A SunCam online continuing education course

Marine Weight Estimation and Control

by

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Course Objective: This Continuing Education course is written for Professional Engineers and others who are designing, or want to design, successful floating vessels.

Course Description: This course is intended to show how important a well-designed and understood weight estimation calculation is to the overall success of a floating structure. Software is provided which establishes a format for the student, that the author has used in the successful design of several hundred ships, boats, barges, submarines, and yachts. There are many examples of ships on video that are examples where proper weight estimation and control was not exercised, resulting in poor trim, heel, bad stability, insufficient freeboard resulting in reduced cargo capacity, underwater swim platforms, and even sinkings during launching. The student's understanding of the critical nature in establishing a proper foundation for the design of floating structures by paying specific attention to the weight estimate. The following topics are covered:

Conceptual Design Estimation
Reference Axes Used In Shipbuilding
Weight Margins
Organization of Weight Groups
Calculation of Moments
Summation of Weight Groups
Determination of Resultant Lever Arms
Basics of Heel and Trim as they relate to the Center of Gravity
Software Program is Provided

Marine weight estimation and control is not-so-glamorous, but one of the most critical aspects of ship design. In fact, it is the foundation of a successful marine design. Unlike weight estimation of land-based objects, which are generally limited to total vertical, individual floor, and component weight only, the ultimate purpose of marine weight estimation and control is two-fold:

- To accurately estimate the weight and location in the vessel relative to the ship's coordinate system before construction so that the ship's stability, heel, and trim can be ascertained so that it will float at the designed draft and with the desired trim and heel;
- To keep track of the evolving weights and centers as the design and construction progresses so that there are no last-minute surprises or major errors to correct, so that the vessel floats properly and has the cargo capacity as designed.

Getting the weight balance of a ship correctly is a bit like balancing it on the point of a pin. While the foregoing may appear to be quite logical and obvious, it is amazing how often an accurate weight estimate is not made or followed up until the ship hits the water. This is a step in the design process that is occasionally overlooked or done poorly, resulting in a vessel with undesirable trim, heel, the need to add ballast to correct the stability, lack of sufficient reserve stability to stay upright in a storm, or even capsizing upon launching or while loading. None of these potential events are inherent to building design, so it can be seen to be the more complicated and important to the success of the ship.

The weight estimate is a basic accounting of weights and locations in the ship of the major items of structure, propulsion, electrical, auxiliary machinery, piping systems and components, outfitting, weapons, and electronics, so that the overall center of gravity location can be determined. Some concepts and nautical terms worth noting are:

- Aft, or After-the direction toward the back end of the ship is referred to as "aft" Aft is an abbreviation for "after" and the two are used interchangeably in nautical terminology.
- Amidships or Midships-the halfway point of the length of the Design Waterline (DWL).
- Ballast-weight added in certain locations in a ship to correct errors in stability, trim and heel or to improve the running characteristics of a ship that has varying draft due to changing loading conditions
- Center of gravity-this is the estimated location in X, Y, and Z coordinates in the ship.
- Design Waterline (DWL)-the Naval Architect's intended maximum draft of the ship

- Draft-the depth of water to which the vessel can safely and legally be loaded. This varies slightly with seasons due to water temperature and salinity, and it is marked as such along with the Plimsoll Mark. This is generally synonymous with the Load Waterline Length (LWL)
- Fore, or Forward-the direction toward thre front end of the ship is referred to as “forward”. Fore is an abbreviation for “Foreward” and the two are used interchangeably in nautical terminology.
- Plimsoll Mark- This is a painted symbol named for its inventor on the hull, looking like a circle with a backwards C to the left and a forward C to the right. This symbol and accompanying water level marks show the legal limits of draft that the ship can be loaded to. This location is sometimes used in weight estimates if the stability calculations figure trim about the midship point rather than either forward or aft perpendicular.
- Reference Axes-As shown in Figure 1, the longitudinal centerline at the base of the ship is called the baseline. All vertical and transverse references are made relative to the baseline. This is abbreviated as BL. The start of the longitudinal axis in American surface ships is generally at a position near the bow, called the Forward Perpendicular. This is abbreviated FP, and it is usually located at the intersection of the design waterline (DWL) and the stem (forward-most vertical structure of the bow). Measurements from the FP proceed aft on American surface ships. Vessels designed and built elsewhere, and all submarines, usually use the aft perpendicular (AP) as the start of the longitudinal reference axis by long-time custom. The location of this historically was where the rudder post was located, but modern ships may have an arbitrary or frame location used for this such as 95-96% of the waterline length.

