Stability Is The Key – Part 1, Initial Stability

Understanding Stability and Sailboat Performance and Safety

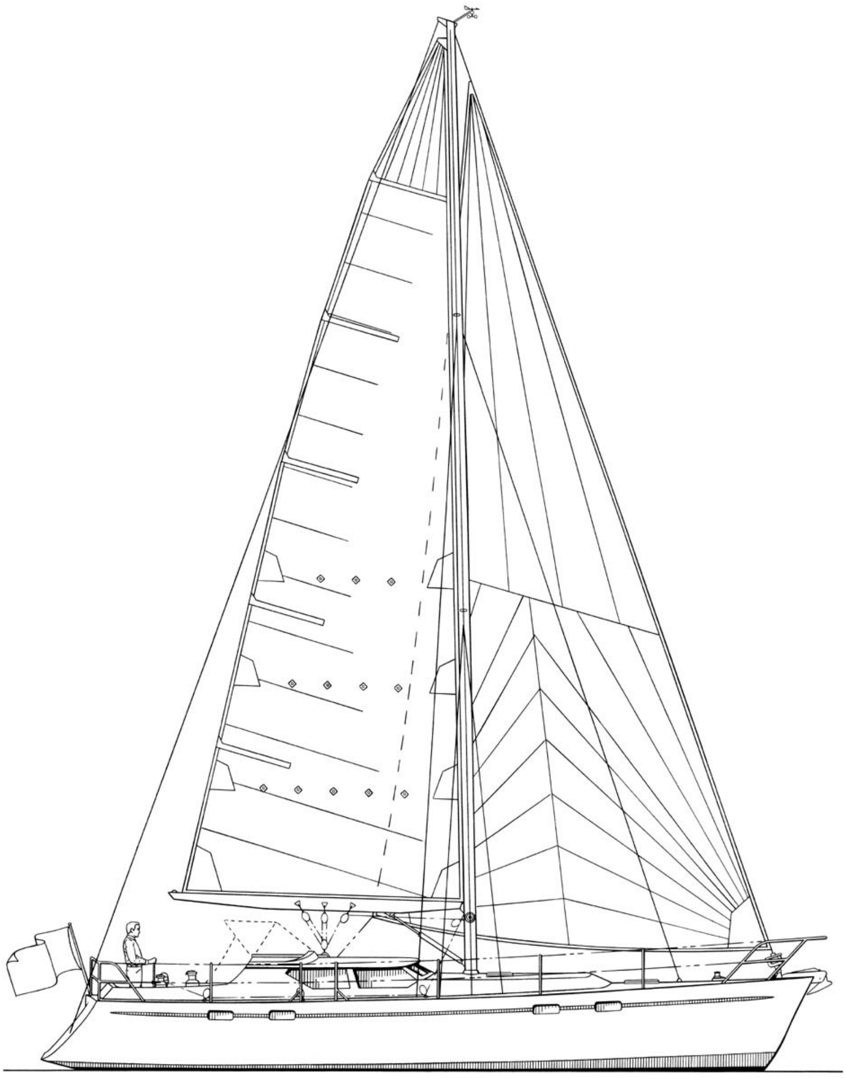
By Dave Gerr, © 2007 Dave Gerr

Hull form, keel shape, rudder location, height and type of rig, sail material, winch package, and so on. All are important factors in performance and safety; but the key to performance and safety for any sailboat is stability. Not only a critical factor in safety, stability provides the power to carry sail; it controls the height and form of the rig; and the size and arrangement of the standing and running rigging. Stability—or the need for it—governs hull form and much about keel shape and through this rudder location and proportions. In short, stability affects—directly or indirectly—almost everything about a boat. What we'll do here and in the following article is take a close look at stability in sailboats. We'll examine what it is, how you can estimate it, and what it means for boat performance and safety.

Right off, we have to make a crucial distinction. There are two aspects of stability—*initial* or *form* stability and *reserve* or *ultimate* stability. It's all too common to find these different aspects of stability confused. In fact, characteristics that generate large initial stability can reduce reserve stability and visa versa. If you come across a discussion of stability that doesn't make this clear distinction and maintain it, you are probably looking at misleading information.

Initial Stability

Initial stability can be thought of as sail-carrying power and thus performance. The greater the initial stability the more sail a boat can fly upwind in heavier air with a taller rig and the faster the boat can go. This is so important that initial stability is sometimes just termed "power," and a boat with great initial stability is referred to as "powerful." Initial stability is also termed "stiffness," and a boat with substantial initial stability is a "stiff boat." A boat with little initial stability is "tender."



