On the Hydromechanics of Vessels and Debris Fields During Sinking Events

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ABSTRACT

When a vessel leaves the surface and plunges to the seabed, a lot of things can happen that will affect its orientation and position on the seabed and the creation and distribution of the debris field. Crushing and catastrophic implosion due to the rapidly increasing hydrostatic pressure has been noted on portions of many wrecks. Extensive damage due to bottom impact and subsequent motions have also been observed and documented. This paper describes the successful numerical modeling of the sinking of several historic vessels. One was in deep water and another in shallow water. In both cases it was possible for the simulation to replicate important details of the debris field. Further work is planned to help explain some of the taphonomy observed as the wreck decays over time as it is acted on by bottom currents, benthic storms and in the shallow case storm waves.

KEY WORDS: hydromechanics of sinking; debris fields; sinking; marine forensics; bottom impact; underwater archaeology;

BACKGROUND

For thousands of years of human history, vessels have left port and never returned. Investigation of shipwrecks as a scientific discipline became possible in the 1960's with the pioneering underwater archaeology work of (Bass1975,& 2005) (Steffy, 1994) and many others.

Underwater Archaeologists and Marine Historians can often provide extensive historical information but lack engineering experience or knowledge to complete the puzzle. Ship design professionals can learn the history as well as provide a unique technical understanding. These collaborations can be very rewarding as all parties stand to gain valuable insights from the other. The SNAME Marine Forensics Committee was formed to bring together professional Naval Architects with the many other specialties involved in this most complicated of pursuits.

Significant advances in the study of deep wrecks were developed by Dr Robert Ballard and the WHOI Deep Submergence Lab (DSL) and others in the 1980's and 90's. James Cameron financed and performed excellent work on the *Titanic* and *Bismarck*. (Cameron, *et al*, 2008)

The term "Debris Field" describes the distribution of the remains of the vessel, cargo, contents and former inhabitants across the seabed. The study of these debris fields can show important aspects of how and why the vessel went down. On the bulk carrier *Derbyshire*, the ship was torn apart by hydrostatic implosions on the way down. and very little of the ship is recognizable on the seabed other than as scattered debris. (Faulkner, 1998). The iron ore carrier *Edmund Fitzgerald* wreck is represented on the bottom by a bow section, a stern section and the middle 200 feet as a debris field of torn and shattered metal. (Kery *et al*,2012) The RMS *Titanic* broke up at the surface and the pieces reached the seabed spread over a broad area. (Garzke *et al*, various) Every one of these debris fields tells parts of the vessels forensic story.

The damage to a vessel and its contents found on the seabed is due to a range of different causes. It is critical to the success of the overall forensic analyses to be able to separate the causative damage from other damage vectors.
The multiplicity of damage vectors includes:

- Damage unrelated to the sinking which occurred over the vessels service life prior to the sinking
- Damage which was causative in the sinking
- Damage which occurred during progressive flooding
- Damage which occurred in the water column on the way down including hydrostatic implosion, and unsecured objects falling off
- Damage due to bottom impact, including collision damage leading to hydraulic outbursts

- Debris dispersion due to objects which came off higher in the water column sinking at different rates through layered currents. Objects that fall slower are carried further by currents.
- Debris dispersion due to the sinking microburst plume and hydraulic outburst plumes
- Damage due to currents, waves, benthic storms, corrosion, and biodegradation in situ.

It can be difficult to tell these apart in a forensic investigation, especially when the investigation does not happen until many years or centuries later. Documenting the prior damage requires digging through whatever records may have survived. Often the cause of sinking is unknown. However different plausible causes can be postulated that can result in telltale damage signatures on the bottom. Searching for these signatures can be a useful diagnostic. Bottom impact can be gentle or very damaging depending on many factors that the methods described in this paper can help determine.

INTRODUCTION

The author has analyzed the sinking behavior of a number of historic vessels including the USS *Monitor* (Kery *et al*, 2012),(Broadwater, 2012), (Peterkin 1985), (Miller 1978), the SS *Edmund Fitzgerald* (Kery *et al*, 2012), the DKM *Bismarck* (Kery unpublished), FS *Bouvet* (Kery unpublished), and several others with varying levels of analyses.

The hydromechanic modeling normally includes hydrostatics in SHCP or Rhino/ Orca3D, various types of seakeeping (ship motions due to waves) analyses, and a hydrodynamic sinking model. The seakeeping hydrodynamics include linear theory RAO's created in Visual SMP (Conrad 2005) or WADAM Multi-body or WASIM (DNV Software). Non-linear seakeeping panel code programs such as WASIM, AEGIR (Kring, 1994) and (Kring *et al*, 2004), or LAMP (Lin *et al*, 2007) are necessary if large storm waves are a significant part of the cause of the sinking. (Ochi, 2003)

For ships such as *Titanic* which sank in relatively calm weather, wave loading is not an important factor. For ships like *Monitor* which sank in storm waves in relatively shallow water, the non-linear model must use a realistic wave theory approach that accounts for the shoaling effect on the longer period portions of the wave spectrum. The programs mentioned above are what the author has used, but others exist that could probably perform similar analyses.

A commercially available general purpose hydrodynamic modeling program named OrcaFlex was used to perform the actual sinking analyses. (Orcina.com)

MODELING CONSIDERATIONS

Modeling the sinking of a vessel requires developing an extensive amount of data in order to fully describe the behavior of the vessel and associated debris. The following quantities may need to be developed but what is required will vary for different vessels and scenarios.

- Three dimensional geometry input files for the various software packages
    - Compartment volumes and permeabilities.
- Weights, volumes and centers
- Moments of Inertia
- Drag Areas & Drag Coefficients
    - Reynolds Numbers
    - Strouhal Numbers
    - Lift surfaces and lift coefficients
- Added and Entrained Masses

The amount of data available to support these analyses can be sparse / inadequate for historic vessels and some level of estimation may be the only available alternative. Data from sister and near sister ships can be useful as can applying what rules and standards were in use at that time. Many details pertaining to rigging, ballast, anchors, water casks, cooking facilities, food stores etc., can be estimated from the standards of the day, (Davis, 1984), (ABS 1921 & 1943) (Biddlecomb, 1880) and by necessity.

Developing the Input Materials

The three-dimensional geometry is extracted from drawings. For vessels after about 1700, there is often some amount of documentation available. (Fernandez-Gonzalez, *et al* 2006) (Ferreiro 2007), For vessels prior to that, it gets much harder to research the necessary input information. Some very early vessels have been completely or partially recovered and the hull shape can be at least partially reproduced from the remains. (Tanner, 2013)(Bass *et al* 1975, 2005)(Steffy, 1994) (Nicolaysen, 1982), (Prince *et al*, 2008)

Typically a set of station offsets is developed and entered into an Excel spreadsheet where it is re-formatted to create the input file syntax required by the different programs. Unfortunately each program requires a different file syntax and this step can be quite time consuming to get the panel meshes to close properly.

Weights, volumes and centers for every item for which reliable data can be found must be assembled into as complete a weight and volume budget, as possible. This can be much more challenging than an ordinary ships weight budget developed in the course of construction.

