TECHNICAL NOTE

THE LOADS ON YACHT ANCHOR CABLES

(DOI No: 10.3940/rina.ijme.2020.a4.235tn)

K Klaka, Australia

KEY DATES: Submitted: 30/05/2020 Final acceptance: 18/09/2020 Published: 04/12/2020

SUMMARY

The loads exerted on an all-chain anchor cable of a 10m yacht were measured during full scale trials in sheltered waters and steady wind. The peak recorded load was found to decrease significantly with increasing scope ratio, whereas the mean load was only weakly affected by scope ratio. The trials results were used to calculate the depth of water in which the pull at the anchor just remains horizontal for a range of wind speeds and cable lengths. The resulting relationship between maximum water depth and cable length is approximately quadratic. The required scope ratio for a given water depth increases with increasing windspeed. The required scope ratio for a given windspeed decreases with increasing depth.

NOMENCLATURE

F_x	horizontal force applied by boat (N)
H	water depth + freeboard (m)
k	a constant
L_c	length of chain (m)
V	wind speed (kn)
w_c	weight of chain in water per metre (N/m)
Scope ratio	$\frac{\text{chain length } L_c}{\text{water depth } H}$

1. INTRODUCTION

The original objective for this research was to calculate how the energy absorption in the anchor cable varied with the proportion of rope to chain, so as to determine whether a chain cable was "better" than a rope cable. A typical result is shown in Figure 1.

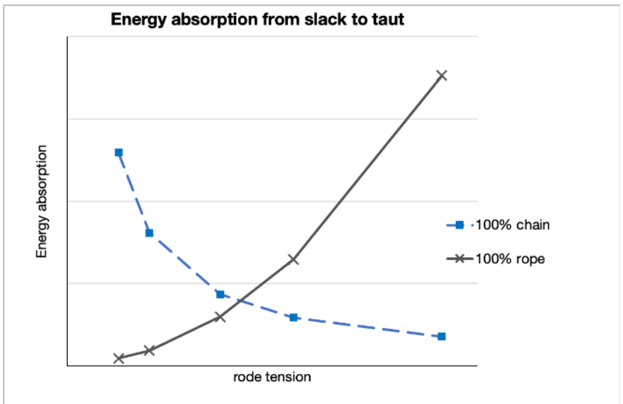

Figure 1 Effect of cable mix on energy absorption

It shows the energy absorbed from when the cable is slack to the limit of horizontal pull at the anchor. For the chain, the catenary has been simplified to the arc of a circle and the energy absorption approximated as the potential energy gained from the vertical movement at the mid-point of the chain. The energy absorption of the rope assumes the rope is neutrally buoyant, so all the energy absorption is in the strain energy. Whilst these results are academically interesting, in order to be of practical value it is necessary to know whether typical anchoring conditions are towards the left or the right of the graph. In order to keep the problem manageable, the objective moved away from examining energy absorption and the effect of cable composition. Instead it focussed on the more fundamental question: "What are the loads exerted on the anchor cable in real life conditions?" Note three important limitations of this work:

- Only the load due to windage is considered; waves and current are not included.
- Only an all-chain cable is considered.
- The calculations have been conducted for a typical 10m, 5t yacht.

The loads due to waves and current vary immensely with circumstances. Data from Poiraud *et al* (2008) indicate that, for a yacht experiencing 45kn wind, 3kn current and 2kn wave-induced surge, the relative contributions to anchor load are:

- Wind: 80%
- Waves: 15%
- Current: 5%

There is a plethora of anchoring trials which measure the force required to drag an anchor, but there is a dearth of real-world measured data for the loads exerted by a yacht on the anchor cable. Do the loads get anywhere close to the loads causing a well-set anchor to drag? If so, at what windspeed is that load reached? In order to answer these questions, anchoring trials were conducted (Klaka & Macfarlane, 2020) to measure the wind-induced loads on the cable. The referenced document is not widely available, so a summary is provided in Appendix A.

