Donald J Dodds 4,415

ANCHOR LOAD REVEALED PART 3

by Don Dodds

INTRODUCTION

Hundreds of thousands of boaters have purchased equipment and anchored successfully, most of the time, knowing only what is contained in the ABYC table. It is also true, that when the wind kicks up, the more prudent of these boaters stand anchor watches (formal or informal), the rest conclude that dragging is just "bad luck," and buy a bigger anchor. It turns out that a big anchor can cover many sins and eventually they get an anchor big enough that it works most of the time.

However, <u>most</u> of the time is not <u>all</u> of the time, which drives the more inquisitive to seek a better way to estimate loads on their anchor. Unfortunately, this path is strewn with confusion and often leads to frustration. The confusion is generated because the theory of anchoring is complex and is probably the least understood of the boating skills. Lack of understanding is always a fertile breeding ground for large numbers of misguided experts. Your choices are blind trust, guessing, or wading through the morass of claims and counter claims searching for truth yourself.

The purpose of this article, one of a series of three, is to help you wade, by giving you methods for estimating static and dynamic anchoring loads. Later articles will present a practical approach to selecting system components and better ways to use your anchor. Along the way, you will tip over many of the cherished idols of anchoring, both theory and practice. The result will be spending less money, anchoring with less effort, and sleeping sounder while swinging on the hook.

It can be shown that the ABYC tables are overly conservative with respect to static loads and under conservative with respect to dynamic loads. As a result, most people are using too large an anchor 99 times out of a 100 when static conditions control. Then the one time when dynamics loads control the situation, the large anchor they have been using turns out to be too small and the disaster they have been trying to prevent strikes anyhow.

The probability of a recreational boat facing extreme dynamic anchoring conditions is rare. Thus, the errors in traditional design have only caused a few disasters. However, if you feel there is some advantage to working smarter, rather than harder and wish to avoid as much bad luck and as many anchor watches as possible, understanding anchor loads and how anchors work can help.

THE PROBLEM

I began to suspect that anchor load calculations when I read that Robert Bavier commonly anchored his 37 foot Apache using a 12 pound Danforth.[1] Following his lead, I routinely anchored my 44-foot cutter successfully on anchors considered by the conventional thinkers as too small, (a 20 pound Danforth or a 35 pound CQR). I got the first hard evidence, when anchoring for two weeks in 25 knot trades. Diving on my anchors to clean the scum from the rode, I found the 35-pound CQR still lying on its side. It was obvious that the load on this anchor had been nowhere near the 1200 pounds designated by the ABYC table.

---

[1] Bavier, Robert, Yachting Magazine, September 1969.

Numerous other events cast doubt on the accuracy of traditional wisdom. For instance, the 127-foot powerboat shown in Figure 1 obviously has considerable windage. The anchor shown (a 32 pound aluminum anchor) on the bow attracted my attention as being atypical for boats this size. The skipper related to me that this anchor held the boat off the beach in a 35-knot blow using a 1/2-inch nylon line with 35 feet of chain on a 5:1 scope. While it was true that the skipper did not use this anchor by choice, (a combination of engine and rode failure forced his decision), he is now a firm believer in its holding power. I, on the other hand, saw it as a testimonial against traditional notions of anchor load. Another professional captain related hauling in his anchor line to find no anchor attached. His large freighter had been lying at anchor sucessfully for several days to nothing but the chain.

Figure 1. 32 pound anchor - 127-foot boat.

[2] Even a brief look at tradition begins to expose confusion.[3] Most individuals get their anchor load information from marine supply houses that use the ABYC

---

[2]

table. Two of the largest, Boating US and West Marine, are typical and do not show a good understanding of the data in these tables. Boating US indicates that these loads are the minimum numbers, with minimum in bold type. West Marine, on the other hand, states, "the ABYC numbers are actual pounds of load and have no safety factor built in. Therefore anchor systems must be based on a value greater than given in the table."

Neither interpretation is true, according to ABYC's Tom Hale, who said in *Practical Sailor*, "The ABYC numbers are overstated and contain a considerable safety factor."[4] The question is how overstated? Both Robert Smith and I have independently measured actual anchor loads on small recreational boats. Table 1 shows a comparison between the loads recommended by ABYC for a 15-knot wind, compared to our measurements.

Table 1. Loads on anchors in a 15-knot wind

Boat	ABYC	Measured	Difference
[5]Cascade 27	125 lbs.	40 lbs.	312%
Catalina 30	175 lbs.	58 lbs.	300%
[6]Grand Banks 36	225 lbs.	84 lbs.	267%
CT44	300 lbs.	70 lbs.	428%
Hunter 43	300 lbs.	68 lbs.	441%
Ave			350%

The traditional overestimate of anchor loads by a factor of 3.5 makes the fate of the vessel in Figure 1 and the other anchor load stories more understandable.

---

[3] _____________, The Load on Your Rode, Practical Sailor, Volume 22 No. 13, July 1, 1996.

[4] _____________, The Load on Your Rode, Practical Sailor, Volume 22 No. 13, July 1, 1996.

[5] Smith Robert, Anchoring -- Selection and Use, 3rd Ed. Portland, Or., Premier Press Inc. 1996

[6] Smith Robert, Anchoring -- Selection and Use,3rd Ed. Portland, Or., Premier Press Inc. 1996

ANCHOR LOADS

There are two basic types of loads on any anchor system, static and dynamic. Static loads come from the relatively steady push generated by constant wind or current forces and dynamic loads are generated when wave action or wind gusts cause the boat to move. Most anchoring is done under primarily static conditions. The dynamic loads on winds under 20 knots, especially in a protected anchorage, are small when compared to the inaccuracy inherent in the calculations.