The volumes displaced by each item are necessary to create the center of buoyancy of the fully and partially flooded vessel. For wooden vessels, the building material makes up a much larger portion of the volume than with iron or steel vessels. The density for calculating the volumes and weights of wooden vessel can vary +/- 20% from one timber to the next for the same species of wood. Multiple types of wood were often used on any given vessel, with little or no surviving documentation of what was used where and why.

Free Surface Affects and Submerged Righting Moments

Note that once a vessel leaves the surface there is no metacentric height defined, because there is no longer a free surface associated with the overall hull.(Bhattacharyya, 1978) The free surface in tanks may be of interest, but for petroleum tanks partially filled with seawater and partially with petroleum, the location of a free surface may be tricky to figure out. Diesel will float on the water but bunker fuel may not and the degree of separation may not be complete in the time scales of the flooding / sinking.

Temperature can be an important factor with heavier fuels which are tarlike or nearly solid at cold temperatures.

The submerged righting moment is a dynamic function not only of the instantaneous centers of gravity and buoyancy but also the centers of drag, each in 3 dimensions. At times a lift force on some components must also be considered, for instance if the ship leaves the surface with the rudder locked/ jammed in a turning condition, as happened on the DKM *Bismarck*. (Cameron *et al* 2008).

Developing the weights, volumes and centers for a historic ship requires extensive study of multiple sources and may require substantial re-engineering. (Kery 2015) describes that step of the process in more detail.

Inertial Properties

Once the weights, volumes and geometry are known the inertia terms can be developed for many of the weight items. On older historic vessels, getting an exact inertia value is often not possible because the details required no longer exist to support the calculations. The results seem to be relatively insensitive to small differences in the inertia values but the calculation stability and accuracy of the results, requires a thorough attempt. OrcaFlex provides default values but those should not be used if a realistic one can be calculated. Using inertial values that are off by several orders of magnitude can cause mathematical stability problems in OrcaFlex.

If a rough value is required for the inertia terms, setting the roll gyradius equal to 0.35 to 0.40 times the beam dimension and the pitch and yaw gyradii to 0.25 times the length between perpendiculars is a reasonable first guesstimate for most mono-hulls. The gyradius k=sqrt(I/m) or I =m k^2. Therefore a rough Ixx is the roll gyradius squared times the mass in compatable units. Iyy = pitch gyradius squared times the mass and Izz = the Yaw gyradius squared times the mass. The existence of significant top hamper in the form of masts, sails & cordage or of side-hamper in the form of paddlewheels and paddle boxes may significantly modify these rule of thumb values.

Drag

The topic of drag areas and coefficients require some consideration. While there are a number of standard reference works in existence, that cover drag coefficient information, none provide precisely the drag for a sinking vessel. (Hoerner 1965), (Pattison, *et al* 1977), (Owens *et al*, 1982), (Seelig, 1999) (NAVSEA DDS 582-1, 1987) (OCIMF, Various) (Haddara et al 1999)

Table 1 shows the drag area, Reynolds number, vortex shedding frequency and normal drag coefficient for a variety of typical drag items.

The first 5 items are similar to right circular cylinders. In cases where a semi-stable Von-Karman vortex street forms behind the object, the drag coefficient can go as high as 4.0. The Strouhal number is shown at a nominal value of 0.2. A thorough explanation of how this varies with shape, Reynolds number, and angle to the flow is beyond the scope of the current paper. The point of the vortex shedding frequency and period columns in table one is to show that these vary across a wide range, and all may coexist and interact with the structure while in freefall.

Table 1: Reynolds and Normal Drag Coefficients for Typical Ship Parts

							Vortex	Vortex	
				Drag	Reynolds	Strouhal	Shedding	Shedding	
Object Description	Length	Width	Height	Area	Number	Number	Frequency	Period	Cdn
	Feet	Feet	Feet	ft^2	at 10knots	at 10knots	Hz	seconds	
Typical Pipe Rail (1-1/2" pipe)	8	0.158		1.2666667	2.09E+05	0.2	21.33	0.05	1.5
1/2" rope	30	0.042		1.25	5.50E+04	0.2	81.07	0.01	1.2
1" rope	30	0.083		2.5	1.10E+05	0.2	40.54	0.02	0.9
Typical Mast	1.9	1.9	50	95	2.51E+06	0.2	1.78	0.56	0.5
Typical Uptake / Smokestack	10	8	25	250	1.06E+07	0.2	0.42	2.37	0.47
Typical Wooden Hull Steamer	260	40	32	1280	5.28E+07	0.2	0.08	11.84	(1)
							Vortex	Vortex	
				Drag	Reynolds	Strouhal	Shedding	Shedding	
Object Description	Length	Width	Height	Area	Number	Number	Frequency	Period	Cdn
	m	m	m	m^2	at 5.144m/s	at 5.144m/s	Hz	seconds	
Typical Pipe Rail (1-1/2" pipe)	2.438	0.048		0.118	2.09E+05	0.2	21.33	0.05	1.5
1/2" rope	9.144	0.013		0.116	5.50E+04	0.2	81.07	0.01	1.2
1" rope	9.144	0.025		0.232	1.10E+05	0.2	40.54	0.02	0.9
Typical Mast	0.579	0.579	15.240	8.826	2.51E+06	0.2	1.78	0.56	0.5
Typical Uptake / Smokestack	3.048	2.438	7.620	23.226	1.06E+07	0.2	0.42	2.37	0.47
Typical Wooden Hull Steamer	79.248	12.192	9.754	118.916	5.28E+07	0.2	0.08	11.84	(1)

(Assumes seawater at 59 degrees F for computation of Density and Kinematic Viscosity) (Pattison et al., 1977)

The drag coefficient expressed for the ship hull in parentheses (Table 1, lower right) is set to unity. When no carefully researched value can be found for a specific shape, this value is used. The actual drag for a ship in forward motion for the portion below the waterline can be found from model test data. Great effort is spent in minimizing this wetted drag for a ship under normal operating circumstances. The portions above water are designed to flow through air at about 1/700th the density of the submerged portions, so less optimization is warranted in the normal course of ship design. Once these are submerged in water on a sinking ship the drag of these normally dry items increases over their air value and often the drag of the top-hamper dominates the drag and center of drag calculations.

While it is possible to lump the drag of all of the stuff that is normally in air, into the drag area for the hull, this is very poor practice. A much higher fidelity response can be achieved by including these items as separate pieces that are fixed as rigid bodies to the hull. That way they can each be applied with the correct drag area and drag coefficient. More importantly their individual drag force is applied at the center of drag of each object which exerts important steering moments on the overall vessel as it sinks in 3 dimensional flow.

For a typical ship the OrcaFlex model would include the hull modeled as a 6D buoy. OrcaFlex has a vessel modeling option, however the vessel data are intended to represent surface vessels (following OCIMF conventions) and it therefore not the best choice for modeling a vessel sinking below the surface. The bowsprit, masts, spars, rudder(s), propulsor(s), deck houses, cranes, turrets, smokestacks, uptakes and other significant weight, inertia and drag objects are modeled as separate buoys attached to the main hull.

