Accepted SNAME Annual Meeting T&R 2003 and *SNAME Transactions* 2003

Modeling Motion and Loads on Stranded Ships in Waves

Michael Simbulan (S)[1], **Alan Brown** (FL), **Jeffrey Mcquillan** (S)[2], **Marte Gutierrez** (N)

Virginia Polytechnic Institute and State University, Blacksburg, VA

[1]LT, USCG [2]LT, USN

ABSTRACT

Currently, salvors use simplified static analysis, experience, and good judgment or "seamanship" to predict post-grounding loads on stranded ships. While this approach provides some basis for the decisions made by naval architects and salvors during design and salvage, it does not accurately predict forces and motions on a stranded ship in waves. In this paper, a model for predicting ship motion and ground reaction forces due to the steady state motion of a stranded ship in waves is presented. The ground reaction model is derived from civil engineering soil applications, tailored for use with a ship motion model. The input to the model specifies the grounded static equilibrium condition, including ground reaction forces. The model is used to calculate steady state motions and loads around the equilibrium condition. Results indicate that wave-induced bending moments on a stranded ship in waves may exceed static grounding-induced bending moments and classification society design standard bending moments.

NOMENCLATURE

K^d - dynamic ground reaction stiffness
K^s - static ground reaction stiffness
K^o - surface static ground reaction stiffness
a_0 - dimensionless frequency ($a_0 = \omega B/V_s$)
ω - frequency of the motion
L - length of foundation or embedded section
B - width of foundation or embedded section
Vs - shear wave velocity in the soil
Vp - pressure wave velocity in the soil
k - stiffness
c - damping
υ - Poisson ratio
G - shear modulus
E - depth of embedment
α - pressure to shear wave celerity ratio (Vs/Vp)
F_{Gi} - component of gravity force acting on ship in the i-direction
F_{Hi} - component of fluid force acting on the ship in the i-direction
$F_{ground\ i}$ - component of the ground reaction force acting on ship in the i-direction
Δ_{jk} - ship inertia matrix
A_{jk} - fluid added mass matrix
B^H_{jk} - fluid damping matrix
C^H_{jk} - hydrostatic stiffness matrix
K^d_{jk} - ground reaction dynamic stiffness matrix
ω - wave frequency
$\bar{x}_k$ - complex ship motion magnitude in k direction
$\overline{F}_{wj}$ - complex wave force magnitude in j direction

INTRODUCTION

The serious consequences of ship grounding and collision necessitate the development of regulations and requirements for the subdivision and structural design of ships to reduce damage and environmental pollution, and improve safety. Tools are also required to aid salvors in post-casualty analysis and impact mitigation. Significant research has addressed the prediction of structural damage suffered by a ship while grounding (Brown et al 2000, Paik 2003), but far less research has considered the motion and loads on a ship after it has grounded (Paik and Pedersen 1997, McCormick and Hudson 2001). Ultimate hull failure, break-up and post-grounding cargo loss depend on the residual ultimate strength of the hull structure and on post-grounding structural loads.

This paper describes the dynamic effect of waves on stranded ship motion and loads. A theoretical analysis of the motions and loads in six-degrees of freedom of a grounded ship in waves is developed with an appropriate soil reaction model to estimate dynamic ground reaction forces. The steady-state grounded motion of the stranded ship in waves around the quasi-equilibrium position is treated as a steady-state linear dynamic problem. Comparisons are made to static grounding results and to current ABS/IACS design rules.

The primary motivation for this work is the hypothesis that wave-induced loads can be significant relative to other loads and must be considered in post-grounding analysis. This work is sponsored by SNAME Ad Hoc Panel #6 and the Ship Structure Committee (SSC).

GROUNDING

A review of ship groundings was conducted to identify the general characteristics and scope of historic grounding events (Cahill 1991, Bartholomew 1990, Bartholomew et al 1992, NAVSEA OOC 2002, ATSB 2002). Based on this data, the following general conclusions and observations are made:

1. Groundings occur on a range of bottom types. The general types of bottom may be classified as:
   - Sand
   - Clay (mud)
   - Soft rock (coral)
   - Hard rock
2. Grounding includes four distinct phases, as illustrated in Figure 1:
   - Phase One - Ship underway
   - Phase Two - Grounding impact event (t = 0 to t = 10 sec)
   - Phase Three - Orientation and translation (t = 10 sec to t = 24$^+$ hours)
   - Phase Four - Steady-state grounded position with steady-state periodic motion in response to waves; starts after one extreme tidal or extreme weather cycle (statistically stationary process); may cycle back to Phase Three with significant changes in tide, weather or sea state.

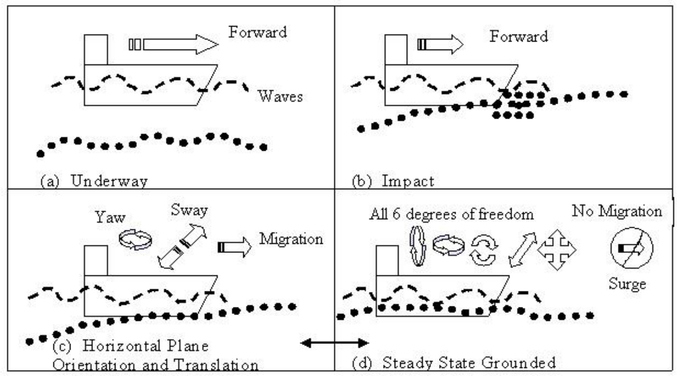

Figure 1 - Four Phases of Ship Groundings

3. The grounded ship orientation cannot be generalized. A ship that grounds may broach if conditions are right, but this is not a certainty. Since ship operators and salvors try to prevent broaching, it cannot be assumed that a ship will broach after grounding. To prevent movement of the ship into a more precarious position until the ship is ready to free, the ship is often stabilized. This is done using anchors (beach gear) or by flooding down.
4. Ships may run aground (Phase Two) bow first or drift aground in any orientation with some portion of the ship length either embedded in the bottom or resting on the bottom, exchanging buoyancy for an equal ground reaction.
5. Groundings may last several hours to several months. As such, the need to understand the motions and loads of the stranded ship are important because both affect rescue and salvage operations. "Stranding salvage is time-critical. Environmental conditions may improve or worsen with time, but the condition of a stranded ship steadily deteriorates" (Bartholomew et al 1992). The continued wave loading and ground reaction on a stranded ship will eventually cause structural damage even on a hull that was initially undamaged from the Phase Two grounding event.

