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Grounded Ambitions: A Lean Approach for Assessing Beachability in Concept Design

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ABSTRACT

Littoral operations have become an increasing interest for defense stakeholders over the last several decades. Many navies currently operate ship-to-shore assets that are designed to travel shorter distances exclusively in the littorals between a ship and the beach. New concepts are being designed to transit much longer distances from shore-to-shore in both blue water and littoral regions. This Concept of Employment (CONEMP) drives these ships to displacements that are orders of magnitude larger. Compared to smaller vessels where seakeeping and maneuverability performance in the surf-zone are a significant area of interest, larger vessels have a comparatively greater risk with respect to the ability of the ship to get far enough up a beach to safely deliver assets and then get off the beach. This research presents the foundation for a new simulation tool to analyze how far up the beach a ship will be able to get given loading condition, initial speed, beach condition, and hull shape. The focus of this research is to provide a low computational-cost method for analyzing the beachability of a ship that still considers the dominating physical phenomena of grounding at early stages of design. The tool will need much faster turnaround times than high-fidelity Reynolds-Averaged Navier-Stokes (RANS) or Finite Element Analysis (FEA) simulations to support the rapid and evolving environment of concept design timelines.

KEY WORDS

Amphibious; Landing; Computational Methods; Ship Concept Design; Beaching

INTRODUCTION

Landing ships and craft play a critical role in delivering people and supplies to areas with limited infrastructure, during both war and peacetime. They have been the vanguard in many operations such as the Normandy landings during WWII, Incheon Bay during Korea, as well as being some of the first on the scene during disaster relief efforts such as during Operation Sea Angel following the 1991 Bangladesh cyclone and Operation Unified Assistance following the 2004 Indian ocean tsunami (Lewis, 2023; Smith, 1995; Tsunami aid: Who's giving what, 2009). Landing ships and craft enabled each of these operations by facilitating the movement of people and supplies in a way that was unachievable by air and ground means. Landing craft remain a major interest to the world's navies, with most major navies having a significant amphibious force in their fleet (Baker, 2023).

Amphibious landing operations conducted by the Allies during WWII often saw the use of Landing Ship Tanks (LST), which were ocean-going ships that would carry heavy equipment such as main battle tanks and smaller landing craft. LSTs could travel long distances in shore-to-shore scenarios, as shown in Figure 1, that smaller landing craft cannot. LSTs were not only important for large amphibious operations, but also for supplying troops in areas with no infrastructure such as the Pacific Islands as shown in Figure 2. The director of the Southwest Pacific forces during WWII, Daniel E. Barbey, said of the LST, "Without these ships there would have been no Southwest Pacific Force. Without these ships the major amphibious invasions of Europe and the Pacific could not have been undertaken" (Barbey, 1969). D-Day, in which over 4,000 landing craft of various types were deployed, was delayed in part due to the required 230 LSTs that were not yet ready, as they were necessary to deploy the five sea assault divisions and heavy armor companies (Koenig & Doerry, 2018).

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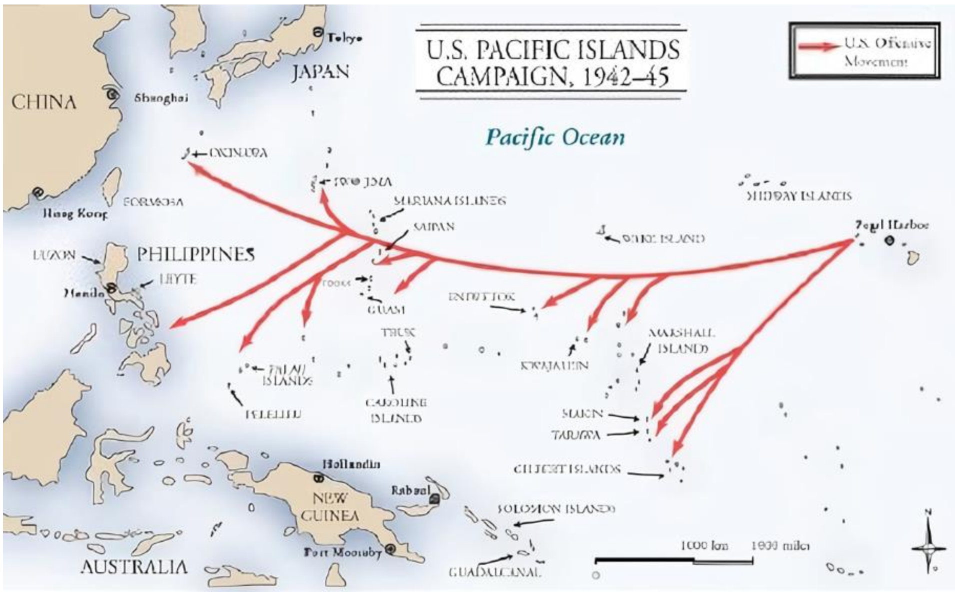

Figure 1: WWII Pacific Island Hopping Campaign (Kuehn, 2015)

Figure 2: LST Unloading Equipment at Iwo Jima (Navy History and Heritage Command, 2016)

Following WWII, changing operational needs drove the amphibious force away from the LST to the Landing Ship Dock (LSD), a type of ship that can carry several coastal, short range landing craft and does not beach itself, unlike the LSTs. The advantages of the LSDs are that they are generally faster than LSTs and can be outfitted for multiple roles when compared to the more restricted LST (Hope, 1991). Across the world, LSDs and LSD type ships like Landing Platform Docks (LPD) and Landing Helicopter Docks (LHD) are either being designed or acquired by many navies due to the flexibility that these types of ships offer (Keane et. al, 2009). The last major LSTs designed by the United States were built in the mid to late 1960s and have since all been decommissioned from the US fleet.

As a result, and demonstrated by the current United States amphibious fleet, most existing vessels that physically land on the beach are small craft like Landing Craft Air Cushion (LCAC), Landing Craft Utility (LCU) and Assault Amphibious Vehicles (AAV) that operate between the larger LSDs, LPDs, and LHDs and the beach. The LCAC, an unconventional landing craft, shown below in Figure 3 has an operation range of 200-300 nm (Naval Sea Systems Command, 2021). The average concept of employment (CONEMP), a use-case-oriented description of a system, for these crafts only necessitates shorter transit distances near the coast. This, in addition to host ship requirements has driven the size of these ship-to-shore crafts much smaller than the LSTs of WWII. LCUs can be better categorized as boats, generally, due to their operational profile between the coast and host ship (Raunek, 2022). Because boats are generally smaller, a major focus during their design is on performance in a near-beach seaway as the waves can have a significant impact on their ability to safely arrive and land on the beach. This has prompted most of the research and development for landing craft to be focused on small craft with an emphasis on how they handle in the surf zone or very large ships that do not contact the beach directly. For purposes of this paper, large ships will be considered as those that must transit open ocean and usually have a displacement greater than 1000 tonnes.

Figure 3: LCAC Unloading (Naval Sea Systems Command, 2021)

The flexibility of the LSD type ships is not without its drawbacks. Reliance on multiple smaller craft to bring equipment and supplies to the shore functionally limits the missions and quantities the ship can deliver. To overcome this limitation, there has been a push in recent years to develop a larger beaching vessel, operationally similar to the LST that can land heavy equipment as well as transit the open ocean. The ability to perform both of these functions means that a large landing ship will be able to operate independently of ports and landing craft. This falls in line with the concept of the fast moving, self-supplied marine littoral regiment (MLR), which will provide mobility and flexibility for littoral combat operations (U.S. Marine Corps, n.d.). In addition to supporting an MLR, a large landing ship will be able to deliver supplies and troops across the area of operations with minimal infrastructure support and aid the Naval Construction Force (SEABEEs) in establishing infrastructure. An artist's rendering is shown in Figure 4 (Harper, 2022).