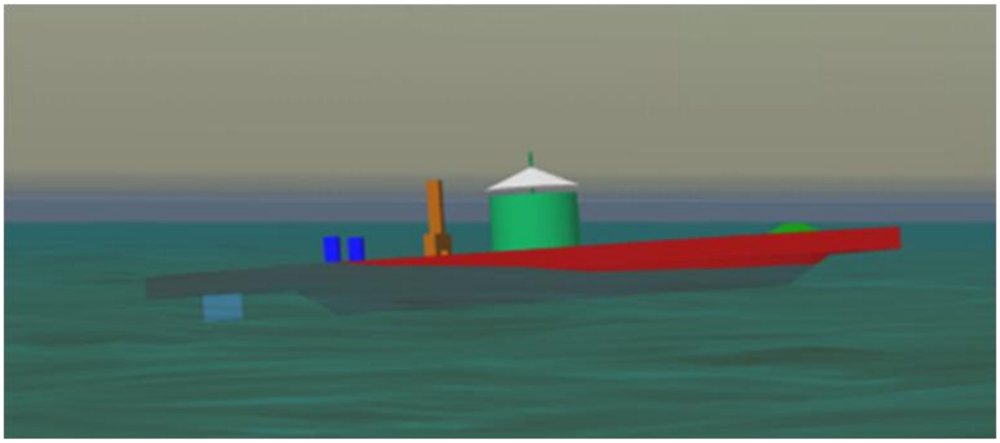


Figure 1: OrcaFlex model of the USS *Monitor*

Figure 1 shows an OrcaFlex model of the USS *Monitor* shortly before it down-flooded and sank December 31st, 1862 off Cape Hatteras. (Kery *et al* 2012) (Miller, 1978)

ORCAFLEX MODELING OPTIONS AND LIMITATIONS

Steering and Propulsion

OrcaFlex allows the user to put in "wings" of user specified geometry and then cause them to rotate about any of 3 axes according to a user specified time series file, with user specified lift and drag coefficients. These can be used to model the forces generated by propellers and paddle wheels. The steering actions of a time series of rudder or ride control fin/wing commands can also be input. The vessel can also be programmed to move along a prescribed course and speed that are input prior to the time series run.

An important limitation is that the version of OrcaFlex the author uses, does not model the turning of a vessel on the surface totally realistically. It can be programmed to execute turns, but the side wards way, heel in a turn and "transfer" commonly seen in an actual ship's turning maneuver are not modeled using that method on OrcaFlex. Instead, to model such behavior, the vessel's motion would need to be modeled using a time history, with the heel, transfer etc. being known *a priori*, and included in the time history file.

Motion in Waves

For vessel body types, OrcaFlex allows the user to import several different types of Response Amplitude Operators developed in separate software. Time series motions can also be imported if desired. The easiest RAO's to work with are standard displacement RAOs where the linear motions as a function of frequency (or period) in m/m of wave height and rotational motions in deg/m of wave height are imported.

A more challenging type are Haskind Load and Moment RAOs (Lewandowski 2004), such as those that can be produced by the zero speed WADAM panel code. These offer the advantage that the motion inputs due to other forcing are included in calculating the resulting motions. A disadvantage is that additional matrices for the restoring forces, added mass and damping matrices also must be imported.

Time series of motions from model tests, sea trials or from numerical time series codes of any kind, can also be imported and used to drive the model.

Visualizations

The surface wave motions in the OrcaFlex graphics are achieved by stretching a mesh. This prevents the surface waves from ever looking realistically steep, but this really only effects the graphical visualizations.

The surface waves are calculated using a wide range of user directed linear or non-linear regular wave theories, or spectra to model irregular sea states. OrcaFlex will not model or display breaking waves. In displaying the waves in a replay of a simulation, the representation of the waves is idealized in order to provide smoother/faster re-rendering as the screen is updated. As a result, steep waves appear to have gradual slopes and rounded crests. However the effect of the steepness of the waves is modeled correctly in the results, driving vessels through RAOs *etc*. and line/buoy objects using Morison's equation.

Flow Alterations

While the water flow is altered by waves decaying with depth and layered currents properly, it is not altered by the pressure or velocity fields or the presence of objects in motion or still.

In modeling a sinking ship, this has three important results that are not modeled in OrcaFlex.

- One is that as a ship leaves the surface, a plume of water is entrained by the ship's motions that forms the "suction" or "down blast", that can pull survivors down with the ship.
- Another is that when the ship hits the seabed, this plume of water continues to impact the bottom for some seconds afterwards and forms a microburst pattern on the bottom that can help scatter artifacts.
- Thirdly, when a large heavy object filled with a mass of water strikes bottom at 10 to 25 knots, a lot of collision crushing occurs. However the ship is filled with water by this time and water is incompressible for the most part. This results in a high pressure impulse that acts on the hull envelope and vents violently through any existing openings.

An example of the third phenomenon is provided by the DKM *Bismarck:* the initial bottom impact crushed the lower bottom up approximately one deck level. This caused a hydraulic outburst that blew the 1/2 inch bottom plating outwards around the ship at the junction to the much thicker armor belt. This is visible everywhere that there was not a large opening such as where the 4 main turrets fell out.

Objects Falling Off

When the USS *Monitor* sank, it rolled inverted at the surface, the turret fell off and the hull subsequently landed on top of it.

Figure 2: Photo Mosaic showing the inverted hull of the *Monitor* resting on the turret

On the RMS *Titanic*, significant hull fragments, several boilers and a large quantity of other debris is present in the debris field that separated from the ship either in the water column or on the way down. These can be modeled as separate parts in OrcaFlex and the user can constrain how and when they leave the hull in three ways.

1. Tether links can be used to tie the object to the ships structure. These can then be released at a user selected instant in time or when the tension in the link exceeds a preset parameter. This can be difficult and time consuming to set up requiring multiple runs and lots of tweaking.
2. Certain shape objects have surface stiffness to represent solid surfaces such as decks and hull sides. If the part falling off is modeled as a 6D buoy, the buoy's vertices will make contact with such solids. If multiple such buoys have similar solids attached to them, they will interact (collide) with one another too. The interaction will prevent these solids from passing through one another.
3. A combinations of links and restraining solids was use in the *Monitor* sinking study to restrain the turret from falling off until the vessel hull was inverted. Links to chunks of flotation were cast off in a pre-

programmed sequence to cause the ship to roll over as described in the survivor accounts. The turret modeled as a cylinder was supported on a floor block, and restrained within a annular ring, where the ring and floor block were fixed to the hull. Once the vessel had rolled far enough, the turret was able to come out of this and fall to the bottom, followed by the body of the wreck that landed on top of it.

Figure 3 shows a screen grab from the OrcaFlex dynamic sinking model of the *Monitor*. The colors shown are user selected to enhance clarity and understanding of the visualization. Attempts with close to the actual colors had significant contrast and clarity issues as it was difficult to see where one part started and the other ended.