At sea, buoyant force equals total ship weight. When a ship runs aground, a ground reaction is created. At equilibrium the ground reaction is defined as the difference between ship weight and buoyancy. It acts approximately through the centroid of the grounded area (Bartholomew et al 1992). The ground reaction can increase if the ship takes on more weight from flooding either by seas or hull damage. If the ship is partially aground then the ship is free to heel and change its trim about the grounded area until both forces and moments are in equilibrium.

Basic techniques used to free a stranded ship include:

- Reduce the ground reaction or draft of the ship
- Push or pull the ship into deeper water
- Increase the depth of water at the site of the stranded ship, or
- A combination of these techniques.

Removing loads like cargo, fuel, mud and floodwater reduces the ground reaction. If the ship is partially grounded then adjusting its trim by moving weights or adjusting ballast may free it. Pushing or pulling the stranded ship requires enough force to overcome the forces of friction, suction and soil buildup. Friction in sand is a function of the ground reaction force so reducing the ground reaction by lightering the ship can aid in extraction. Friction in mud is the product of shear strength and contact area so loosening the mud around the hull can also aid in extraction. The suction force can be decreased by rocking the ship or by scouring the surrounding soil, which will allow water to flow to the hull. Dredging and scouring can be used to increase the water depth at the stranded ship. Sometimes channels are created for the ship to float into deeper water. Tides may also increase the water depth at the stranded ship site, but only temporarily. Examples of typical decisions that need to be made by the salvor are:

- Hurry the operation to avoid adverse weather or tides,
- Stabilize the stranded ship,
- Remove/destroy some or all of the cargo,
- Request more help and money, or
- A combination of these choices

Currently these decisions are made in an ad hoc manner based on a simplified use of static analysis along with experience and sound engineering/seamanship judgment. Some courses of action intended to avoid disaster may have significant adverse impact on the safety of personnel, the environment, and salvage costs. Examples of these actions are:

- Efforts to refloat or ballast,
- Rigging of anchors, cables and support vessels that are necessary to stabilize the stranded ship,
- Lightering or burning of fuel, and
- Use of explosives.

The salvor must have all the necessary information to accurately predict the impact of alternative plans of action or no action.

A literature search indicates there have been few studies on the motions and loads on a stranded ship in Phase Four of ship groundings (Figure 1). Most of the research on ship groundings focuses on the damages sustained by the structure of the ship during the grounding event - Phase Two. This research does not extend to the motion of and loads on a ship after it has grounded. The only specific studies found on the motions of a grounded ship were done by McCormick (1999), and later McCormick and Hudson (2002). In McCormick's study, the planar motions of a grounded, broached ship are linearized and solved. The hydrodynamic reactions are analyzed using linear wave theory, and the seabed is treated elastically using a quasi-elastic discrete model. In follow-on work, McCormick and Hudson developed a two-degree of freedom model to predict the wave-induced migration of a structurally intact ship that was grounded, partially embedded, and broached. In their scenario, the ship migrates up a mildly sloping, sandy sea bottom without rock. They compare results from their theoretical model to results obtained from their experimental study in a wave tank.

The most relevant work involving a suitable model of soil reactions for this study comes from civil engineering. In foundation studies, the soil-structure interaction is very important for structures subjected to earthquakes, machine vibrations, and offshore structures subjected to wave loading. Civil engineers have studied soil dynamic behavior for some time and have developed simple and consistent methods to model the soil reactions. These same techniques are used in this work, tailored to the grounded ship application.

MODELING GROUND (SOIL) REACTION

Mainstream work on soil dynamics began in the mid-1900s with machinery foundation vibrations and the requirement to reduce the effects of earthquakes. More recently, the development of offshore gravity platforms, which use large concrete foundations to anchor themselves to the ocean floor, has increased the need for understanding soil dynamics. By the late 1970's, the capability existed to compute the dynamic stiffness of foundations of arbitrary shape in horizontally stratified soil deposits when linear elastic behavior could be assumed. In 1985 the first rigorous and comprehensive treatment of the topic with applications in both machine foundations and seismic problems was performed by Wolf and Weber (1986).

Alternate methods for modeling this problem include: the direct finite element method, the substructure method and lumped-parameter models. The direct finite element method models the region of soil adjacent to the soil-structure interface explicitly with finite elements up to an artificial boundary. A large number of degrees of freedom arise from discretizing the adjacent soil region, which requires large computational time.

The substructure method decomposes the global soil-foundation-superstructure system into subsystems, each of which can be analyzed separately using the most appropriate techniques. The structure is modeled with an interconnection of masses, dashpots and springs or equivalently by finite elements. Once the structure is discretized at the nodes located on the structure-soil interface and in its interior, the dynamic equations of motion are developed. The other substructure, the unbounded soil extending to infinity, has equations that are regular and linear. A boundary-integral equation is used to calculate the interaction force-displacement relationship. The responses of the individual subsystems are combined by imposing the interaction conditions along the separating surfaces. The substructure method is preferred over the direct finite element method in most civil engineering applications.