2. TYPES OF CATENARY

There are three distinct geometries for when an anchor cable is pulling at an anchor:

- At low loads there is some chain lying along the seabed i.e. the catenary shape does not reach the anchor and the pull on the anchor is horizontal (Figure 2).
- At some higher load the catenary shape stops just at the anchor, such that the pull at the anchor is horizontal but there is no chain on the seabed (Figure 3).
- At even higher load the catenary shape does not finish at the anchor; the chain is pulling at an angle above the horizontal (Figure 4).

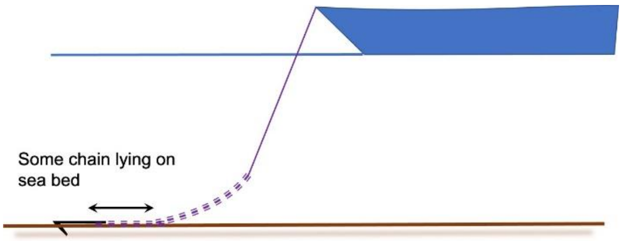

Figure 2 Low load: catenary ends before anchor

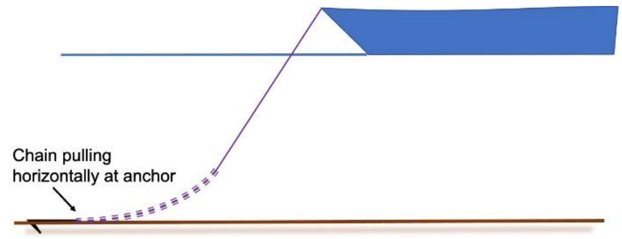

Figure 3 Catenary ends at anchor

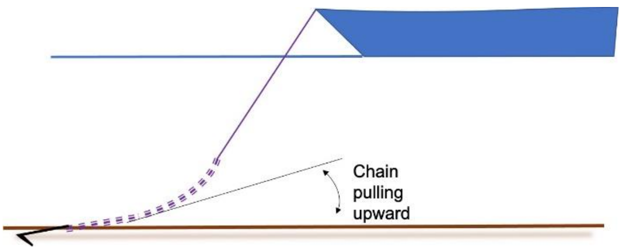

Figure 4 High load: catenary angled up at anchor

The holding power of an anchor reduces dramatically as the pull from the chain starts to rise above horizontal. A zero angle of pull is a conservative limit of safe operation. This corresponds to the second of the above three geometries. Therefore it is useful to calculate the load on the chain that will create the geometry in Figure 3.

3. ANCHOR HOLDING POWER

A great deal has been written about the relative holding power of different anchor types e.g. (Poiraud *et al*, 2008; Allisy, 2009; Gree, 1984). During the trials described in Klaka & Macfarlane, (2020) the highest load recorded in 23 kn wind was 1020 N. (Allisy, 2009) tested the holding power of 13 anchors, coincidentally including the same type and size of anchor used in Klaka & Macfarlane, (2020). Allisy (2009) reports that the anchor showed a holding power of 7260 N in hard sand, and 6490 N in “muddy sand”. Extrapolating the results in Allisy (2009) and applying them to the trials results in Klaka & Macfarlane, (2020), the anchor would not have pulled out until at least 50kn wind speed at a scope ratio of 2.4:1, and at least 70kn wind speed at a scope ratio of 5:1. This is without considering loads induced by waves, current or excessive yawing.

4. EFFECT OF WIND SPEED ON ANCHOR LOAD

There are numerous tables and graphs published, giving figures of load versus wind speed for different sizes of vessel. Many of these are adapted from, or quoted as, the tables published by the American Boat and Yacht Council e.g. (Poiraud *et al*, 2008). However, research has shown that the loads in those tables are unrealistically high, by a factor of between 3 and 5 (Nicholson, 2012; McNeill, 2007). This is in part because the tables were intended as design loads for deck fittings related to anchoring (cleats etc.), so they include large structural safety factors. This means that the tables are of very limited value for calculating the actual anchor cable loads at different wind speeds. Rather than trying to modify the ABYC tables, the load figures used in this paper have been extrapolated from the those measured during the sea trials reported in Klaka & Macfarlane, (2020). The trials were conducted in a steady wind, in a single water depth using three different scopes. The results are plotted in Figure 5, together with a trendline. Similar trends are shown in (Nicholson, 2012).