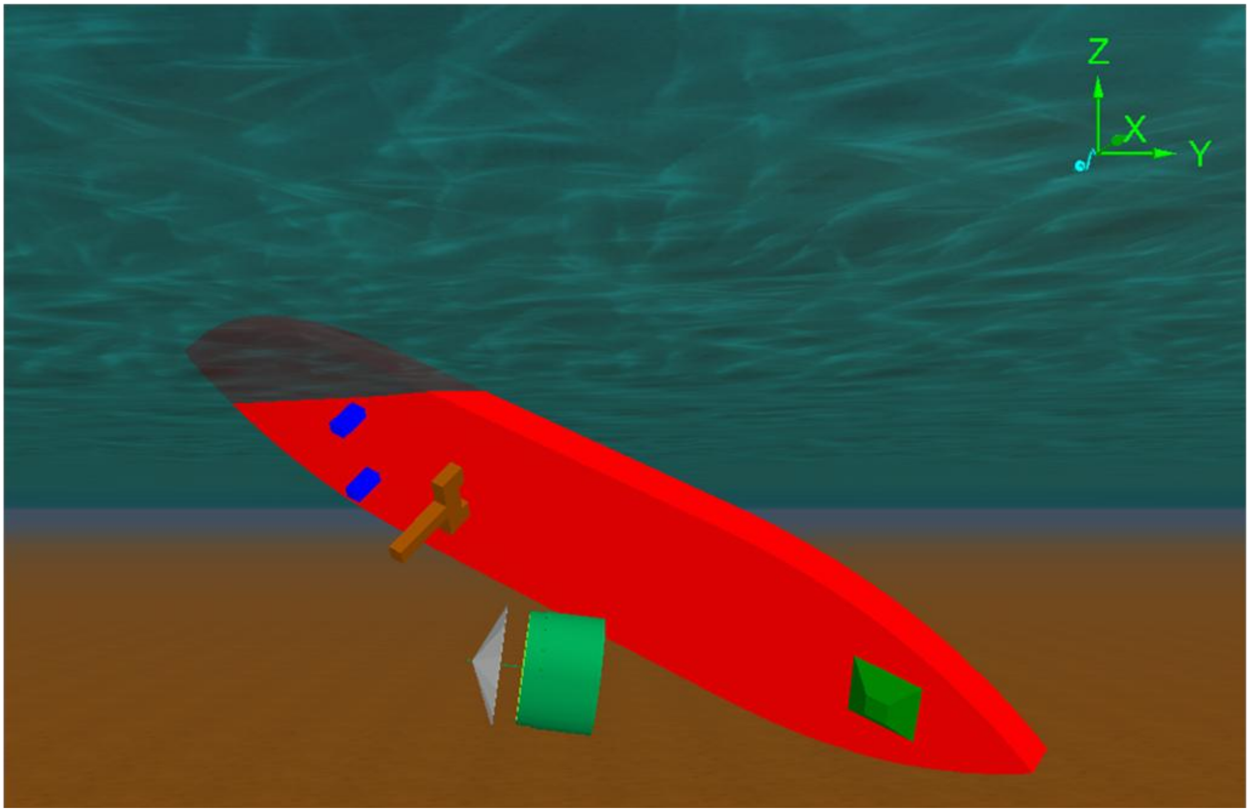


Figure 3: Snapshot of the USS *Monitor* Sinking Model as the Turret Falls Off.

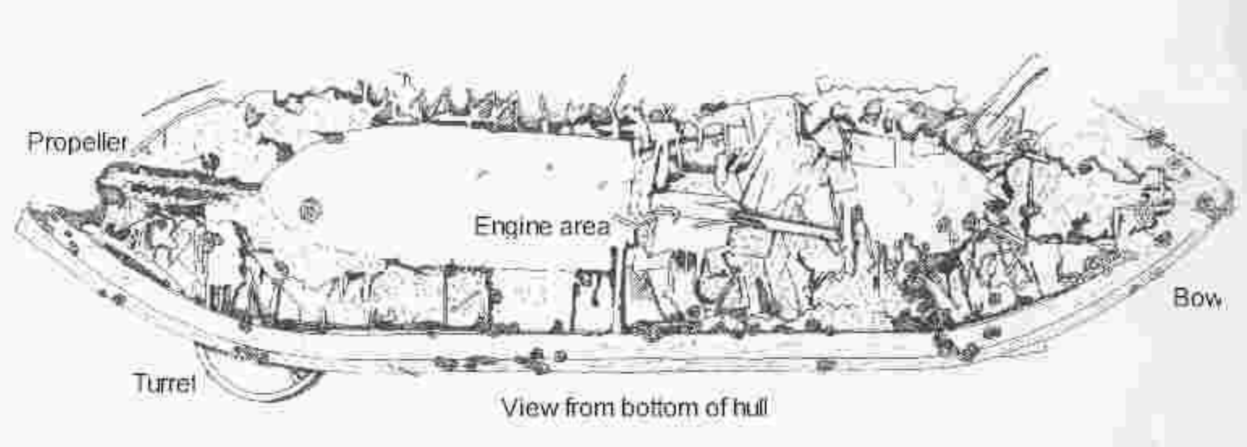


Figure 4: NOAA Plan view Sketch of *Monitor* on the Bottom as She was Found

GENERAL RESULTS

For ships which have grounded or sank in very shallow water like the *Costa Concordia* there is no time or room for the ship to change its orientation by much. The *Concordia* actually rolled over after part of the hull was supported by the seabed.

In shallow water, in this case defined as a few ship lengths, or a few hundred feet, like the *Monitor*, *Andrea Doria* (Sims *et al*, 2008) or *Lusitania*, (Garzke *et al* 1996) there is not much that can happen in the water column on the way down simply because the time in which that might happen is very short. In some cases, one end of the ship strikes the seabed before the other end has completely left the surface. In deep water, defined as many ship lengths or thousands of meters, such as in the cases of the *Bismarck*, *Titanic* or *Central America*, (Klare 1992), (Kinder, 1998), the time to reach the seabed is substantial and many gyrations are possible. The methodology described herein allows this to be visualized with a physics-based model for the first time.

Terminal Velocity

Modeling a sinking vessel as it falls through the water column is based upon the simple terminal velocity equation where the downward forces due to weight, less residual buoyancy is balanced against the drag forces pushing upwards.

$$(W-B)= p/2 * Cd * A * V^2 \qquad (1)$$

Where W is weight, B is buoyant force, $p/2$ is the fluid density over 2, A is an area, Cd is a drag coefficient, based on how the area term is defined, and Vis the velocity which is squared. Equation 2 is equation 1 rearranged to isolate the velocity term

$$V_{terminal} = \mathrm{sqrt}((W-B)/(p/2*Cd*A)) \qquad (2)$$

There are a number of complicating factors

- The area term and Cd term vary from object to object and also by direction of travel.
- The velocity at any instant in time in the water column is a 3 dimensional vector quantity that includes the current, wave induced turbulence and the body's motion through the water. OrcaFlex allows this to be determined automatically. It also automatically accounts for longer period wave components feeling the bottom will be alterened into elliptical circulation patterns while, while shorter period waves may continue to act as deep water waves moving in a circular pattern.

The debris, including the main body of the wreck, is acted upon by various currents, that occur in different layers of the water column. For this we must assume that the currents in each layer move the object, "down current", at the current's speed, and direction for as long as the object is in the layer. In the Gulf Stream for instance, this can mean drifting due North at 4 knots in the upper water column, drifting slowly East or West in the mid water and drifting back due South near the bottom at up to 2 knots.