Static Loads

Static loads are generated by wind and current acting on the exposed areas of the boat. These loads are a function of the hull size and shape and the density and velocity of the fluid (air or water) acting on the hull.

The equation for calculating the magnitude of both wind and current static loads comes from classical fluid dynamics and has the general form shown in equation 1[7].

$$F = C\left(\frac{\rho V^2}{2}\right)A \qquad \textbf{Eq 1}$$

Where F is the desired force,

C is a drag coefficient that varies with the situation,
ρ is the density of the fluid (air or water),
V is the velocity of the fluid,
A is the area exposed to the force of the fluid.

The density and velocity are easily obtained, which leaves us with the drag coefficient "C" and the exposed area "A." These two innocuous coefficients depend on the shape of the object and the amount of turbulence in the fluid.[8]

---

[7] Vennard, John K, Elementary Fluid Mechanics, Wiley & Sons, 1954, page 340.

Current Loads

Current forces are relatively well behaved because current velocity is generally low enough to produce laminar flow around the boat. Most of the time anchoring is done in currents less than 2 knots. The notable exception to this practice is anchor in river currents particularly by fisherman.

The water drag coefficient's (C_W) value is dependent on the boat's bottom condition but can generally be consider to be about 0.087. Making the appropriate substitutions and dimensional conversions, this equation becomes;

$$F_c = 0.05\ A_c V_c^2 \qquad \text{(Drag in Water)} \qquad \textbf{Eq 2}$$

Where F_c is the force of the current on the hull in lbs.

A_c is the area of the wetted surface in square feet.

and V_c is the current velocity knots.

This leaves us with only the wetted area (A_c) to calculate. Getting an exact value for the wetted area is rather laborious. Getting an area that is related to common boat parameters requires erring on the side of safety. One estimate of the wetted area would be the surface area of a prism having the dimension of the beam (B), waterline length (l_{lwl}) and draft (D).

$$A_c = 2l_{lwl}\,(D^2 + B^2/4)^{1/2} \qquad \textbf{Eq 3}$$

This is not so easily calculated but can be done with the aid of any scientific calculator. Once the wetted area is calculated it is a simple matter to get the water load from Equation 2. This equation produces values that are about 10% below those measured by Robert Smith. To cover these and other errors a common

---

[8] Marchaj, C.A. Aero-Hydrodynamics of Sailing. New York: Dodd, Mead & Co, 1979. Page 262.

procedure is to add a safety factor. This can be done by increasing the C_W coefficient to 0.07 resulting in the final equation 4 for calculating current loads.

$$F_c = 0.07\ A_c V_c^2 \qquad \text{(Drag in Water)} \qquad \textbf{Eq 4}$$

Wind loads

In order to calculate wind loads it is first necessary to deal with the drag coefficient for air (C_a). C_a is considerably more difficult to assess because the parts of the boat exposed to wind are generally more complex than boat bottoms and wind velocity, ergo turbulence, increases significantly. Wind boils rather than flows by the boat. The velocity changes as much as 40 percent and the direction as much as 20 degrees within a matter of minutes. So, in nature there is no such thing as a constant 30-knot wind. These are just a couple of the reasons why values given in the literature vary from 0.06 to 1.9.

Here physics plays a dirty trick, for the more accurately we determine C_a the more boat specific and more complex the math. Thus if one chooses to use simple equations and apply them to a wide variety of boats, like most anchoring experts, large safety factors must be introduced. For example, Bamford,[9] William Van Dorn[10] and Jack West[11] all admit to incorporating large but undefined safety factors. Unfortunately, all report slightly different numbers from which we must select only one. Fortunately, the safety factors are so large; it makes little difference, which is selected. I recommend using Van Dorn equations where C_a is 1.1796 producing a simple coefficient;

$$F_a = 0.004\ A_a V_a^2 \qquad \text{(Drag in Air)} \qquad \textbf{Eq 5}$$

---

[9] Bamford, Don, Anchoring All Techniques for all Bottoms, Seven Seas Pres, 1985, page 52

[10] Van Dorn, William G., Oceanography and Seamanship, Dodd, Mead & Co, 1974, page 291.

[11] West, Jack, Ground Tackle and Anchoring Techniques, Yachting, November, 1975, page 50.

Now we must deal with the area (A_a), which is based on the actual combined area of the hull, rigging, and appurtenances exposed to the force of the wind, modified by hydrodynamic effects, which can either <u>increase or decrease</u> the effective area. Does the term, "involved calculation," come to mind? To further complicate these calculations, most boats, lying to a single anchor, move back and forth exposing a varying amount of beam to the wind. So, even if we took the trouble of calculating the exact A_w, it would vary continually from 0.5 to 2 times the calculated value depending on the boats current position with respect to wind direction. Do I hear some muffled screams?

Once again, most anchor experts, including myself, traditionally throw up their hands and again employ simplifications with even larger safety factors. The simplification is generally to calculate the area by using some common boat parameters like the beam (B) times the cabin height (H).

