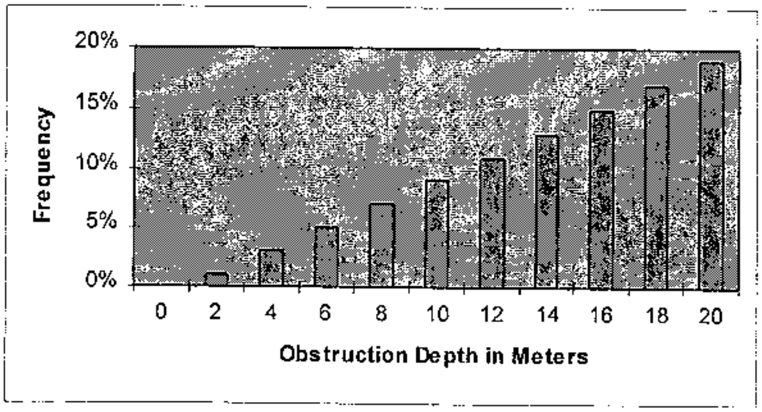

Figure 4.2: Obstruction Depth Distribution

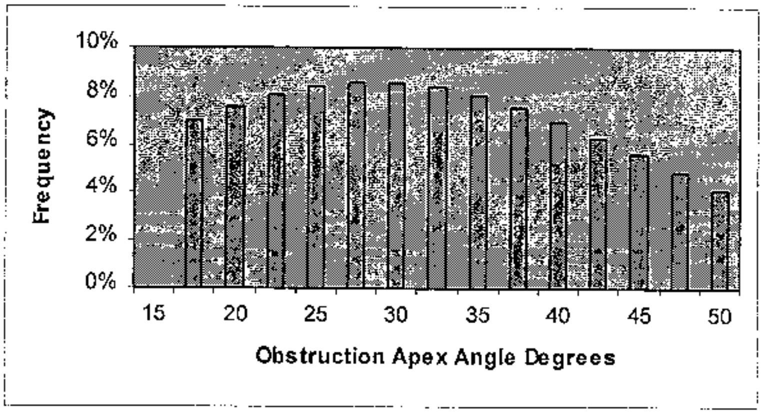

Figure 4.3: Obstruction Apex Angle Distribution

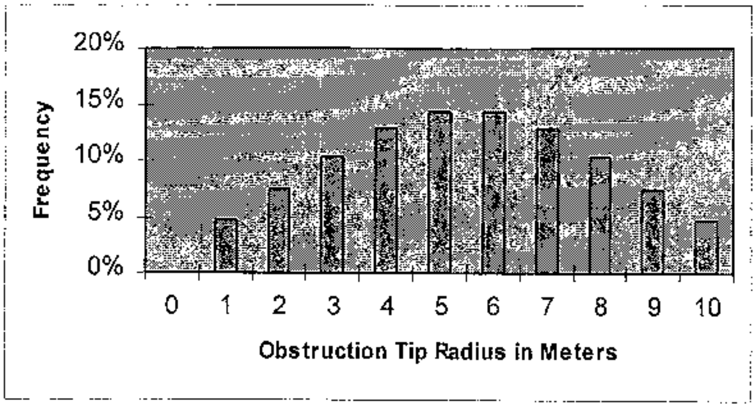

Figure 4.4: Obstruction Tip Radius Distribution

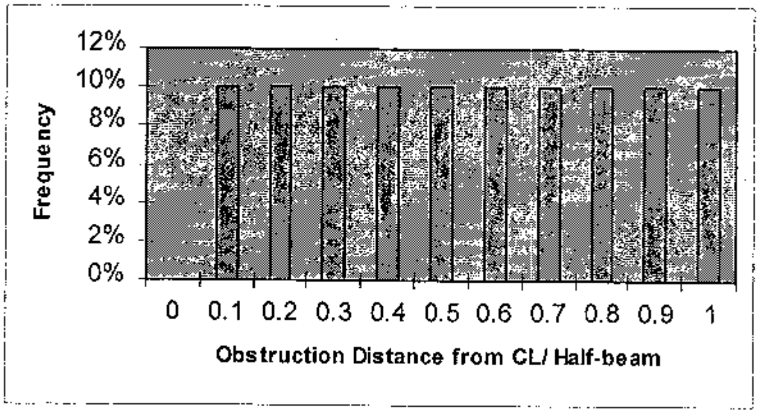

Figure 4.5: Distribution of Rock Location Relative to the Centerline

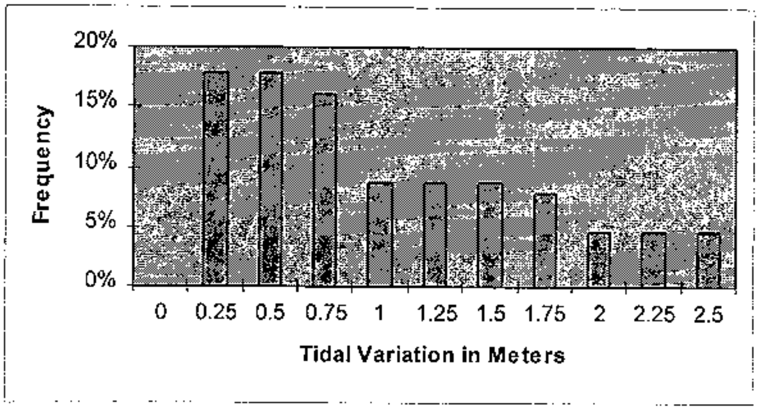

Figure 4.6: Tidal Variation Distribution

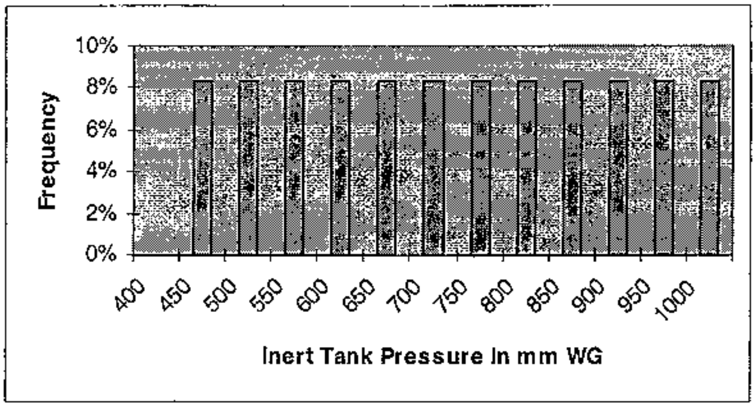

Figure 4.7: Distribution of Inert Tank Pressure in Cargo Tanks

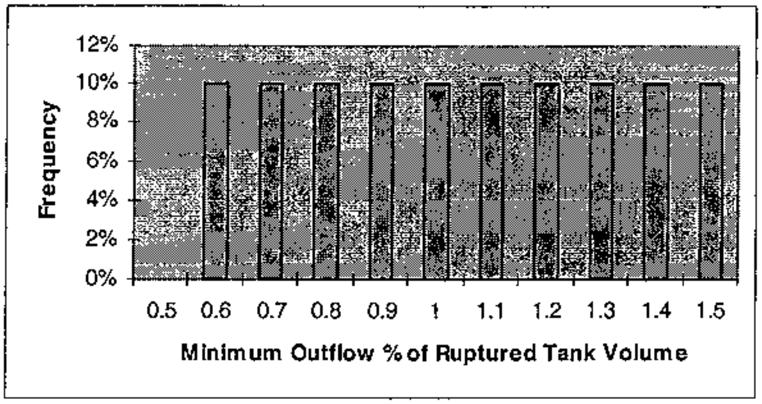

Figure 4.8: Distribution of Minimum Outflow from Tanks Adjacent to Sea

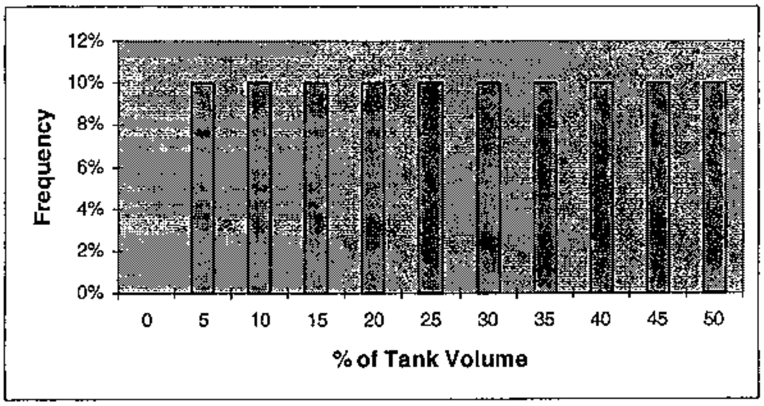

Figure 4.9: Distribution of Capture of Oil into Ballast Tanks

## 4.2 Vessel Description

Grounding analysis was carried out for 150,000 DWT and 40,000 DWT single-hull and double-hull tankers. Profiles, plan views, and midship sections of the vessels shown in Figures 4.10 and 4.11 illustrate the vessels' subdivision into cargo and ballast spaces.

Table 4.2 lists cargo tank capacities for each vessel. Structural dimensions for the bottom structure are shown in Table 4.3. Material was assumed to be elastic-plastic with a 15% rupture strain.

The designs, which are based on existing tankers, were selected, because both double-hull and single-hull designs of the same capacity were available. However, it must be kept in mind that the results are specific to these designs. General conclusions cannot be drawn on the behavior of double- and single-hull tankers based on these results only. Particularly, it must be noted that the double-bottom height in the 150,000 DWT tanker is larger than in most tankers in this size range.