A more direct and computationally efficient approach uses a lumped parameter model of the soil reactions. In this method, the complex behavior of the soil-structure interaction is modeled using simple springs and dashpots with added mass. The lumped parameter model is exact for the static case and for the asymptotic value at infinite frequency. The coefficients are frequency dependent.

Wolf and Weber (1986) require that the lumped-parameter model consider the following variables of the foundation-soil system for all translational and rotational degrees of freedom:

- The shape of the foundation-soil (structure-soil) interface
- The nature of the soil profile
- The amount of embedment
  - Surface - no embedment
  - Embedded - with soil contact along the total height of the wall or only part

To improve the effectiveness of the lumped parameter method, parametric analyses are used to determine soil stiffness and damping coefficients under varying conditions of embedment. The standard lumped parameter method models the static stiffness of the soil half-space using a simple spring with stiffness coefficient k. This provides an exact result for static loading. The coefficients of the dashpot, c, and mass, M, are two free parameters that are selected to match as closely as possible the response of the total dynamic system, which may be determined by boundary element or finite element methods. A curve-fitting technique is applied to the total system's dynamic response and not to that of the soil alone as in the substructure method.

Pais and Kausel (1985) analyze existing data from other researchers that use complex and expensive procedures, such as finite element and boundary element methods, to model soil dynamics and soil-structure interaction. They plot the data presented by various other researchers and curve fit lumped-parameter equations to match the data as accurately as possible. They combine traditional stiffness and damping coefficients (k, c) into a single complex dynamic stiffness for each degree of freedom, Equation (1):

$$K^d = K^s\,(k + i a_0 c) \qquad (1)$$

where k and c are functions of a_0, ν (Poisson's ratio) and degree of embedment E/B (E = depth of embedment).

In the derivation of the stiffness equations, it is assumed that:

- The elastic medium, which supports the ship, is a homogeneous, isotropic, and semi-infinite body.
- The ship is rigid.
- The ship maintains full contact with the soil.
- There is no slip between the ship and soil.
- The soil remains linear elastic.
- The ship grounding length and embedment are symmetric.
- The soil rate dependency is introduced via a damping coefficient by a dashpot in the lumped parameter model.
- The effective added soil mass is much smaller than the mass of the ship and is neglected in this analysis.
- For the purpose of calculating ground reaction, the hull shapes of the ships are modeled as:
  - Rectangular box shape for cargo type ships
  - Wedge shape for warships
  - Cylindrical shape for submarines
- The geometry of cargo ships is further simplified by not considering a bulbous bow or bilge radius. The warship geometry does not account for sonar domes.
- The embedded portion of the ship hull is approximated as a rectangular embedded foundation as illustrated in Figure 2.

The motion is described in six degrees of freedom - three displacements and three rotations. The soil model allows for a partially embedded ship.

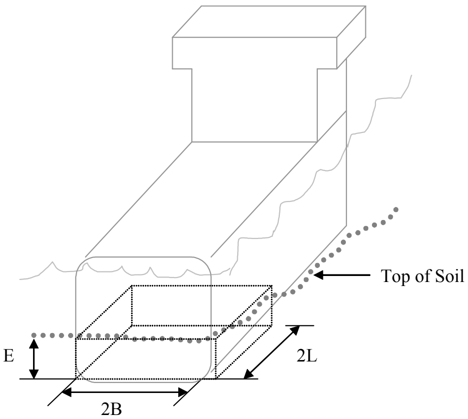

Figure 2. Stranded and Embedded Ship Modeled as Rectangular Embedded Foundation

It is assumed that the foundation length is greater then the foundation width, L > B. The dependence on Poisson's ratio, ν, is assumed to be the same for embedded and surface foundations. The influence of Poisson's ratio on the variation of the stiffnesses with frequency is not taken into account. The amount of material damping is also assumed to be independent of the value of Poisson's ratio.

To model the embedded rectangular foundation, the static stiffnesses of a surface rectangular foundation are required. Equations (2) to (7) calculate surface static stiffnesses, K^O. The superscripts *o, s*, and *d* refer to the stiffnesses for a static surface, static embedded and dynamic embedded foundation, respectively. The coupling stiffnesses are neglected in the surface foundation equations because their values are very small. These equations approximate data found by boundary integral methods for a square foundation with additional terms to model the effect of the L/B ratio in rectangular foundations. The equations compare well with the results for square foundations calculated by Abascal (1984), Dominguez (1978), and Wong and Luco (1978) and with the results for rectangular foundations in Wong and Luco (1978), and Dominguez (1978).

Surge: $$K_{Hx}^{O} = \frac{[6.8(L/B)^{0.65} + 2.4]GB}{(2-\nu)} \quad (2)$$

Sway: $$K_{Hy}^{O} = \frac{K_{Hx}^{O}(2-\nu) + 0.8(L/B-1)GB}{(2-\nu)} \quad (3)$$

Heave: $$K_{V}^{O} = \frac{[3.1(L/B)^{0.75} + 1.6]GB}{(1-\nu)} \quad (4)$$

Roll: $$K_{Rx}^{O} = \frac{[3.2(L/B) + 0.8]GB^3}{(1-\nu)} \quad (5)$$

Pitch: $$K_{Ry}^{O} = \frac{[3.73(L/B)^{2.4} + 0.27]GB^3}{(1-\nu)} \quad (6)$$

Yaw: $$K_{t}^{O} = [4.25(L/B)^{2.45} + 4.06]GB^3 \quad (7)$$

With the static stiffness for surface rectangular foundations defined, the equations for embedded rectangular foundations are developed. The equations assume that stiffness depends linearly on the depth of embedment, *E*. The determination of the stiffness of rectangular embedded foundations is a very complex problem and little data is available. Dominguez (1978) presents results for square and rectangular (L/*B* = 2) embedded foundations and Abascal (1984) analyzes a square foundation. In both studies the maximum amount of embedment analyzed was equal to the width of the foundation, *E/B* = 2. Based on this data Pais and Kausel (1985) develop Equations (8) thru (15) for embedded static stiffnesses as a function of embedment:

Surge: $$K_{Hx}^{S} = K_{Hx}^{O}[1.0 + (0.33 + \frac{1.34}{1+L/B})(E/B)^{0.8}] \quad (8)$$

Sway: $$K_{Hy}^{S} = K_{Hy}^{O}[1.0 + (0.33 + \frac{1.34}{1+L/B})(E/B)^{0.8}] \quad (9)$$

Heave: $$K_{V}^{S} = K_{V}^{O}[1.0 + (0.25 + \frac{0.25}{L/B})(E/B)^{0.8}] \quad (10)$$

Roll: $$K_{Rx}^{S} = K_{Rx}^{O}[1.0 + E/B + (\frac{1.6}{0.35+(L/B)})(E/B)^2] \quad (11)$$

Pitch: $$K_{Ry}^{S} = K_{Ry}^{O}[1.0 + E/B + (\frac{1.6}{0.35+(L/B)^4})(E/B)^2] \quad (12)$$

Yaw: $$K_{t}^{S} = K_{t}^{O}[1.0 + (1.3 + \frac{1.32}{L/B})(E/B)^{0.9}] \quad (13)$$

Coupling of Surge and Roll:
$$K_{HRx}^{S} = \frac{1}{3}(E/B)K_{Hx}^{S} \quad (14)$$

Coupling of Sway and Pitch:
$$K_{HRy}^{S} = \frac{1}{3}(E/B)K_{Hy}^{S} \quad (15)$$

There are two types of damping in the real system: one introduced by the loss of energy through propagation of elastic waves away from the foundation and the other associated with internal energy losses within the soil due to hysteretic and viscous effects. The equivalent damping corresponding to the elastic-wave propagation is called geometric damping or radiation damping. The lumped damping parameter for any particular foundation-soil system includes both the effects of geometric and internal damping.

Dominguez (1978) and Abascal (1984) present data showing the variation of stiffnesses in the low frequency range ($a_0 < 1.5$ from Dominguez and $a_0 <$

2.0 from Abascal) which corresponds to frequencies less than 0.33 rad/sec and 0.44 rad/sec for a ship with a beam of 50 feet grounded in clay (mud); or 2.62 rad/sec and 3.5 rad/sec in hard rock. This is within the frequency range of ocean wave energy.

It is assumed that the variation of the stiffnesses with frequency is the same for surface and embedded foundations because of the lack of better data. With these assumptions, Pais and Kausel (1985) develop the following lumped-parameter equations for dynamic stiffness: (valid for $\alpha<2.45$)

Surge: $$K^d{}_{11} = \overline{K}^d_{Hx} = K^S_{Hx}\,(k + i a_o c) \qquad (16)$$

where: $k = 1.0$ and $c = \dfrac{4[L/B + E/B(\alpha + L/B)]}{K^S_{Hx}}$

Sway: $$K^d{}_{22} = \overline{K}^d_{Hy} = K^S_{Hy}\,(k + i a_o c) \qquad (17)$$

where: $k = 1.0$ and $c = \dfrac{4[L/B + E/B(1 + \alpha L/B)]}{K^S_{Hy}}$

Heave: $$K^d{}_{33} = \overline{K}^d_{V} = K^S_{V}\,(k + i a_o c) \qquad (18)$$

where: $k = 1.0 - \dfrac{d a_o^2}{b + a_o^2}$ and $c = \dfrac{4[\alpha L/B + \frac{E}{B}(1 + L/B)]}{K^S_V}$

$$d = 0.4 + \frac{0.2}{L/B} \text{ and } b = \frac{10.0}{1 + 3(L/B - 1)}$$

Roll: $$K^d{}_{44} = \overline{K}^d_{Rx} = K^S_{Rx}\,(k + i a_o c) \qquad (19)$$

where: $k = 1.0 - \dfrac{d a_o^2}{b + a_o^2}$ and $b = 2.4 - \dfrac{0.4}{(L/B)^3}$

$$c = \frac{4[\frac{1}{3}(E/B) + \frac{1}{3}(E/B)^3 + \frac{\alpha}{3}(L/B)(E/B)^3 + (E/B)(L/B) + \frac{\alpha}{3}(L/B)]}{K^S_{Rx}} \bullet \frac{a_o^2}{f + a_o^2} + D\frac{f}{f + a_o^2}$$

$$f = 2.2 - \frac{0.4}{(L/B)^3} \text{ and } D = \frac{\frac{4}{3}(\alpha\frac{L}{B} + 1)(E/B)^3}{K^S_{Rx}}$$

Pitch: $$K^d{}_{55} = \overline{K}^d_{Ry} = K^S_{Ry}\,(k + i a_o c) \qquad (20)$$

where: $k = 1.0 - \dfrac{0.55 a_o^2}{b + a_o^2}$ and $b = 0.6 + \dfrac{1.4}{(L/B)^3}$

$$c = \frac{4[\frac{1}{3}(L/B)^3(E/B) + \frac{\alpha}{3}(E/B)^3(L/B) + \frac{1}{3}(E/B)^3 + (E/B)(L/B)^2 + \frac{\alpha}{3}(L/B)^3]}{K^S_{Ry}} \bullet \frac{a_o^2}{f + a_o^2} + D\frac{f}{f + a_o^2}$$

$$f = \frac{1.8}{1.0 + 1.75(L/B - 1)} \text{ and } D = \frac{\frac{4}{3}(L/B + \alpha)(E/B)^3}{K^S_{Ry}}$$