$F_c = 0.01\ BHV_c^2$ (Sailboat Drag in air) **Eq 6**

or

$F_c = 0.006\ BHV_c^2$ (Powerboat Drag in air) **Eq 7**

Presently this is about the best that can be done. However, before we leave this section let us examine briefly the size of the safety factors in these numbers by generalizing equation 6 and 7 into;

$F = C_f\ V^2$ **Eq 8**

Where C_f is a single factor depending on the boat. By measuring the forces on the boat for any given wind velocity C_f can be calculated and used to predict the force for other values of wind velocity. Fortunately, a few measurements of this type exist. Robert Smith has done it for a 27 foot Cascade sloop and a Grand Banks 36.

I have also done it for my 44-foot cutter, a Catalina 30, and a Hunter 34 & 43. Although data from seven boats is not statistically meaningful, it does produce some interesting results.

Table 2 C_f Factors.

Boat	C_f	Safety Factor
Cascade 27	0.178	2.23
Catalina 30	0.258	2.10
Grand Banks 36	0.375	2.55
Hunter 34	0.319	2.30
C&C 36	0.302	2.32
Hunter 43	0.387	2.89
CT 44	0.315	2.06

The safety factor are all greater than 2. This is an improvement over the 3.5 safety factor built into the AYBC table, but still leaves us using an anchor that <u>may</u> be more than twice as large as needed. Note the underscore on may, all that can be said from this limited amount of data is that something is wrong with the present methods of predicting anchor loads. Until more data and/or a better method comes along it is prudent to stick to the equations given above.

Dynamic loads

Dynamic loads on anchors are a more complex issue than static loads. Happily, dynamic loads are relatively unimportant in protected anchorages until the wind velocity rises above 25 knots or waves approach 3 feet in height. Traditionally, dynamic conditions are handled by doubling the static loads. Whereas this is the traditional solution, it is not always a safe solution especially for those using chain rode. A better solution is to have a basic understanding on how dynamic loads effect your system, and how to best reduce these loads.

The dynamic loads are caused by the anchor resisting boat movement and are a function of boat weight, rate of change in boat movement (deceleration) and mooring line elasticity. Changes in boat movement come from two sources; wind gusts and wave action. The loads generated by wind gusts are an order of magnitude less than those caused by wave action. Therefore, if we design the system to adequately handle wave action, dynamic wind loads will be lost in the noise. This leaves us wave theory and rode elasticity to explore.

The motion of an individual water molecule in a fully developed wave system has a sinusoidal shape as shown in Figure 2. If we could follow a particle of water with our eye as the wave swept by, it would trace a circular path with no windward translation relative to the surrounding water.

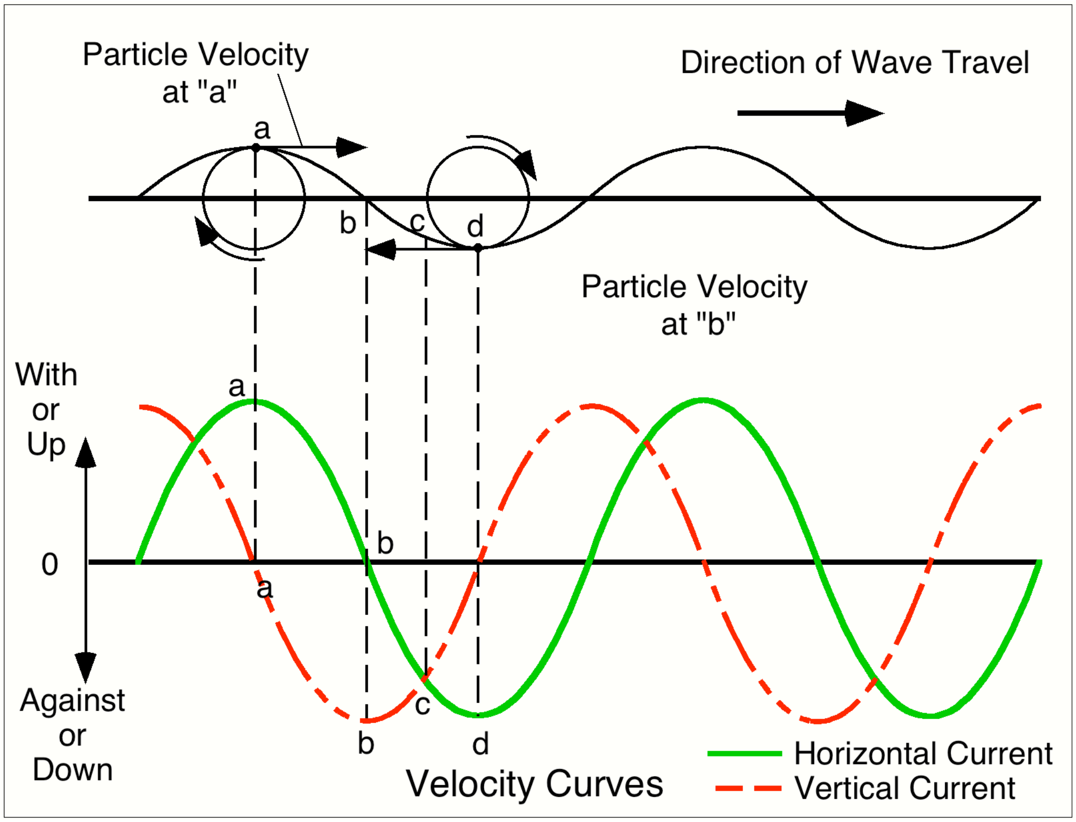

Figure 2 Particle motion in a Sinusoidal Wave.