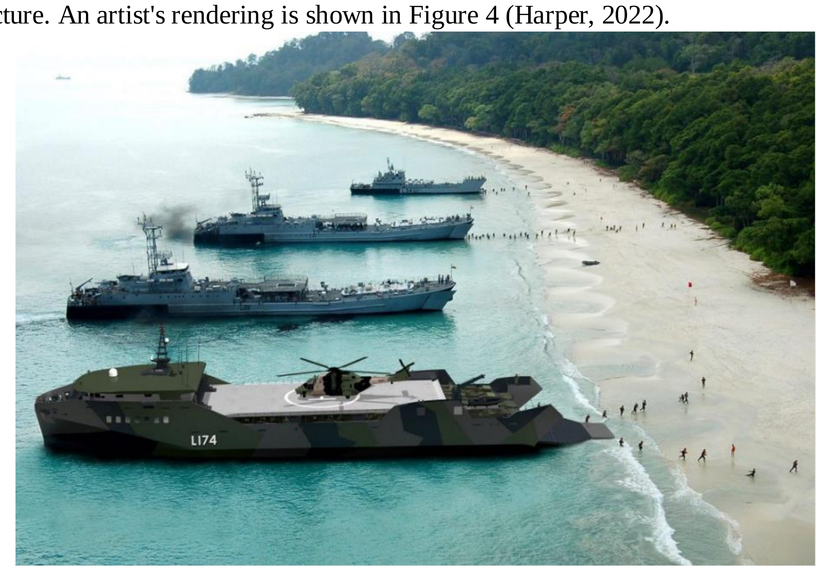

Figure 4: Artist's Rendering of Potential Large Landing Ship (Harper, 2022)

Due to the shift towards LSD type ships and small beaching craft, a knowledge gap exists for large, LST-like, landing ship design; which makes the acquisition of these ships particularly high-risk. Additionally, since WWII, ground vehicle weights have increased, with the heaviest vehicles, main battle tanks, increasing from 30.3 tons during WWII, to 61 tons when the

M1 Abrams was first developed, to the massive 75 tons the Abrams is currently (Larson, 2021). This increase in weight creates design challenges in landing these heavy vehicles, posing risk to new landing craft designs. Increased costs and complexities since WWII also means that ships are harder to build and replace, with Fletcher class destroyers costing $102 million in current USD per ship while the Arleigh Burke Flight III costs $1.45 billion per ship (Hill, 2023). Increased cost means that high risk factors, such as beaching ships' ability to get up the beach, need to be more heavily scrutinized in the early design stages.

To address knowledge gaps, larger ship acquisition costs, and increasingly short timeframes, modeling and simulation is being implemented across the ship design space to maximize ship performance regarding mission requirements (Cole, 2022). Modeling and simulation, a capability that didn't exist in a comparable state to the modern era when LSTs were designed, provides a low-cost solution to address potential risks in ship designs. To pare down risk and address the knowledge gaps specific to large landing ship beaching, this paper outlines the theory for developing a simulation tool for the large ship beaching problem.

If there was a tool that filled the knowledge gap identified, it would provide a critical new capability in the ship concept design space. Currently, the impacts of ship design characteristics on hydrodynamic performance, like resistance and seakeeping, are well known. Additionally, there exist an array of available ship design analysis tools to determine the seakeeping and resistance performance of a ship. This is not the case for beaching analysis; therefore, there is a need for development of an analysis method to accurately assess the beaching problem and determine the relationship between ship design characteristics and beaching performance. With a method available to assess beaching characteristics quantitatively, a trade off in performance for these three areas of hydrodynamic design can be determined, driving ship design forward and delivering well rounded ships to complete the specified mission.

Application of this tool in the design spiral paired with beaching Top Level Requirements (TLR) will be a driving factor for hull shaping and displacement. Using provided requirements for the beaching environment, ramp angle, ramp length, and fording depth, a designer would be able to assess bow shaping impacts and determine necessary ship conditions for beaching such as trim and displacement. These discoveries would inform the amount of payload the vessel would be able to carry, the arrangement and amount of ballast tanks to meet a required trim, and the opportune bow shape for a beaching operation. These impacts are critical components of the design of beaching ships and this tool provides a way for ship designers to identify risk and communicate capabilities of concept designs in a quantitative and comprehensive manner.

BACKGROUND

The United States Defense Acquisition Process can be summarized into multiple milestones as shown in Figure 5. Discussion in this paper is pre-Milestone B with a focus on Milestone A, Material Solution Analysis. According to Defense Acquisition University (DAU), "Phase activity will focus on identification and analysis of alternatives, measures of effectiveness, key trades between cost and capability, life-cycle cost, schedule, concepts of operations, and overall risk" (DOD Instruction 5000.84 "Analysis of Alternatives", 2020) During preliminary design, naval architects must deal with several technical challenges with tight timelines and budgets. Despite only 5% of costs being expended in preliminary design, 60%-80% of lifecycle costs are usually determined from decisions made in this stage. Visually, this is demonstrated in Figure 6. Being able to perform analysis early in the design process is a necessary way to buy down risk and lower program costs (Gaspar, 2011).

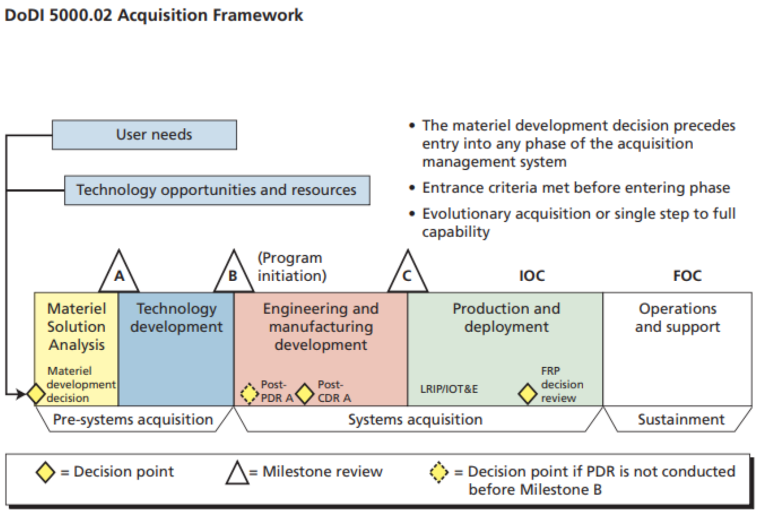

Figure 5: Defense Acquisition Lifecycle (Drezner, et al., 2011)

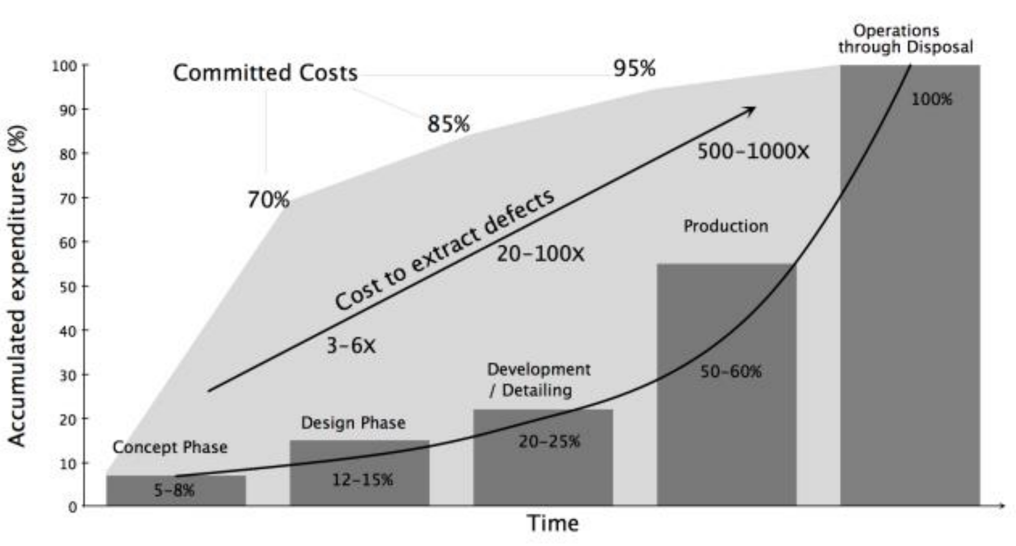

Figure 6: Overall Ship Cost by Milestone (Gaspar, 2011)

Due to the numerous, interrelated aspects of ship design, naval architects often refer to the design process as the design spiral shown in Figure 7 (Gaspar, 2011). Starting very broad and assessing one aspect of the design at a time, the design should eventually converge to meet requirements. It is expected that as the design changes, setbacks will occur, and specific aspects of the design will need to be assessed multiple times. For example, as displacement increases, draft increases and resistance on the hull form must be re-assessed. If resistance increases too much, larger engines must be selected to meet speed requirements, which will again increase displacement and have additional impacts on ship performance and cost. To add more complications, requirements at this stage of design are often fluid and design teams must adapt quickly and be flexible to these changes.