Yaw: $$K^d{}_{66} = \overline{K}^d_{t} = K^S_{t}\,(k + i a_o c) \qquad (21)$$

where: $k = 1.0 - \dfrac{d a_o^2}{b + a_o^2}$ and $b = \dfrac{0.8}{1 + 0.33(L/B - 1)}$

$$c = \frac{4[(L/B)(E/B) + \frac{\alpha}{3}(L/B)^3(E/B) + (L/B)^2(E/B) + \frac{1}{3}(L/B)^3 + \frac{1}{3}(L/B)]}{K^S_t} \bullet \frac{a_o^2}{f + a_o^2}$$

and $f = \dfrac{1.4}{1 + 3(L/B - 1)^{0.7}}$

Coupling Sway and Roll:

$$K^d{}_{24} = \overline{K}^d_{HRx} = \frac{1}{3}(E/B)\,\overline{K}^d_{Hx} \qquad (22)$$

Coupling of Surge and Pitch:

$$K^d{}_{15} = \overline{K}^d_{HRy} = \frac{1}{3}(E/B)\,\overline{K}^d_{Hy} \qquad (23)$$

Additional coupling is also generated due to moments around the origin in the equations of motion (COG in this project) because the ground reaction force is not located at the origin, Equation (24). Otherwise $K^d{}_{jk} = 0$.

$$\begin{aligned} K^d_{42} &= -z_{ground} K^d_{22} \\ K^d_{51} &= z_{ground} K^d_{11} \\ K^d_{53} &= -x_{ground} K^d_{33} \\ K^d_{62} &= x_{ground} K^d_{22} \end{aligned} \qquad (24)$$

where (x_{ground}, y_{ground}, z_{ground}) is the location of the ground reaction relative to the origin (COG).

Since it is assumed that the ship maintains contact with the soil without slip or separation, all friction and suction effects depend on internal soil properties and response. Separation effects are neglected in this analysis because of their complexity, but may require consideration in future work.

Table 1 - Average soil properties [15]

	Sand	Clay (Mud)	Soft Rock (Coral)	Hard Rock
Shear wave velocity, V_s (ft/sec)	1,250	625	2,500	5,000
Poisson's Ratio, ν	0.45	0.499	0.35	0.25
Density, ρ ($10^3 lb_f$-sec^2/ft^4)	4.35×10^{-3}	4.04×10^{-3}	4.66×10^{-3}	4.97×10^{-3}
Shear Modulus, G, ($10^3 lb_f/ft^2$)	6.79×10^3	1.58×10^3	29.1×10^3	124.2×10^3

Soil properties listed in Table 1 are used in this analysis. They represent average properties obtained from the literature.

STATIC EQUILIBRIUM CONDITION

The magnitude and location of the static ground reaction is determined by comparing the attitudes and positions of the ship before and after stranding. This approach is based on the method presented in the U.S. Navy Salvage Engineer's Handbook (Bartholomew et al 1992). Four different grounding scenarios are considered:

- stranding on one pinnacle
- stranding on two pinnacles
- stranding on shelf
- stranding on penetrable shelf

One of the following inputs are required to calculate ground reaction:

- The observed drafts of the vessel in the stranded condition, or
- The actual depth of water at each grounding location.

Ground reactions are calculated by finding the difference between the total weight of the ship for the current loaded condition and the buoyancy of the vessel as determined by integration of the hull offsets (Lost Buoyancy Method).

When the observed drafts of the vessel are specified in the stranded condition, hull buoyancy and center of buoyancy are calculated by integration of hull offsets to the defined waterline. The center of gravity is defined by the specified load case. The center of ground reaction is determined by balancing weight, buoyancy, and ground reaction moments. For a ship stranded on one pinnacle, the longitudinal center of ground reaction is required to be within the length of the ground contact. For a ship stranded on two pinnacles, the longitudinal positions of the two grounding points (assumed to be at the center of each pinnacle) are required. Ground reaction at each pinnacle is determined by balancing weight, buoyancy, and ground reaction moments about the other pinnacle. For a ship stranded on a shelf, the forward and after ends of the shelf are specified. The center of ground reaction must be within the grounded length.

For ships stranded on a shelf, ground reaction is distributed as a trapezoid if the center of ground reaction falls within the center third of the grounded length. If the center of ground reaction lies outside the center third of the grounded length, ground reaction is distributed as a right triangle. The right angle is fixed at the end of the shelf nearest the center of ground reaction. The height and base length are adjusted so the center of area coincides with the center of ground reaction.

Ground reaction distributions values for each section or strip of the hull are added to the ship's weight distribution values for each section. Beam, draft and sectional area in the grounded condition are also calculated for each section. Along with principal characteristics and bottom or soil characteristics, these are primary inputs to the ship motion and loads model. The first step in the ship motion calculation is to insure that these inputs represent a consistent still water equilibrium condition.

STRANDED SHIP MOTION AND LOADS PROGRAM (SSMLP)

Ship motion is predicted using strip theory in six degrees of freedom: surge, sway, heave, roll, pitch, and yaw with zero forward speed in the frequency domain (Salveson et al 1970). A simplified multipole method using Lewis forms is used to determine 2-D added mass and damping coefficients. This is advantageous because only load waterline beam, draft and sectional area are required for the equilibrium position of the stranded ship. Surge coefficients are calculated using Journee's (2001) empirical method based on theoretical results from 3-D calculations. The primary differences between this model and typical strip theory seakeeping models is the inclusion of the ground reaction forces, the assumption that the ship has zero forward speed and the calculation of waterplane motions and characteristics around the center of ground reaction vice the center of flotation. Strip theory is fast and reliable for a first approximation of grounded ship motions and loads. Once it is determined that the magnitude of these loads is significant, model testing and a more sophisticated analysis may be performed.