The velocity of the water particle along this circular path is called the orbital velocity and is related to the wave height and period. Studying Figure 2 note that the solid green curve is the horizontal velocity component and the dotted red curve is the vertical velocity component of the orbital velocity. At point "a," the wave top, vertical motion is zero and horizontal motion is maximum in the direction with the wind. While at point "b" the motion in the horizontal direction has slowed to zero and the vertical motion downward is maximum. At point "c", both velocity components are equal in magnitude but the horizontal motion is increasing in negative magnitude (Against the wind) while the vertical motion is decreasing in the downward direction. At point, "d" the particle has stopped moving down and is moving at its maximum rate against the wind.

In other words, if the boat floats free on the surface, with no other forces acting on it, it will move first one way then the other and no force is felt by the boat; it is just carried along with the water motion. It is only when this motion is resisted by mooring or anchor lines that force comes into play. The amount of force is directly dependent on two factors: the water velocity and the amount of resistance. The maximum amount of force is generated when the boat is not allowed to move at all. We can get a handle on this maximum force by using Newtonian physics, the equations for orbital velocity, and parameters of fully developed wave systems.

The result of all that math produces a maximum acceleration due to wave action of about 0.1g. This means that the maximum dynamic force is about 0.1 the boat's weight (displacement). Obviously, the maximum dynamic force does not act very often or more anchor systems would fail. Something else must be affecting anchor performance, that something else is the elasticity or stretch of the anchor rodes.

As stated earlier, if the boat is free to move with the water, then the relative velocity between the boat and the water is zero and no force is felt by the mooring lines. From Figure 2 we saw how the horizontal velocity starts at zero increase to a maximum at 1/4 wave length, decreases to zero at 1/2 the wave length, then repeats the process flowing in the other direction. Thus, if the boat is free to move only half a wavelength no net movement will occur and no force will develop. So now we have two bounding conditions; F=0.1 Weight at zero movement, and F= 0 at movement = L/2. What we don't know is how the load varies between these two points.

Figure 3 shows three possible paths. It is possible but highly improbable that it takes path one. Most probably, the path is a regular path somewhere in the shaded area between path two and three. Thus path 2, the straight line is both, a limiting and a simple, analytical condition; two desirable traits. Regardless of the path we choose to accept as the real path, the path does not tell us what the dynamic load is only that load lies somewhere along that line.

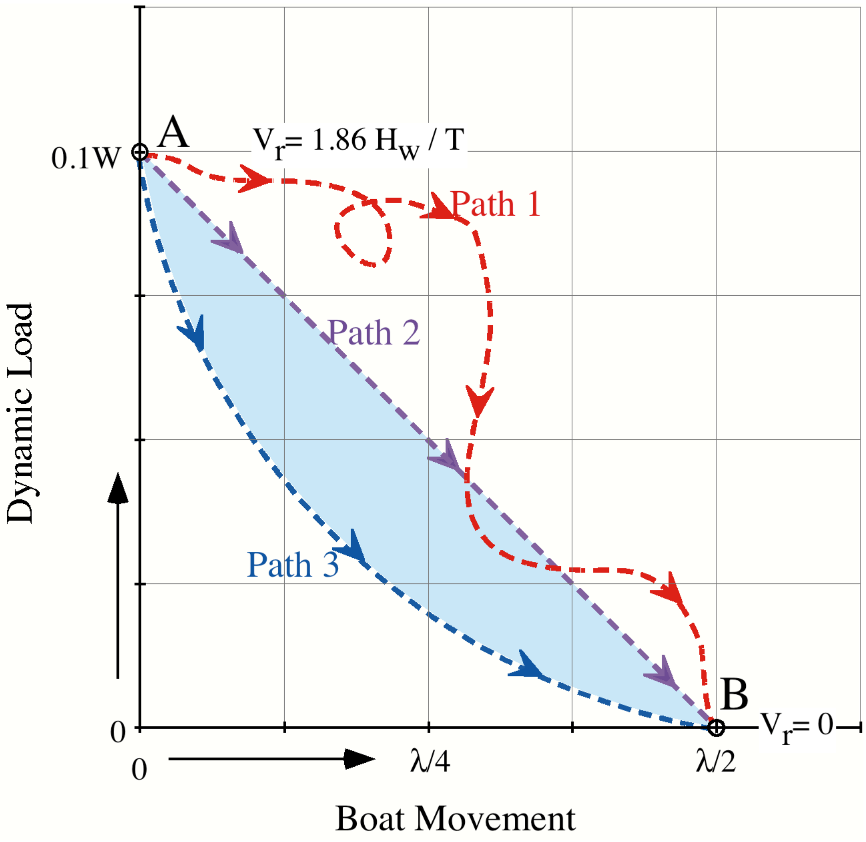

Figure 3 Relationship Between Force and Displacement

To find the load we need to turn to the elasticity of the mooring line, which is dependent on the load and the rode material. Anchor rodes are normally made from either nylon or chain. Let us first look at nylon. The data on twisted nylon, below 50 % load, given in table 3 is from New England Ropes. Above 50% load the data is extrapolated and is not as accurate.

Keep in mind that this data is for a new line. Use tends to reduce the line's strength and ability to stretch; further, as the line approaches failure the relationship between stretch and load becomes more erratic, so it is not prudent to use this data much above 80% of new strength.

Table 3 Twisted Nylon Line Elongation characteristics

Percent Load	Percent Elongation
5	10
10	13.9
15	16.3
20	17.9
30	19.9
40	20.9
50	21.8
70	23.7
80	25.7
90	29.7
95	33.6

Plotting this data on the same axis as Figure 3 we get the situation shown in Figure 4.