Table 4.3: Cargo tank capacities (SH = single hull, DH = double hull)

| **150K SH** | **Gallons** | **150K DH** | **Gallons** | **40K SH** | **Gallons** | **40K DH** | **Gallons** |
|---|---|---|---|---|---|---|---|
| **1 C** | 3,951,288 | **1 P/S** | 2,593,272 | **1C** | 792,528 | **1 P/S** | 505,560 |
| **1 P/S** | 2,911,920 | **2 P/S** | 3,254,064 | **1 P/S** | 413,688 | **2 P/S** | 626,472 |
| **2 C** | 4,793,184 | **3 P/S** | 3,248,784 | **2 P/S** | 585,552 | **3 P/S** | 629,376 |
| **3 C** | 4,792,392 | **4 P/S** | 3,249,048 | **3 C** | 808,632 | **4 P/S** | 630,168 |
| **3 P/S** | 3,402,960 | **5 P/S** | 3,249,048 | **3 P/S** | 592,944 | **5 P/S** | 503,712 |
| **4 C** | 4,192,584 | **6 P/S** | 3,074,016 | **4 C** | 808,104 | **6 P/S** | 630,168 |
| **5 C** | 4,368,936 | **Slop P/S** | 1,083,192 | **5 C** | 808,104 | **7 P/S** | 628,320 |
| **5 P/S** | 1,859,088 | | | **5 P/S** | 591,624 | **8 P/S** | 590,832 |
| **Slop P/S** | 849,024 | | | **6 C** | 783,816 | | |
| | | | | **6 P/S** | 560,736 | | |

Table 4.4: Principal structural dimensions for the bottom structure (SH = single hull, DH = double hull)

| | **SH150K (mm)** | **DH150K (mm)** | **SH40K (inch)** | **DH40K (inch)** |
|---|---|---|---|---|
| **Bottom plating** | 18 | 20 | 0.90 | 0.82 |
| **Bottom longitudinals** | 650x180x13/25 | 625x150x13/25 | 20x7x.44/.75 | 18x4x58#[7] |
| **Inner bottom plating** | N/A | 17 | N/A | 0.55 |
| **Inner bottom longitudinals** | N/A | 625/150/12.5/25 | N/A | 18x4x42.7# |
| **Transverse frames/ Floors** | 1750x450x14.5/30 | 14.5 | 5'1x4x.5/1[8] | 0.5625 |
| **Longitudinal girders** | N/A | 14.5 | 10'1x20x.625/1 | 0.5 |
| **No of longitudinal girders** | N/A | 2 (20.16m from CL) | 2 | 4 |
| **Longitudinal spacing** | 850 | 850 | 3' | 2'6" |
| **Frame spacing** | 5200 | 5200 | 2'9" | 11'6" |
| **Double bottom height** | N/A | 3340 | N/A | 7' |
| **Material** | HT32 | HT32 | MILD/HT32 | MILD |

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[7] Stiffeners in DH40 are cut-off channels.

[8] SH40 has both ordinary and deep transverse frames. The input to DAMAGE included ordinary frames only.

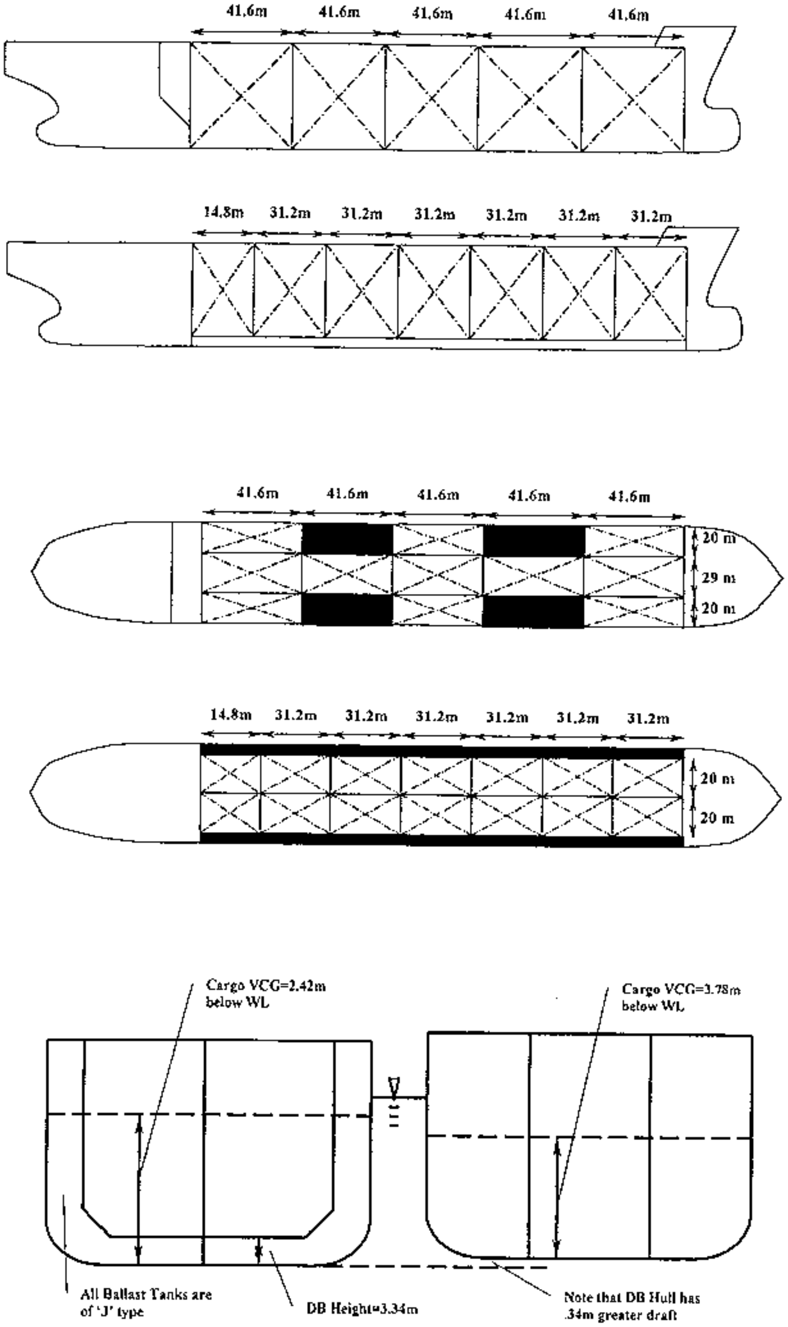

Figure 4.10: Profile, Plan View and Midship Section for the 150,000 DWT Ships.

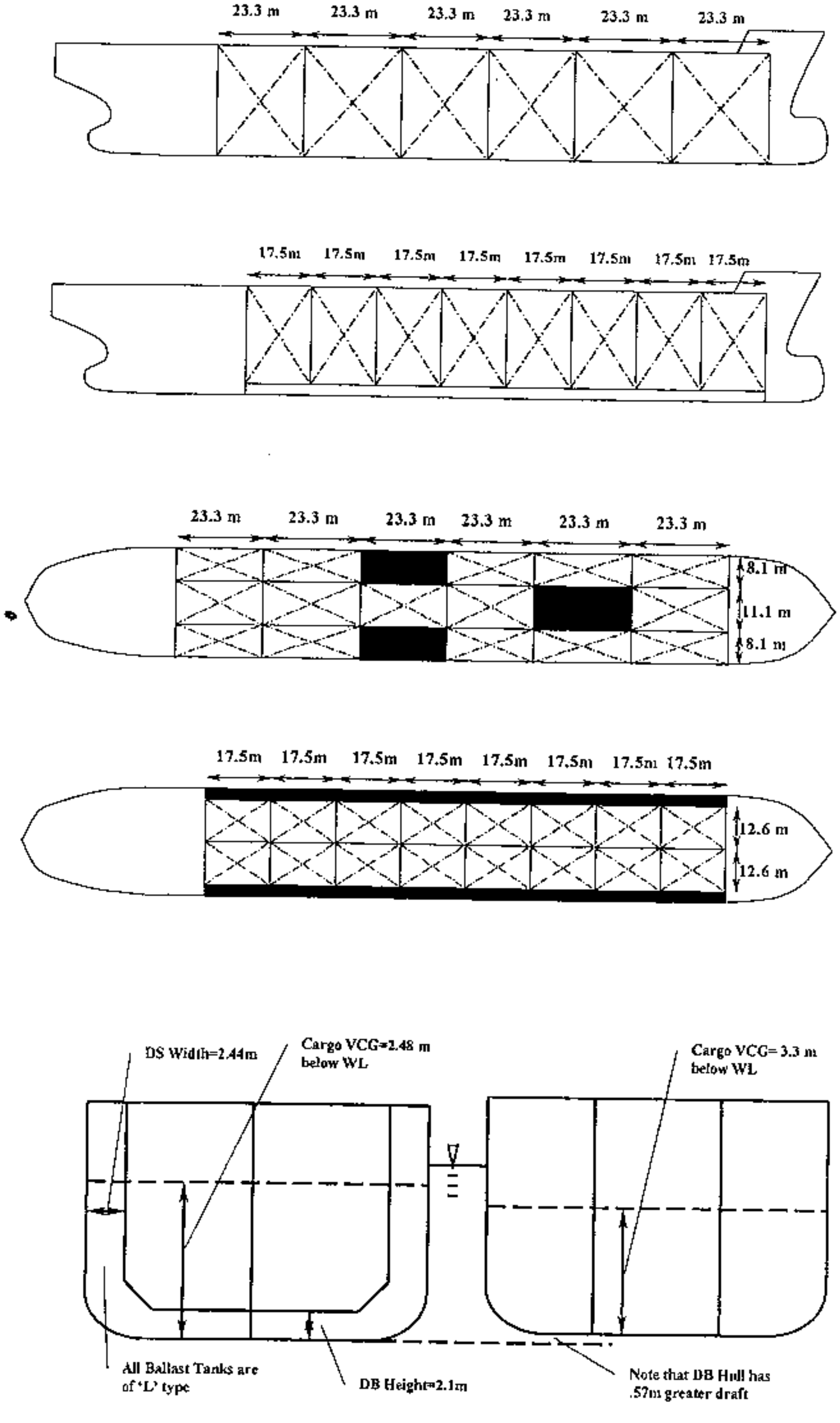

Figure 4.11: Profile, Plan View and Midship Section for the 40,000 DWT Ships.

## 4.3 Structural Damage and Outflow Analysis

The accident factors described above were sampled using Monte Carlo simulation to generate 10,000 grounding events, and the structural damage and oil outflow was analyzed for each vessel in all the events. Since DAMAGE requires the input to be changed manually for each grounding scenario, a program was written to allow batch runs for the 10,000 grounding cases. The program also read the structural damage output from DAMAGE, and calculated the corresponding outflow for each grounding scenarios. Description of this program can be found in Appendix A.

The ships were assumed to be in fully–loaded condition adjusted so that each vessel carried the same quantity of cargo and maintained an even-keel condition. The cargo was crude oil with a density of 0.84 g/cm$^3$. The friction coefficient was assumed to be 0.3[9] in all calculations. The parameters defining the vessel condition and the liquids carried are shown in Table 4.4.

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[9] Friction coefficient values 0.3-0.4 are typically used in grounding analysis (Simonsen 1998).