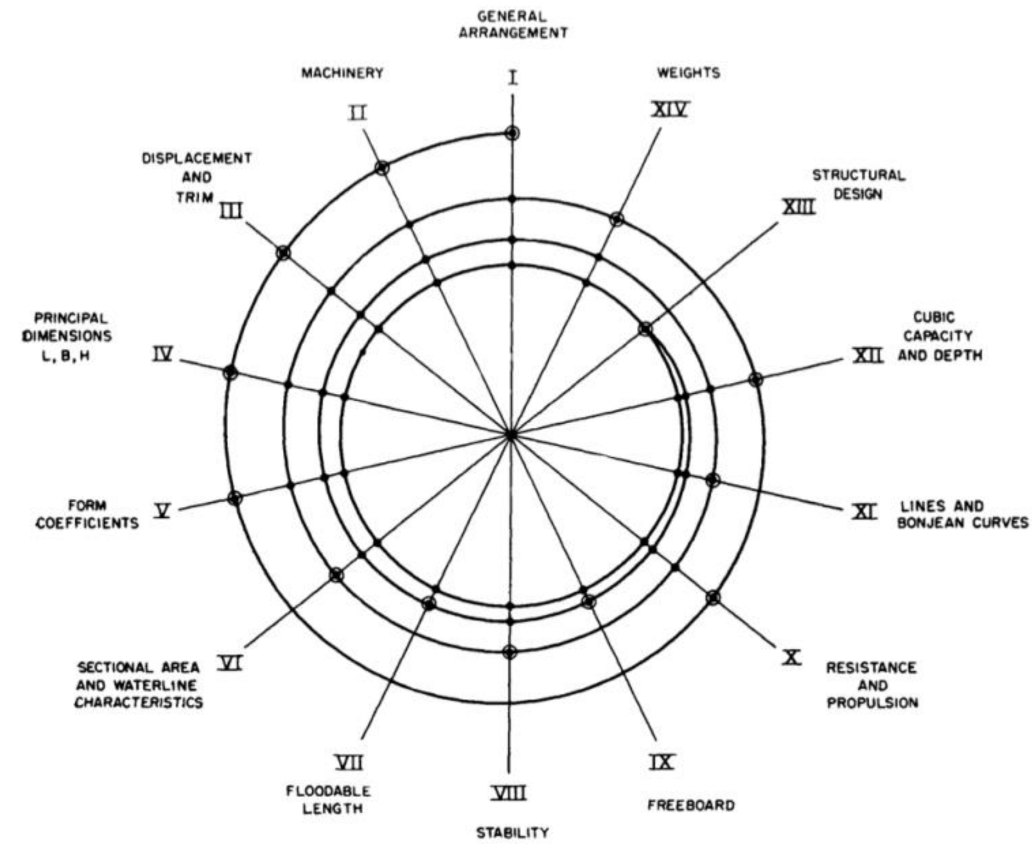

Figure 7: Ship Design Spiral (Gaspar, 2011)

Concept design makes up various aspects of the solutions analysis and concept refinement steps shown in Figure 8 (Schank, et al., 2014). Project durations often range from small 3-month excursions to large multiyear efforts. Each type of project having its own complexities and complications. In comparison to other design stages, this is a relatively short period of time for a ”typical” USN ship design cycles shown in Figure 9. Examples of the work naval architects do include integration studies, Analysis of Alternatives (AoAs), Requirements Evaluation Teams (RETs), and full ship concept designs sometimes referred to as indicative designs. During the CVX AoA, roughly 70 ship studies were developed and evaluated (Raber & Perin, 2000). The magnitude of these design programs creates a dire need for tools to deliver fast, accurate results. Fortunately, developments in recent years have made analysis in many areas of ship design quite agile. In the example of an AoA, it is necessary for technical experts to have the ability to assess several designs against Key Performance Parameters (KPPs). Design Space Exploration (DSE) is another growing area of interest in naval architecture in which a full range of parameters are varied in order to study a wider scope and gather quantifiable data to inform decisions (Robertson, et.al., 2022). DSE is increasingly valuable in situations when there may be design bias or a lack of clarity in requirements. An effort conducted at Naval Surface Warfare Center (NSWC) Carderock Division generated 2,916 individual hull forms to evaluate the impacts of varying hull characteristics on resistance, stability, and seakeeping (Strickland, Devine, & Holbert, 2018). Doing such analysis on hull shape provides valuable insight as to the preferred design for resistance, seakeeping, or other metrics such as beachability. This makes DSE yet another use case for a beaching tool that is capable of accurate results and short run times. The concept design environment can be fluid, fast paced, and often necessitates naval architects to be able to quickly run analysis, often with turnaround times less than 24 hours, or against hundreds to thousands of design points. Although concept design is a small portion of the overall ship design life cycle, it informs and drives the rest of the cycle, making it a critical step in ship acquisition.

Notional Durations of Acquisition Phases for Naval Ships

Phase	Duration (years)
Solutions analysis	1 to 3
Concept refinement	2 to 4
Design and build	4 to 7
Testing and trials	1 to 2

Figure 8: Notional Acquisition Durations for USN Vessels (Schank, et al., 2014)

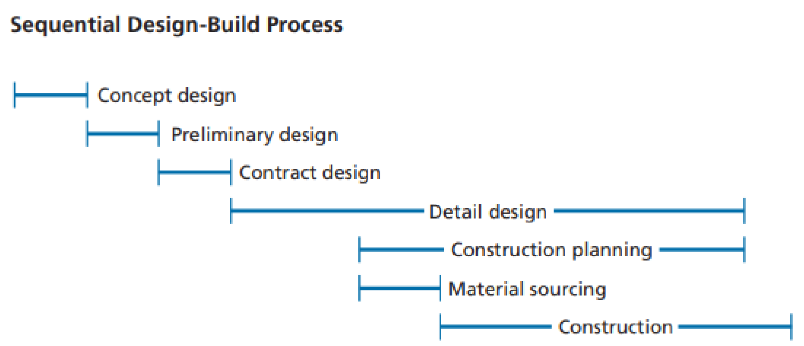

Figure 9: Ship Design Lifecycle (Schank, et al., 2014)

As mentioned previously, a majority of the beaching vessels currently in service are small craft (less than 1000 tons displacement) that can be carried by larger ocean-going ships. Extensive research has been done and is currently being executed to characterize the performance of these craft. The University of Iowa with the support of the Office of Naval Research (ONR) has recently executed research on surf zone dynamics and beachability of a small, single operator, craft called Quadski in which they experimentally and numerically defined the dynamics of the craft while beaching (Behra, 2020; Yamashita, et al. 2022). The Quadski work considers both the hydrodynamic and ground reactions when analyzing craft dynamics, with both interactions being major focuses of this paper. However, since the Quadski is small compared to the operational environment, there is a major concern with the seakeeping capabilities of the craft. It also has wheels that enable the craft to more easily get up a beach. This means that a majority of the research, has been allocated to the hydrodynamic reactions of the craft with respect to waves in the near-beach zone. In addition, the grounding work that has been completed uses a coupled CFD-MBD (computational fluid dynamics, model based definition) approach to define ground reactions, which is computationally expensive and complex. As shown in Figure 10, this approach requires a well-defined mesh that is recalculated at every time step to account for soil deformation, driving up computation costs. The same group also worked on a lower fidelity solution which uses data from higher fidelity models to drive outputs, however this means large changes in the design will require additional simulations with the high-fidelity model (Yamashita, et al., 2023). Since concept design often requires significant design changes, this approach is not a viable method. In summary, due to high computational costs, long set up and run times of high-fidelity codes, as well as a heavy focus on seakeeping, small craft beaching research is not applicable to pre-Milestone B applications or for scaling to larger ship sizes.