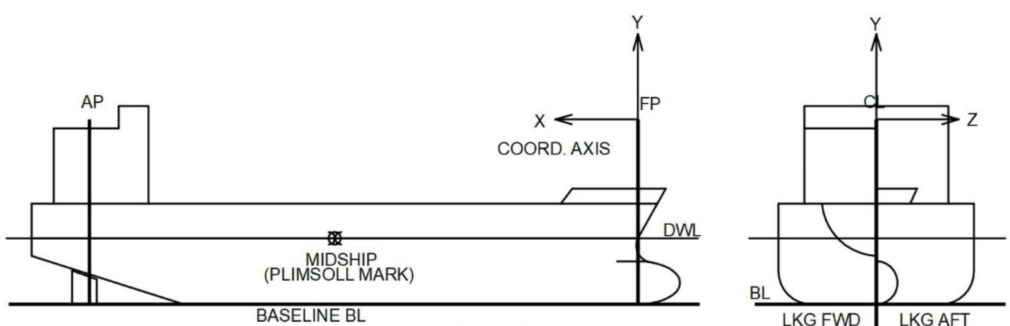

FIGURE 1

- Longitudinal Center of Buoyancy (LCB)- the longitudinal distance of the location of the center of the buoyant forces on the immersed volume of the hull from the vertical datum (FP, AP, or Midships).

- Longitudinal Center of Flotation (LCF)- the longitudinal distance of a point on the top waterline of the immersed hull, measured from the longitudinal reference datum, about which the hull trims when acted upon by the separation distance between the LCG and LCB. It is similar to a teeter-totter pivot point. The LCF is seldom the same distance from the longitudinal reference point as the LCB.
- Longitudinal Center of Gravity (LCG)-this is the position of the forward or aft location of each item accounted for in the weight estimate, and the total ship, measured from the longitudinal reference axis. If a midship reference axis is being used, distances of weight items and/or the ship forward of amidships are considered negative, and distances measured aft of amidships are considered aft so that aft trim, which is generally desirable, is positive.
- Port and Starboard-port is the left side of the ship when looking forward, and starboard is the right side.
- Vertical Center of Gravity (VCG, or KG)-This is the height above baseline (BL) of each item accounted for in the weight estimate, plus the total ship. KG is a stability term that means the height of the center of gravity from keel. VCG is the position of the vertical center of gravity.
- Transverse Center of Gravity (TCG)-This is the transverse distance to port (-) or starboard(+) of each item accounted for in the weight estimate, plus the total ship.
- Trim-the fore-and-aft level of the ship. Trim that is down by the stern is as shown in Figure 2 below. Trim down by the bow is where the bow is deeper than the stern compared to level.

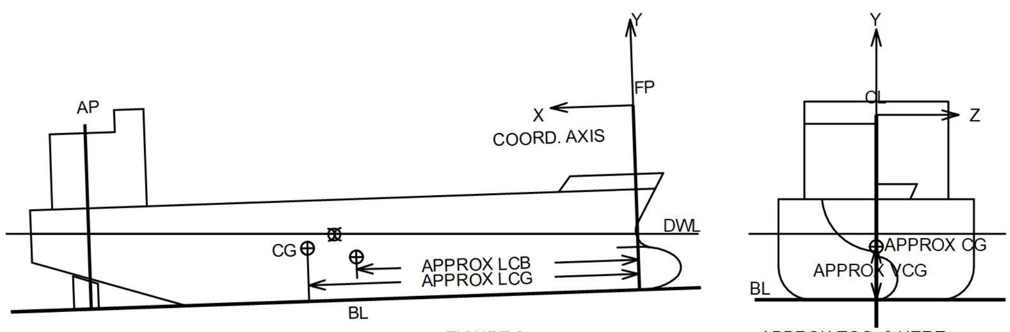

FIGURE 2

- Trim Lever- The distance from the LCB to the LCG. Multiplying the displacement by the trim lever gives the trimming moment. The greater the trim lever length, the greater is the trim.