Table 4.4: Vessel Condition Before Grounding (SH = Single Hull, DH = Double Hull)

| | **SH 150K** | **DH 150K** | **SH 40K** | **DH 40K** |
|---|---|---|---|---|
| **Displacement (MT)** | 175,907 | 175,940 | 47,448 | 49,410 |
| **Cargo oil (MT)** | 149,635 | 149,635 | 35,949 | 35,922 |
| **Draft MS (m)** | 16.78 | 17.12 | 10.58 | 11.17 |
| **Draft FP (m)** | 16.78 | 17.12 | 10.58 | 11.17 |
| **Draft AP (m)** | 16.78 | 17.12 | 10.58 | 11.17 |
| **Summer Load Line (m)** | 16.785 | 17.205 | 10.614 | 11.303 |
| **VCG (m)** | 13.35 | 14.71 | 7.526 | 9.26 |
| **Waterplane area (m^2)** | 11,506 | 11,513 | 4,800 | 5,014 |
| **GMt (m)** | 6.96 | 5.15 | 3.243 | 2.91 |
| **GMl (m)** | 306.65 | 299.75 | 276.54 | 263.19 |
| **LCF (m)** | 0.85 fwd of MS | 0.58 fwd of MS | 0.131 aft of MS | 2.81 aft of MS |
| | | | | |
| **Density of :** | | | | |
| **Cargo (g/cm3)** | 0.84 | 0.84 | 0.84 | 0.84 |
| **Fuel Oil (g/cm3)** | 0.98 | 0.98 | 0.98 | 0.90 |
| **Diesel Oil (g/cm3)** | 0.90 | 0.90 | 0.90 | |
| **Lube Oil (g/cm3)** | 0.85 | 0.85 | 0.85 | 0.92 |
| **Fresh Water (g/cm3)** | 1.00 | 1.00 | 1.00 | 1.00 |
| **Salt Water (g/cm3)** | 1.025 | 1.025 | 1.025 | 1.025 |
| | | | | |
| **Tanks full %:** | | | | |
| **Cargo tanks (ex. slops)** | 98 | 98 | 98 | 98 |
| **Slop tanks** | 66 | 89 | | |
| **Fuel Oil** | 96 | 96 | 96/95 | 96 |
| **FO settling, service, overflow** | 20 | 20 | | |
| **Diesel Oil** | 96 | 96 | | |
| **DO service** | 20 | 20 | | |
| **Fresh water** | 98 | 98 | 98 | 100 |
| **Fore Peak Ballast Tank** | 3.5 | 11 | 0 | 100/11.2 |
| **Other Ballast Tanks** | 0 | 0 | 0 | 0 |

The program DAMAGE outputs the vertical, horizontal and longitudinal extent of damage, and this information was used to determine the damaged tanks. The oil outflow from damaged cargo tanks was calculated based on the principle of hydrostatic balance. The pressure balance was calculated at the lowest point of the damaged tank. Similar to the assumptions in the *IMO Guidelines* [IMO 1996], capture of some oil in the ballast tanks was assumed, and a minimum outflow was assumed from a damaged cargo tanks adjacent to seawater due to dynamic effects. The *IMO Guidelines* assume a constant value for capture and minimum outflow, whereas the calculations presented here were based on a range of values sampled from the initial distributions for these variables to account for the uncertainty in the definition of the variables.

The outflow calculation was done in the vessel's initial condition (conceptual analysis) and it did not include a damage-stability analysis (survivability analysis)[10]. A comparison of the conceptual analysis with a survivability analysis was carried out in [Tikka 1998] for double hull tankers with a range of tank arrangements in four size ranges. The error in the mean outflow was small for conventional tank arrangements (typically less than 6 percent), and the error in the zero outflow probability was insignificant (less than 0.1 percent) with no tide, when conceptual analysis was used. At lower tides the error percentages were smaller. Large errors were found for tank arrangements without centerline bulkheads, which no longer cannot be built according to MARPOL regulations.

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[10] Conceptual analysis assumes that the ship is aground on a shelf at a draft equal to the initial draft. Survivability analysis takes into account changes in the ship's condition and includes a damage stability analysis. If the vessel does not meet the MARPOL damage stability criteria, all oil is assumed lost.

## 4.4 Outflow Results

In 2,724 out of the 10,000 grounding scenarios, the 150,000 DWT double-hull tanker ruptured its cargo block resulting in a spill. The 40,000 DWT double-hull tanker spilled only 612 times out of the same 10,000 scenarios. The smaller tanker had fewer spills, because its draft is smaller and the obstruction depths were the same for all tankers. The damage extents for the 150,000 DWT double-hull tanker are shown in Figure 4.12.

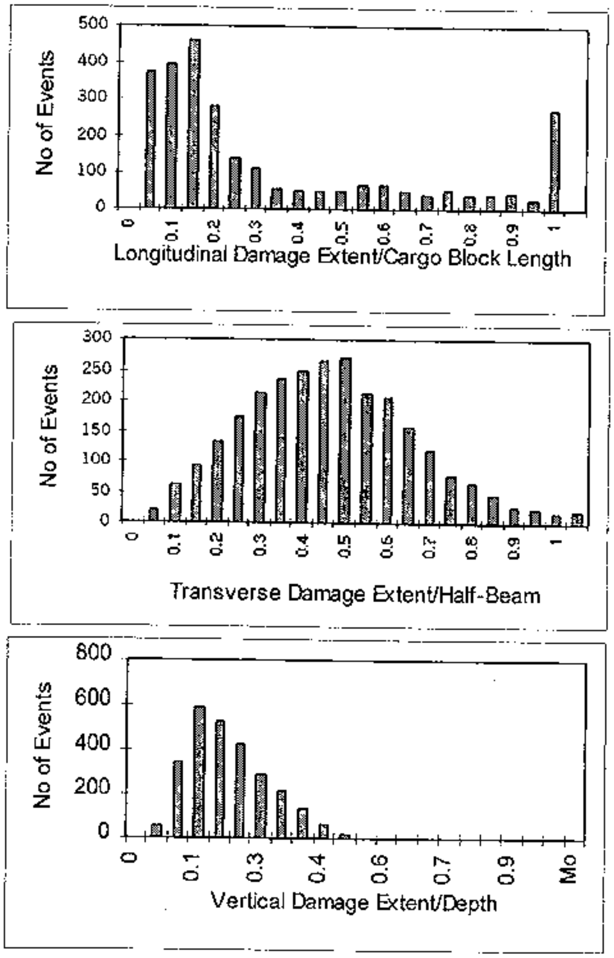

Figure 4.12: Damage Extent Distributions for the 150,000 DWT Double-Hull Tanker

It must be noted that the distributions include only the cases in which the inner hull was ruptured resulting in oil outflow. If the cases in which the outer hull ruptured but inner hull did not were included, the relative frequency of large damage extents, particularly in the transverse and vertical direction, would be smaller. Therefore a direct comparison with the damage distributions in the *IMO Guidelines*, which represent damage to a single hull, is not possible. However, even if the difference in the data is taken into account, the calculated distributions indicate a higher frequency of larger damage extents than the damage distributions in the *IMO Guidelines*, which are based on limited historical damage data. This is a result of the high speeds in the initial distributions used to generate the grounding scenarios. In order to make the analysis applicable to comparative studies, we sampled from a range of possible grounding scenarios and did not just replicate those found in historical accidents. However, the sampling distributions could be refined for specific locations and conditions, if additional data is available.

A linear regression analysis between the outflow and the input variables indicated, as can be expected, a strong dependency between outflow, vessel speed, rock eccentricity and tidal variation. Since the displacement of the vessel has been kept constant in the analysis, the speed determines the kinematic energy to be dissipated during the grounding event. The rock eccentricity determines which tanks in the transverse direction are damaged. Tidal condition establishes the pressure of the seawater in the calculation of the hydrostatic balance. The most severe accidents are a result of either a long damage that ruptures several tanks in the longitudinal direction, a damage that is shorter but ruptures both tanks in the transverse direction, or a combination of the two. A low-tide condition increases the outflow. The results of the linear regression are shown in Table 4.5.

Table 4.5: Linear Regression Between the Outflow and the Sceanrio Variables ($R^2=0.76$)

| | Coefficients | Standard Error | t Stat |
|---|---|---|---|
| Intercept | 0 | #N/A | #N/A |
| Speed | 2175 | 28 | 77 |
| Obs. Depth | 255 | 40 | 6.4 |
| Obs. Apex | -27.5 | 20.6 | -1.33 |
| Obs. Tip | -437 | 86 | -5.0 |
| Rock Ecc. | -13908 | 432 | -32 |
| Tidal Var. | 2606 | 176 | 14.7 |
| Tank Pres. | 2.0 | 0.613 | 3.3 |
| Capture % | -10.6 | 8.2 | -1.28 |
| Min Outflow | -527 | 451 | -1.16 |

Obstruction depth is also an important variable, but the regression analysis included only the accidents, which resulted in a spill. Therefore, since the cargo block was already ruptured, the obstruction depth was less significant.

The summary of the outflow results and the comparison between the double-hull and single-hull tankers is shown in Table 4.6.

Table 4.6: Results for 40,000 DWT and 150,000 DWT Double-Hull and Single-Hull Tankers

| | **40,000 DWT** Tanker | | **150,000 DWT** Tanker | |
|---|---|---|---|---|
| **Outflow in million gallons** | **Double** | **Single** | **Double** | **Single** |
| **Number of spills** | 612 | 1,833 | 2,724 | 5,911 |
| **Average outflow given a spill** | 0.84 | 0.66 | 3.91 | 4.28 |
| **Average outflow in all events** | 0.05 | 0.12 | 1.06 | 2.53 |
| **Maximum outflow** | 5.04 | 3.25 | 19.35 | 17.44 |
| **Minimum outflow** | 0.16 | 0.07 | 0.87 | 0.86 |

The double bottom was found to be effective in reducing the number of spills. The 150,000 DWT single hull spilled more than the double hull in 84 percent of the grounding events, and the 40,000 DWT single hull spilled more in 82 percent of the events (including the events when the double hull did not spill). There were no cases in which the double hull spilled and the single hull did not. The single-hull tankers had more small and medium spills, whereas the double-hull tankers had more, although still only a few, very large spills. The double-hull tankers had a larger maximum spill size. These large spills occur in extreme grounding scenarios with speeds 15-17 knots, low tides and small obstruction depths.

The 150,000 DWT double-hull tanker had a smaller average spill size, given a spill, than the single-hull tanker, but in the 40,000 DWT size the double-hull tanker had a larger average spill size. The smaller tankers have fewer spills than the larger ones, because of their shallower drafts. The obstruction depths were the same in both analyses.

Oil outflow distributions for the single and double-hull tankers in grounding are shown in Figures 4.13-4.18, and the data can be found in Appendix D. It is important to note that the distributions shown are specific to the selected grounding scenarios and vessels, and no general conclusions on single-hull and double-hull designs can be made based on this analysis only.