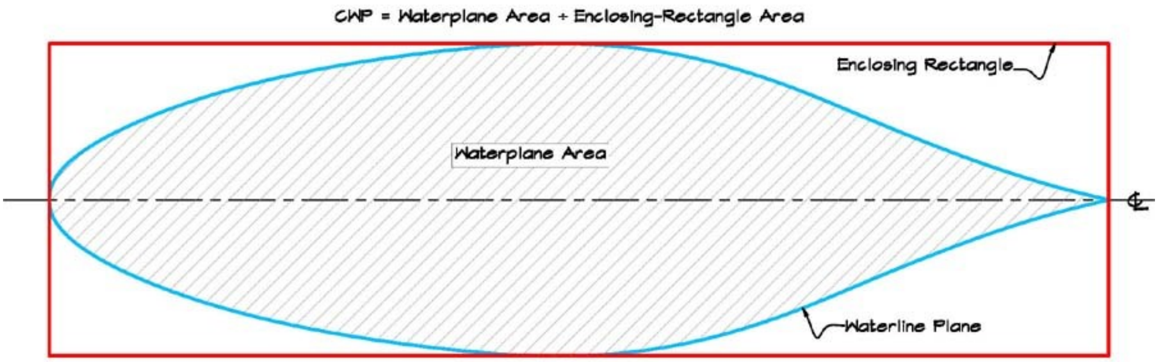
There's a great deal of misinformation about initial stability. You may read that hard bilges increase initial stability, or that other aspects of hull section shape affect initial stability. Such statements are not strictly accurate. In fact, initial stability is generated by the boat's waterplane area, combined with how far above or below the waterplane the boat's center of gravity is. All the other hull-form factors are secondary. (This approach assumes a more-or-less "normal" hull form, with the hull sides rising very roughly vertically from the water. If the hull were truly circular in section above and below the waterline—like a submarine—then these assumptions wouldn't apply.)

The Transverse Waterplane Moment of Inertia

The waterplane creates initial stability—broadly speaking—by it's resistance to being rotated about it's centerline. Designers evaluate this by a quantity called the "moment of inertia of the waterline plane." This sounds intimidating but it's actually fairly simple to estimate.

Looking at the drawing, next page, you'll see a typical waterplane with a rectangle around it that exactly encloses it. The ratio of the area of the waterplane to the full rectangle is known as the coefficient of the waterplane, CWP. It so happens that this coefficient is fairly constant for average sailboats as follows:

Light, Find-Ended Sailboats = 0.65
Average Modern Sailboats = 0.66
Wide-Sterned Downwind Sleds = 0.68
Heavy Full-Ended Sailboats = 0.69



Coefficient of Waterline Plane (CWP)

If in doubt, use a CWP of 0.67 and you'll be close enough.

Transverse moments of inertia can sound high falutin' and complex, but hang in there for a minute and we'll see it's straightforward enough. So, what is it? For engineers, it's the geometric quantity found by taking the square of the sum of the areas on either side of the centerline. This gives that area's resistance to being rotated about the centerline or axis. The ItWP can be estimated fairly accurately, by the following simple formula:

$$\mathrm{ItWP} = \left(\frac{\mathrm{CWP}^2}{11.7}\right) \mathrm{x\ WL,\ ft.\ x\ (BWL,\ ft.)}^3$$

ItWP = transverse moment of inertia of the waterplane, ft.^{4}
WL = waterline length, ft.
CWP = coefficient of waterline plane
BWL = beam waterline, ft.