The invention of the spreadsheet has made the job of weight estimation much easier since it can be programmed to do the summations, determinations of weight centers, load conditions used in stability calculations, and other derivative mathematical information. The mass properties functions of AutoCad and similar graphics programs are also a great tool for calculating weights and centers of oddly shaped components.

Open Spreadsheet Program

Depending on the size of the ship and the accuracy required, a final weight estimate may be anywhere between about a hundred, to many thousands of line items. Large shipyards often employ weight calculating engineers, whose sole job is to calculate the weight and centers of each part in the ship as it is finalized. Smaller shipyards often have one person doing this task, sometimes to the exclusion of all else.

The general organization of the weight estimate is as follows:

- Create a spreadsheet with the vessel's name, build number, revision number or letter, and the date in the top line.
- Leave a few lines to describe what revisions were made to the weight estimate since the last one. This comes in real handy as the design and construction progresses; it's probably a large source of neglect for those who don't pay much attention to the need for an accurate estimate.
- Thirteen columns are used to hold data pertinent to each weight line item. The top headings should read "E/C/A", "Item", Unit Wt", "Area", "Qty", "Weight", "LCG", "LMoment", "VCG", "VMoment", "TCG", TMoment", and "Remarks"
- The "E/C/A" column is an indicator of whether the item is estimated without calculation, calculated, or actual. This comes in handy as the design progresses through to completion and as in indicator of the accuracy of the estimate.
- The "Item" column should contain each identifiable item larger than about 50-100 pounds in the beginning. As the design progresses, more items will be added as more of them are designed, selected, or otherwise known.
- For each item, a description of the part, along with its pertinent weight, area, and position information should be entered.
- For each item, the weight multiplied by the location equals the moment. For example, weight x Longitudinal position =L Moment (see Figure 3).

	ITEM	unit, area or lgth	WEIGHT LB	fr. FP L ARM FT	L MOMENT FT-LB	V ARM FT	V. MOMEN FT-LB	T ARM FT	T. MOMENT FT-LB	
c	hull transv frames	1345	5114	28.86	147590	2.04	10433	0.00	0	WT*L ARM= L MOMENT
c	hull longl frames	1312	5380	28.86	155267	2.04	10975	0.00	0	WT*V ARM= V MOMENT
c	hull girders	489	2445	28.86	70563	2.04	4988	0.00	0	WT*T ARM= T MOMENT
c	hull stanchions	133	663	28.86	19134	2.04	1353	0.00	0	
c	diagonals	372	1858	28.86	53622	2.04	3790	0.00	0	
c	main deck	1465	18679	28.86	539076	4.00	74716	0.00	0	
c	bottom plating	1462	29818	28.86	860547	0.08	2385	0.00	0	
c	side plating	430	8779	28.86	253362	2.08	18260	0.00	0	
c	transom+bow plating	195	3975	28.86	114719	2.00	7950	0.00	0	
c	brackets	8	81	28.86	2338	2.00	162	0.00	0	
c	half-pipe fenders	166	1575	28.86	45455	3.75	5906	0.00	0	
c	upper deck	1340	13668	28.86	394458	14.08	192445	-0.41	-5604	
c	upper dk beams	704	5086	28.86	146782	14.00	71204	-0.41	-2085	
c	upper longl frames	638	2711	28.86	78239	13.88	37629	-0.98	-2657	
c	deckhouse sides	514	5243	28.86	151313	8.00	41944	-2.00	-10486	
c	main to upper pilasters	80	1153	28.86	33276	9.08	10469	-1.93	-2225	
c	main dk handrails	167	608	28.86	17547	7.42	4511	0.00	0	
c	main dk courses	835	944	28.86	27244	5.72	5400	0.00	0	
c	main dk stanchior	113	190	28.86	5483	5.72	1087	0.00	0	
c	main dk toerail	167	284	28.86	8196	4.08	1159	0.00	0	
c	stairs	104	1125	28.86	32468	9.00	10125	1.92	2160	
c	stair handrails	65	236	28.86	6811	12.74	3007	1.92	453	
c	stairs courses	320	362	28.86	10447	11.15	4036	1.92	695	
c	stairs stanchions	70	118	28.86	3405	10.67	1259	1.92	227	
c	awning pilasters	83	439	28.86	12670	19.18	8420	0.00	0	
c	crossbars	147	518	28.86	14949	24.91	12903	0.00	0	
c	awning pilaster f	78	267	28.86	7706	18.87	5038	0.00	0	
	hull struc. per calcs		111319		3212666		551555		-19522	
	1.5% welding margin		1670		48190		8273		-293	SUM WT/SUM L ARM= L MOMENT
	3% margin		3340		96380		16547		-586	SUM WT/SUM V ARM= V MOMENT
	Total Structure %	#DIV/0!	116328	28.86	3357236	4.95	576375	-0.18	-20401	SUM WT/SUM T ARM= T MOMENT