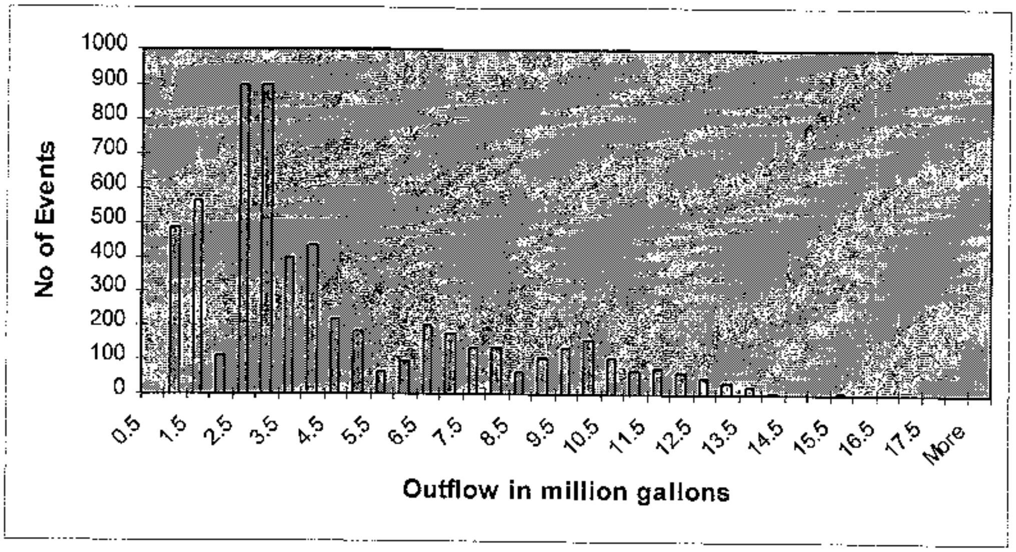

Figure 4.13: Outflow Distribution for a 150,000 DWT Single-Hull Tanker

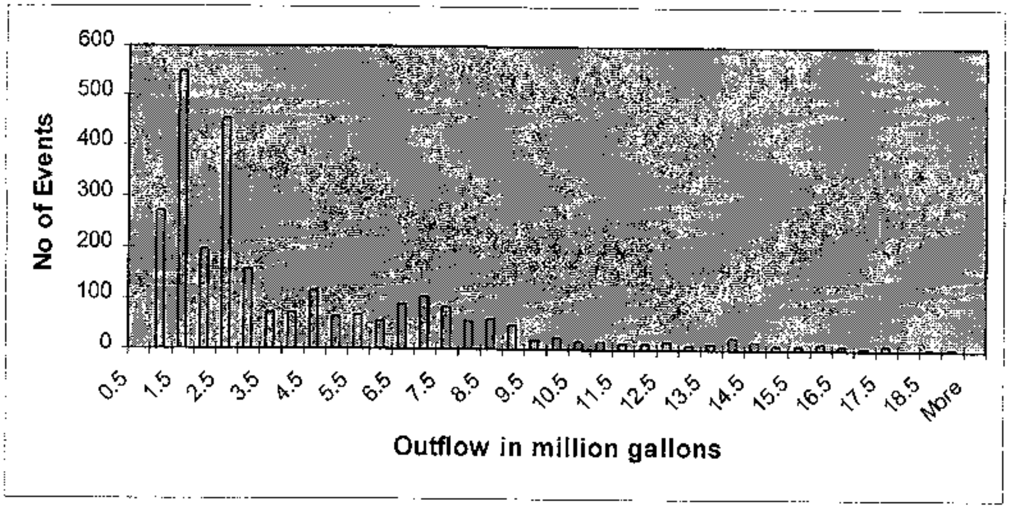

Figure 4.14: Outflow Distribution for a 150,000 DWT Double-Hull Tanker

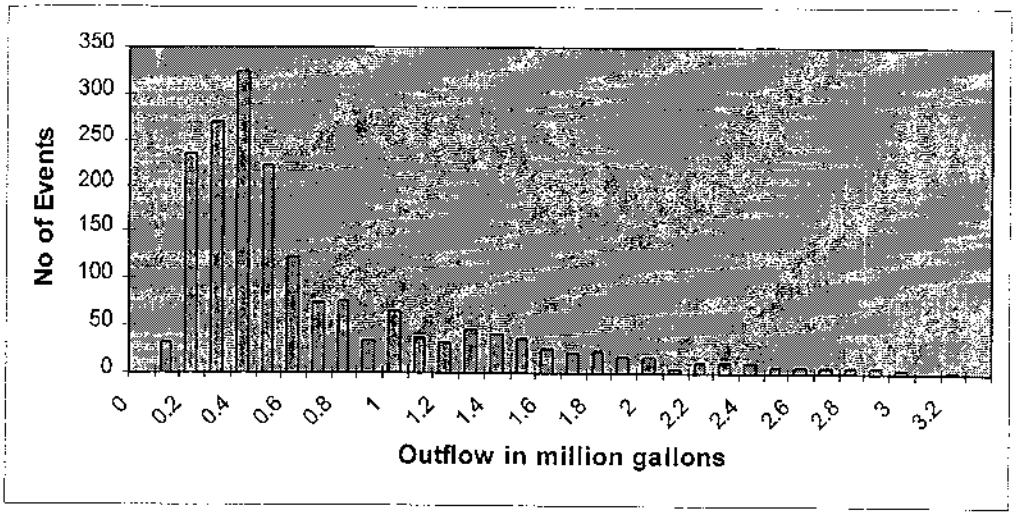

Figure 4:15: Outflow Distribution for a 40,000 DWT Single-Hull Tanker

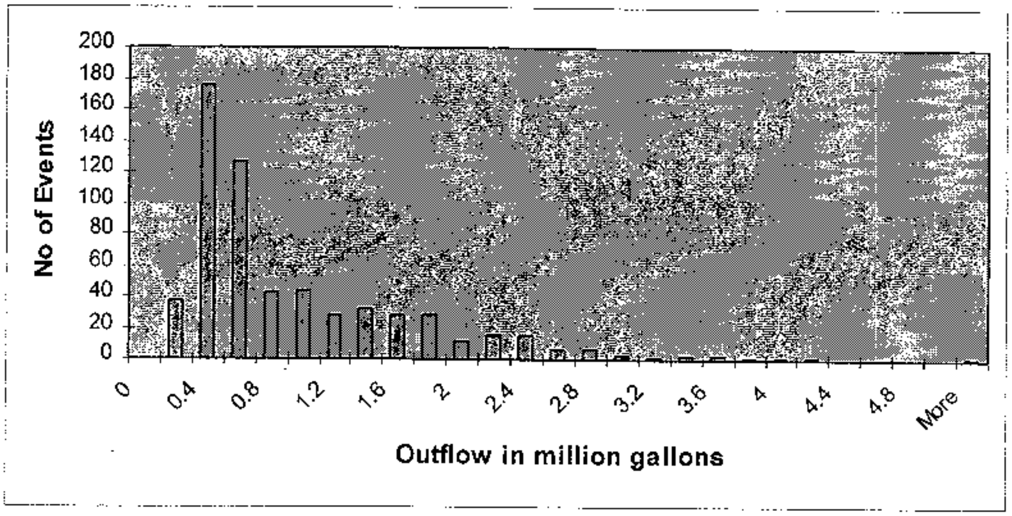

Figure 4:16: Outflow Distribution for a 40,000 DWT Double-Hull Tanker

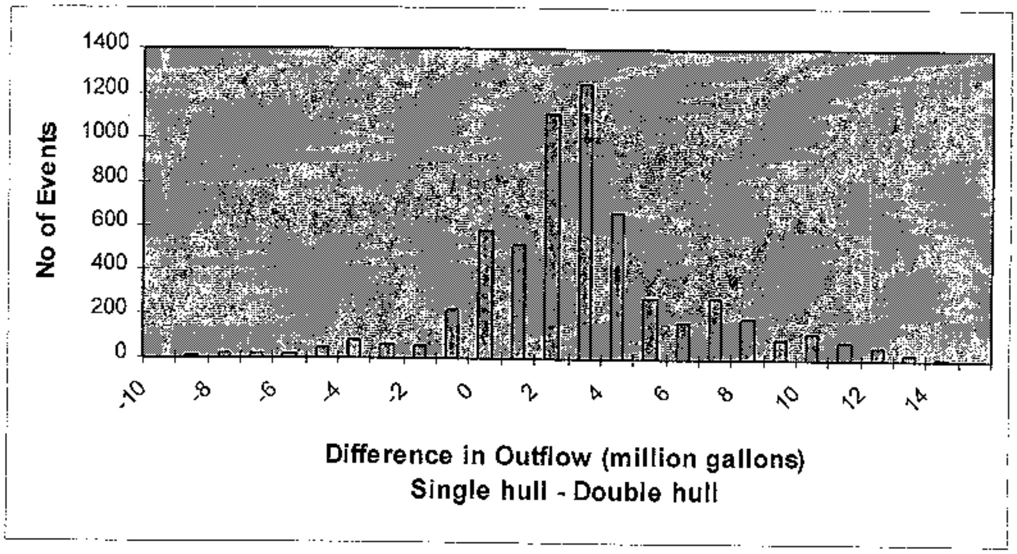

Figure 4.17: Distribution of Outflow Difference for 150,000 DWT Single-Hull and Double-Hull Tankers

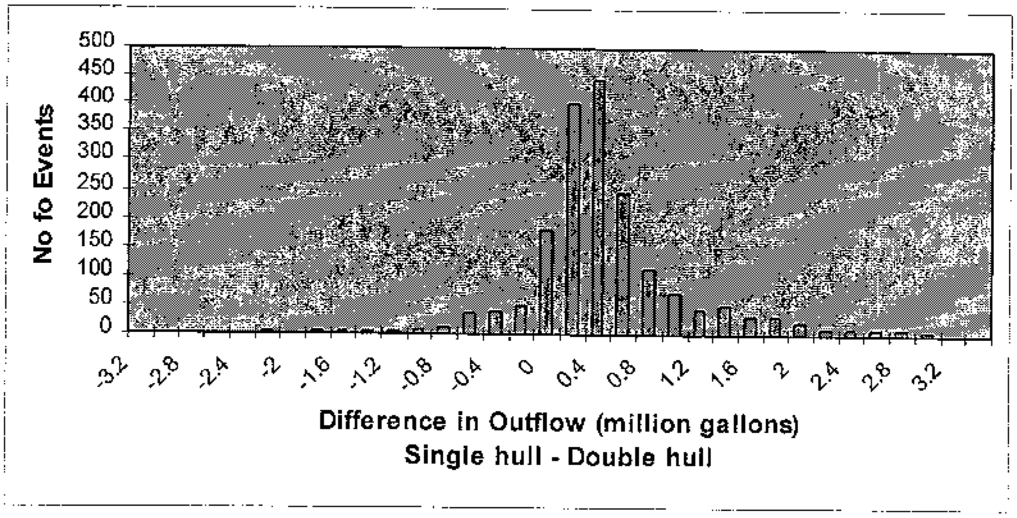

Figure 4.18: Distribution of Outflow Difference for 40,000 DWT Single-Hull and Double-Hull Tankers

Since the 150,000 DWT double-hull tanker had an unusually high double bottom, the effect of the double bottom height on the number of spills was studied, and the results are shown in Table 4.7. For comparison, the reference 150,000 DWT double-hull design in the *IMO Guidelines* has a 2.32 meter high double bottom. The base case of 3.34 meters corresponds to the B/15 double-bottom height recommended by Card's study in 1975.