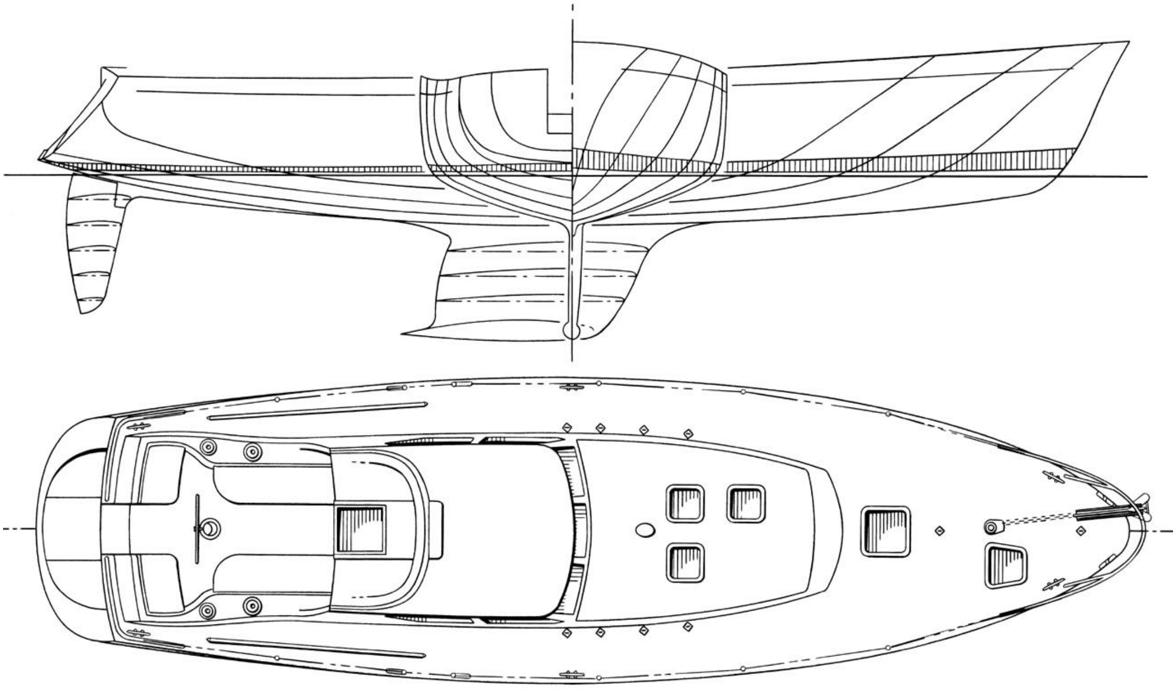
This is easy enough, all you need is the coefficient of the waterline plane, and you can approximate the moment of inertia very closely indeed. As we've seen, CWP is the ratio of the actual area of the waterplane to the area of a rectangle that would just enclose it, a rectangle equal to DWL times BWL, or:

Say we had a 44-foot LOA modern cutter (see sailplan drawing page 1 and lines and deck plan page 3). The waterline is 38.83 ft. and BWL is 11.4 ft. We can figure CWP is 0.66 so. We can move right on to determine ItWP.

$$\mathrm{ItWP} = \left(\frac{0.66^2}{11.7}\right) \mathrm{x\ 38.83\ ft.\ WL\ x\ (11.4\ ft.\ BWL)}^3 = 2{,}142\ \mathrm{ft.}^4$$

Effects of Large Waterplane Moment of Inertia

The important thing to note is that the greater the waterplane's moment of inertia and the lower the boat's center of gravity is located, the greater the initial stability will be; and that the moment of inertia is the biggest influence on initial stability. Also—if you examine the formula—you'll see that initial stability increases as the cube of the beam. That means that even small increases in beam will create a big increase in sail-carrying power. The tendency is thus to make boats as wide as possible to increase initial stability—sail-carrying power.



Of course, if you just made a deep-bodied hull wider (while keeping it's same depth of hull), you'd end up with a far more stable hull, but also with a heavier boat. You'd need a really huge sailplan, and such a heavy hull would have limits to its top speed.

Instead—for performance—the key is to make the hull as wide and shallow as practical. Such a boat has lots of initial stability for it's weight and so can have a lot of sail area for its weight. A wide shallow hull like this, can be quite light (have a low displacement-length ratio) and further will have a flat underbody aft that it can plane on. We're defining here the unlimited offshore racers (like the unlimited 60s) that are so wide they look almost like triangles viewed from above. These hulls have the maximum initial stability for their displacement and their displacement is very low. Similarly, A Scows and modern planing dinghies have wide flat hulls, for "power" and for planing; but also rely on crew weight—shifting ballast—to further increase righting moment. (The unlimited 60s have shifting ballast too—water ballast and/or canting keels. More about this later.)

The ultimate in initial stability is achieved in multihulls. By spreading two or three hulls wide apart, with nothing between them in the water, they generate more initial stability for their weight than any monohull—by far. Properly proportioned, a cat or tri's slender hulls create very low resistance. It adds up to Fast(!) with a capitol F. We'll look at multihull stability in more detail in a future article.