FIGURE 3

The organization of the parts should be in groups that make items easier to find later. The U.S. Navy has developed a Ship Work Breakdown Schedule (SWBS) code numbering system for organizing the parts, and some sort of system similar to it is quite useful. The Navy SWBS system is as follows:

- 000-099 Technical, Naval Architectural design information
- 100-199 Structural parts such as hull plating, frames, bulkheads, stringers, girders, brackets, deck plating, superstructure plating, stanchions, etc.
- 200-299 Propulsion equipment such as engines, shafting, propellers, gearboxes, etc.
- 300-399 Electrical Power Distribution items such as switchboards, cables, subpanels, breakers, batteries, etc.
- 400-499 Command and Control electronics and mechanical systems such as steering controls, intercoms and telephones, navigation electronics, etc.
- 500-599 Auxiliary machinery systems such as pumps, piping, valves, strainers, etc. for all fluid systems
- 600-699 Outfitting items such as anchors, chain, lifeboats, carpets, wallcoverings, paint, deck coverings, handrails, furniture, etc.

- 700-799 Combat Systems such as guns, ammo, missiles, launchers, fire control radars and control panels, torpedoes, torpedo data computers, etc.

For commercial vessels and yachts, portions of this breakdown system, or others made up by the designer or builder are used. At the end of each group it is helpful to sum the weights and moments so that the fraction that each group makes up in the ship is known for later estimation purposes. It is also helpful to the builder to have estimated the steel and/or aluminum structural weights so they can estimate the purchase cost before the build contract is made.

The Centers of Gravity for each group are found by dividing the respective sum of moments (longitudinal, vertical, or transverse) by the sum of item weights in that group. Click on summary cells to see the math and see bottom of Figure 3.

The weight estimate, as an estimate, is likely to contain many approximations and oversights of specific weights, especially in the preliminary stages. Therefore, each of the groups should have a contingency margin added to their weight sums and moments, at the same longitudinal and transverse center of gravity for the group, and these margin amounts should vary with the level of accuracy of the weight estimate. The vertical center of gravity margin should be slightly higher, say anywhere up to 0.75 feet. In the very early preliminary stage, it is best to use 15% for weight of structure, propulsion, and auxiliary systems, and about 40% for electrical, electronics, and outfitting. As the design progresses and actual equipment is selected, the margins can be reduced to 10%, and then 3% of the structure, propulsion, and auxiliary systems, and 20%, and later 10% for electrical/electronic/outfitting items. Actual items, where known, with actual weights and locations should be added to the estimate as the design progresses. And an additional margin for welding of 1.5-2% should be added in the structure group if the hull is built of metal. Composite/fiberglass vessels may also need a similar margin for structural tabbing and excesses of resin and cloth.