These results are specific for the analyzed grounding scenarios and the assumed distribution of obstruction depths. However, they indicate that the double-bottom height is an important parameter when designing tankers to minimize oil spills. The impact of the changes in the double-bottom height on the stability, damage stability, and structural design of the tanker were not analysed in this study, but they should be taken into account, if this type analysis is used in selecting double-bottom dimensions.

Table 4.7: Effect of the double bottom height on the number of spills.

| Double bottom height | No of spills | Difference |
|---|---|---|
| **0 m (single hull)** | 5,911 | 0% |
| **2 m** | 3,805 | -36% |
| **2.5 m** | 3,373 | -43% |
| **3 m** | 2,979 | -50% |
| **3.34 m (base case)** | 2,724 | -54% |
| **3.5 m** | 2,652 | -55% |

## 4.5 Structural Modifications

Finally, the effect of simple structural modifications on the outflow performance of the 150,000 DWT double-hull tanker were investigated. The modifications included changes in the outer bottom and inner bottom plating thicknesses, and an increase in the number of longitudinal girders and transverse floors in the double bottom.

Table 4.8 shows the principal characteristics of the ship and structural characteristics of the base ship.

Table 4.8: Base Ship Principal Characteristics and Structural Details

| | |
|---|---|
| **Length Between Perpendiculars (m)** | 261 |
| **Breadth (m)** | 50 |
| **Depth (m)** | 25 |
| **Draft Amidships (m)** | 17.12 |
| **Displacement (metric tons)** | 179940 |
| **Cargo Oil Capacity (metric tons)** | 149635 |
| **Outer Bottom Thickness (mm)** | 20 |
| **Outer Bottom Longitudinals** | 625x150x13/25 |
| **Inner Bottom Thickness (mm)** | 17 |
| **Inner Bottom Longitudinals** | 625x150x13/25 |
| **Double Bottom Height (mm)** | 3340 |
| **Number of Transverse Floors** | 46 |
| **Transverse Floor Thickness (mm)** | 14.5 |
| **Number of Longitudinal Girders** | 2 (20.16m from CL) |
| **Longitudinal Girder Thickness (mm)** | 14.5 |
| **Longitudinal Spacing (mm)** | 850 |
| **Frame Spacing (mm)** | 5200 |
| **Material** | HT32 |

First, modifications were made without changing the rest of the structure. Then, more promising modifications were selected for further study. These cases were modified to minimize the increase in steel weight according to SafeHull 7.0 Phase A requirements (2001 Rules). For example, in the cases where plating thickness was increased, the stiffener size could be reduced. An "average" stiffener size was then used in DAMAGE in the specific area, since only one type and size stiffener can be specified in DAMAGE for a particular structure, for example the outer bottom. The modifications are summarized in Table 4.9. Cases 2, 4, 6, 8, 10 and 11 involved only one structural change whereas cases 3, 5, 7 and 9 involved reduction in stiffener size according to SafeHull requirements. Table 4.10 shows the relevant structural dimensions of the base ship, and the corresponding dimensions analyzed in the modified ships. The stiffener sizes in SafeHull can be found in Appendix C.

Table 4.9: Case Descriptions

| | |
|---|---|
| **Case 1** | Base Ship |
| **Case 2** | 5mm added to outer bottom |
| **Case 3** | 5mm added to outer bottom, stiffeners reduced |
| **Case 4** | 10mm added to outer bottom |
| **Case 5** | 10mm added to outer bottom, stiffeners reduced |
| **Case 6** | 5mm added to inner and outer bottom |
| **Case 7** | 5mm added to inner and outer bottom, stiffeners reduced |
| **Case 8** | 10mm added to outer bottom, 5mm added to inner bottom |
| **Case 9** | 10mm added to outer bottom, 5mm added to inner bottom, stiffeners reduced |
| **Case 10** | 2 extra transverse floors added per cargo tank |
| **Case 11** | 2 extra longitudinal girders added |

Table 4.10: Scantling Summary

| | **Outer Bottom Thickness (m)** | **Outer Bottom Stiffener** | **Inner Bottom Thickness (m)** | **Inner Bottom Stiffener** | **Number of Longitudinals** | **Number of Transverse Floors** |
|---|---|---|---|---|---|---|
| **Case 1** | 20 | 625x150x13/25 | 17 | 625x150x13/25 | 2 | 46 |
| **Case 2** | 25 | 625x150x13/25 | 17 | 625x150x13/25 | 2 | 46 |
| **Case 3** | 25 | 600x125x13/24 | 17 | 625x150x13/25 | 2 | 46 |
| **Case 4** | 30 | 625x150x13/25 | 17 | 625x150x13/25 | 2 | 46 |
| **Case 5** | 30 | 600x125x13/23 | 17 | 625x150x13/25 | 2 | 46 |
| **Case 6** | 25 | 625x150x13/25 | 23 | 625x150x13/25 | 2 | 46 |
| **Case 7** | 25 | 600x125x13/24 | 23 | 625x125x13/23 | 2 | 46 |
| **Case 8** | 30 | 625x150x13/25 | 23 | 625x150x13/25 | 2 | 46 |
| **Case 9** | 30 | 600x125x13/23 | 23 | 625x125x13/23 | 2 | 46 |
| **Case 10** | 20 | 625x150x13/25 | 17 | 625x150x13/25 | 2 | 58 |
| **Case 11** | 20 | 625x150x13/25 | 17 | 625x150x13/25 | 4 | 46 |

## Comparison of Damage Extents

Table 4.11 lists the average damage extents and the percent difference compared to the base case for the spill occurrences. The damage extent is the maximum damage in each case. Figures 4.19-4.21 give a graphical illustration of the average damage extents. Case 8, where 10mm is added to the outer bottom and 5mm is added to the inner bottom, had the least structural damage. It must be noted that since the average damage extents are for spill occurrences only, changes in the vertical damage, once the inner bottom is ruptured, are not very significant to the resulting outflow. Average vertical damage in spill scenarios ranged from 4.81m to 5.01m and the double bottom height on the studied tanker was 3.34m.

Table 4.11: Average Damage Extents When a Spill Occurs[11]

| | Average Long. Damage (m) | % Difference | Average Transverse Damage (m) | % Difference | Average Vertical Damage (m) | % Difference |
|---|---|---|---|---|---|---|
| **Case 1** | 73.51 | | 10.36 | | 4.92 | |
| **Case 2** | 69.80 | -5.04% | 10.24 | -1.13% | 4.88 | -0.72% |
| **Case 3** | 70.35 | -4.29% | 10.27 | -0.84% | 4.89 | -0.52% |
| **Case 4** | 66.02 | -10.19% | 10.12 | -2.29% | 4.83 | -1.74% |
| **Case 5** | 66.60 | -9.40% | 10.15 | -2.00% | 4.84 | -1.53% |
| **Case 6** | 66.92 | -8.96% | 10.16 | -1.90% | 4.86 | -1.13% |
| **Case 7** | 67.01 | -8.84% | 10.16 | -1.90% | 4.85 | -1.33% |
| **Case 8** | 63.76 | -13.26% | 10.05 | -2.96% | 4.81 | -2.14% |
| **Case 9** | 64.40 | -12.39% | 10.08 | -2.67% | 4.83 | -1.74% |
| **Case 10** | 72.53 | -1.33% | 10.31 | -0.45% | 4.91 | -0.11% |
| **Case 11** | 70.03 | -4.73% | 10.06 | -2.87% | 4.84 | -1.53% |

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[11] Case 1: Base ship; Case 2: 5mm added to outer bottom; Case 3: 5mm added to outer bottom, stiffeners reduced; Case 4: 10mm added to outer bottom; Case 5: 10mm added to outer bottom, stiffeners reduced; Case 6: 5mm added to inner and outer bottom; Case 7: 5mm added to inner and outer bottom, stiffeners reduced; Case 8: 10mm added to outer bottom, 5mm added to inner bottom; Case 9: 10mm added to outer bottom, 5mm added to inner bottom, stiffeners reduced; Case 10: 2 extra transverse girders added per cargo tank; Case 11: 2 extra longitudinal girders added