Righting Arm and Righting Moment

Designers need hard numbers to evaluate stability. This is found through the righting arm (known as "GZ") which in turn gives righting moment "RM." When a boat is upright—since the hull is symmetrical about the centerline—the center of buoyancy is also on the centerline, right below the center of gravity. The vertical center of gravity is termed "VCG," or just "G." When the boat heels the resulting asymmetrical bulge in the hull shape shifts the center of buoyancy to the immersed side. The center of gravity doesn't move except to angle over slightly with the boat. The result is that the center of buoyancy (in the heeled condition) is separated from the VCG by a horizontal distance athwartships. This distance is the righting arm GZ. It call the righting arm because the buoyancy is pushing up against whatever force is heeling the boat (presumably the wind on the sails) and it pushing up through the lever arm which is the righting arm. The greater the GZ the greater the stability at a particular angle of heel.

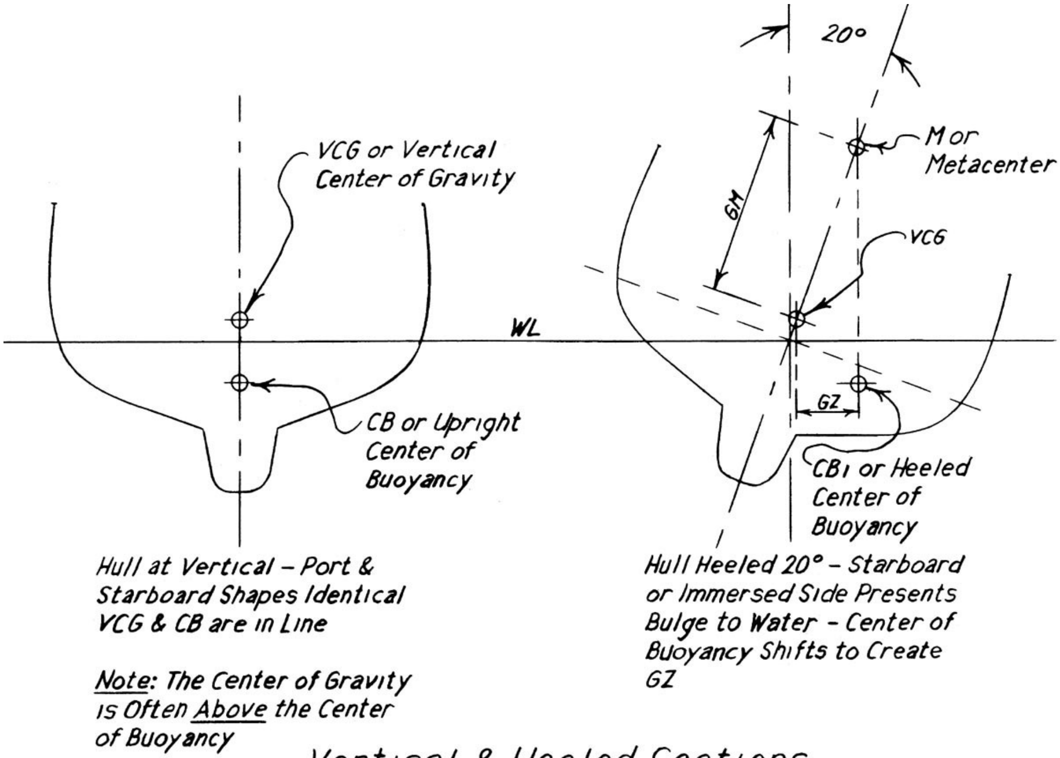
The force pushing up through the heeled center of buoyancy is equal to the displacement of the boat. A moment is just a force times a distance, so the righting moment is the righting arm times the displacement, or:

RM = GZ x Disp.

An 18,000-pound boat with a GZ of 0.95 feet, at 20 degrees of heel has a GZ20° of 0.95 ft., and an RM20° of 17,100 foot pounds [0.95 ft. GZ x 18,000 lb. disp. = 17,100 ft.lb].

Estimating Vertical Center of Gravity

At small angles of heel (up to about 15 degrees), the moment of inertia of the waterplane (which we discussed earlier) allows you to estimate quite well the GZ and RM, without separately calculating the location of the heeled CB. This is done by finding the metacentric height, "GM." GM has a very precisely defined relationship with GZ, so if you know GM you can find GZ or visa versa.