The mean load was only weakly affected by scope ratio. The load due to windage was also calculated empirically, from the same methods used in (ORC, 2019), modified to allow for cruising yacht configurations. The result was 435N, which is within 10% of the measured load. The peak recorded load was found to decrease significantly with increasing scope ratio. The trendline fitted to the peak load data is an inverse power law:

$$\text{peak load} = \frac{1550}{\sqrt{\text{scope ratio}}} \tag{1}$$

Equation 1 has an error of less than 5% for the range of scopes likely to be used in practice.

However, the loads measured during the trials were at only one windspeed (fortunately the wind was quite steady), so the next task is to extrapolate the results to all windspeeds. This is easily achieved by making the reasonable assumption that windage varies as the square of windspeed.

$$F_x = kV^2 \tag{2}$$

where:
F_x = the force due to windage
k is a constant for a particular boat.
V = wind speed

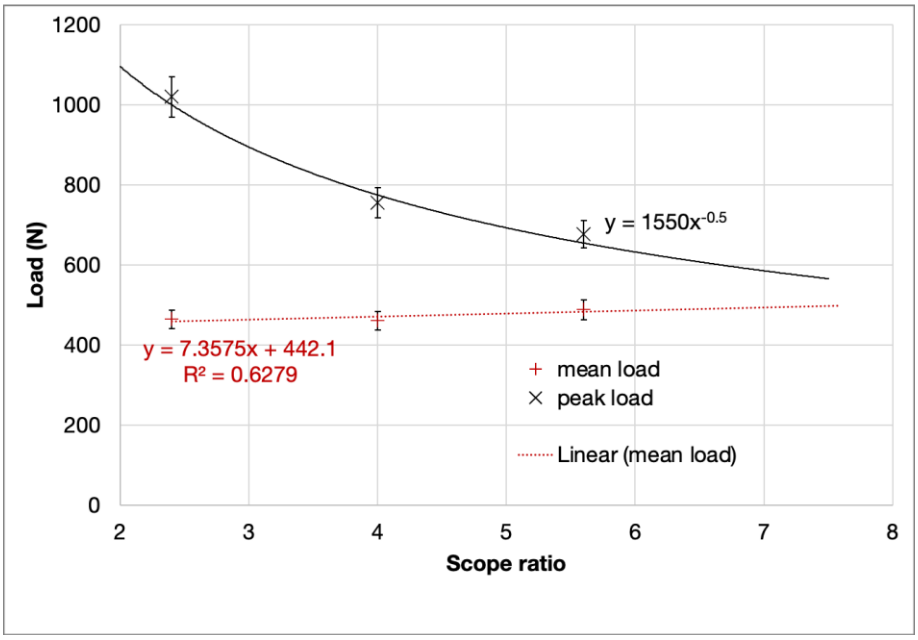

Figure 5. Load variation with scope

There are two approximations in this assumption:

- Wind speed increases with height above sea level, so the windage of each component of the boat depends not only on its shape and size but also its height.
- The force coefficient C_n for a particular shape has been assumed to be a fixed number, but it varies with Reynolds number.

In most circumstances these approximations make less than 10% difference.

F_x and V are known for the anchor trials, so k can be calculated for the boat used in those trials. The trials were conducted in 23.2kn wind speed, so combining Equation 1 and Equation 2:

$$F_x = \frac{1550}{(23.2)^2 \sqrt{\frac{L_c}{H}}} V^2 \qquad 3)$$

where:

H	water depth + freeboard (m)
L_c	length of chain (m)

5. CATENARY EQUATIONS

The mathematics of the catenary, detailed in Appendix B, reveals the relationship between load, chain length and water depth to be:

$$H = -\lambda \pm \sqrt{\lambda^2 + L_c^2} \qquad (4)$$

where:

$$\lambda = \frac{F_x}{w_c}$$

w_c weight of chain in water per metre (N/m)

Therefore, if an appropriate chain weight w_c is selected and the load F_x is calculated from Equation 3, then for a given wind speed V and cable length L_c, the limiting depth of water H in which the pull at the anchor remains horizontal can be calculated.