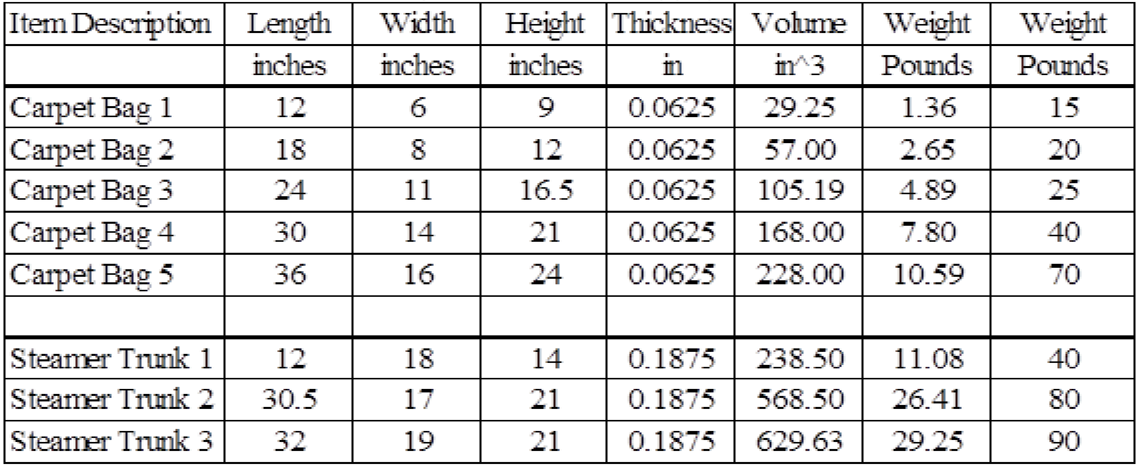
The Fall of Separate Items

One recent OrcaFlex experiment involved looking at how far a variety of common objects described in table 2, released at the surface, would drift in several hundred meters of water, before striking the seabed in a strong current.

These sizes and shapes were used with drag data for 3D objects from Hoerner (1965) to produce the input data shown in table 3.

The scatter pattern illustrated in figure 5 is due to the current acting for longer on the objects that fall more slowly. For those objects with little or no righting moment (CG to CB separation), significant tumbling can occur. This causes some chaos in the speed and direction of fall as different faces with different drag properties change their 3 axis angles with respect to the instantaneous flow velocity.

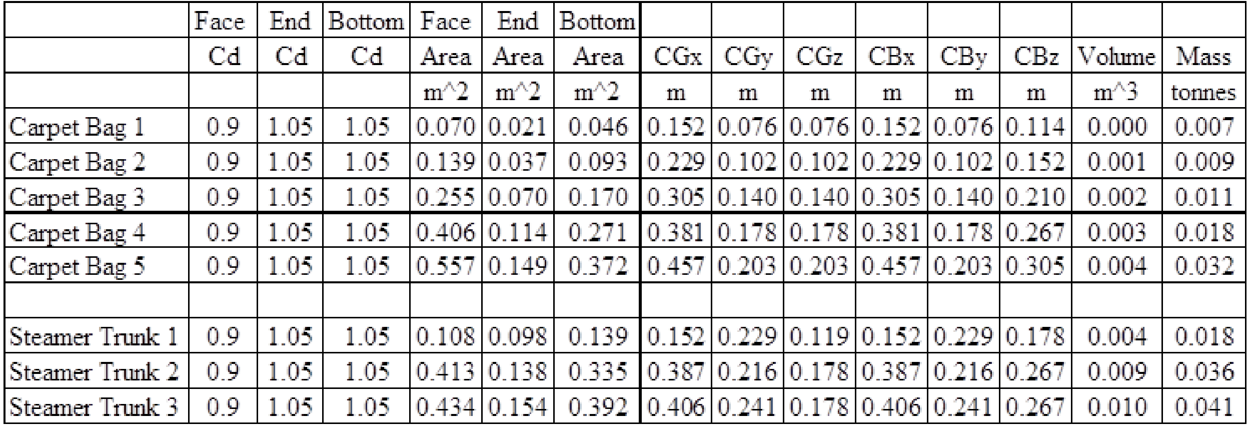
Table 2: Table of Sizes & Weights for Early Luggage Items



Item Description	Length	Width	Height	Thickness	Volume	Weight	Weight
	inches	inches	inches	in	in^3	Pounds	Pounds
Carpet Bag 1	12	6	9	0.0625	29.25	1.36	15
Carpet Bag 2	18	8	12	0.0625	57.00	2.65	20
Carpet Bag 3	24	11	16.5	0.0625	105.19	4.89	25
Carpet Bag 4	30	14	21	0.0625	168.00	7.80	40
Carpet Bag 5	36	16	24	0.0625	228.00	10.59	70
Steamer Trunk 1	12	18	14	0.1875	238.50	11.08	40
Steamer Trunk 2	30.5	17	21	0.1875	568.50	26.41	80
Steamer Trunk 3	32	19	21	0.1875	629.63	29.25	90

A units change was necessary to put the data into the default units of the OrcaFlex program.

Table 3: Relative Drag Properties for inclusion in Terminal Velocity Calculations



	Face	End	Bottom	Face	End	Bottom								
	Cd	Cd	Cd	Area	Area	Area	CGx	CGy	CGz	CBx	CBy	CBz	Volume	Mass
				m^2	m^2	m^2	m	m	m	m	m	m	m^3	tonnes
Carpet Bag 1	0.9	1.05	1.05	0.070	0.021	0.046	0.152	0.076	0.076	0.152	0.076	0.114	0.000	0.007
Carpet Bag 2	0.9	1.05	1.05	0.139	0.037	0.093	0.229	0.102	0.102	0.229	0.102	0.152	0.001	0.009
Carpet Bag 3	0.9	1.05	1.05	0.255	0.070	0.170	0.305	0.140	0.140	0.305	0.140	0.210	0.002	0.011
Carpet Bag 4	0.9	1.05	1.05	0.406	0.114	0.271	0.381	0.178	0.178	0.381	0.178	0.267	0.003	0.018
Carpet Bag 5	0.9	1.05	1.05	0.557	0.149	0.372	0.457	0.203	0.203	0.457	0.203	0.305	0.004	0.032
Steamer Trunk 1	0.9	1.05	1.05	0.108	0.098	0.139	0.152	0.229	0.119	0.152	0.229	0.178	0.004	0.018
Steamer Trunk 2	0.9	1.05	1.05	0.413	0.138	0.335	0.387	0.216	0.178	0.387	0.216	0.267	0.009	0.036
Steamer Trunk 3	0.9	1.05	1.05	0.434	0.154	0.392	0.406	0.241	0.178	0.406	0.241	0.267	0.010	0.041

Over the entire duration of fall, each object will have a range of directional terminal velocities.

Similar studies have been performed on taconite pellets and anthracite coal chunks across a representative range of sizes and densities. Note that the material density and not the bulk density should be used in terminal velocity calculations. The bulk density is reduced by the void fraction between the chunks of material, and will result in an underestimation of the terminal velocity. The near field wake-on-wake effect of a large mass of similar objects falling together is not known to the author. Here the grey trace capability of the OrcaFlex software as shown in figure 5 is especially useful as it is the only way to see the path of a small object in a large water depth. In this instance color coding and the ability to drag the simulation forward and backwards in time with a slider bar improved understanding of the results. Also to aid in visualization, each body was modeled graphically as a 3m cube, while the drag areas, volumes and other quantities used in the actual calculations are as in table 3.