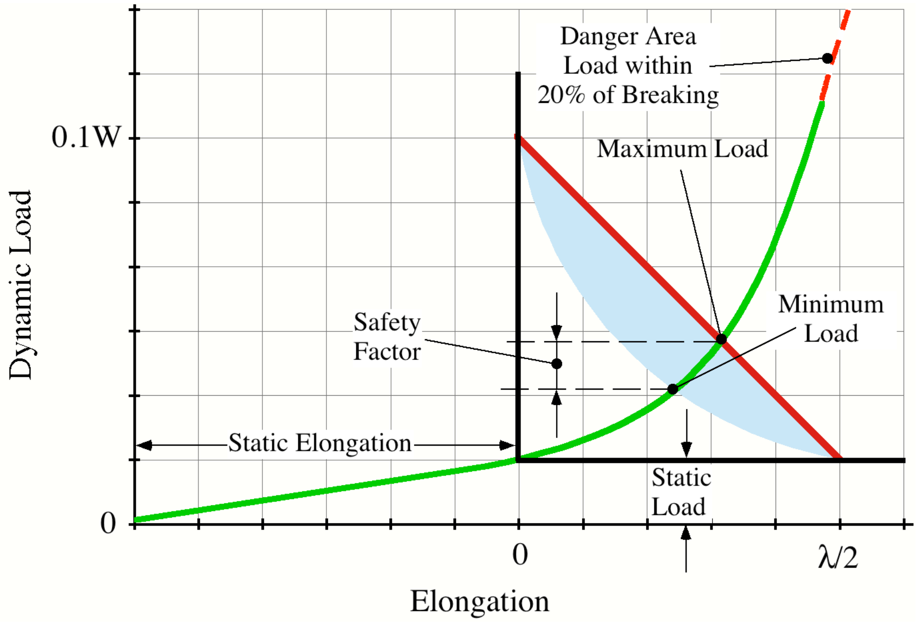

Figure 4 Composite Plot

The axis of the curve in figure 3 is displaced along the elongation curve such that the elongation due to the static load and the static load are the origin for the dynamic load curve. The elongation curve intersects both path 2 and 3. These intersection points give us essentially the maximum and minimum dynamic loads for these conditions. The difference between these values gives us an idea of the safety factor inherent with this analysis. Depending on how and where the elastic line crosses the two paths, the increase in safety factor varies from about 0.5 to 1. Using the conservative approach with some specific examples allows us significant insight into the dynamic load process.

Figure 5 is a plot for a vessel displacing 35,000 pounds in a 30-knot wind using 300 feet of Nylon rode. The green curve is a control curve, which is a ½-inch diameter twisted rode, the blue curve is a 3/4 inch diameter twisted rode and the magenta curve is a 1/2 inch diameter braid rode.

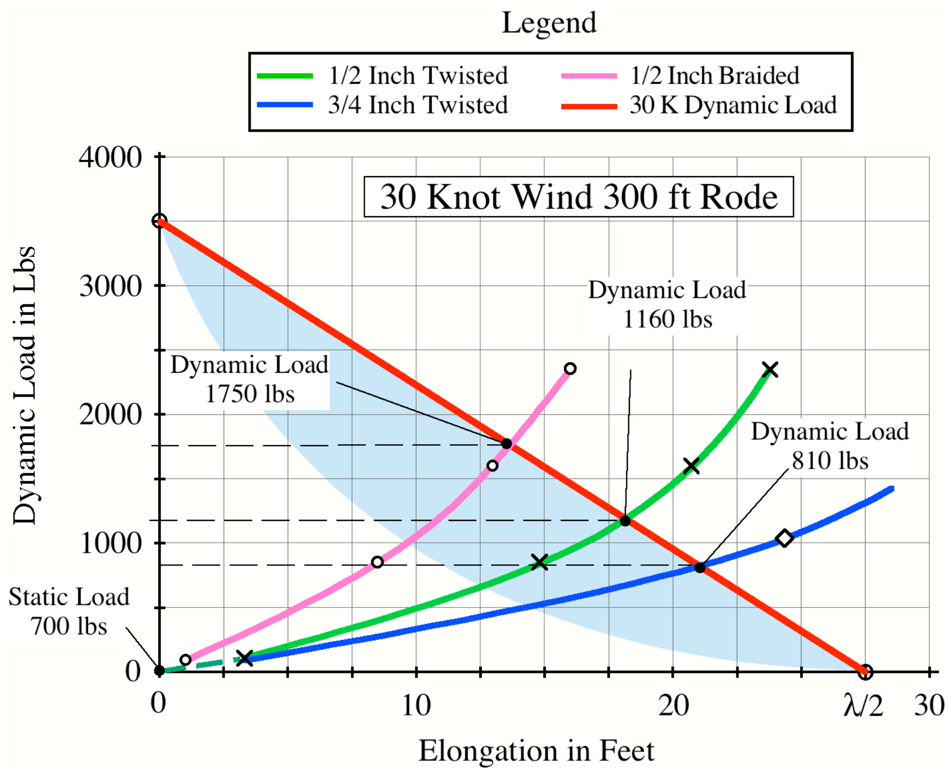

Figure 5 Dynamic Load Change with Diameter and Line Construction

Notice here that the dynamic load under these conditions on the 1/2 twisted line is about 1160 lbs, the static load is 700 lbs therefore the total load is around 1800 pounds. This is an increase of the static load of about 2.6, which is considerably more than the 2.0 rule of thumb for dynamic loads. If we use the less elastic, braided line, the dynamic load increases to 1750 lbs, a real incentive to avoid braided anchor lines. Somewhat of a surprise is the drop in dynamic load to 810 lbs when the apparently stiffer 3/4 line is used. This is only true for low initial static loading, below 5% breaking strength, as the initial load rises to the 60-knot wind conditions shown in Figure 6 the situation changes and the 3/4 rode is stiffer, increasing the dynamic loads.