6. RESULTS

The results are shown in Figure 6.

The relationship between water depth and chain (cable) length is approximately quadratic. If the required scope ratio were independent of water depth, then the curves would be straight lines.

The required scope ratio for a given water depth increases with increasing windspeed. Furthermore, the required scope ratio decreases with increasing depth. This conclusion is in line with common practice (Poiraud *et al*, 2008; Gree, 1984). In terms of real-life scenarios, the results show that, for the 10m yacht with 50m chain, the maximum depth in which it can anchor in 30kn winds is 12.5m and in 40kn winds it is 8.5m. Again, these results correspond reasonably with common practice. It is important to recall that:

- Only the load due to windage is considered; waves and current are not included;
- This is for an 8mm diameter all-chain cable;

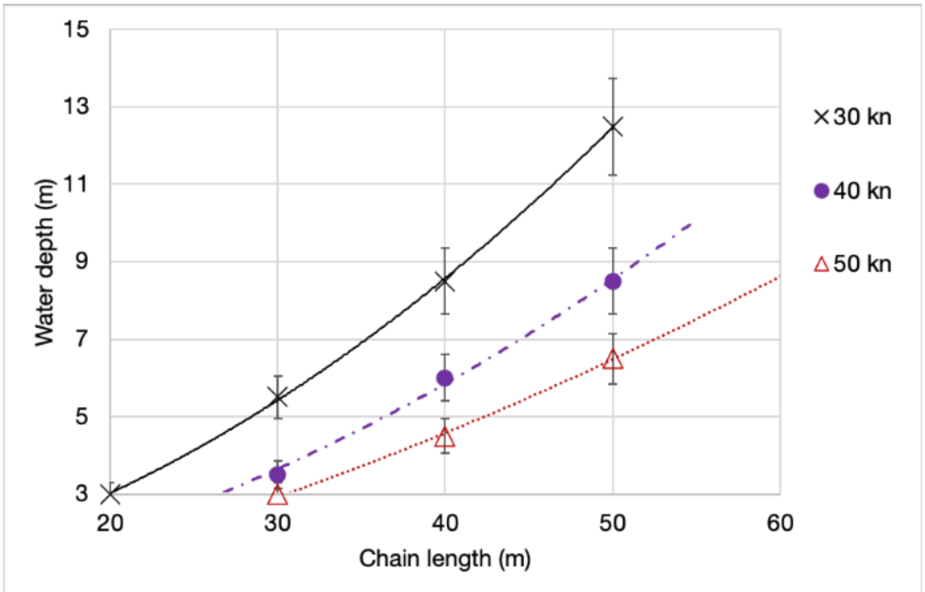

Figure 6 Maximum anchoring depth for chain to remain horizontal at anchor: 10 m yacht

- The windspeeds are at 10m reference height. Most masthead anemometers will be higher, yielding readouts typically 5 - 10% greater, due to the vertical wind gradient, e.g. a reading of 32kn from a masthead anemometer 18m above water corresponds with a windspeed of about 30kn at 10m reference height.
- The calculated water depths are for when the chain just starts to lift above horizontal at the anchor (Figure 3). This offers a margin of safety because most anchors will tolerate a pull angle of a few degrees above horizontal before they start to drag (Figure 4). The exact angle depends on many factors, including type of seabed and type of anchor.
- The results are for a 10m yacht; they do not scale in any straightforward manner. The relationship between windage frontal area and vessel length is weak, and the relationship between frontal area and windage is highly non-linear due to the vertical wind gradient. The weight of chain w_c also plays an important role.

7. CONCLUSIONS

The peak recorded load was found to decrease significantly with increasing scope ratio, whereas the mean load was only weakly affected by scope ratio.

The relationship between maximum water depth and cable length is approximately quadratic.

The required scope ratio for a given water depth increases with increasing windspeed.

The required scope ratio for a given windspeed decreases with increasing depth.