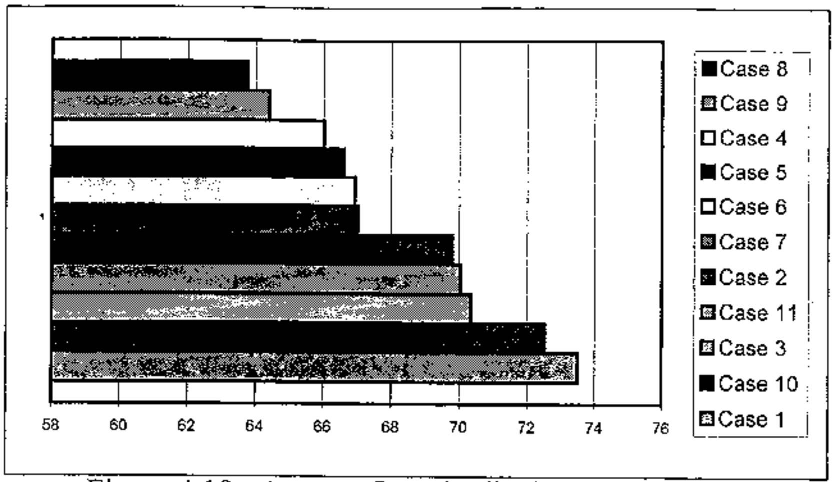

Figure 4.19: Average Longitudinal Damage Extent

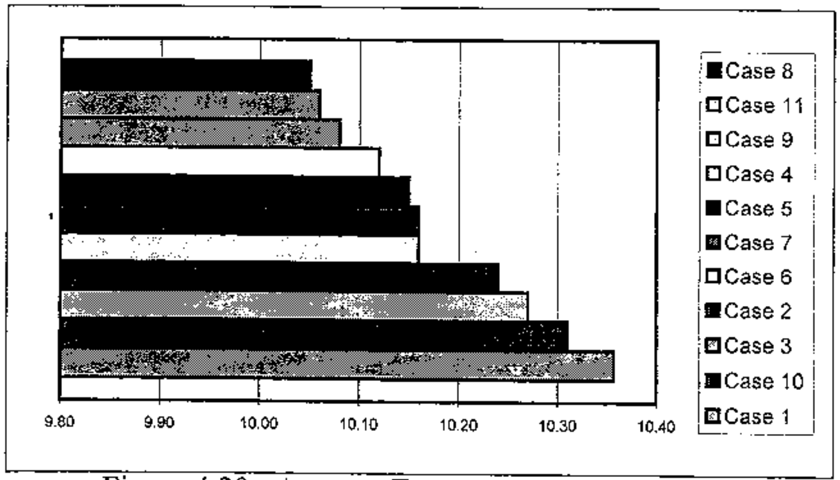

Figure 4.20: Average Transverse Damage Extent

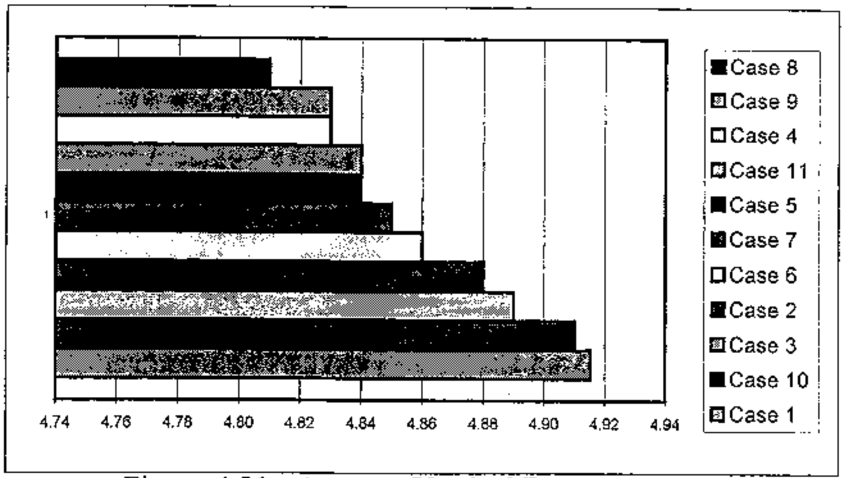

Figure 4.21: Average Vertical Damage Extent

## Comparison of Spill Occurrences and Oil Outflow

Table 4.12 lists the number of spills occurrences, the total oil outflow, and the average oil outflow that occurred when rupture of the inner bottom resulted from the grounding scenario. The percent difference is given relative to Case 1 (original design). Each of the cases with structural modifications resulted in fewer oil spills and less oil outflow than the original ship. Case 8, where 10mm is added to the outer bottom and 5mm is added to the inner bottom, had the most reduced oil outflow, while Case 10, where 12 extra transverse floors are added, had the least effect.

Table 4.12: Comparison of Spill Occurrences and Oil Outflow[12]

| | Number of Spill Occurrences | % Difference | Total Oil Outflow (mil. gallons) | % Difference | Average Oil Outflow (mil. gallons) | % Difference |
|---|---|---|---|---|---|---|
| **Case 1** | 2724 | | 10644 | | 3.91 | |
| **Case 2** | 2636 | -3.23% | 9931 | -6.70% | 3.77 | -3.59% |
| **Case 3** | 2654 | -2.57% | 10060 | -5.49% | 3.79 | -2.99% |
| **Case 4** | 2571 | -5.62% | 9282 | -12.79% | 3.61 | -7.61% |
| **Case 5** | 2589 | -4.96% | 9426 | -11.44% | 3.64 | -6.82% |
| **Case 6** | 2573 | -5.54% | 9362 | -12.04% | 3.64 | -6.88% |
| **Case 7** | 2580 | -5.29% | 9404 | -11.65% | 3.65 | -6.72% |
| **Case 8** | 2503 | -8.11% | 8795 | -17.37% | 3.51 | -10.07% |
| **Case 9** | 2518 | -7.56% | 8922 | -16.18% | 3.54 | -9.32% |
| **Case 10** | 2685 | -1.43% | 10450 | -1.82% | 3.89 | -0.40% |
| **Case 11** | 2611 | -4.15% | 9878 | -7.19% | 3.78 | -3.18% |

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[12] Case 1: Base ship; Case 2: 5mm added to outer bottom; Case 3: 5mm added to outer bottom, stiffeners reduced; Case 4: 10mm added to outer bottom; Case 5: 10mm added to outer bottom, stiffeners reduced; Case 6: 5mm added to inner and outer bottom; Case 7: 5mm added to inner and outer bottom, stiffeners reduced; Case 8: 10mm added to outer bottom, 5mm added to inner bottom; Case 9: 10mm added to outer bottom, 5mm added to inner bottom, stiffeners reduced; Case 10: 2 extra transverse girders added per cargo tank; Case 11: 2 extra longitudinal girders added

**Comparison of Steel Weight**

The ratio of the increase in steel weight to the oil outflow saved was used to measure of the effectiveness of the structural modifications. Table 4.13 lists the steel weight per unit length of the longitudinal structure, as calculated by SafeHull (transverse structure is not included). The steel weights for Cases 10 and 11 were not recorded, because the comparison with the original weight is not meaningful without the weight of the transverse structure.

Table 4.13: Steel Weight Per Unit Length[13]

| | Steel Weight (MT/m) | % Difference in Steel Weight (Compared to Case 1) |
|---|---|---|
| Case 1 | 16711 | |
| Case 2 | 17055 | 2.06% |
| Case 3 | 17005 | 1.76% |
| Case 4 | 17398 | 4.11% |
| Case 5 | 17337 | 3.75% |
| Case 6 | 17420 | 4.24% |
| Case 7 | 17363 | 3.90% |
| Case 8 | 17764 | 6.30% |
| Case 9 | 17695 | 5.89% |

The case 8, which was shown above to have the least spills and the least outflow has also the greatest increase in steel weight. Figure 4.22 illustrates the relationship between the added steel weight of the structure (represented by extra steel weight), and the "saved" oil outflow. The graph indicates an almost linear the relationship between the increase in steel weight and saved oil outflow.

The ratio of the saved oil outflow to the increase in steel weight is shown in Figure 4.23. The modification with the largest ratio has the least cost for the benefits gained. Case 2, where 5mm is added to the outer bottom, has the best ratio, but the differences between the cases are small.

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[13] Case 1: Base ship; Case 2: 5mm added to outer bottom; Case 3: 5mm added to outer bottom, stiffeners reduced; Case 4: 10mm added to outer bottom; Case 5: 10mm added to outer bottom, stiffeners reduced; Case 6: 5mm added to inner and outer bottom; Case 7: 5mm added to inner and outer bottom, stiffeners reduced; Case 8: 10mm added to outer bottom, 5mm added to inner bottom; Case 9: 10mm added to outer bottom, 5mm added to inner bottom, stiffeners reduced

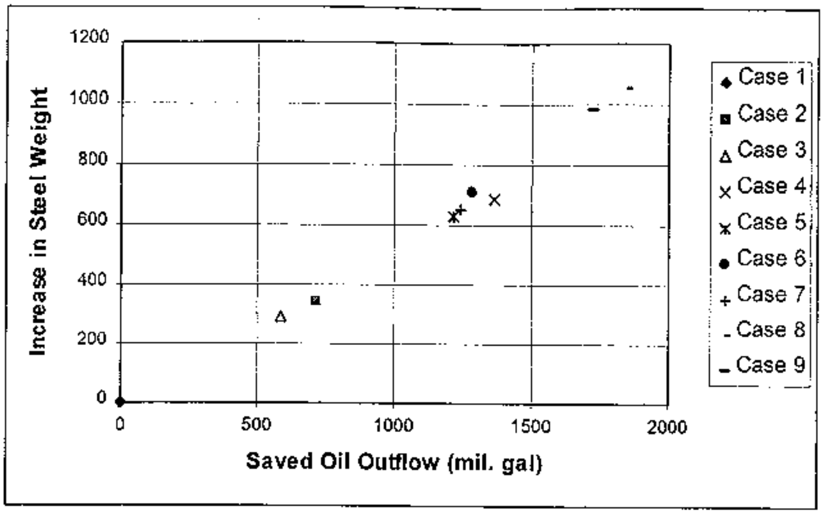

Figure 4.22: Increase in Steel Weight vs. Saved Oil Outflow

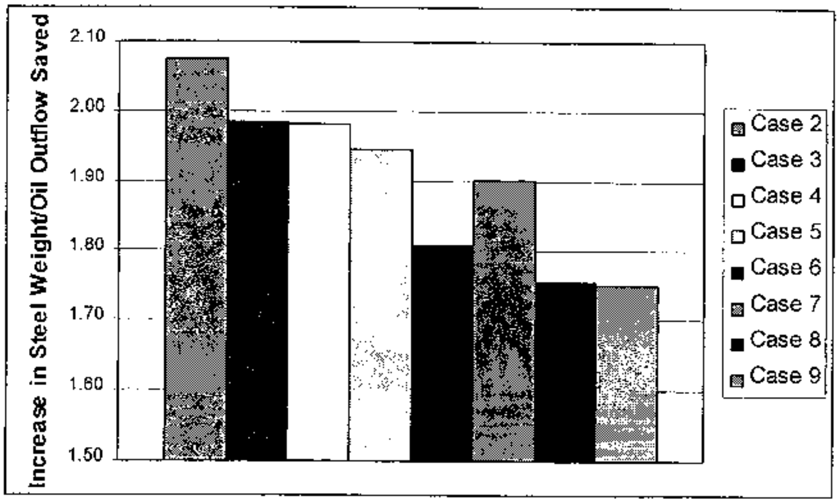

Figure 4.23: Ratio of Increase in Steel Weight to Oil Outflow Saved

These results would indicate that the reduction in oil outflow is a linear function of the added steel weight, but the effectiveness of the modifications is reduced when the steel weight is increased. It is more efficient to add steel to the outer bottom than to both the inner and outer bottom. However, it must be kept in mind that the oil outflow is not the final consequence of a spill, and the conclusion on the effectiveness of the modifications can change when the actual consequences of spills (environmental damage and economic losses) are included in the analysis.

# 5. CONCLUSIONS

The analyses and results presented in this report include:

1. Validation of a computational tool DAMAGE, which uses a simplified approach to predict damage extents in ship grounding.
2. Illustration of the use of DAMAGE to predict structural damage in selected grounding scenarios for various structural arrangements.
3. Sensitivity analysis of damage results to input parameters.
4. Illustration of the use of DAMAGE to predict structural damage in a large number of grounding scenarios for various structural arrangements.
5. Analysis of oil outflow in a large number of grounding scenarios, and a regression analysis between input and output variables.
6. Investigation on the effect of structural modifications on the oil outflow.