NIL Terminal Velocity Condition

Some objects such as Remotely Operated Vehicles (ROVs) are deliberately ballasted to be near neutrally buoyant in sea water. This buoyant force is based upon the volume times the density of the fluid. However the ocean has density layers that are properties of salinity, temperature and hydrostatic pressure. Other oceanographic devices known as Swallow floats and RAFOS floats are deliberately ballasted to float at a specific mid water density level. Ocean gliders use this density layering and a carefully controlled change in buoyancy to provide propulsion as the glider rises and falls in the water column.

While Nil Terminal Velocity is a special case, it is an important one as ROVs that have been lost at sea when the cable has parted, may drift at midwater depths for years without ever going to the surface or the bottom. Eventually something will corrode through and something will fall off or flood changing the weight or the buoyancy enough to allow upwards or downwards motions. Some artifacts from a ship sinking such as articles of clothing may drift for miles before reaching the bottom because they have a large area and negligible weight.

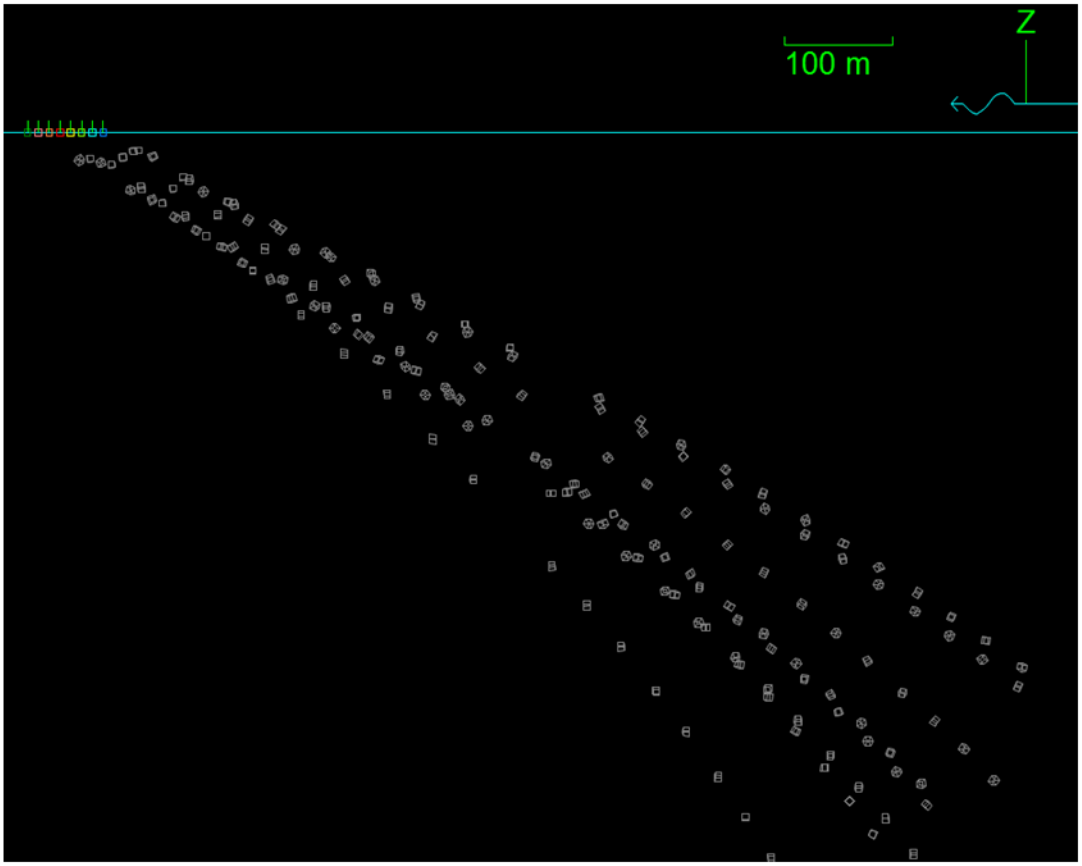


Figure 5: Spread due to Differences in Drag and Weight

Directional Failure of Restraints

Several boilers on *Titanic*, and turrets on *Monitor* and *Bismarck* fell out of the ship on the way to the bottom. They all have the same thing in common. Their primary attachment to the ship was by gravity. Under normal operating circumstances, all of the forces and accelerations acting on these objects could be constrained by a cradle or socket and some minimal amount of horizontal restraint. When the vessel rotated during the sinking process to orientations that exceeded what those restraints were designed for, they were no longer able to prevent the objects from leaving the ship. The techniques described herein can be used to model these objects separating from the body or pieces of the wreck and falling independently.

Sensitivity to CG/ CB / CD Locations

Figure 6 shows two similar views of an example Schooner in the OrcaFlex model. The left panel is a shaded 3D view available in OrcaFlex. The relatively crude rendering is a result of the way that the author created the 3d wireframe and better graphics are possible in many cases. The right panel is the wireframe mode. This vessel was developed from an amalgam of different sources as being "typical" for the purpose of illustrating different aspects of the results the modeling has accomplished thus far.

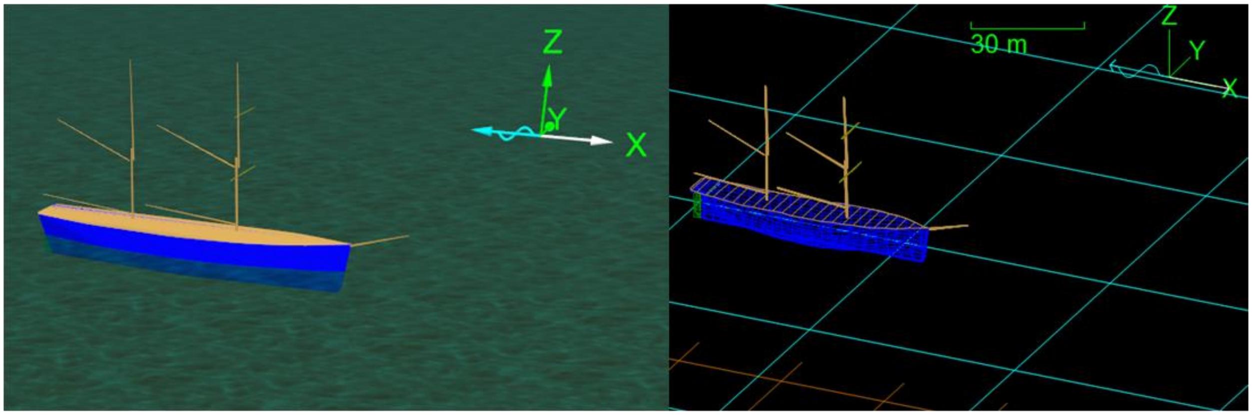


Figure 6: Two Views of example schooner

Figure 6 shows the ship with bare poles. It's possible to add in all of the ratlines, standing rigging, running rigging, and even sails to some degree with lift and drag properties versus angle of attack *etc*. To some degree this makes it possible to "sail" the ship on the surface if desired while responding to the wind, waves and currents in a fairly realistic manner.