Once the sums of all groups are determined, the vessel Lightweight (LW, formerly Lightship) and overall Center of Gravity (CG) can be determined. The LW is the total sum of all weight groups without cargo, crew, passengers, and provisions. Operating fluids in the machinery and piping are included in the Light Weight. The LW is important because this weight and the location of the Centers of Gravity (LCG, VCG, and TCG) for the entire vessel are the foundation required to do the stability calculations.

Since many of the structural plans are only drawn to show one side of the ship, be careful to double the weights of those items that are the same port and starboard. It is a common error to neglect this and can result in serious error.

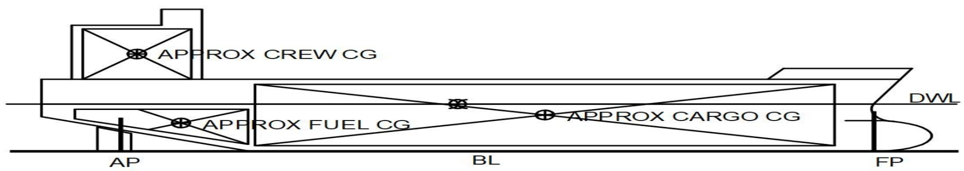

FIGURE 4

The next group of weights to estimate are the cargo, fluids, and personnel-related loads. This group is also called the Deadweight of the ship. Generally, there are three loading conditions studied in the stability calculations, so it is helpful to do these in the weight estimate. For most weight and stability estimates, a Departure Load (100% load of cargo and potable water, 95% load of fuel, and 10% load of gray and black water (sink & shower drain water if contained in a tank, and sewage) is used. All personnel are accounted for at their operating stations, and provisions are figured at some figure like 5 pounds/day/person. Yachts may have a somewhat large load of soda, beer, and liquor as well as extra dishes, water toys for guests, a hot tub, extra tenders, etc relative to cargo vessels. The 50%, mid-voyage load is also figured, using 100% load of cargo, 50% of fuel, 50% potable water if the ship doesn't have watermakers, 50% gray and black water, and 50% of provisions. The Arrival (10% Load) condition has 100% cargo, 10% fuel, potable water as above, provisions, and 100% gray water and sewage. The fuel usage is generally considered to empty the storage tanks first, leaving 10% in each tank with any remainder in the Day Tank (the tank full of filtered fuel that is filled for the day's running needs).

The distribution of cargo, operating fluids, personnel, their effects (personal items), ballast (both solid and fluid), and provisions is made to give the best overall trim and heel of the vessel in the stability calculations. As the design develops, the designer goes back and forth comparing the weight estimate with the stability calculations to determine which combination of loads in which places and tanks will give the least amount of change in trim and heel over the entire operating range of fuel loads. This process optimizes the compartment and tank arrangement to provide suitable operating conditions of the ship.

Weight Margins

Weight margins are included in each weight group to account for unknown amounts of weight that can be expected to be added later as details are developed. In the Preliminary stage, weight margins as high as 25% for structure, propulsion, auxiliary machinery, and 40% for electrical distribution, electronics and navigation equipment may be suitable. In the Contract stage of design, where drawings have progressed to the level of Class submittal drawings and those with suitable detail for shipyards to bid on, these margins may be reduced to levels like 10% since more detailed weights are known at this stage. During th Detail phase of design, where the ship is under construction and equipment has been ordered, the margins may be reduced to 3%. In the structure group, and additional 1.5% margin is added to cover welding.