The following conclusions are made based on the above analyses:

1. The software DAMAGE was selected as the best simplified method for analyzing structural damage in grounding. The program is easy to use and it has the widest range of applicability of the published simplified methods. The validation study indicates that the internal mechanics without the effect of ship motions is captured well by DAMAGE, and DAMAGE predictions on the average values of penetration and internal forces are good. DAMAGE predicted longitudinal damage extent well in the studied cases. However, the analytical formulas for the failure modes are limited to local behavior of the structure. For example, DAMAGE cannot predict possible inner bottom rupture caused by the internal double-bottom structure pushing the inner

bottom. Further review is recommended on the prediction of structural component response to confirm that DAMAGE is an accurate tool for structural design evaluation. This will require additional data from either actual groundings or large-scale model tests.

2. The main limitations of DAMAGE to predict structural damage in selected grounding scenarios for various structural arrangements are:

   a. The structural model includes only the cargo block. The effect of the bow and the stern on the structural behavior in the damage region is neglected.

   b. The model is built with conventional structural members, and the material used is limited to ones that can be described with the stress-strain curve and the assumed failure modes. Innovative structural designs using new materials would require extensions to the current program.

   c. DAMAGE is limited to modeling powered head-on grounding on a single pinnacle. Other types of obstructions or groundings (i.e. grounding on a reef or soft soil, drift grounding) cannot be currently modeled in DAMAGE.

   d. All available methods to predict structural damage in grounding lack an accurate model for initiation and propagation of fracture [Hansen and Simonsen, 2001]. This is a general limitation that makes comparison of the behavior of different materials in grounding impractical at the moment.

The limitations are significant, if the program is used to predict damage extents in an absolute sense. However, when used in a comparative analysis, the method is valid unless the limitations create bias towards one of the alternatives, which does not appear to be the case in the analysis presented here. Powered head-on groundings on a single pinnacle do not cover all possible grounding scenarios, but by varying the input variables, including speed and pinnacle shape, they can represent a large variety of scenarios. The lack of bow and stern models is not significant, if alternatives to the double bottom structure are studied. If innovative structural arrangements are used the program must, and can, be modified. Comparison of the behavior of different materials is questionable until there is more research on the initiation and propagation of ductile fracture.

3. The deterministic analysis indicated that the damage extent results are very sensitive to the rock elevation, rock shape and transverse location, ship velocity and displacement. The results were found sensitive also to the value of the friction coefficient and the trim angle. The sensitivity of the damage results to the input variables defining grounding scenarios reinforced the need to carry out a probabilistic analysis for a large number of grounding scenarios to study the relative performance of structural designs.

4. DAMAGE provides a good tool for probabilistic analysis involving large amounts of input and output data since it is easy to use and the computation is fast. As was discussed above, the limitations of DAMAGE are not as significant in a comparative analysis as they are in predicting absolute damage extents. Therefore, DAMAGE was found applicable, and the best available simplified tool for predicting structural damage in a large number of grounding scenarios for the selected structural arrangements.

5. The outflow calculation was combined with the damage extent calculations to study the oil outflow distributions in a large number of grounding scenarios. A linear regression analysis between the outflow and the input variables indicated a strong dependency between outflow, vessel speed, rock eccentricity and tidal variation. The most severe accidents are a result of either a long damage that ruptures several tanks in the longitudinal direction, a damage that is shorter but ruptures both tanks in the transverse direction, or a combination of the two. A low-tide condition increases the

outflow. The ostruction depth is also important in determining whether the cargo block is ruptured, but after the rupture has occurred changes in the elevation do not have a strong impact the oil outflow.

6. The results presented in the paper indicate that a double bottom is effective in reducing the number of spills, and the reduction depends strongly on the height of the double bottom. A double-hull tanker had smaller spills than the single-hull tanker in the majority of the grounding events, but the double-hull tanker had more, although still only a few, very large spills. Simple modifications to the bottom structure were not found to be very effective in reducing the number or the size of the spills. It must be noted that the oil outflow is not the ultimate consequence of a grounding accident. Since it must be assumed that the realtionship between the oil outflow and the economic and environmental impacts is not linear, the oil outflow results must be combined with consequence measures to assess the relative performance of alternative designs. This type of analysis might change the conclusion on the effectiveness of the structral modifications.

# 6. RECOMMENDATIONS

The report illustrates a tanker grounding analysis, that takes into account the effect of the structure and the internal subdivision in the calculation of oil outflow. The approach used in the paper has many applications. It can be used to:

1. Compare vessel outflow performance between designs.
2. Study the effect of structural modifications.
3. Provide input into risk-analysis studies to evaluate the effectiveness of designs to minimize consequences of oil spills.

To further the study on the crashworthiness of ships in grounding, the following future work is recommended:

1. Validation data should be collected to further test the applicability of the existing simplified methods to predict structural response in grounding. The data must include detail information on the grounding scenarios, vessels, and the damage extents. A list of required data is given in Appendix B.

2. Since the damage extents are strongly dependent on the grounding scenarios a simulation of a large number of grounding scenarios is recommended. The grounding scenarios used in this study were based on limited data. Further work on defining grounding scenarios is recommended.

3. DAMAGE, developed by the joint MIT-Industry Project on Tanker Safety has been shown to be a useful program for the prediction of structural damage in grounding. Maintenance of the program as well as improvements to it are recommended. The following specific improvements are recommended:

    a. The add-on program that provided batch run capability as well outflow calculations for DAMAGE was written for the specific vessels used in the study. Development of a general program applicable to all types of ships is recommended.

b. Adding a capability to predict other than powered head-on groundings is recommended.

4. The probabilistic grounding analysis done in this project provides a basis for analyzing risks of tanker traffic. A complete risk analysis will require determination of the probability of occurrence of grounding scenarios in the area of study, and the assessment of the consequences of the oil outflow. This type of risk analysis is being carried out at the Technical University of Denmark for the Danish waters as a part of the ISESO project [Hansen and Simonsen, 2001]. A risk analysis of tanker traffic in US waters (selected locations) is recommended. This type of analysis will provide a foundation for simulation tools that can be used in risk-based rule development.

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# APPENDIX A

# BATCH-RUN CAPABILITY AND OUTFLOW CALCULATIONS FOR DAMAGE

## 1 Introduction

### 1.1 Program Scope

The program determines the oil outflow for each grounding scenario, which is defined by input files generated by the program. The ship general particulars and structural information are fixed for all cases.

The program consists of 7 major parts as follows:

1. Reading of case-by-case input file.
2. Generation of the input files in DAMAGE format.
3. Execution of the DAMAGE calculation engine.
4. Reading of grounding history file.
5. Evaluation of conditional series to determine where the damage boundaries lie.
6. Calculation of outflow using 'conceptual analysis'.
7. Generation of a case-by-case report of the damage and outflow information.

These actions are all controlled by a PERL script, which performs each task in turn.

### 1.2 Language Selection

PERL, which stands for Practical Extraction and Report Language, is a scripting language based on C/C++ and UNIX syntax. It was chosen for this application because of its effectiveness in reading data from text files and for automatically generating fixed-format files and reports. The language itself does not have extensive mathematical capabilities, and for making processor-intensive calculations it is not efficient, because each script must be compiled and executed in real-time. However, for the tasks outlined above - reading a large number of different cases and generating a fixed-format input file for each case - it has excellent facilities. The programs for this application are PERL scripts, which can be executed and compiled in real time. They are further subdivided into sections and each section is discussed below.

## 2 Input Section

The input section of the script reads the case-by-case input file into memory and generates for each execution step an appropriate DAMAGE input file for the grounding calculation. DAMAGE input file generation is accomplished by reading each of the input variables (from the case input) into an array and then writing a file containing the correct values for that case (according to the index) at each program step. After this file has been written, a system call is made to the DAMAGE calculation engine, which uses the just-written input file to calculate the grounding scenario. Since only a few ships were analyzed for this particular work, the ship geometry part of the input file is the same for each file, making the scripts ship-specific.

## 2.1 Input File Format

The input file contains the following columns:

1. Case Number
2. Ship velocity (in knots)
3. Rock elevation (measured from the bottom of the ship at full-load draft)
4. Rock Angle (apex angle - in degrees)
5. Rock Tip Radius (m)
6. Rock Transverse Position (eccentricity - measured in meters)
7. Tidal Variation (in m)
8. Inert Gas Pressure (in mm WG)
9. Ballast Tank Capture Percentage

The rest of the DAMAGE input file is ship-specific. The ship-geometry section of the script generates the design-specific part of the input file.

## 2.2 DAMAGE Input File Format

The DAMAGE input file is called by the calculation engine executable 'grounding.exe'. This executable file can be found in the \data\process directory of the DAMAGE 5.0 installation. The 'grounding.exe' file calculates the grounding scenario described in a file called 'in.' An 'in' file is generated for each case by the PERL script and after 'in' file generation has been completed, a system call is made to the 'grounding.exe' program and the grounding history file 'grnd.hst' is generated. The DAMAGE input file 'in' has the following sections:

1. Global Controls
2. Global Ship Parameters
3. Ground Characterization
4. Ship-Ground Interaction
5. Striking Ship Characterization
6. Ship-Ship Interaction
7. Structural Information

Each of these sections and their generation by the script are discussed below.

### 2.2.1 Global Controls

The global controls section contains information about the type of calculation DAMAGE will perform. For all calculations performed during the course of this work, grounding settings were used.

### 2.2.2 Global Ship Parameters

This section contains information on the ship's general particularsfor example length, breadth, depth, and metacentric height. This information is constant for all cases.

### 2.2.3 Ground Characterization

This section contains information about the rock size and shape. The parameters included in this section are rock tip radius and rock tip angle. These parameters are varied on a case-by-case basis.

### 2.2.4 Ship-Ground Interaction

This section contains information about the ship relative to the ground. The parameters included in this section are ship forward speed, trim angle, friction coefficient, rock transverse position, and rock elevation (measured from the baseline). All of these parameters except trim angle and friction coefficient were varied on a case-by-case basis.

### 2.2.5 Striking Ship Characterization

This section is only used for collision scenarios. Since only grounding scenarios were analyzed, this section was not used.

### 2.2.6 Ship-Ship Interaction

This section is only used for collision analysis.

### 2.2.7 Structural Information

The structural information is contained in several sections. Since all cases are performed for constant ship geometry, structural information is not changed on a case-by-case basis. However, in order to compare ships, new structural information must be entered.

## 2.3 Ship Geometry Section

Since the ship geometry is the same for each case, this part of the script does not change. For each case, the same information is written into the DAMAGE input file. This information contains the ship's particulars, the material information, and structural scantlings. For a different design, a new script must be created which contains the correct ship-specific information. This information can be obtained by modifying the ship using the DAMAGE user interface and then executing a DAMAGE calculation. After the calculation has been executed from the DAMAGE program, the relevant information can be copied from the input file generated by DAMAGE and pasted into the correct part of the script. It should be noted that each script is ship-specific and can only be used for analysis of a specific ship. Additionally, the outflow calculation is ship-specific.