Hull at Vertical – Port & Starboard Shapes Identical VCG & CB are in Line

Note: The Center of Gravity is Often Above the Center of Buoyancy

Hull Heeled 20° – Starboard or Immersed Side Presents Bulge to Water – Center of Buoyancy Shifts to Create GZ

Vertical & Heeled Sections

The "M" in GM stands for the metacenter, which is the imaginary center location on the boat's centerline, which the boat rotates around when heeling. The confusing thing here is that this imaginary center stays almost in the same spot at small angles of heel (under 10 degrees) and then it gradually begins to shift location. Regardless, to determine stability you have to find the metacenter and the vertical center of gravity, VCG.

The sidebar (next page) shows how to find the metacenter relative to the vertical center of buoyancy, "VCB," and how to find the VCB as well. This is straightforward, plug-in-the numbers stuff. Finding the location of the VCG; though, is another story.

There are only two exact methods of locating VCG. One is to carefully measure the weight and location of every single item and component of a boat—structure, fittings, gear, crew, stores, fuel and water, mast and rigging, etc.—and find the moments for each item. Sum the moments and sum the weights and use these results to calculate the location of the vertical center of gravity. This is one of the most tedious jobs a designer has to do; but it's required to have a precise understanding of where the VCG (and LCG) is. The other truly exact method is to conduct an inclining experiment on the boat and work backwards to find the location of VCG.

Both of these methods are beyond the scope of this article and are more than you need to get a good general estimate of a boat's stability. On the other hand, you can't determine stability without some reasonable estimate for the location of VCG.

You can use the following estimate. For most average cruising sailboats the VCG is above the waterline (not below it).

Heavy cruising boats with low ballast ratios (under 30%), high superstructures, and shoal keels, figure VCG about 2.5% of WL length above the WL.

Moderate cruising boats, with average superstructures, ballast ratios between 30% and 38% and average draft, figure VCG about 1.2% of WL length above the WL.

Performance cruiser racers with average or low superstructures, ballast ratios greater than 38 percent, and deepish fin keels, figure VCG about 0.05% of WL length above the WL.

Stripped out racers, with low superstructures, little accommodations, ballast ratios above 40%, and deep fin keels, figure VCG at about 1.2% of WL length *below* the WL.

You can enter this information in the formulas in the sidebar to find the GM and thus GZ and RM for any boat.

Estimating GZ at Various Angles Of Heel

This information allows you to find GM. GZ is estimated as follows for varying angles of heel:

GZ 1° = GM x 0.017 (exact)
GZ 10° = GM x 0.174 (very close)
GZ 20° = 0.96 x GM x 0.342 (reasonably close estimate)
GZ 30° = 0.78 x GM x 0.5 (fair ballpark estimate)

In all cases, GZ will increase steadily—for boats of normal form—from 1 degree through 30 degrees.
The critical angles for design are 30° for rigging calculations and 20° for sail-carrying power.

Evaluating Sail-Carrying Power

The standard way to evaluate how stiff a boat is relative to its rig is to estimate what angle it will heel to, with all working sail up, hard-on the wind, at 13.7 knots apparent wind. This is the Dellenbaugh-angle calculation.

You only need the initial GM to determine this:

Dellenbaugh angle = 57.3 x Sail Area x Heeling Arm GM x Disp.

Where:
Sail Area = the area of the main and 100% foretriangle, sq.ft. (no overlapping headsails or spinnakers included);
Heeling Arm = distance from the center of lateral plane of the hull (CLP) vertically up to the center of effort on the sails (CE); Disp. = displacement, lb.

The center of lateral plane (CLP) is the geometric center of the keel, rudder, and hull underbody. It can be estimated as 40 percent of draft. (It can be found exactly using a cutout and balancing it or in a CAD program.) So, heeling arm is the height from the WL up to the center of pressure on the sails plus 40 percent of draft.

Using the information above, you can estimate the Dellenbaugh angle for any boat you have the waterline length, waterline beam, displacement and sailplan. The Dellenbaugh angle should fall between the upper and lower line on the chart. If it falls above, the boat is tender—almost certainly too tender. If it falls below, the boat is quite stiff. This is good if the boat has a moderate to high sail-area displacement ratio. However, if the boat does not have at least a moderate sail-area displacement ratio, it indicates that the boat is under canvassed.