In deriving the equations of motion, the following assumptions are made:

- The equilibrium condition for the ship is known.
- The ship has zero forward speed.
- Incident waves are regular
- The heading of the ship has a constant angle, μ, measured in a counter-clockwise direction from the wave direction of travel. This may be achieved by the steady ground reaction alone, or with the added effect of stabilizing salvage efforts such as beach gear.
- There are no transient effects due to initial conditions; linear dynamic motions and loads are harmonically oscillating with the same frequency as the wave excitation.
- The motions are small relative to the inertial reference frame. This assumption is valid for a stable ship with a hard grounding and significant ground reaction.
- The vessel rotates in the sway, pitch and roll degrees of freedom about a point which is above the center of the ground reaction at the waterline.

The equations of motion with gravitational, fluid and ground reaction forces acting on the ship are then:

$$\sum_{k=1}^{6}\Delta_{jk}\ddot{x}_k(t)=F_j(t)=F_{Gj}+F_{Hj}+F_{Groundj} \quad (j = 1, 2..6) \qquad (25)$$

Rearranging and transforming to the frequency domain results in:

$$\sum_{k=1}^{6}\left[-\omega^2(\Delta_{jk}+A_{jk})+i\omega B^H_{jk}+(C^H_{jk}+K^d_{jk})\right]\bar{x}_k=\bar{F}_{wj} \quad (j = 1, 2..6) \; (26)$$

with incident and diffracted wave excitation forces on the right and ground reaction forces included with fluid stiffness, damping, inertia and added mass coefficients on the left. This provides six equations and six unknowns with frequency-dependent coefficients. The equations are solved at discrete frequencies for unit amplitude incident regular waves. Response Amplitude Operators (RAOs) for grounded ship motions and bending moment at each section are developed. RAOs are applied to various wave energy spectra to predict significant motion and bending moments in irregular waves.

The purpose of this initial model is to determine with minimum effort whether wave-induced loads on a grounded ship are significant and must be considered. It is realized that the linear and deep water approach taken in this analysis is suspect. Non-linear and breaking incident waves, body geometry (ships frequently heeled, not wall sided), shallow bottom effects (wave form, phase and group velocities), current and wind may require non-linear time-domain analysis for reasonable prediction. Immediate improvements should include using finite or shallow depth zero speed Green Functions to calculate coefficients. A rigorous solution must properly account for flow in the small gap between bottom and hull. Grounding is the extreme shallow water case.

CASE STUDIES AND RESULTS

Two case studies were performed using this model. The first case study analyzes grounding motions and bending moments in a simple box barge. The box barge case was used to troubleshoot the model, generate preliminary results, and assess model behavior. The second case study analyzes the grounding of a Series 60 tanker. The Series 60 tanker was chosen because it is the same vessel modeled in the Paik and Pedersen paper (1997) that considers static grounding bending moment, and it provides a more realistic case study for comparison to class society design bending moments.

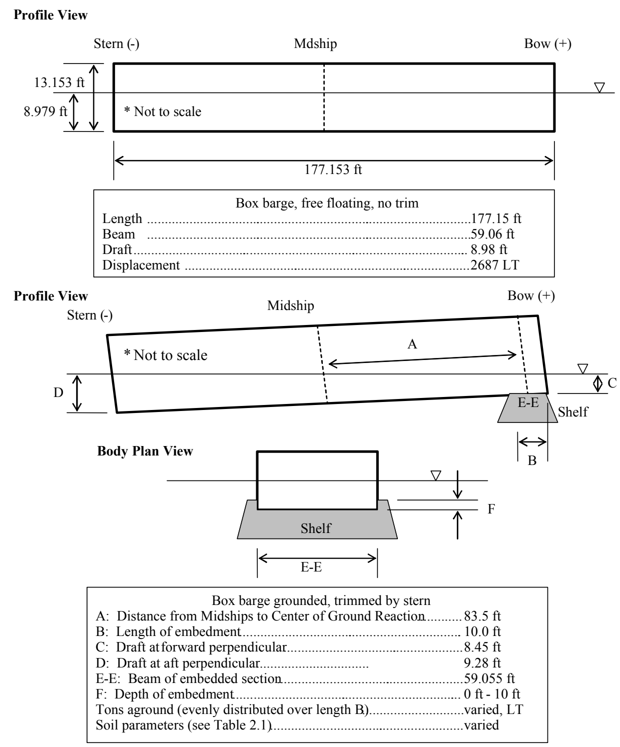

Figure 3 - Box Barge Case

Box Barge Case

The box barge case is illustrated in Figure 3. The matrix of studies performed with this case is illustrated in Figure 4. Motion and bending moment are calculated for 364 conditions. The decrease in draft at the center of the ground reaction from free floating is called the vertical displacement. An increase in vertical displacement as caused by a falling tide results in an increase in ground reaction as shown in Table 2. Motion results are assembled as RAO plots. These plots were assessed for consistency and reasonableness in the process of troubleshooting the model. Bending moment plots were compared to still water results and IACS/ABS design values.

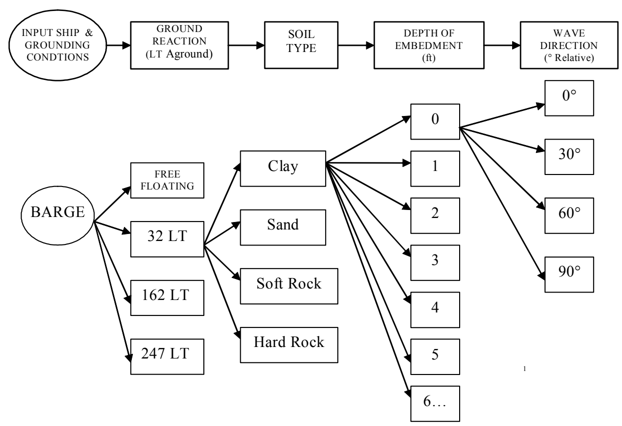

Figure 4 - Box Barge Study Matrix

Table 2 - Ground Reaction vs. Vertical Displacement

Tidal change	Draft fwd (ft)	Draft aft (ft)	Ground Rxn (LT)
floating	8.98	8.98	0
-0.5	8.45	9.29	32
-1.5	6.80	10.06	162
-2.5	5.70	10.60	247

Figure 5, Figure 6 and Figure 7 are typical RAO plots showing the decrease in motion with depth of embedment, the effect of grounded ship orientation relative to the waves and the effect of bottom type. Figure 7 shows very little heave motion for soft and hard rock and a resonance shift to higher frequencies with increasing soil stiffness (clay to sand to rock).