# 3 DAMAGE Usage

The program DAMAGE was used as a 'black box' external to the script. As stated before, after the writing of the input file is completed, the calculation is executed and this automatically generates grounding scenario output in the form of a time history file called 'grnd.hst.' Then the script opens the time history and reads it in much the same way as the input file was read before, with each column of data being read into a separate array. These arrays are used to determine the extent of the bottom rupture at each time step and the position of that rupture. This information is then used in calculating the outflow for the case.

# 4 Outflow Calculations

Outflow calculation is performed using 'conceptual analysis', i.e. the ship is assumed to remain at the initial draft and trim, and hydrostatic balance is calculated for these conditions. The outflow is determined by calculating hydrostatic balance in the tanks, including the effect of inert gas pressure and tidal conditions. In the case of a double-hull tanker, a percentage of the oil is assumed captured into the ballast tanks. The hydrostatic balance between the mixture contained in the ballast tank and the outside water is first calculated and then the balance between the cargo and the double bottom mixture is calculated.

## 4.1 Hydrostatic Balance Calculation

The outflow calculation will be further explained in this section.

### 4.1.1 Reading of Damage Time History

The calculation of outflow begins with the reading of the damage time history file. This is followed by generation of arrays containing innage information for non wall-sided tanks. These arrays will be used for linear interpolation of the tank volume for a hydrostatically determined height of fluid in the tank.

### 4.1.2 Calculation of Double Bottom Fluid Density

This step applies only to outflow calculation for the double hull tanker. Since the pressure on the outer bottom of the ship is known (given by the ship's draft and the SW density) and the double bottom fluid density is also known (weighted average of the seawater and oil densities), the height of fluid in the double bottom, and the resultant pressure at the ship's inner bottom can be calculated. The density of fluid in the double bottom is determined by a weighted average using the captured oil percentage for the case in question:

$$\rho_{DB} \equiv X_{capture} \times \rho_{OIL} + \left(1 - X_{capture}\right) \times \rho_{SEAWATER}$$

Where $X_{capture}$ is the percentage of the flooded double bottom volume, which retains oil. In this manner, the capture percentage is accurately accounted for in the hydrostatic balance calculation for each time step. This step will be performed for the double-hull tanker only.

### 4.1.3 Hydrostatic Balance Calculation

The hydrostatic balance calculation is performed on basis of fluid heights. The equivalent height of fluid is calculated in order to ensure that the pressure at the bottom of the ship is equalized between the inside and the outside. The pressure due to the IG pressure is included in the hydrostatic balance, as well as the loss of seawater head due to the tide going out (tide is one of the case-by-case input variables). For the double hull ship, the calculation of height inside the double bottom is given by:

$$H_{mixture} = \frac{(DRAFT - TIDE) * \rho_{SW} - IGPRESS - \rho_{DBmix} * H_{DB}}{\rho_{MIX}} + H_{DB}$$

Where $H_{DB}$ is the height of the double bottom in meters. The height of the fluid in the cargo tanks after capture and hydrostatic balance is given by:

$$H_{cargo} = \frac{(DRAFT - TIDE) * \rho_{SW} - IGPRESS - \rho_{DBmix} * H_{DB}}{\rho_{OIL}}$$

Once these heights are known, it is simple to calculate the outflow and the volume of captured oil using the innage tables for the tanks.

All fluid heights are determined using 'conceptual analysis', i.e. the ship is assumed to float at her initial draft and trim conditions. The time saved by using this method of calculating hydrostatic balance is substantial.

### 4.1.4 Conditional Evaluation of Damage

Evaluation of tank damage is done by a series of nested conditional loops which examine the bottom rupture variable for each time step along with the transverse extent of the damage in order to determine which tank(s) is/are damaged for that time step. If the tank has been determined damaged in a previous time step evaluation, the outflow is not counted twice. The script walks through all steps in the time history to determine how many tanks are damaged and then calculates the outflow for each tank based on the final height of the fluid in the cargo and ballast tanks as previously explained. The outflows are then totaled and after the last time step has been examined, the script moves on to the generation of results.

## 5 Results

The final output of the program is in the form of an ASCII text file, which contains case-by-case information about the critical inputs for the case, the extents of the damage, the itemized outflows, and the total outflow. This file has much the same structure as the original input file (in that it is organized on a case-by-case basis in columns). The output file lends itself to easy import into a spreadsheet program, thus allowing for easy statistical analysis of the results.

# APPENDIX B

# VALIDATION DATA

## Data Requirements for DAMAGE

The following is a list of data requirements for the program DAMAGE. Some of the data, such as material stress-strain characteristics and friction coefficient, is difficult to obtain, and assumed values and sensitivity analyses must be used instead. Global ship parameters are important, as they determine the effect of motions on the damage extent. For the bottom structure, information on longitudinal structural members is important. Grounding scenario data are necessary as the results are highly dependent on them.

1) Material Properties
   a) Young's modulus
   b) Poisson's ratio
   c) .02% yield stress
   d) Tensile stress-strain characteristics
      i) yield stress or 0.2% proof stress
      ii) ultimate tensile stress
      iii) strain to rupture

2) Ship
   a) Length (LBP)
   b) Breadth
   c) Depth
   d) Breadth of flat bottom
   e) Draft amidships
   f) Displacement
   g) Waterplane area
   h) LCF
   i) Longitudinal metacentric height
   j) Number of tanks in longitudinal direction
   k) Location of transverse bulkheads; bulkhead thickness and stiffener dimensions
   l) Location of longitudinal bulkheads; bulkhead thickness and stiffener dimensions
   m) Bottom structure
      i) single/double
      ii) spacing and dimensions of transverse floors and longitudinal girders
      iii) spacing and dimensions of longitudinal stiffeners

3) Grounding scenario
   a) Impact velocity
   b) Trim angle

c) Friction coefficient
d) Rock location relative to the ship's centerline
e) Rock elevation relative to the ship's baseline
f) Rock geometry

## Structural Damage Data

To compare calculated results with actual grounding damage, information on the damage extents is needed. As a minimum the maximum damage extents in three dimensions should be available, but a complete drawing showing the damage would be desirable. If calculations are compared with large-scale model tests, the measured grounding forces can be compared with the calculated forces.

# APPENDIX C

## STIFFENER INFORMATION IN SAFEHULL

Note: Cases are defined in Table 4.10.

| | Keel Stiffener ID# | Keel Stiffener Size | Outer Bottom Stiffener ID# | Outer Bottom Stiffener Size | Inner Bottom Stiffener ID# | Inner Bottom Stiffener Size |
|---|---|---|---|---|---|---|
| Case 1 | **1-2** | **600x125x12.5/22** | **1-15** | **600x125x12.5/22** | **1-18** | **600x150x12.5/23** |
| | | | **16** | **650x150x12.5/25** | **19** | **725x150x12.5/25** |
| | | | **17-18** | **675x150x12.5/24** | **20** | **300x100x12.5/16** |
| | | | **19** | **825x150x12.5/24** | | |
| | | | **20-22** | **650x150x12.5/25** | | |
| | | | **23** | **700x150x12.5/25** | | |
| Case 3 | **1-2** | **600x100x12.5/25** | **1-13** | **550x125x12.5/25** | **1-18** | **600x150x12.5/23** |
| | | | **14-15** | **550x125x12.5/24** | **19** | **725x150x12.5/25** |
| | | | **16-17** | **600x150x12.5/22** | **20** | **300x100x12.5/16** |
| | | | **18** | **700x150x12.5/25** | | |
| | | | **19** | **725x150x12.5/24** | | |
| | | | **20** | **600x150x12.5/21** | | |
| | | | **21-22** | **600x150x12.5/22** | | |
| | | | **23** | **625x150x12.5/24** | | |
| Case 5 | **1-2** | **600x100x12.5/24** | **1-13** | **550x125x12.5/24** | **1-18** | **600x150x12.5/23** |
| | | | **14-15** | **550x150x12.5/20** | **19** | **725x150x12.5/25** |
| | | | **16** | **600x125x12.5/24** | **20** | **300x100x12.5/16** |
| | | | **17** | **600x125x12.5/25** | | |
| | | | **18** | **725x150x12.5/22** | | |
| | | | **19** | **700x150x12.5/25** | | |
| | | | **20** | **600x125x12.5/24** | | |
| | | | **21-22** | **600x150x12.5/22** | | |
| | | | **23** | **625x150x12.5/24** | | |

|  | Keel Stiffener ID# | Keel Stiffener Size | Outer Bottom Stiffener ID# | Outer Bottom Stiffener Size | Inner Bottom Stiffener ID# | Inner Bottom Stiffener Size |
|---|---|---|---|---|---|---|
| Case 7 | 1-2 | 600x100x12.5/25 | 1-13 | 550x125x12.5/25 | 1-18 | 625x125x12.5/23 |
|  |  |  | 14-15 | 550x125x12.5/24 | 19 | 700x150x12.5/25 |
|  |  |  | 16-17 | 600x150x12.5/22 | 20 | 450x125x12.5/23 |
|  |  |  | 18 | 700x150x12.5/25 |  |  |
|  |  |  | 19 | 725x150x12.5/24 |  |  |
|  |  |  | 20 | 600x150x12.5/21 |  |  |
|  |  |  | 21-22 | 600x150x12.5/22 |  |  |
|  |  |  | 23 | 625x150x12.5/24 |  |  |
| Case 9 | 1-2 | 600x100x12.5/24 | 1-13 | 550x125x12.5/24 | 1-18 | 625x125x12.5/23 |
|  |  |  | 14-15 | 550x150x12.5/20 | 19 | 700x150x12.5/25 |
|  |  |  | 16 | 600x125x12.5/24 | 20 | 450x125x12.5/23 |
|  |  |  | 17 | 600x125x12.5/25 |  |  |
|  |  |  | 18 | 725x150x12.5/22 |  |  |
|  |  |  | 19 | 700x150x12.5/25 |  |  |
|  |  |  | 20 | 600x125x12.5/24 |  |  |
|  |  |  | 21-22 | 600x150x12.5/22 |  |  |
|  |  |  | 23 | 625x150x12.5/24 |  |  |
| Case 12 | 1-2 | 650x150x12.5/25 | 1-15 | 650x150x12.5/25 | 1-18 | 700x150x12.5/25 |
|  |  |  | 16 | 750x150x12.5/24 | 19 | 875x150x12.5/25 |
|  |  |  | 17 | 750x150x12.5/25 | 20 | 525x150x12.5/22 |
|  |  |  | 18 | 900x150x12.5/24 |  |  |
|  |  |  | 19 | 925x150x12.5/24 |  |  |
|  |  |  | 20 | 725x150x12.5/24 |  |  |
|  |  |  | 21-22 | 725x150x12.5/25 |  |  |
|  |  |  | 23 | 800x150x12.5/25 |  |  |

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