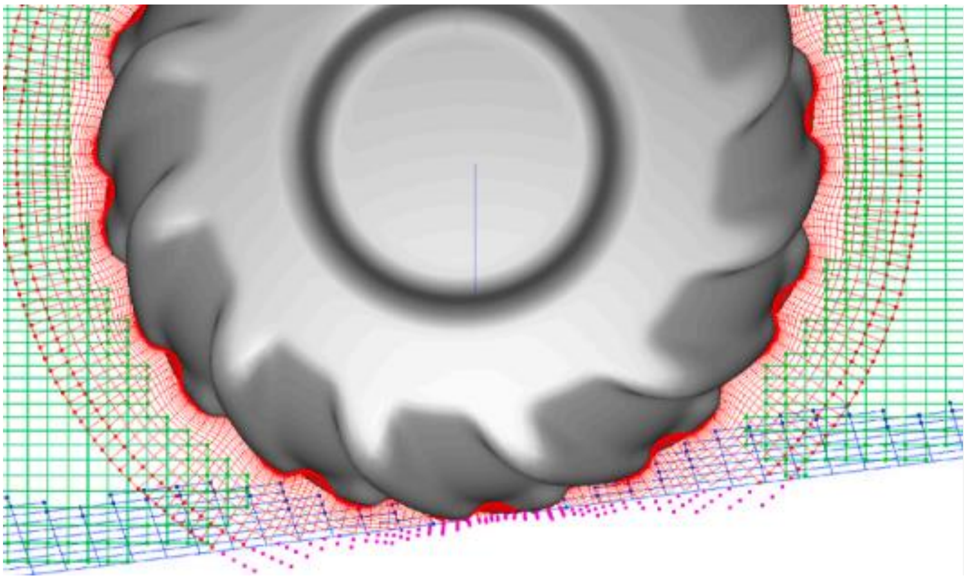

Figure 10: Boundary Mesh of the Wheel of the Quad Ski (Yamashita, et al., 2022)

Separate work has been done to characterize the deformation of saturated soil using LS-DYNA, a commercial structural deformation code that has large material libraries and experimental validation, making it ideal for quick simulation development (Flores-Johnson, et al., 2016). However, these studies and LS-DYNA solve material interactions on the grain scale, which leads to high computational costs and heavy reliance on user knowledge for setup (Flores-Johnson, et al., 2016; Sturt, et al., 2021). It has been used in applications of saturated sand deformation, making it applicable to the beaching problem, however, LS-DYNA does not calculate hydrodynamic interactions making it difficult to use in landing vessel applications (Flores-Johnson, et al., 2016). Additional research has been done on the effects of ship-structure interactions on larger commercial ships; generally, regarding the effect of grounding of the ship or the effect of a ship striking an offshore platform. Many of these studies used Finite Element Analysis (FEA) approaches within LS-DYNA to quantitatively define the effect of ship strikes on the sea floor as well as offshore platforms (Nguyen, et al., 2011; Yu, et al., 2016). Like other LS-DYNA codes, the main issue with these methods is that they require long setup times, large amounts of computational resources, and high user expertise, making them unsuitable for a concept design problem. Research done by Hansen, et al. (1995) attempted to define how far a ship will travel up a beach during grounding. They utilized a pressure method to calculate soil reaction, which was experimentally verified as shown in Figure 11. (Sterndorff & Pedersen, 1996). This method, while less computationally complex than LS-DYNA, still required a significant amount of computational resources and would require additional experimental data to support the analysis of vessels with other than simple, conventional bows.

Figure 11: Full Ship Grounding Experiments Conducted by Sterndorff & Pederson (1996)

In other technical disciplines related to naval architecture, there are concept design tools, such as Total Ship Drag (TSD) for resistance prediction and Ship Motion Program (SMP) for seakeeping evaluation, that allow naval architects to evaluate concepts rapidly (Wilson, et al., 2011). These concept design tools, while physics-based, generally have less fidelity than some of the more computationally intensive tools, however, they provide a reference point to compare multiple designs and inform the stakeholder on the best path forwards. These tools have quick setups and run times, which make them appealing for the fast-paced environment in pre-Milestone B work, but lack both accuracy and flexibility compared to more expensive solutions.

TSD is a low-fidelity tool that provides resistance predictions within seconds by reducing the physical problem using potential flow and Thin Ship Theory assumptions. A critical component of TSD that makes it well suited for early stage design work is that it is relatively easy to use. For example, the simulation is relatively insensitive to the input mesh, removing the need for sensitivity studies and allowing for reduced set up times. The low-cost of TSD make this tool ideal for evaluating a large trade space of concepts. The validation of TSD explains that TSD, "does a good job of providing quick and reasonably accurate evaluations for typical US Navy hull forms." (Wilson, et al. 2011).

The studies previously mentioned have demonstrated that there is work being done to evaluate beaching in a high-fidelity environment, however, there is a need for beaching analysis programs equivalent to TSD. Only one known method exists for evaluating beaching in a low fidelity realm: a quasi-static state solution, solving an energy balance equation. Based on a paper written by Pedersen (1995), this method considers a two phased approach in which; the first phase considers a ship with velocity V contacting a sloped beach and trims about a prescribed contact point until the ships trim is equal to the beach slope, and a second phase that considers the hull to then slide up the beach with the entire keel in contact with the beach. The second phase is only entered in this calculation if there is kinetic energy remaining after the ship reaches the trim of the beach. This model is limited in that the flat sloped beach is considered to not deform. This limits the effect of the beach on the ship to a simple frictional force in accordance with Amontons-Coulumb law, using a constant kinetic friction coefficient, μ (Pedersen, 1995).

The major limitations of this method are: the two phased quasi-static approach, and the severely limited consideration of hull shape on beach deformation. The quasi static approach limits the actions to large time-step phases where the physics is simplified using different methods in each phase. In both phases, this method ignores the interactions between the relevant physical features. For example, any translation of the hull up the beach as it rotates about its contact point in phase I is neglected. Additionally, ignoring hull shaping would reveal the same result for two hulls approaching the beach with the same velocity and mass, one having a broad blunt bow with a bulb and another with a skinny sharp bow, so long as they had the same contact point. Considering the large scale impacts of bow shaping on other hydrodynamics, like fluid resistance, this is a major problem that the current strategy overlooks and severely limits designers' ability to compare beaching results across a trade space of differing hulls, a common activity in pre-Milestone B. Therefore, ignoring the deformation of sand is an overly-broad simplification of the interaction and has resulted in low confidence in the results. Additionally, no validation of this method has ever been performed. Given this evaluation method, any engineer would be ill prepared to answer the questions they are currently being asked.

PROPOSED APPROACH

Language like beaching, beachability, or grounding are all terms that need definition before proceeding. For the purposes of this paper, beaching and grounding are synonymous in defining the act of a vessel impacting, riding up on, and embedding into a beach. This maneuver is intentional and a critical part of the prospective vessel's CONEMP. This does not include accidental grounding (i.e. a sandbar). Beaching and grounding start when the hull, likely to be near the intersection of the bow and keel, contacts the beach and ends when the vessel comes to a static equilibrium. Beachability is a qualitative measure of how reliably and safely a ship can deliver a payload from ship to shore.