If our example boat had a sail area of 854 square feet,

Finding Righting Arm “GZ” and Metacentric Height “GM”

GZ is the lever arm that the heeled buoyancy works through to create righting moment. GM is the vertical distance from VCG up to the metacenter (M)—see illustration page 4. M is important because for small angles of heel—and we’re discussing initial stability—it’s easy to find from a formula without knowing much else about a boat.

You do this by finding BM, the distance from the heeled center of buoyancy up to M—another basic calculation:

BM = ItWP ÷ Disp., cu.ft.

We already found ItWP, so—if our 44-foot cutter had a displacement of 19,190 pounds—it’d have a displacement of 299.84 cu.ft. (19,190 lb. 64 lb./cu.ft. saltwater = 299.84 cu.ft.). So:

$2{,}142 \text{ ft.}^4 \div 299.84 \text{ ft.}^3 = 7.14 \text{ ft. BM}$

We just have a couple more steps and we can find the center of buoyancy (CB or B), and then GZ for any small angle of heel.

First we have to locate the vertical center of buoyancy. That’s estimated using the Moorish approximation, as follows:

$$\text{VCB} = \frac{1}{3}\left(\frac{\text{Hull Draft, ft.}}{2} + \frac{\text{Disp., cu.ft.}}{\text{WPA, sq.ft.}}\right)$$

Hull draft (also called “fairbody draft” or “draft canoe-body,” DCB) is the draft to the bottom of the hull proper, excluding the keel, rudder, etc.

Since we took the CWP as 0.66, the area of the waterplane is 38.83 ft. DWL x 11.4 ft. BWL x 0.66 = 292.1 sq.ft.

Hull draft is easy to estimate from most profile drawings that show the underbody (though it’s best to take it of a proper lines drawing or from construction or joiner-section drawings). In our case it’s 2.0 ft. That’s all the information we need to estimate VCB:

$$\frac{1}{3}\left(\frac{2.0 \text{ ft. Hull Draft}}{2} + \frac{299.84 \text{ cu.ft. Disp.}}{292.1 \text{ sq.ft. WPA}}\right) = 0.67 \text{ ft. VCB}$$

To find the GZ or righting arm, we first have to find the GM, or the distance from the VCG (or G) to the metacenter (M). This is the one area where we have to really estimate.

Referring to the estimated locations of VCG, In our case we’ll use , say, 1.7% of DWL and that puts VCG at 0.66 ft. above the DWL.

Looking at the drawing (page 7) you can see that GM equals BM minus VCG plus VCB, or:

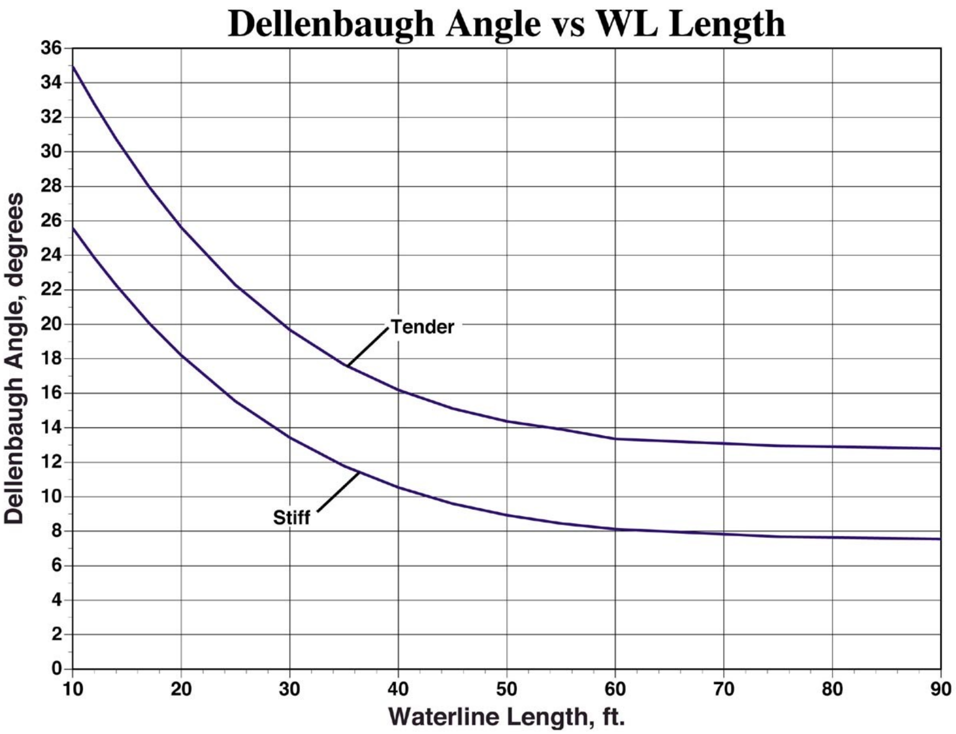
GM = BM - (VCG + VCB)