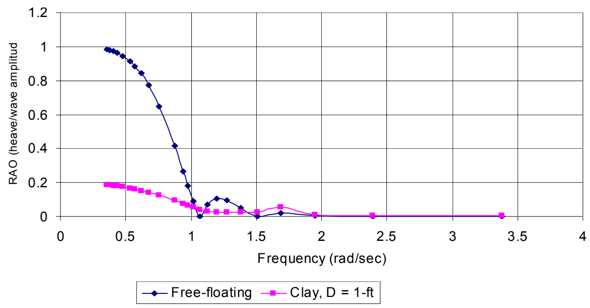

Figure 5 – Heave RAO, free-floating vs. grounded, stern seas

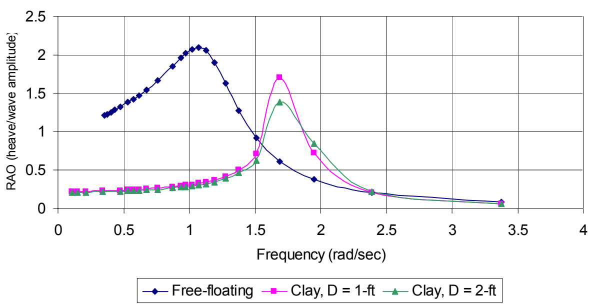

Figure 6 – Heave RAO, free-floating vs. grounded, beam seas

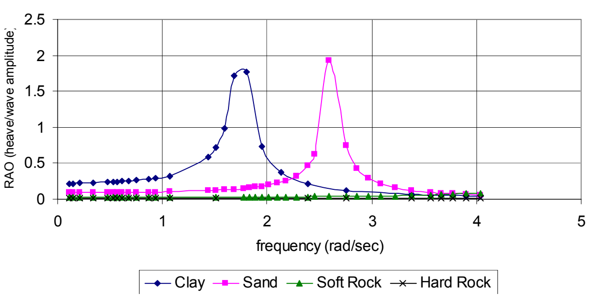

Figure 7 - Heave RAO, bottom type varied, beam seas

Paik and Pedersen (1997) present a "grounding-induced" bending moment formula which relates static bending moment in a grounded ship to vertical displacement at the grounding point. Figure 8 compares grounded still-water bending moment results from SSMLP to the Paik-Pedersen formula. Results are very consistent with only small differences. The Paik-Pedersen formula assumes a point load (at the FP in this case) and SSMLP assumes the same load distributed over the first 10-ft of the barge. The Paik-Pedersen formula is continuous over the length of the hull and SSMLP calculates bending moment values for discrete sections of the hull.

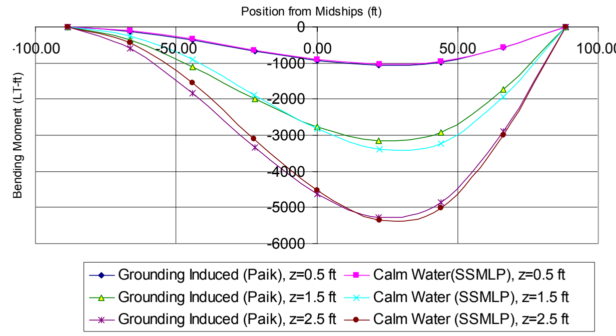

Figure 8 – Grounded Still-Water Bending Moment Calculated Using SSMLP and Paik and Pederson (1997)

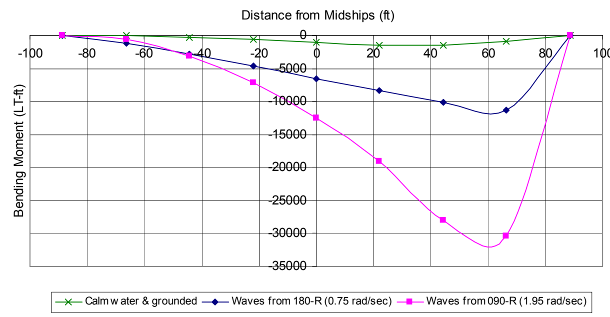

Figure 9 – Grounded Vertical Bending Moment in Regular Waves, clay, 1 ft embedment, H=1 ft

Figure 9 and Figure 10 show longitudinal vertical bending moment in regular and irregular waves. The irregular wave case assumes a Bretschneider Spectra with one foot significant wave height and stern seas. Maximum bending moment typically occurs close to the center of ground reaction.