Note in Figure 6 that the blue curve, which is the elasticity curve for 1/2 inch twisted nylon taken from the Figure 5, has essentially moved down and to the left to become the green curve. This translation effectively increases the slope of the curve and causes the intersection to occur between the 70 and 80 % breaking strength values. Loading used nylon line to this extent greatly increases the chance of failure. The magenta line is the 3/4-diameter line, which now loaded on the steeper portion of the elasticity curve shows to be stiffer. This stiffness increases the dynamic load from about 15% from 2800 to 3250 pounds. However, the 3/4-inch rode is loaded less than 40 % of its breaking strength. Thus reducing its probability of failure, but the increased loads also increases the possibility of other anchor system components failing. Finally, note here that the dynamic load on the 1/2-inch line is almost exactly 2 times the static load for a total load of 5600 lbs. Thus, the rule of thumb (double of static loads to account for dynamic loads) works for 1/2 but not for 3/4-inch rode.

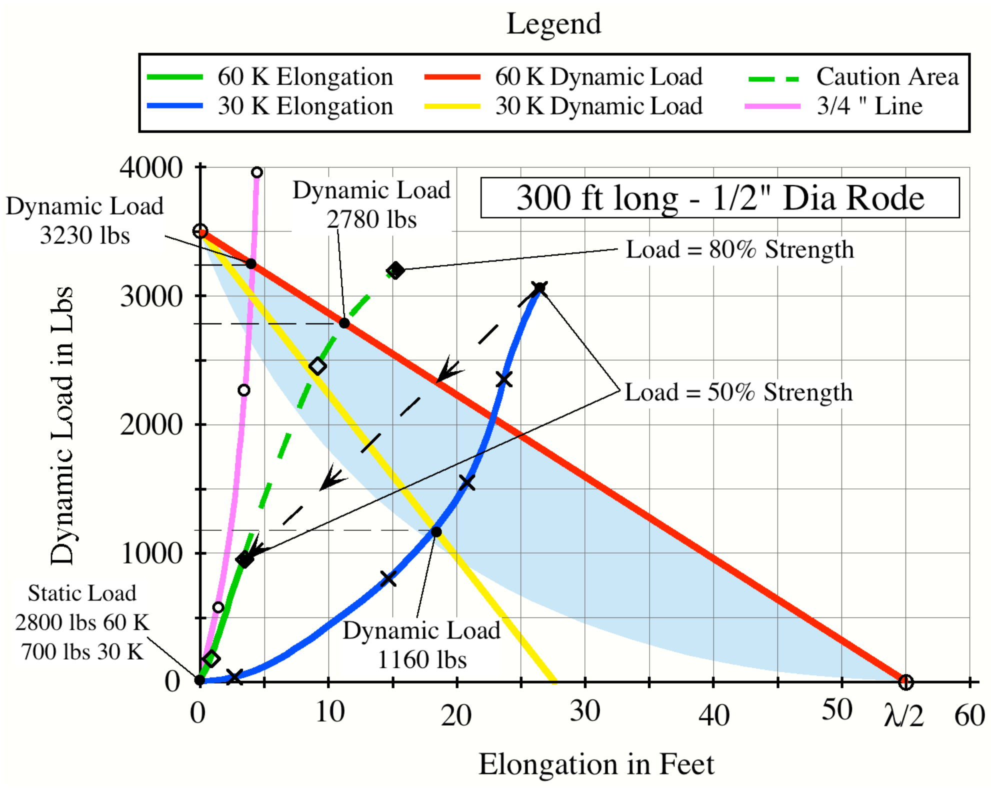

Figure 6 Dynamic Load Change with Wind Velocity.

Since nylon elongation depends on the amount of line available to stretch, before we leave nylon, let us look at what happens if we increase the rode length.

Under the conditions in Figure 7, we can reduce the dynamic load from 2050 to 780 pounds by lengthening the rode 450 feet. This points to the significant value of a long rode in dynamic conditions for nylon. Unfortunately, this is not the case for chain.