For our 44-foot cutter:

7.14 ft. BM - (0.66 ft. VCG + 0.67 ft. VCB) = 5.81 ft. GM and a heeling arm of 27.3 feet its Dellenbaugh angle would be:

Dellenbaugh angle = 57.3 x 854 sq.ft. x 27.3 ft. 5.81 ft. GM x 19,190 lb.
Dellenbaugh angle = 11.98°, say 12°

For a boat of 38.8 feet WL, this plots between the acceptable curves, and is toward the lower curve, indicating a stiff boat with a properly proportioned rig.



Shifting Ballast

So far, we've only looked at the initial stability generated by the hull. For performance (power) you can never have too much stability and another way to get more stability is by using shifting ballast. If you take a weight from the centerline and place it outboard on the weather rail, it will add a righting moment (it's distance from the centerline times its weight) to the boat's form righting moment. More righting moment is more power. Whether on a dinghy or a maxi, people often make the most convenient shifting ballast. Indeed, boats from A Scows, to International Canoes, to the Laser generate huge amounts of sail-carrying power from their human shifting ballast. Even a maxi gets a noticeable boost with 10 or 12 bruises perched on the rail.

For crew on the rail, you can estimate the total righting moment by calculating the righting moment of the hull as above, and then sketching the midships section to scale. Sketch the crew to scale perched on the rail or hiking out (as appropriate). Measure the horizontal distance to the heeled center of buoyancy at the heel angle and multiply the distance by the weight of the crew on the rail to get the added righting moment. Then add the hull righting moment to the crew righting moment.

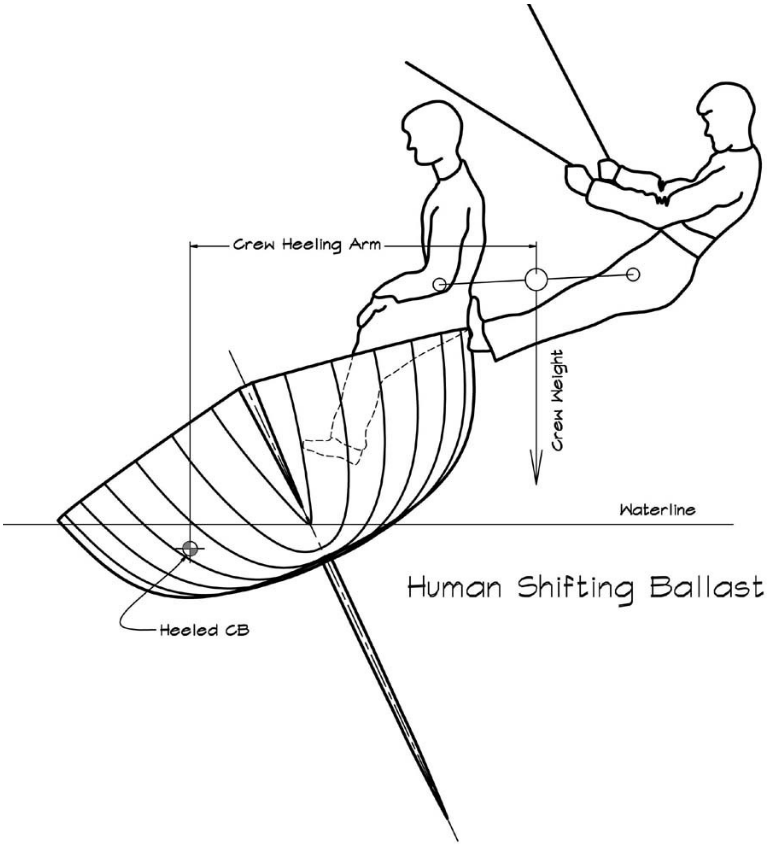
Modern unlimited offshore racers use water ballast for the same reason. Pumping up a tank on the windward side with a ton or so of water will give just the same sort of boost to stability that 12 or 13 big fellows on the rail will. The water won't complain or require meals, and you can dump it overboard when it's no longer useful. This essentially gives you a boat of variable displacement. Heavier displacement with a higher righting moment for heavy-air upwind work; lighter displacement with a smaller righting moment for downwind work.