This generic vessel is left as shown for the purpose of having a model that runs quickly which can be used to show some of the sensitivities discovered as a result of the modeling efforts to date. No specific casualty type is envisioned for this model, the ship is just filled up with seawater and allowed to plunge. The location of the centers of gravity and buoyancy are varied to show the sensitivity of the ships attitude in freefall and on bottom impact based upon their relative locations.

The motions during a typical sinking experiment are shown as a grey trace in figure 7. The model took about 3 seconds to run this 60 second simulation, so it runs in much faster than real time on this cheap COTS desktop. The replay was stopped just as the ship hit bottom and wound back to the position shown. The current runs from right to left at 2 knots. The ship leaves the surface and moves slightly up current at first, then the stern rotates down and it begins to slide backwards to strike the bottom stern first. Both of these longitudinal motions are due to the ship having much less drag area in the fore and aft direction than in the vertical direction. The list to starboard is due to the CG being set about 1 meter away from the CB in the transverse direction. If the water depth were greater, this typically causes the wreck to execute a spiral path on the way down. As it is, the ship lands and comes to rest on the seabed, about 90 degrees to the orientation it left the surface in.

The original runs for this vessel were in over 1000m or water depth, but it becomes difficult to see in the illustrations at that distant scale so the depth was adjusted for a better visual experience.

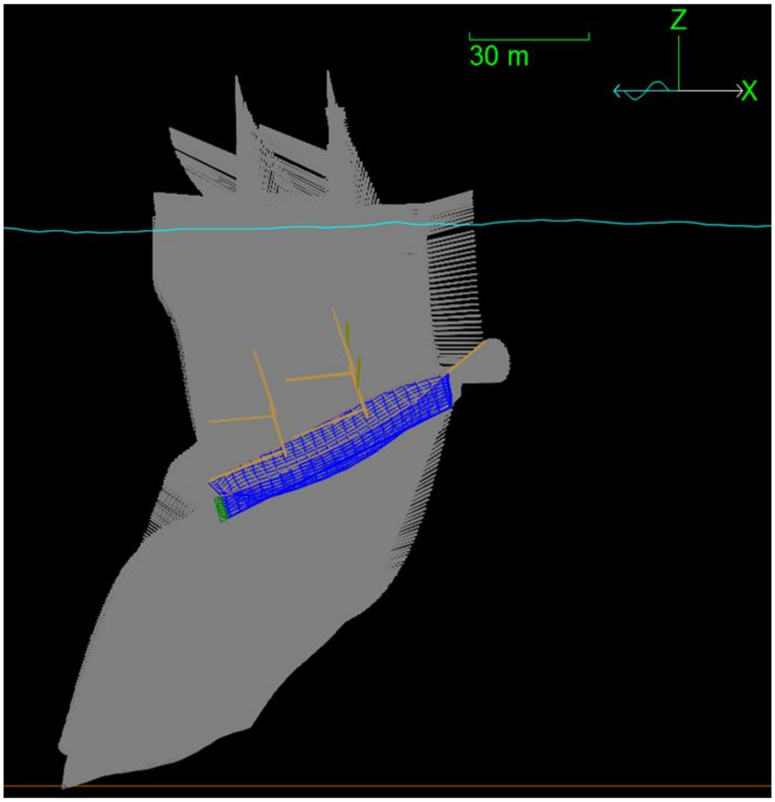


Figure 7: Schooner sinking showing flutter

Shifting the CG forward or the CB aft causes the vessel to plunge bow first. Shifting them the other way, has the opposite effect. In either case the vessel surges in the down direction picking up forward or sternward speed. This increases the drag on the top hamper which causes a righting moment that acts to decrease the hull angle and reduce the speed. This causes the flutter pattern observed.

While these generalities are true and logical as far as they go, every vessel is different. Calculations of the CB, CG and inertia can get you in the vicinity of the right values if there is enough information still in existence to construct them. The exact wind, wave and current conditions are rarely available, but in many cases approximate values or ranges can be developed, (Kery & Fisher 2012) (Kery *et al* 2012) For *Monitor* and *Edmund Fitzgerald* that sank due to storms, getting the wave climatology as close as possible is important. For *Titanic* and *Andrea Doria*, the waves were not a factor and can generally be neglected.

A variation of input parameters around the plausible values can be performed relatively easily once the models are built. Examination of the observed debris field, and any impact or slide scars, allows selection of which scenarios are the most likely. From there the most plausible runs can be further refined to see if an even-closer agreement between the modeled artifacts and those found in the debris field can be achieved.

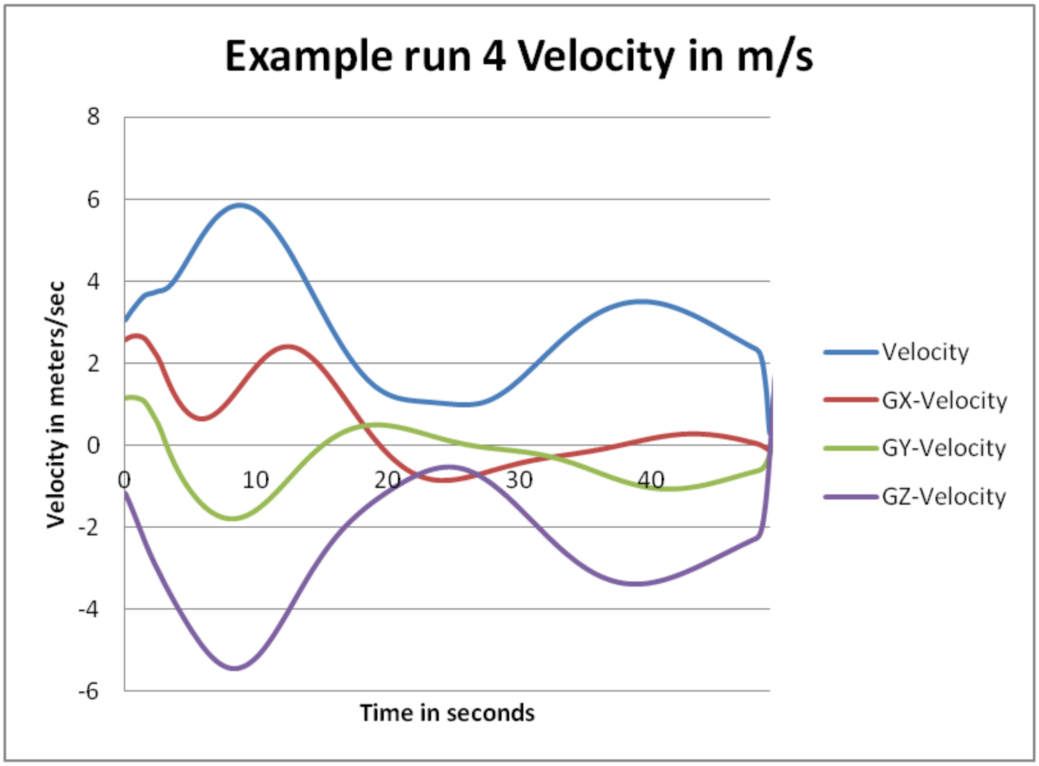


Figure 8: Example numerical output available

Figure 8 is an example of the quantities such as attitude, terminal velocity, drag on specific items modeled separately can be exported from OrcaFlex as a time series file in Microsoft Excel format.
In this case the vertically downwards terminal velocity Gz reached a maximum of over 5m/s (10 knots) but struck the seabed going a little more than 2 m/s or about 4 knots. The GX and GY velocities show other characteristics of the flutter phenomenon. Physical model tests confirm that this flutter is experienced in reality. (Kery unpublished, Garzke *et al* unpublished)
It is also easy to output .avi format movie files that can be played outside the program on common video players. These can also be pulled into video editing software to add titles or commentary etc.