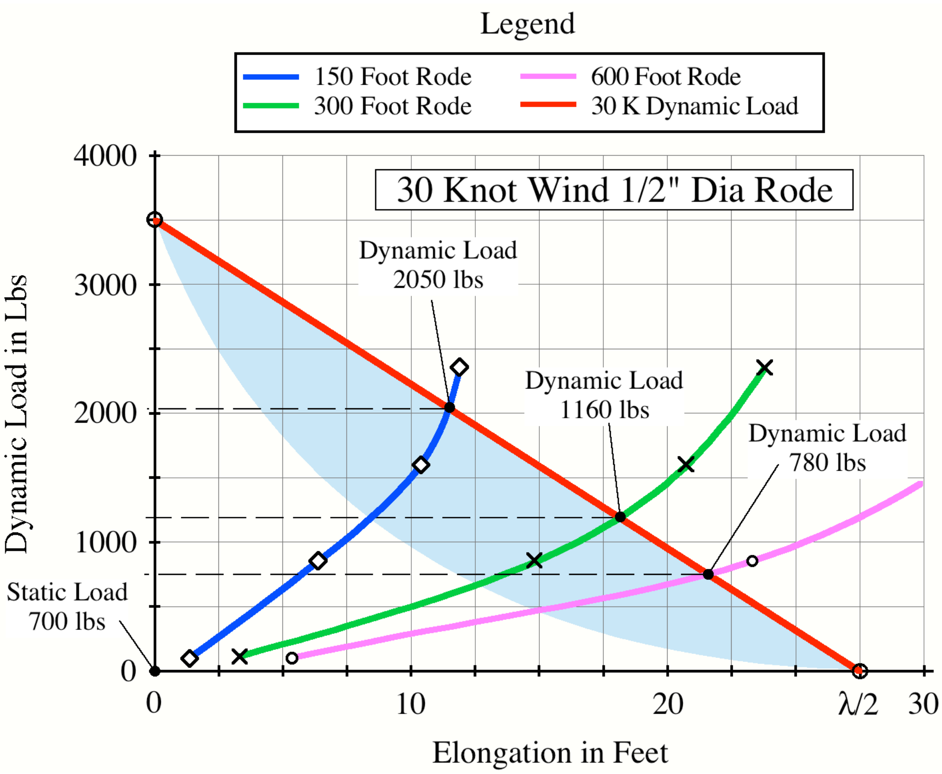

Figure 7 Dynamic Load Change with Nylon Rode Length.

A chain rode must rely on slack in the catenary curve to provide the necessary elasticity and the amount of available slack has been shown by Van Dorn to be more dependent on water depth rather than rode length.[12] This concept is illustrated in Figure 8. Under no load, the two boats, depending on their scopes, lie with chain hanging vertically down at point B and C. All that is accomplished using the large scope is to move the boat farther from the anchor. Under load, the boat's maximum movement is from point B to points B' and C to C' allowing 26 and 28.5 feet of dynamic movement respectively. The additional 2.5 feet (compared with over 50 feet using 1/2 inch nylon) of movement allowed in the chain rode does not materially reduce the dynamic load on the system.

---

[12] Van Dorn, William G., Oceanography and Seamanship, Dodd, Mead & Co, 1974, page 411.

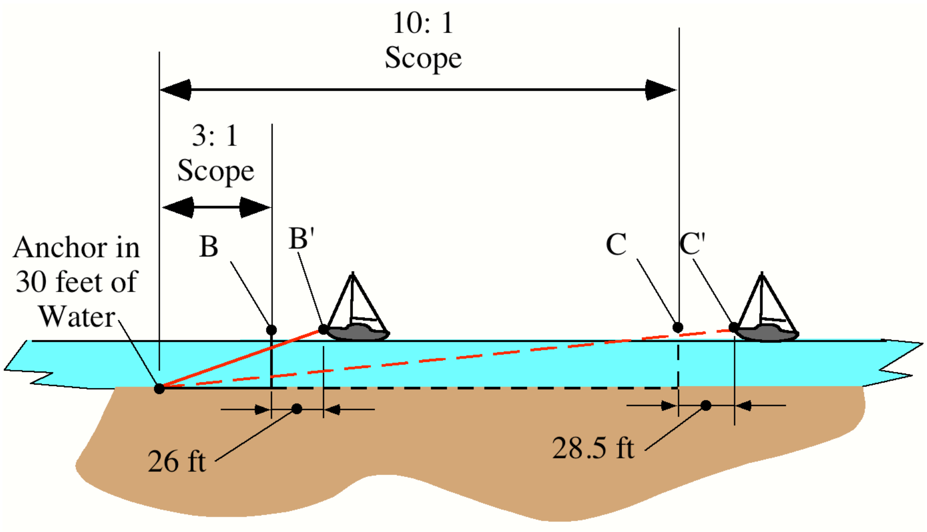

Figure 8 Movement of Boat Using All Chain Rode

Using the example boat data and the chain elasticity data in Table 4 taken from catenary calculations made by Van Dorn, we can make several performance comparisons of the effects of chain rode.

Table 4 Elongation Characteristics for Chain

Load as Percent of Breaking Strength	Elongation as Percent of Depth
15	63
50	76
80	81
100	88

Figure 9 compares nylon rode and chain rode in a 30-knot wind. Note that under these conditions the chain (blue line) more than doubles the nylon rode's (green line) dynamic load. This is a good example of what happens in shallow water with all chain rode and explains the numerous anchor failures which occurred under these circumstances in Cabo San Lucas in December 1982.[13]

---

[13] Larry Pardey, Ultimate Gear Test, Sail Magazine, June 1983, page 62

The high dynamic loads can be mitigated by moving the boat to deeper water as shown by the pink curve in Figure 9. If the boat were anchored in about 150 feet of water the elasticity available would be similar to the nylon rode and likewise so would the dynamic load. Very few recreational boaters carry the 750 feet of chain needed to anchor safely at that depth. Given poor dynamic conditions and limited rode it would be better to anchor in as great a depth as possible as illustrated in Figure 10.