8. ACKNOWLEDGEMENTS

Many thanks to Richard Macfarlane who designed and built the anchor trials equipment, helped with the anchoring trials, and provided an excellent sounding board for my ideas. The plan was for him to put the trials equipment on his 13m yacht in Greece and carry out further trials in 2020, but COVID-19 travel restrictions have delayed those plans.

9. REFERENCES

1. ALLISY D. (2009) *Which anchor is best?* from Voiles et Voiliers, reprinted in Yachting Monthly November 2009.
2. GREE A. (1984) *Anchoring and Mooring.* Adlard Coles Ltd. ISBN 0229117023
3. KLAKA K. & MACFARLANE R. (2020) *Yacht anchor trials 9th February 2020*. Report KKM 20-2. Self-published K. Klaka.
4. MCNEILL P. (2007) *Digging in.* Yachting Monthly, January 2007 pp51.
5. NICHOLSON D. (2012) *Anchor testing and rode loads.* Practical Sailor, April 2012. https://www.practical-sailor.com/sails-rigging-deckgear/anchor-testing-and-rode-loads (Accessed 17th June 2020)
6. OFFSHORE RACING CONGRESS (2019) *ORC VPP documentation.* ORC, London https://www.orc.org/
7. OKE T.R. (1978) *Boundary layer climates.* Methuen & Co. ISBN 0415043190.
8. POIRAUD A., GINSBERG-KLEMMT A., & GINSBERG-KLEMMT E. (2008) *The complete anchoring handbook.* International Marine/McGraw Hill. ISBN 0071510214.

APPENDIX A

ANCHORING TRIALS SUMMARY

Klaka & Macfarlane (2020) is not readily available so the components relevant to this paper are summarised here.

A1. EQUIPMENT AND SETUP

The vessel used was a Van de Stadt 34 design. Principal characteristics are given in Table A1.

Table A1 Principal dimensions

LOA (m)	10.34
LWL (m)	8.0
Bmax (m)	3.3
Draft (m)	1.8
Canoe body draft (m)	0.55
Mass (kg)	5300

The vessel was equipped with a 16kg Delta anchor and 50m of 8mm diameter chain. A 3-strand nylon snubber of approximately 14mm diameter and 1.5m long was used.

A measurement and acquisition system was built by Richard MacFarlane for the trials. It is colloquially known as the Magic Anchor Box (MAB). It comprises a load cell, GPS and pitch tilt sensor. It also accepts the analogue signal from a separate anemometer. An internal Arduino Due board is used for data capture and pre-processing. Power was from dry-cell battery pack with ample capacity for one-day tests. The MAB recorded at 5Hz sample rate.

The MAB was deployed on deck behind the anchor winch. The aft end was tied back to the mast, with the forward end tied to the anchor snubber. The other end of the anchor snubber was attached to the anchor cable with a chain hook. The anemometer was lashed to the pulpit on the centreline of the vessel, approximately 2.5m above sea level.

Yaw was measured by observing the yacht's magnetic compass.

A2. TRIALS DESCRIPTION

The trials were conducted on 9th February 2020. The yacht was anchored in a water depth 5.2m. The anchorage is an area about 200m in diameter, fully sheltered from waves. There was a breakwater of 5m height about 100m to windward for these trials, offering slight shelter from the south-west wind.

The anchor was set in a seabed of sandy mud and dug in by the effects of windage and by motoring in reverse. About 1.5m of snubber line was deployed.