The accurate weight estimate should be completed in advance of launching, so that the launch behavior of the vessel can be predicted and planned to be a success. Like a child at birth, launching a ship is perhaps the most dangerous condition the ship will encounter in its lifetime. Side launches result in heel angles as high as 50 degrees or more, depending on the VCG. End launching has a momentary condition where just the stern is afloat and therefore the VCG is momentarily very high. If the VCG is too high, the vessel will capsize, as in the video you may have seen a few years ago of the blue trawler yacht that capsized as it was slid down the launch way. Errors such as this, and the embarrassment to the owners and damage to the vessel are avoidable if the estimate is accurate beforehand and the vessel is ballasted as needed to keep it upright in all launch conditions.

Once the vessel is successfully in the water, a test of stability is performed (called an Inclining Test) to verify the weight estimate and calculate the actual displacement (weight) and location of Center of Gravity. The details of this test are described in another CE class and will not be gone into here, but the results of this test let the designer know how accurate the estimate was, where margins may need to be modified on similar ships to be even more accurate, and the details form the basis of tracking the stability condition of the vessel for the rest of its operational life. At regular intervals, such as ten years, the stability and weight data are verified by a Naval Architect per Class requirements and modified as necessary due to weight additions or deletions so that the reserve stability of the vessel continues to meet requirements to be safe to operate. If the VCG is too high due to loading and/or insufficient ballast, this is what happens: https://commons.wikimedia.org/wiki/File:Coast_Guard_rescue_Golden_Ray_14.jpg

Weight Control

The usefulness of an accurate and regularly updated weight estimate cannot be overestimated. Updating the weight estimate at calendar or milestone construction intervals will allow the designer to track changes in the locations of the centers of gravity and displacement (weight), as well as trends in good or bad directions. The weights and locations of centers can be graphed to visually show the trends of weight increase versus margin reduction as construction proceeds. An advantage of updating at construction milestone intervals is that the hull and superstructure modules are lifted into place on the building way as they are completed, and the crane scale data can be used to get an accurate weight of large blocks of the ship. The longitudinal and transverse weight centers can also be mathematically determined if the sling angles and lengths are known, along with crane lifting weights. The module weights can replace whole sections of structural item detail when in place, however, the overall weight centers of the detail groups should be maintained unless the actual longitudinal or transverse weight centers can be determined mathematically as above. The VCG will not be determinable until the Inclining test results shown the VCG for the whole ship.

The location of the LCG determines how level the hull floats lengthwise, and the TCG determines how level it floats transversely. Keeping a close eye on the trends as the design gets more accurate tells the designer if the heel and/or trim is getting better or worse. If so, certain weight items should or could be relocated to improve the desired and designed condition of the vessel. It also tells the designer at an early stage if additional ballast may be needed to correct heel or trim, and most importantly, if the weight of the vessel is approaching either the structural draft design limits or reserve stability limits.