Beachability is generally, quantitatively measured as an achievable fording depth or required ramp length or angle. Factors, such as the final position of a ship after beaching can be used to inform ramp design or evaluate against current ramp characteristics. Ramp angle defines the angle from the horizontal that the ramp contacts the beach. Ramp length defines how far, in any dimension, the ramp can extend from the hinge point. Fording depth represents the distance from the point where the ramp contacts the beach to the water free surface. This functionally represents the maximum depth of water the payloads will encounter during the beaching operation. Different payloads will have different requirements for each of these criteria. For example, vehicles with large separation between axels might have a minimum ramp length or maximum ramp angle to prevent chassis contact with the hinge point of the ramp. Other payloads might have fording depth requirements like vehicles, which cannot have their exhaust stacks submerged otherwise they risk down flooding into the engine. Additionally, ramp length, ramp angle, and fording depth can have significant impacts on the duration of the beaching mission, which can be a critical component of performance.

Assumptions

The proposed tool will consider a simplification of the physics of beaching to reduce runtime to fit within the discussed concept design framework. The considered physics include: kinetic energy transformed to potential energy from the vessel moving up the beach, energy losses from deformation of the beach, and other hydrostatic losses. These aspects of the physics have to take into account hull shape. The problem needs to be solved as a time series to capture the simplified physics to capture small changes in the state of the ship and the interaction of these changes over time. The theoretical assumptions that are taken to reduce the computational complexity of this problem are listed below. Should future Verification and Validation (V&V) efforts determine that any of these assumptions have significant detrimental impacts on the simulation, modifications will be made to remove or modify that assumption.

- The origin will be at the intersection of the stem and the waterline when the ship contacts the beach with the positive X axis traveling away from the bow of the ship. That means the stern will be at a negative length from the origin at t = 0. The Y axis will be 0 on the centerline, negative to port and positive to starboard. This assumes that the contact point is on the centerline. The Z axis travels from keel to weather deck with Z=0 at the waterline. The coordinate system can be seen in Figure 12.

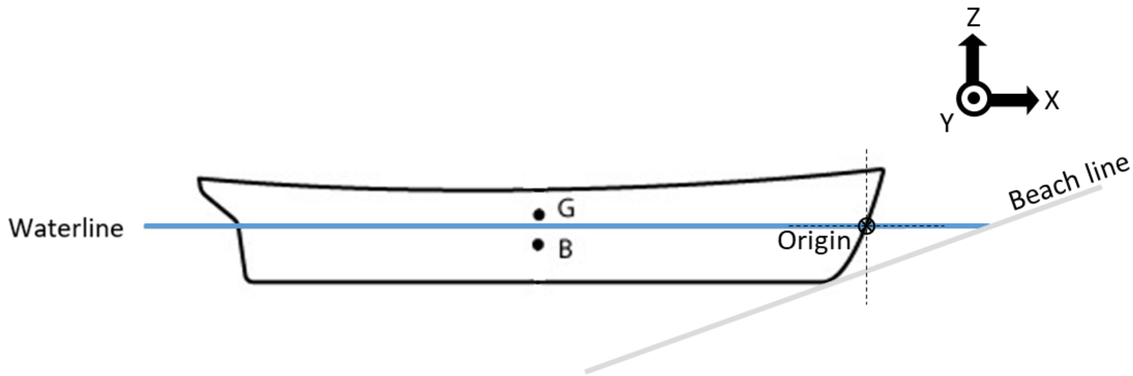

Figure 12: Coordinate System for beach modeling

- Sand is treated as a dense fluid with no viscous impacts on the simulation;
- Buoyant force from the beach acts normal to the beach surface;
- Sand friction will be calculated as a solid-on-solid interaction;
- Beach surface is a flat plane with a specified slope about the Y axis;
- Representative beach geometry will not undergo deformation as simulation progresses;
- Displaced sand moves vertically and once it is moved it is no longer considered in the simulation;
- C_F, coefficient of wetted frictional drag, is calculated via the ITTC '57 equation (Zubaly, 1996);
- C_r, coefficient of wetted residual drag, will be provided via external, supplementary analysis;
- Shallow water effect can be ignored at reasonably low speeds;
- Water is calm, environmental and ship generated waves can be ignored;
- Ship is not powered forward after contact with the beach;
- Ship motion is restricted to three degrees of freedom: surge, trim, and heave;
- Ship will rotate about a traditionally calculated center of flotation (CF);
- This simulation will occur ignoring the effects of a third fluid, being air.

The primary objective of this model is to consider the interaction of the hull form with the beach. Simplification of the beach definition, deformation, and interaction with the hull will be critical to the design purpose of this tool. Modeling the true physics of sand that can become saturated due to fluid interactions with the hull is an unreasonable problem to solve with current technology due to the sheer amount of interactions (Goodman, 2017). The proposed solution is to use first principles and basic definitions of fluids and solids interactions to reduce the complexity of the problem.

While a major component of the hull-beach interaction is the displacement of sand, capturing the true mechanics of this would likely require complex and computationally expensive meshes like the one shown in Figure 10. In order to account for the beach deformation in a computationally feasible manner, the beach will be assumed to be a dense fluid and be in a constant shape and location. As a fluid, there is a simple computation to determine the normal force from the beach. This assumption is supported in a paper by Kang in Equation 1 which relates the buoyant forces (F_{ZB}) of granular media to, ρ, density of sand, g, gravity, and V, volume of displaced sand. This relation is reliant on an experimentally determined coefficient, K (Kang et al 2018). This assumption allows a computationally efficient method for accounting for the normal force caused by the beach.

$$F_{ZB} = K\rho g V \qquad \text{Equation [1]}$$

A difficult component of treating the sandy medium as a fluid is that it would complicate the computation of frictional force between the beach and the hull. The classic computation of force, shown in Equation 2, requires an empirically determined coefficient (Zubaly, 1996). A literature review reveals that no coefficients of frictional drag for a sandy beach handled as a fluid exists. Additionally, existing research has proven that the friction of a solid and a saturated granular medium adheres to the Amontons-Coulumb law which requires a direct relation of the quantity of frictional to the normal force on the medium. (Divoux & G'eminard, 2007). For these reasons, it is assumed the most reasonable approach to calculate the frictional force of the beach on the hull as if they act as solids. This assumption not only supports the Amontons-Coulumb law but also allows this simulation to utilize existing empirically derived frictional coefficients of sand which are only relevant for the solid-on-solid interaction.

$$Force = \frac{Coefficient * Density * Surface\ Area * Velocity^2}{2}$$

Equation [2]

An additional complicated component of the beach problem is how to define the beach geometry, particularly complicated by handling the sandy beach as it acts as both a fluid and a solid. In order to simplify the problem, initial geometry of the beach is assumed to be a flat plane at an average slope representative of the desired operational area. This assumption seems reasonable considering beach topography changes relatively rapidly overtime when compared to acquisition timelines, and therefore modeling specific beach geometry is unnecessary, and computationally costly. It is known that as the hull displaces sand, some will rise above the presumed surface of the beach. This deformation would be influenced by the topography of the beach. If the beach is assumed to be flat then it must also be assumed that the sand is dissipated after it is deformed. With these assumptions, a geometrically varied and physically complex composite material is simplified to three inputs; a coefficient of friction, C_f, a beach slope, θ, and density, ρ_B.

While the physics of the interaction between the hull and the beach are considered primary in this simulation, the hydrodynamic and aerodynamic physics are considered secondary. Considering the relatively slow speeds associated with the beaching mission and the relatively large size of the ships of focus, fluid dynamic impacts are assumed to not be critical to consider to a high level of fidelity. Air resistance and wind heeling is assumed to be reasonably small, and can be ignored. Additionally, hydrodynamic effects and problems are generally complicated to implement and expensive to run. Assuming forward approach speeds, V_0, are less than roughly 5 knots, it should be reasonable to assume that hydrodynamics associated with forward speed and momentum can be neglected or simplified. For the purposes of calm water resistance, it is assumed that the coefficient of residual drag is constant throughout the simulation. With the availability of reliable resistance tools, residual resistance or C_r, will be provided externally for a single initial speed condition. Frictional fluid resistance or C_F will be approximated with the ITTC '57 equation. Sinkage due to sea floor interactions will be neglected at this level of detail due to a lack of inexpensive and reliable computational methods and for consistency with the already neglected seafloor topography.