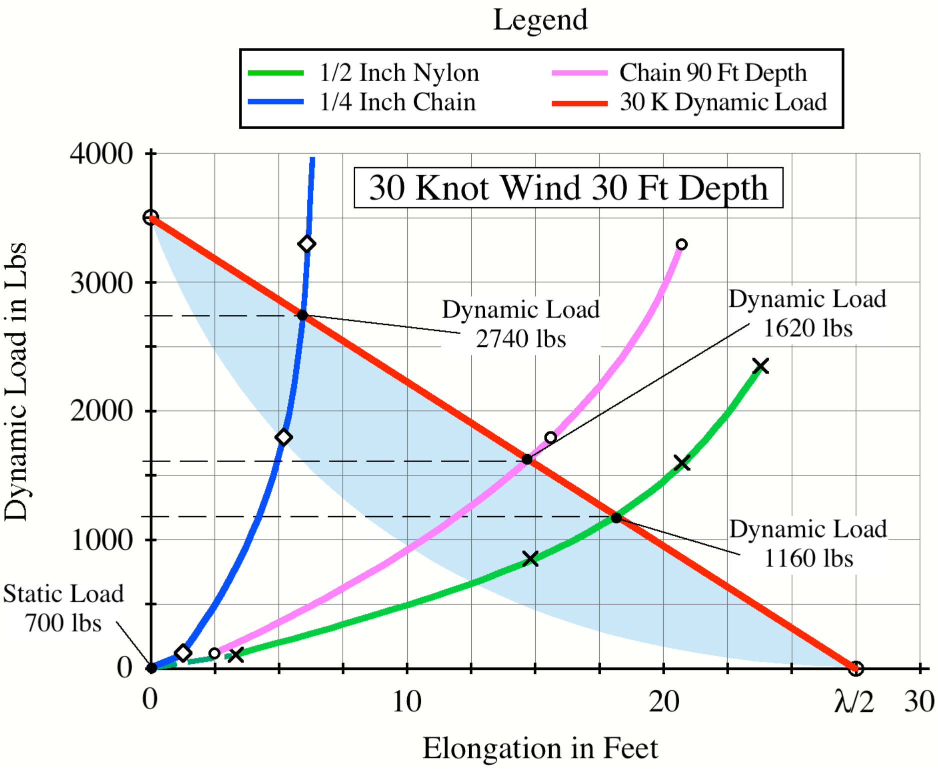

Figure 9 Comparison of Dynamic Load on Nylon and Chain Rode.

There is a lot of information in the above paragraphs, but as a minimum, we have found that dynamic loads depend on;

Boat displacement,

Wind velocity,

Fetch,

Storm duration,

Rode material,

Rode construction

Rode length,

Rode diameter,

Rode breaking strength

Water depth,

Load path.

Unfortunately evaluating the interaction of all these variables requires a rather complex equation for a direct solution. Again we use the time honored approach of simplifing and adding yet another safety factor.

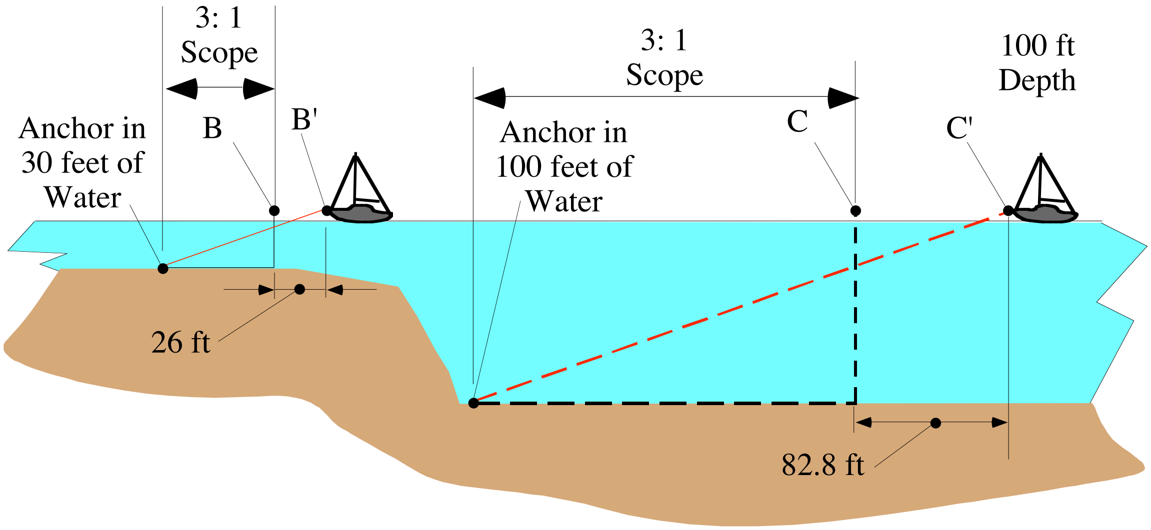

Figure 10 Maximum Elasticity with 300 ft of Chain.

It turns out that a suitable safety factor is dependent upon the type of rode and the displacement. Table 5 summarizes dynamic loading factors taken from representative calculations of dynamic load. In this table, shallow water is defined as less than 120 feet deep.

Table 5 Dynamic Safety Factor

Rode Type	Dynamic Loading Factor
Shallow Water Chain	1.5+disp/10000
Deep Water Chain	2.25+disp/35000
Braided Nylon	3.0+disp/35000
Twisted Nylon	2.0+disp/35000

Whereas this approach reduces the multiple safety factors, it still does not give the boater a realistic view of anchor loads. For those who want to experiment with the effect of various parameters, but don't want to do the math, you can download a spreadsheet, put in your boat's parameters and let the spreadsheet estimate the loads on your system.