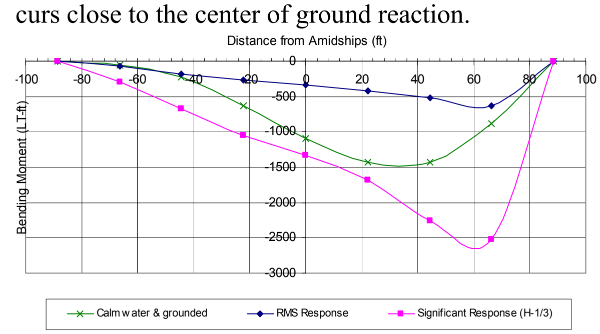

Figure 10 – Grounded Vertical Bending Moment in Irregular Waves, clay, 1 ft embedment, $H_{1/3}$=1 ft, 180°R

The ABS/IACS design bending moment (M_{ABS}) for the barge sagging condition is (ABS, 2003):

$M_{ABS} = M_{free\text{-}floating,\ still\ water} + M_{wavesagging} = -22216$ LT-ft

where:

$$M_{wavesagging} = k_1 C_1 L^2 B (C_b + 0.7) \times 10^{-3} \qquad (27)$$

and:

$$k_1 = 1.026$$

$$C_1 = 10.75 - \left(\frac{300 - L}{100}\right)^{1.5}$$

$C_b = 1.0$, block coefficient

L, Length of vessel

Figure 11 shows the barge maximum grounded vertical bending moment in irregular waves as a function of significant wave height. The maximum bending moment for a significant wave height of 4-5 feet exceeds the maximum free-floating ABS/IACS design bending moment, demonstrating that wave-induced bending moments on the grounded barge can be significant in moderate sea states.

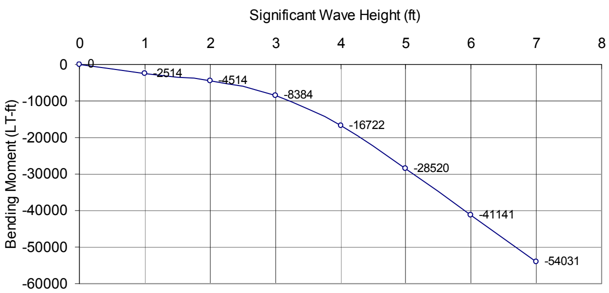

Figure 11 - Maximum Vertical Bending Moment in Irregular Waves, clay, 1 ft embedment, 180°R

Tanker Case

A Series 60 tanker similar to the ship modeled in Paik and Pedersen (1997) is chosen for a second case study. Principal characteristics and grounding scenario are provided in Table 3.

Still water bending moments are -1016.9 MN-m (sag), and 1125.2 MN-m (hog). ABS/IACS free-floating wave bending moments are -1716.40 MN-m (sag) and 1612.45 MN-m (hog). Total ABS/IACS design bending moments are:

-1016.85 MN-m+-1716.40 MN-m = **-2733.25 MN-m** (sag)
1125.24 MN-m + 1612.45 MN-m = **2737.69 MN-m** (hog)

Static bending moments calculated using Paik and Pedersen (1997) require a vertical displacement of 1.8 meters at midship to be equivalent to the ABS/IACS design hogging bending moment and 5.4 meters at the bow to be equivalent to the ABS/IACS design sagging bending moment.

For the bow-grounded (sagging) condition, Figure 12 shows maximum grounded vertical bending moment in irregular waves as a function of significant wave height. The maximum bending moment for a significant wave height of 4 meters exceeds the maximum free-floating ABS/IACS design bending moment, again demonstrating that wave-induced bending moments can be significant and exceed design limits in moderate sea states.

Table 3

Principal dimensions of Series 60 Tanker	
Length between perpendiculars	190.5 m
Breadth	29.26 m
Depth	15.24 m
Design draft	10.36 m
Displacement	49230 ton
Deadweight	38400 ton
Block coefficient	0.83
Waterplane coefficient	0.81
Waterplane area	4521.0 m^2
Description of Grounding Scenario:	
Bow grounded	
Length of embedment	19.05 m
Breadth of embedded section	29.26 m
Center of ground reaction (from bow)	9.525 m
Bottom (soil-type)	Clay
(1) Ground reaction	11449 kN
1-m vertical displacement at grounding point.	
(2) Ground reaction	22867 kN
2-m vertical displacement at gounding point	
Depth of embedment	0 m - 3 m
Wave direction (following and beam seas)	180ºR, 090ºR

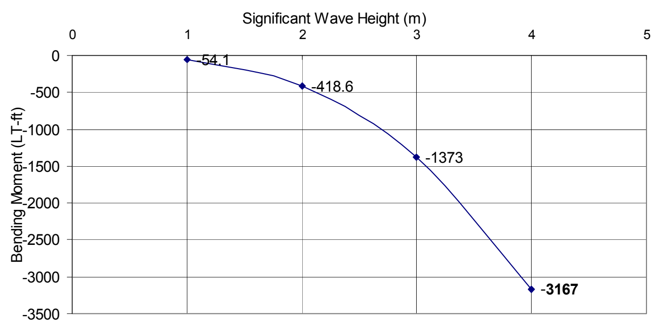

Figure 12 - SSMLP bending moment for tanker grounded in clay, stern seas, irregular waves

CONCLUSIONS

This paper describes a simple preliminary model for predicting the dynamic effect of waves on stranded ship motion and loads. A theoretical analysis of the motions and loads in six-degrees of freedom of a grounded ship in waves is developed with an appropriate soil reaction model to estimate dynamic ground reaction forces. The steady-state grounded motion of the stranded ship in waves around the quasi-equilibrium position is treated as a steady-state linear dynamic problem. Comparisons are made to static grounding results and to current ABS/IACS design rules.

It is concluded that the dynamic bending moment on a grounded ship in waves can be significant and must be considered in grounded ship loads and residual strength analyses.

Future work should address the following:

- Model testing and model assessment
- Shallow water effects including Green Function motion coefficients, wave form, phase and group velocities and the effect of flow in the small gap between bottom and hull
- Other non-linear effects including breaking incident waves and body geometry (ships frequently heeled, not wall sided)
- More appropriate near-shore wave definition and spectra
- Non-linear soil effects
- Grounded hull stabilization and the effect of beach gear
- Application of model to actual grounding case study with data such as New Carissa or LST 93 Valdivia

The most immediate need is for model testing to assess the preliminary computational results, determine if preliminary conclusions are correct, and determine if model improvements are required or warranted.

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