As discussed at length in the background and introduction to this paper, the majority of recent research prior to this study has been invested in the interaction of small bodies in near-beach surf zone waves. Previous studies underline how difficult the seakeeping problem in the surf-zone is to simulate. In order to simplify the proposed simulation presented in this study, it is assumed that the ships used in this model are reasonably large (i.e. less than 1000 tonnes) to ignore significant wave-induced motions. Additionally, it is assumed that wave-induced motions do not have significant impacts on the final location of the ship with respect to the beach. Neglecting seaway-induced motions enables the simulation to be fixed in roll, sway, and yaw which offers additional computation cost savings and is relevant since the beach and hull geometry are assumed to be symmetric across centerline, y=0.

Proposed Solution

The backbone of this beachability tool is a time-domain solution, executed as a series of computations at discrete steps through time and space. The tool will be implemented in python in a modular format such that future levels of detail and fidelity could be easily added, based upon need and resources.

The hull form will be modelled as a coarse surface mesh and the fluid free surface will be modelled as a z-plane at location z=0 with the hull located such that the baseline is at the given load condition waterline. The code will begin at time = 0 and i=0 at the moment of impact with i being the time iterator and time being a scalar in seconds. The hull form will move forward in the x-direction through the stationary free surface (water) and into the static beach surface. At each time step the transformation of kinetic energy, KE_i, will be determined as follows in Equation 3, until the ship reaches zero kinetic energy. Based on Equation 4, the ship will have achieved a static condition, zero velocity, on the beach at this final iteration.

$$KE_i = KE_{i-1} - \Delta PE - W_w - W_B - W_D \qquad \text{Equation [3]}$$

$$KE_i = (m_s * v_i^2)/2 \qquad \text{Equation [4]}$$

KE_i will be determined as the remainder of kinetic energy at each iteration after considering the change in potential energy, ΔPE, as defined in Equation 5, work done on the wetted hull by water, W_w, as defined in Equation 6, work done by the friction with the beach, W_B, as defined in Equation 7, and work done by deforming the beach medium, W_D,as defined in in Equation 8. The change in potential energy will be variable with respect to the heave, z, of the ship at each time step with respect to the constants gravity, g, and ship mass, m_s.

$$\Delta PE = PE_i - PE_{i-1} = m_s * g * (z_i - z_{i-1}) \qquad \text{Equation [5]}$$

$$W_w = \left(\frac{\rho_w * SA_w * v_i^2 * C_T}{2}\right) * \Delta x$$

Equation [6]

$$W_B = (m_B * g * C_f) * \Delta x \qquad \text{Equation [7]}$$

$$W_D = W_{DZ} = \mathrm{m}_{Bk} * g * \Delta z_{Bk} \qquad \text{Equation [8]}$$

Work done by the water, as defined in Equation 6 is the force caused by the fluid multiplied by the distance the ship travelled in the direction of the resisting force, Δx. The resistance on the hull caused by the fluid is proportional to the fluid density, ρ_w, wetted surface area, SA_w, velocity, v_i, and the coefficient of total drag, C_T. The wetted surface area, SA_w, will be computed at each iteration. The coefficient of total drag is a summation of residual, C_r, and frictional, C_F, coefficients of drag per Equation 9. As stated in the assumptions, the residual coefficient of drag will be provided by an external simulation. The frictional coefficient of drag will be computed via the ITTC '57 approximation in Equation 10 which related C_F to the Reynolds number, Re, defined with respect to length on waterline, LWL, ship velocity, v_i, and dynamic viscosity, μ, as defined in Equation 11 (Zubaly, 1996).

$$C_T = C_r + C_F \qquad \text{Equation [9]}$$

$$C_F = \frac{0.075}{\log(Re - 2)^2}$$

Equation [10]

$$Re = \frac{(v_i * LWL)}{\mu}$$

Equation [11]

Work done by the friction with the beach, W_B, will be calculated as a coefficient, C_f times a normal force in Equation 7. The normal force is assumed to be equal to the weight of the vessel that the beach will support. Based on the assumption that the sandy beach acts as a dense fluid, this weight is being determined using the assumption that the deformed beach provides a buoyant force according to Archimedes principle (Kang et. al, 2018). This force will be determined at each times step via Equation 12, mass of the displaced beach, m_B, times gravity. The calculation of m_B can be seen in Equation 12 where ρ_B is the density of sand and ∇_B is the volume of displaced sand.

$$m_B = \rho_B * \nabla_B \quad \text{Equation [12]}$$

As stated in the assumptions, deformation of the beach will not be explicitly modelled geometrically, however the simulation will still consider the work done in the act of moving the displaced sand. To approximate this deformation work, W_D, the change in potential energy of the displaced sand will be determined at each iteration via Equation 8. The mass of sand that is displaced, m_{Bk}, will be determined at each time step as the difference in the total mass of the beach the ship displaces from the previous time step as explained by Equation 13. In order to determine the change in potential energy of the sand a segmented approach will be used, iterating over the mass, m_{B_k}, and calculating the vertical distance Δz_{Bk} required for that mass to be entirely above the beach plane as show in Figure 13.

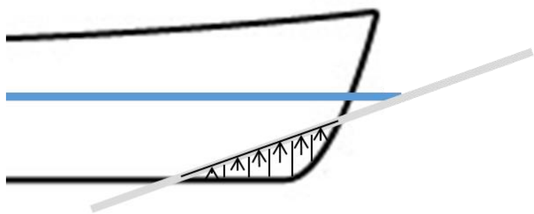

Figure 13: Sand Displacement

$$m_{B_k} = m_{B_i} - m_{B_{i-1}} \quad \text{Equation [13]}$$

Expanding and transforming Equation 13 by inserting Equations 4, 5, 6, 7, and 8 results in Equation 14. This allows Equation 3 to be rewritten in terms of v_i in Equation 14. This equation represents the proposed total energy conservation considered at each time step during the simulation. An additional system of equations will be required at each time step to determine the location in space of the hull form as it pitches and heaves. The pitch and heave of the hull will be calculated with a moment and force balance equations, Equation 15 and Equation 19 respectively. The moment balance equation, Equation 15, requires the sum of the moments caused by the buoyant force from the water, $m_w d_w$, buoyant force from the beach, $m_B d_B$, and the weight of the ship, $m_s d_g$ to equal zero. It is assumed that the sum of the mass of displaced water, m_W, and the mass of displaced sand, m_B, is equivalent to the mass of the ship, m_s as shown in Equation 19. It is assumed that the ship exclusively rotates around the center of floatation, CF_x, with the moment arms d_w, d_B, and d_g calculated as the difference between the center of action and the center of floatation in Equation 16, Equation 17, and Equation 18. The center of action for buoyancy due to water and beach are determined to be the center of volumes, x_{wCV} and x_{BCV} respectively. The center of action of the mass of the ship is the center of gravity, CG_x, and is a required input to the simulation.

$$v_i = \sqrt{\frac{2}{m_s} * \left(\frac{m_s * v_{i-1}^2}{2} - m_s * g * (z_i - z_{i-1}) - \left(\left(\frac{p_W * SA_W * v_{i-1}^2 * C_T}{2}\right) + \left(\mathrm{m}_B * g * C_f\right)\right) * \Delta x - \left(\mathrm{m}_B * g * (z_{Bk} - z_{Bk-1})\right)\right)}$$

Equation [14]

$$\sum M_{CF} = 0 = m_w d_w - m_s d_g + m_B d_B \quad \text{Equation [15]}$$

$$d_w = x_{wCV} - CF_x \quad \text{Equation [16]}$$

$$d_B = x_{BCV} - CF_x \quad \text{Equation [17]}$$

$$d_g = CG_x - CF_x \quad \text{Equation [18]}$$

$$\sum F_z = 0 = (m_s - \mathrm{m}_w - \mathrm{m}_B) * g \quad \text{Equation [19]}$$

Algorithms and Methods

The initial information required at the start of the simulation at which point the ship has just initiated contact with the beach and i=0, is listed below. The hull geometry is proposed to be a coarse surface mesh in the form of a PLY file. CAPSTONE, a HPCMP CREATE product can easily create simple surface meshes, from many of the classic geometry file types used in naval architecture. PLY is accepted in python mesh libraries Trimesh and VEDO (Haggerty, et al., 2019) (Musy, et al., 2021). These open source python libraries are proposed for handling mesh intersections. Working in python allows for plug-ins to the Leading Edge Architecture for Prototyping Systems (LEAPS) tool suite (Shaeffer, et al., 2020). Longevity of tools in the concept design space rely on integration with existing products or projects. Python is a well-known language commonly used in the naval architecture realm, therefore, generation of a python based tool will allow for integration in many existing projects.