All shifting ballast works best at low angles of heel, generating additional righting moment up to about 45 degrees, with the maximum increase at angles up to about 25 degrees. After 45 degrees, much of the gain from shifting the ballast to the side is lost to the higher center of gravity, and as the boat approaches 90 degrees, the shifting ballast will actually reduce stability, unless it's shifted in toward the center and down again.

The general rule about shifting water ballast for offshore work is that you shouldn't build in tanks that would heel the boat more than 10 degrees in zero wind with no sail up. This has to do with reserve stability—safety. Almost every shifting-water-ballast boat gets caught with the water tanks filled on the wrong (lee) side occasionally. With the tanks limited to creating 10 degrees of added heel, then the boat will only heel an additional 10 degrees with the water ballast, and isn't going to be in substantially greater danger of capsizing when caught on the wrong side.

Canting keels are the other common method of shifting ballast. Canting keels, which were originally suggested by L. Francis Herreshoff, had their first real implementation on the 1980, 55-foot *Red Herring*, designed by Dave Hubbard. The canting keel swings to the windward side to move the center of ballast further upwind, generating more righting moment like any shifting ballast. The drawback to canting keels is that when the keel is swung over to windward it is at just the wrong angle to generate lift to counteract leeway. Canting-keel boats require additional lateral plane in fore-n-aft centerboards, or in daggerboards.

There's another drawback—canting keels are very complex to engineer and to maintain in good working order. They also require additional careful attention and operation by the crew.



Human Shifting Ballast

Thoughts on Initial Stability and Performance

It's clear that wide shallow hulls have greater sail-carrying power for their weight, so why don't all boat's have wide shallow hulls? The answer is that initial stability—critical as it is—isn't the whole picture by a long shot. Reducing resistance, increasing waterline length, improving comfort, and maximizing reserve stability are all vital as well.

We've seen that stability increases as the cube of the beam, but it also increases directly with length. A boat that is otherwise the same as another, but has been stretched to be 1.2 times longer will have 1.2 times the stability. It also has something else—a longer waterline. The longer the waterline, the higher the hull's speed potential. Given the same parent hull, you could, say, increase speed by making the hull wider and shallower. This would increase sail-carrying power so you could install a bigger rig and go faster. But, you reach a limit at hull speed (roughly 1.4 x the square root of the waterline length in feet, in knots). After that, the boat has to be light enough and flat enough aft to start some planing. Alternately, you could make the boat 20 or 30 percent longer. This would increase stability by 20 or 30 percent, which would allow a larger rig. The longer waterline would give higher top speeds before planing, and higher average speeds in general. Such a longer and proportionately narrower hull could still plane in the right conditions, given the proper run (underbody aft).

Wide shallow hulls tend to pound upwind (and sometimes downwind). They can be difficult to steer because—when they heel—they are far more asymmetrical than a similar narrow hull. They can also lift their rudder out of the water when heeled reducing steering control upwind (or in a spinnaker broach downwind). This is the reason twin rudders are so prevalent on the unlimited 60s; the lee rudder is always fully immersed for improved control on a wide hull.

The ultimate drawback to wide, shallow hulls is their reserve stability is usually very poor, which we'll look at this closely in the next article. Generally, moderately slender hulls—longer for the same displacement—with a carefully thought out waterplane moment of inertia, and a low enough VCG, will be better all-around performers than wide shallow hulls. The moderately slender hull will also be easier to mange and more comfortable in a seaway. I like narrowish hulls and have designed a number. I've even designed an extreme unlimited-60 that had just nine and a half feet beam (photo below). Its DL ratio is a true 40 as built. There is nothing to hold a hull like this back. The problem for ordinary sailboats is that to get the VCG low enough for adequate stability, we had to put a 5,000-pound torpedo of lead at the bottom of a 14-foot-deep composite fin. Not exactly suited to normal cruising use!

Multihulls achieve the best results in terms of initial stability or sail-carrying power and performance relative to weight. They can have the very low resistance of slender hulls combined with very high initial stability.

In part two, we'll take the other tack and examine the absolutely essential considerations of reserve stability.