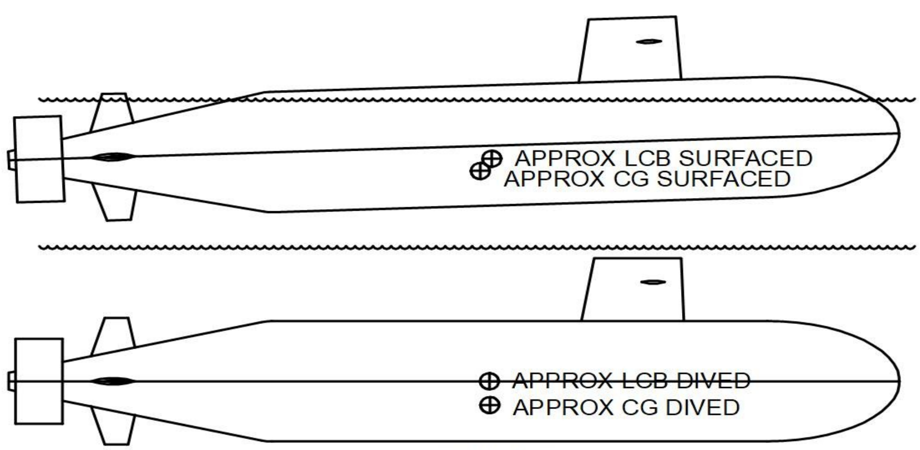

FIGURE 7

The weight and location accuracy requirements for submarines are even greater than surface ships, because they have a much narrower margin of buoyancy. A typical American nuclear submarine uses both lead blocks and seawater ballast, has a buoyancy reserve of about 8% of the surfaced displacement; if the actual displacement is too light with maximum seawater ballast, it will not submerge, and if too heavy when ballasted with seawater, especially when deeply submerged, it will not surface. And if the wrong amounts of ballast are loaded in the ballast tanks fore and aft or transversely, the submarine will not float level. Surface ships have similar trim and heel issues due to ballast, but with buoyancy reserves of over 30% when in Departure condition, they are not as critical as submarines.

One truth of ship design is that they almost always get heavier and the VCG always goes up as the design progresses, and the degree to which this happens is critical for the designer to know early enough to counteract it if necessary. The author has saved his employers millions of dollars in contract penalties and embarrassment in front of clients by catching design problems such as these early enough to solve them in a satisfactory manner.

Ballasting

Once the ship has been inclined to determine the actual location of the center of gravity, one can determine whether ballasting will be required. There are two types of ballast-solid and liquid. Solid ballast, such as lead ingots, lead shot, concrete, steel blocks or shot, or other dense materials are used when permanent ballast weight is required to correct trim, heel, and/or the location of the center of gravity. Permanent ballast is generally placed low in the ship, where it may not only improve the trim and/or heel, but also lower the vertical center of gravity, thereby improving the stability (the tendency for a ship to remain upright). For example, in a ship that has too much trim down by the bow, placing the ballast in a far aft location will minimize the amount of ballast needed because of the long lever arm of the ballast weight from the longitudinal center of gravity (LCG), but it will also lower the vertical center of gravity because the ballast lever arm relative to the baseline is well below the vertical center of gravity (VCG), which is often as high or nearly as high as the main deck. In the 1970's the Ticonderoga Class cruisers https://commons.wikimedia.org/wiki/File:Starboard_bow_view_of_USS_Ticonderoga_(CG-47)_underway_in_rough_seas_BALTOPS_1985_DN-ST-86-02754.jpg) were designed to have a taller superstructure on top of a Spruance Class destroyer (https://commons.wikimedia.org/wiki/File:USS_Spruance_(DD-963)_underway_after_her_Mark_41_VLS_modernization,_circa_in_June_1987_(NH_96851).jpg) hull to save the hull design expense during those inflation-ridden times. As a result, the cruiser needed an additional 300 tons(!) of concrete ballast in the bottom to meet the Navy's stability requirements compared to the Spruance destroyer. If this had been an original design, such an amount of ballast would be considered a design error, however because it was done to save the cost of designing an all new hull, it was an acceptable compromise-although an intensive weight-saving program was also required to lower the weight of the superstructure in order to minimize amount of required ballast, which had an effect on the maximum speed and maneuvering ability.

Submarines are a special case when it comes to solid ballast, in that VERY accurate weight estimation must be done, and strict control of the amount of lead blocks that are placed in the liquid ballast tanks, versus the volume of liquid that they take the place of, must be accounted for so that the sub has enough reserve buoyancy to surface, but enough liquid ballast to dive quickly.

Liquid ballast is used in most large vessels to control trim, heel, vertical center of gravity, and draft when not carrying cargo. Liquid ballast can be seawater, fresh water, or fuel, but in some rare cases such as German U-Boats, mercury was used. Tankers, for instance, before 1990 when single skin tanks were allowed, used to fill the cargo tanks up with fresh or seawater so that they ran “in ballast” at a draft somewhat similar to their “in cargo” draft. Those that used fresh water often went back to fill up in Saudi Arabia “in ballast” and sold the fresh water to help offset the expense of going back from Europe or the United States without a petroleum cargo. However, with the environmental issues of draining the oily cargo tanks into the sea, tankers, like all other ships requiring liquid ballast, now have separate liquid ballast tanks from cargo and fuel tanks so that fuel and petroleum are no longer discharged with the ballast water. Older naval ships and diesel submarines, however, often still have seawater-compensating fuel tanks, where fuel is sucked out of the tank at one end, and seawater can enter at the other end. This minimizes the effect on ship stability, and it will cause these ships to become about 15% heavier as the fuel is burned off.