Inputs:

- Coarse Hull Surface Mesh
- Ship Velocity (v_0)
- Ship Loading Condition
- Density of Water
- Beach Slope
- Density of Sand
- Coefficient of Friction of Sand

The proposed processes for the simulation are discussed below with the aid of flow charts in Figure 15 and Figure 16. These flow charts follow the color based key in Figure 14. Blue rectangles represent information that discuss inputs or conditional changes. Yellow squares use a calculation that is either represented by an equation in this paper or a query mesh intersections. Red triangle is a decision, evaluating against a criteria, typically in the form of an IF statement. Green ellipse represent output information.

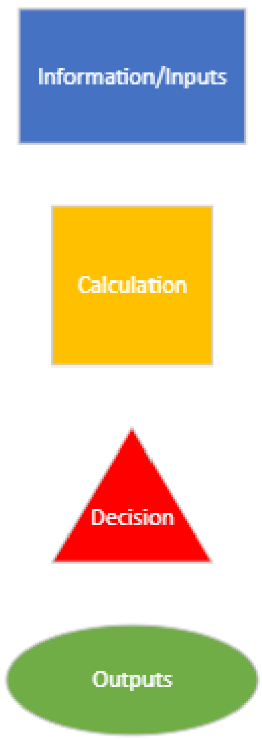

Figure 14: Flow Chart Key

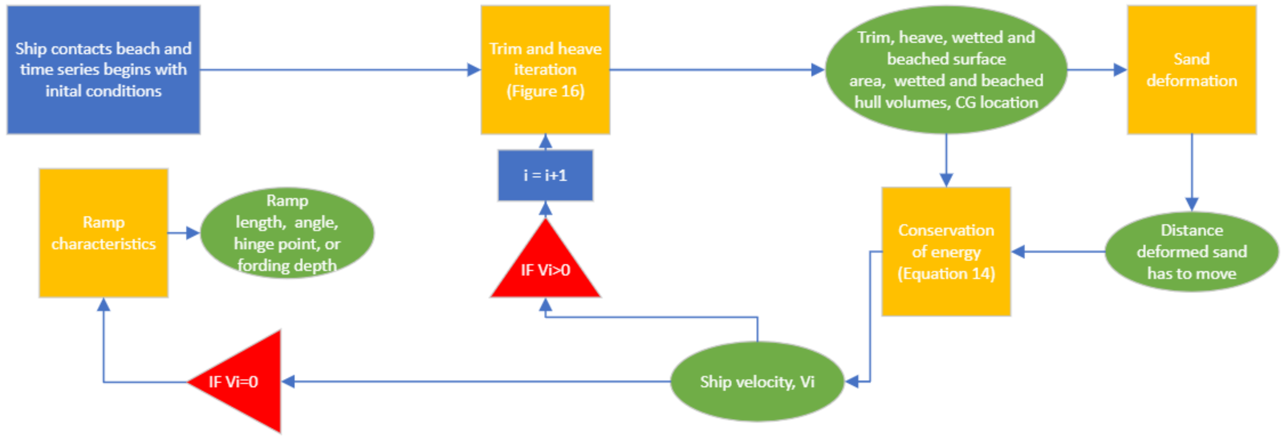

Figure 15: Beaching Tool Flow Chart

The objective of this simulation is to output ship position when ship reaches a static condition. The simulation will iterate over time and space to determine ship velocity, v_i, and hull position at each time step until the ship comes to a static equilibrium, $v_i = 0$, which is represented in the bottom left red triangle in Figure 15. Given this information, ramp characteristics and beachability can be determined easily. At the start of each time step, the new hydrostatic condition of the ship is calculated based on the workflow in Figure 16. Given the updated hydrostatic condition, change in velocity at each step is calculated via the conservation of energy given in Equation 3 and Equation 14. The simulation will continue to iterate until the ship velocity approaches very near to zero and is assumed to have met a static equilibrium.

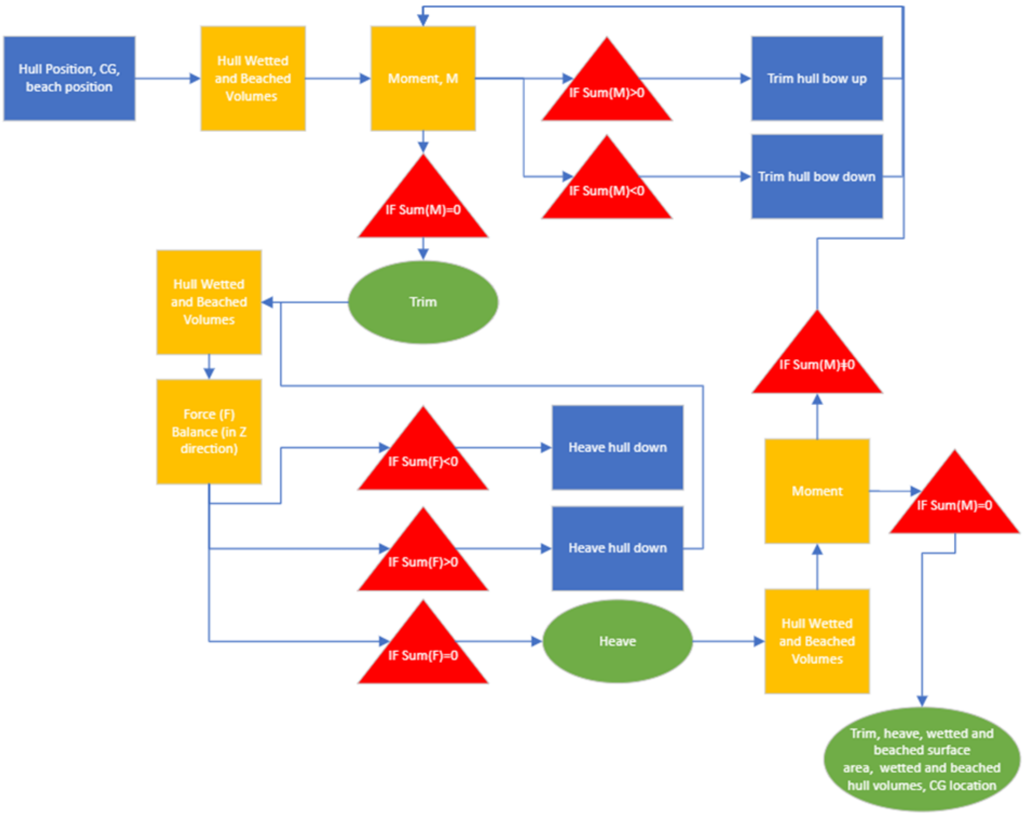

Figure 16: Trim and Heave Iteration Flow Chart

Separate trim and heave iterations occur at every time step. These loops are separate, but also dependent. This can be seen after the output of the force iteration returning to a moment calculation box on the right in Figure 16. The result is an iterative solution towards determining the ship's hydrostatic condition at each time step. In order to reduce computational time, the step size used in the iterative solution will be adaptive, dependent on how far the solution is from equilibrium. A critical component of this calculation is that the hull geometry directly drives the outcome which is a notable improvement over existing state-of-the-art beachability analysis in early-stage design discussed previously.

Following the flow chart in Figure 16, starting in the top left, these loops require information about the hull geometry, beach surface, wetted surface, and hull characteristics. The tool queries the mesh intersections to calculate wetted and beached volumes. The beached volume can be seen in yellow in Figure 17 and 18. Multiplying these volumes by their respective densities and distances to the center of rotation, CF, gives a moment balance equation seen in Equation 15. The assumed convention is a counterclockwise moment with the ship approaching the beach from the left being positive as seen in Figure 17. It is clear that a positive moment results in bow up trim and a negative moment results in bow down trim. The force and resulting moment are predicated on treating sand as a dense fluid that acts a buoyant force on the hull through the beached volumes centroid (Kang, et al. 2018).