IMPACT MECHANICS

When a vessel that is flooded with water, and trailing a wake of turbulent water, strikes the seabed, many things can happen.
When the FS *Bouvet* was near-simultaneously mined and shelled, she rolled over and sank in the Dardanelles campaign of WW 1, in 58 seconds. *Bouvet* struck the relatively soft bottom such that the stern was buried and the bow remains sticking out of the bottom at about a 15 degree angle to the horizontal. (Kolay *et al*, 2013) Recent sonar images show that it is still in that attitude 100 years later.

Monitor capsized and sank by the stern according to survivors testimony. She was found upside down resting on the turret as shown in figures 2,3,4.

The German battleship *Bismarck*, rolled over at the surface such that her 4 main turrets fell out, then she sank with the bow leaving the surface last. Evidence discovered by Ballard and Cameron, show that she struck the bottom right side up with the bow striking first. *Bismarck* landed on unconsolidated sediment on the flank of a seamount and proceeded to slide down hill to her final resting place some 1500 meters away from where she first struck.

The impact at an estimated 25 knots crushed the relatively thin bottom upwards about one deck, which caused a massive pressure increase inside the ship in any area where there was not already a hole for the pressure to vent through. It is likely that some of this passed through any holes in the bottom further liquefying the sediment underneath and reducing the friction to facilitate the slide already in progress. Cameron notes that that the side shell is blown outwards in many places along the junction at the bottom of the armor belts, due to the pressure finding the weakest local structure to tear vents through. There is some indication that the Titanic's bow section also experienced some impact crushing and hydraulic outburst.

Considerable plastic but also elastic deformation of the vessel and her contents occurs on impact, much like in a car crash. The impact energy can rip objects free of their mountings and cause them to be found in positions different from where they were located on the vessel in service.

Any object plunging through the water column carries a certain amount of water with it trapped in the boundary layers and as added mass. Additional water must fill in behind which forms a downward traveling plume that follows the vessel. When the object strikes bottom, the plume continues to come down for some few seconds later. The descending plume cannot pass through the bottom so it spreads out as an inverted mushroom cloud pattern called a micro-burst. Between these micro-burst and hydraulic outburst created currents and turbulence, many objects can be blown around out away from the body of the wreck. In the absence of a strong bottom current to blow it off the impact site, the sediment disturbed by the microburst and the impact, eventually settles back on top of the wreck and debris field.

STRENGTH MODELING

The strength modeling of a vessel undergoing bottom impact has not been attempted and may remain impossible for several reasons.
One is the cost of developing a finite element model to handle the massive complexity of a ships statically-indeterminate structure. The model would have to be designed to allow significant plastic deformation.
The second is the uncertainties about the properties of materials. Text books give strengths of steels that are based upon a minimum result from a given number of ideal test specimens. A ship is composed of a much more complex geometry of material that is at least as strong as that minimum number but may be significantly stronger. However any given piece of material may have experienced a significant amount of fatigue or corrosion pitting or work hardening and may have multiple heat effected zones. The intermittent welding may or may not exactly match what is on the drawing and the shape may or may not have been formed to the dimensions on the drawing.

For wooden vessels, the strength of the material is directional and there can be a wide scatter in mechanical properties from one board to the next. The end attachments are prone to splitting along the grain. The material in a wooden vessel is also prone to dry rot, and marine borer attack.
Therefore modeling of the strength of any vessel can only ever reach a conclusion based upon theoretical values.

Taphonomy

The term taphonomy is borrowed from archaeology and is based on two Greek words which can be translated roughly as "Law of Burial." In our context it is everything that happens after the wreck comes to rest. Corrosion sets in, wood is eaten by marine borers, structure weakened by the ravages of time collapses. In some cases currents and wave energy help scatter or scour the wreck and move the material around or bury it. Corals and other sessile life forms can start to grow on any substrate that is different from the barren bottom around it and in some cases can completely encase wreck material. In the cases of the *Lusitania* and the *Monitor*, it is likely that the wrecks were depth charged during the second world war. Understanding the taphonomy and how the wreck site may have been reworked, must be factored in when comparing the model results to the wreck and debris field geometry.

Summary

The analyses and techniques described herein can be used in the forensic analyses of vessels that sank, to help explain the attitude and dispersion of the wreck and objects in the debris field. This is a relatively new technical capability for which there are few if any precedents in print. The author believes that this may be useful to underwater archaeologists as well as contemporary investigators attempting to understand the sinking of modern vessels.

Accuracy, Verification, and Validation

An old saying goes: "All models are wrong, but some models are useful". The modeling techniques described herein are useful in reconstructing events that happen in the course of a shipwreck, or sinking of any object. The typical error bands on the drag, lift and added mass information can easily be +/- 20%. The calculation of as exact as possible a weights and centers engineering model, can be pursued with due diligence and arrive at a fairly credible result. A plausible wind, wave and current condition can often be developed. None of these are likely to be better than a best effort engineering estimate.

The documented conditions of the wreck and debris field on bottom can be used to test the plausibility of model runs in which the uncertainty of the input parameters is systematically varied. This is treated as a complex group of boundary conditions. It is often possible to figure out what landed first and what landed later based on what's on top of something else. Lighter objects are likely to have traveled further, but also objects that separated higher in the water column. Items such as that can be used to help figure out the most plausible answer from the range of answers that the modeling provides. In many cases these debris field items warrant additional independent modeling whereby they are detached at the surface or higher in the water column and allowed to free fall independently.

Given the systematic uncertainty of the inputs in many cases, any rigorous analysis of mathematical and physics based accuracy is a moot point. A series of scale model tests could be developed where the inputs are precisely known and the model could be verified that way, but at this point, that data set does not exist. The parametric analyses format allows the relative importance and sensitivity to each of the major input parameters to be evaluated but that body of work is also in the future.
Eventually a body of knowledge based upon the systematic study of multiple shipwrecks will allow a detailed best practice procedure to evolve. The results presented herein are the first steps down that voyage of discovery.

Acknowledgements

The Author would like to thank the members of the SNAME Marine Forensics Committee for their continued interest and innumerable contributions over the years. I would especially like to recognize my mentor, colleague and friend Bill Garzke for the years of encouragement and idea bouncing that have kept me going on this. I also recognize the CSC Distinguished Engineers program that made working on this paper and presentation possible. I would like to thank a number of individuals for their technical reviews prior to submission and their many helpful suggestions. These are: Dr Larrie Ferreiro, Dr James Delgado, Dr Francisco Fernandez-Gonzalez, and Dr. Alistair Arnott. Thank you all.

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