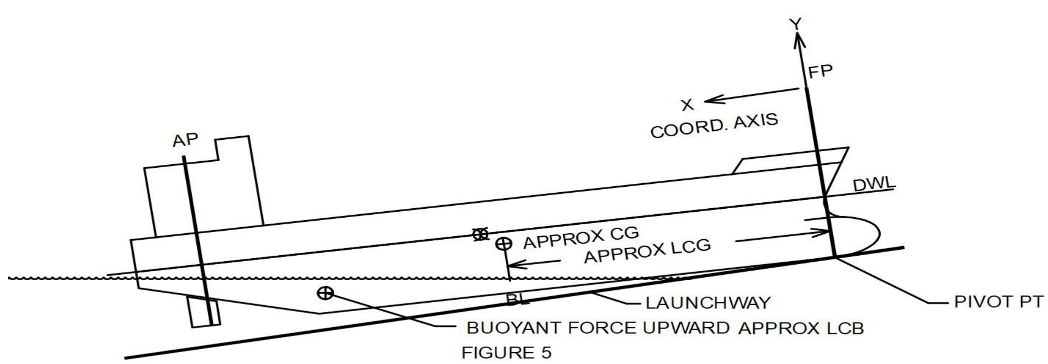

Figure 8: End Launching

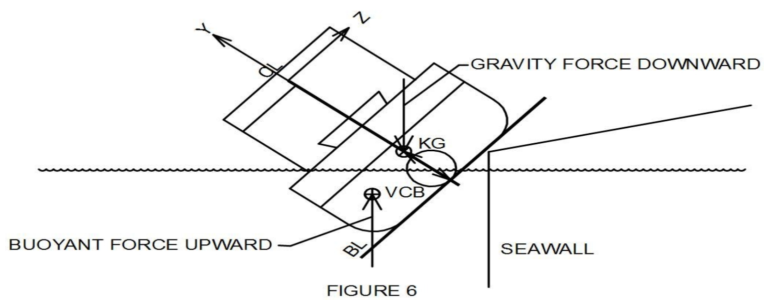

Figure 9: Side Launching

Launching

Launching a ship is a special case of weight estimation, because midway through launch there is a momentary time where the full buoyancy has not developed yet, but part of the ship is afloat. In this case the vertical center of gravity shifts upward and it could cause the ship to capsize if there is insufficient ballast in the bottom to keep it upright. Maybe you saw the launching of an 90' trawler yacht in Oregon a few years ago, (https://www.youtube.com/watch?v=v7UBznKKCck) where the yacht started rolling over onto its port side as it was lowered down the launch ramp, and ended up floating on its side instead of the bottom. This will make any Naval Architect have a very bad day! Another example (https://www.youtube.com/watch?v=ofylixqKoYo) of a launching gone wrong was the video available on YouTube.com that shows a barge loaded with cement Easter Island heads being flooded down, theoretically, to make an undersea SCUBA sculpture park off Pompano Beach, Florida. That one immediately rolled over and sank to the bottom upside down! A proper weight estimate and proper knowledge of vessel stability, particularly submarine stability, would have prevented that tragedy.

Sources of Weight Information

Thanks to the internet, weight information on specific components as well as hull materials is getting easier to come by. Marine component manufacturers are getting better at providing the weights of smaller components, and even find centers of gravity on some components such as diesel engines and transmissions. Another good source is the Society of

Aircraft Weight Engineers Handbook, and the various general engineering handbooks for specific material densities. However, some parts, such as steel or aluminum bulkheads, frames, etc will still have to be calculated on the spreadsheet. A source of further information on marine weight estimation is Volume 1 Chapter II, Section 2 in Principles of Naval Architecture, published by the Society of Naval Architects and Marine Engineers (1988).