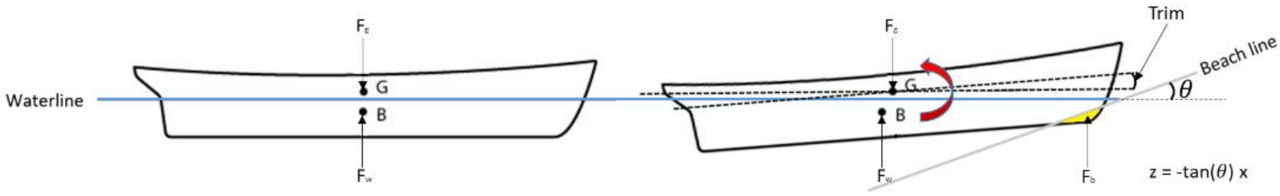

Figure 17: Trimming Moment

The trim angle will be adjusted as shown in the top right of the flow chart in Figure 16 until the moment is balanced, within a given tolerance, to zero using Equation 15. The updated trimmed position will provide new wetted and beached volumes to the force calculation in the middle of Figure 16. Equation 19 will then balance the forces in the z direction. With a positive force convention being up, if the force is positive the hull will experience positive heave and, if negative, negative heave. These heaving forces are shown in Figure 18. After $\sum F_z \approx 0$, the moment is calculated once more. If $\sum M \approx 0$ the hull mesh is queried.

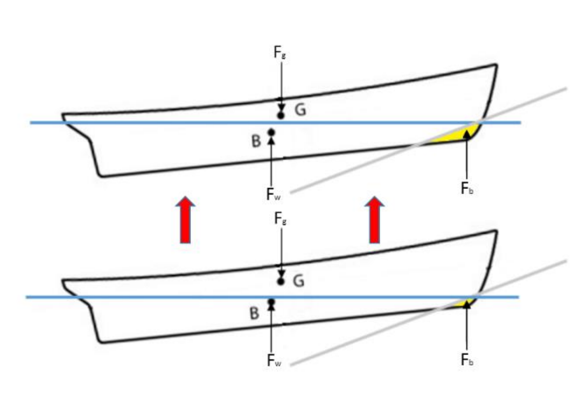

Figure 18: Heaving Force

CONCLUSIONS

As discussed in this paper, beaching has had a long and critical history in navies under taking amphibious operations around the globe. Delivering reinforcements and resources is vital to successfully providing disaster relief and maintaining a forward position in war. Both large and small beaching vessels are necessary to accomplish this during times when port infrastructure is contested or not available. Following WWII, the focus regarding beaching has shifted toward smaller craft. However, due to advances in technology and an uncertain warfighting environment, much is unknown as to the needs of the future. Looking objectively at the current amphibious fleet, a lack of knowledge in the areas of large beaching ships has been identified. This gap is aimed to be addressed through the development of a low fidelity beaching analysis tool.

With such a tool, naval architects will be able to quickly and accurately assess risk and costs associated with designing a large beaching ship. For the development of this tool, a first principals' approach has been taken to develop a time-series based simulation using conservation of energy. In order to evaluate a bounded and simplified trade space, the critical physical components of the beaching problem needed to be identified and fully considered. The interactions that will be evaluated or simplified in this tool are primarily focused on the beach-ship problem. Confirmation of these simplifications and assumptions is difficult due to a lack of Subject Matter Experts (SMEs) in the beaching domain problem and existing body of knowledge. Specifically, little research has been aimed at the hull form and beach interaction problem compared to the seaway induced motions problem. Due to the lack of available expertise, a verification and validation (V&V) effort will be required to provide confident use of this tool within ship acquisition frameworks. As previously noted, decisions made early in the design, especially at the preliminary design stage, can ultimately determine the future success of a ship acquisition program.

Future work

The effort to develop the simulation discussed in this paper is intended to be completed by the end of FY24 (September 2024). A validation effort is planned to begin in late FY24 and completed in FY25. Due to a lack to higher fidelity simulation data, model testing is being pursued. Utilizing modeling expertise at NSWC Carderock Division and partnership with the model test basin at the Engineering Research and Development Center (ERDC) (ERDC Overview, n.d.), testing results can be obtained which a beaching tool should be able to emulate within some tolerance. Planning for this level of model testing began in early Calendar Year (CY) 24. Scaling as well as other unidentified topics are of concern and will be addressed as planning is refined and resources and time are available.

Additionally, future efforts aim at considering developmental improvements to the simulation based on time and resources. There are two notable features which have been identified. Firstly, the development of a method to objectively assess and compare the beachability of different concepts and enable automated design space exploration. The primary measure for beachability is the ability of the ship in its beached position to deliver its payload to the beach. This payload can vary depending on CONEMP. Different types of payloads have different requirements usually revolving around fording depth, ramp angle, and ramp length. These ramp characteristics that will enable objective assessment of beachability are included in the flow chart in Figure 15 with the path once $v_i = 0$ is satisfied. The approach is to find the intersection of a ramp line, starting at the hinge point with slope of ramp angle, and beach line, with the beach slope. Then, the vertical distance from the waterline to that intersection point has to be measured and reported as the fording depth. This final calculation has not been discussed as part of the current effort of the tool. This information is critical to the beaching design problem and can be calculated external to the tool, based on the solved final ship position. Integration in the tool is intended to reduce additional steps, total time, and errors.

Secondly, since these ships eventually need to extract themselves from the beach, it would be useful to integrate both beaching and extraction into the same tool. There are two possible methods for a vessel to get off the beach: under propeller load, utilizing the assistance of kedge anchors, or a combination of both. The force that the propeller and kedge anchor must overcome to get off the beach will be a result of wetted drag from water, skin drag from beach, etc... This will require additional investigation, however, it is likely to have an overlap with planned capabilities within the base version of the tool.

In later developments of the tool, adding options for specifying ship thrust throughout the simulation, seaway conditions, and beach approach angle are all areas of interest. In practice, many beaching vessels continue to generate thrust from the propellers after impact with the beach in order to increase the distance they can travel up the beach. In order to assess this, additional sources of power will need to be included in the energy balance. For seaway conditions and approach angles, a 6 degree of freedom (DOF) analysis will be required and assumptions of symmetry will have to be overcome. This adds more complexity to the simulation, however, is not unusual for tools to offer both 3-DOF and 6-DOF analysis options. This will be further considered and researched as development continues.

Rather than just adding additional features, future developments will also attempt to improve fidelity while retaining rapid assessment capability. This means exploring other potential simplifications and existing theory, such as resistive force theory (RFT) to achieve more defined ground reaction forces. RFT is a theory that uses linear superposition of experimental results to generate lift and drag forces on a body independent of the body's orientation (Zhang & Goldman, 2014). The advantage of using RFT for this project is that it can be computationally inexpensive while still being relatively high fidelity since it relies on experimental data to drive responses. Additionally, there are many well documented sources about its use in different environments since the theory was developed in the 1950's (Marcotte, 2016). There are a few potential disadvantages of RFT. It has only been used to predict interactions at very low Reynolds numbers (Re ~ 10^{-2}), beaching will mostly occur at higher Reynolds numbers (>Re ~ 10^{5}) so it will need to be explored if RFT can be reasonably scaled up (Rodenborn, et al., 2013, Zubaly, 1996). Most RFT tools also require experimental testing to quantitatively determine the reactions of the granular material and that is an expensive and lengthy process. Some work has been done to empirically define these reactions which may be useful for this project (Marcotte, 2016). RFT is just one of many potential methods for improving fidelity that could be explored. Hopefully, this paper will encourage conversation and gather attention from experts in the field with knowledge of other applicable theories. Truly and accurately solving the beaching problem could have wide impacts and will require collaboration from various disciplines beyond naval architecture.

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