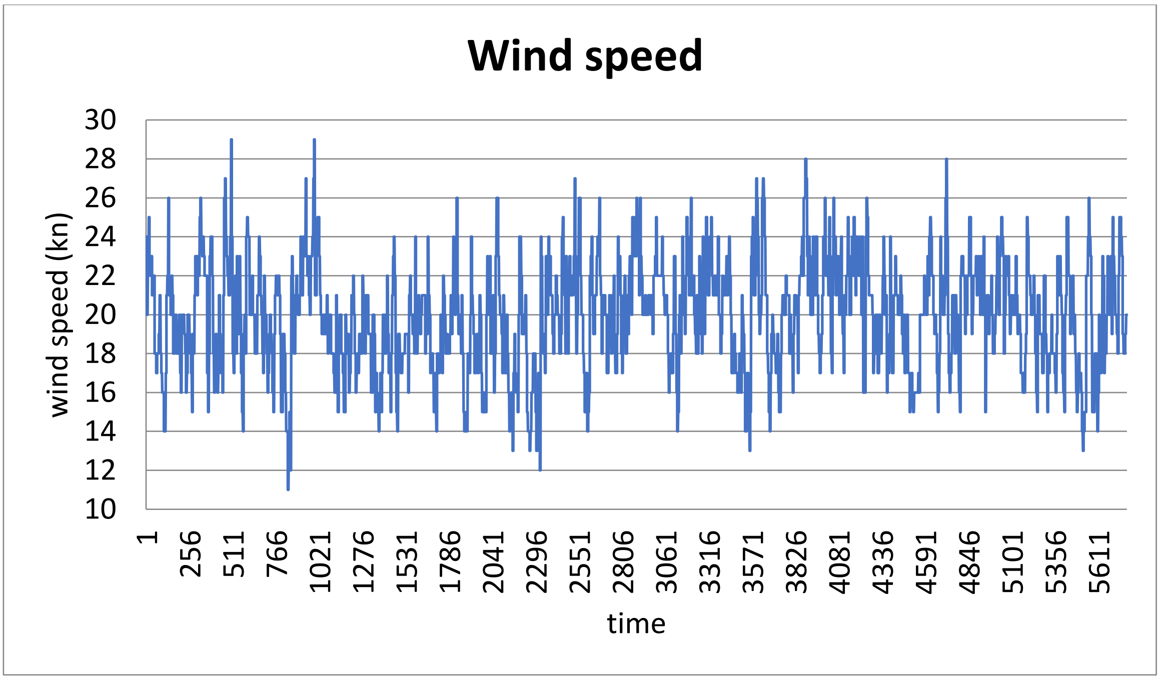

Figure A1 Wind speed measured on board during trials

The on-board anemometer record of Figure A1 shows an average wind speed of 20kn which was consistent over the duration of the trials. The standard deviation was 2.9kn and the highest recorded value was 29kn, i.e. three standard deviations above the mean.

It is standard practice when comparing wind data from different locations to correct them to a common datum of 10m above the surface. The vertical wind velocity profile can be represented by a power law, with a height exponent of 0.11 recommended over open water for neutral stability atmosphere.
(https://en.wikipedia.org/wiki/Wind_profile_power_law)

An alternative formulation is to use a log law and a roughness length (Oke, 1978). For roughness lengths typical of a warm sea breeze blowing over limited fetch water, the two formulations yield results that differ by less than 0.3kn.

Therefore the 20kn average wind speed recorded at 2.5m above sea level corresponds to a speed of 23.2kn at 10m height, and the peak recorded speed of 29kn corresponds to a speed of 33.8kn at 10m height.

Waves were estimated visually at a maximum height of less than 0.1m.

A3. ERRORS

WIND DATA

The anemometer had previously been calibrated by tying it to a car, driving at various speeds then comparing the readout with the GPS speed. This did not take into account the sea breeze that was blowing at the time, but at car speeds of more than 20kn the calibration was probably accurate to within less than 5%. The output had a resolution of 1kn, which amounts to about ± 5% error. This is taken to be the accuracy of the instrument.

ANCHOR LOAD

The anchor load cell had been calibrated up to 10kN against a certified load cell and was found to agree within ± 1%. The output has a resolution of 10N and an apparent offset of 20N. Temperature was found to affect the output by 3% per 10°C. The calibration used was for a temperature of 22°C, which corresponds closely with the air temperature during the trials. The load cell had also been checked for long-term drift, and none was found over a 14-hour period, other than from the temperature effects already described.

OTHER

Water depth is accurate to ±0.1m.
Cable length deployed is accurate to ±2m.
Yaw range estimated as accurate to ±5°.

A4. RESULTS

The time series were plotted and manually inspected. Segments showing quasi-steady conditions were identified and processed independently.

The results are shown in Table A2 and the corresponding time series are shown in Figure A2.

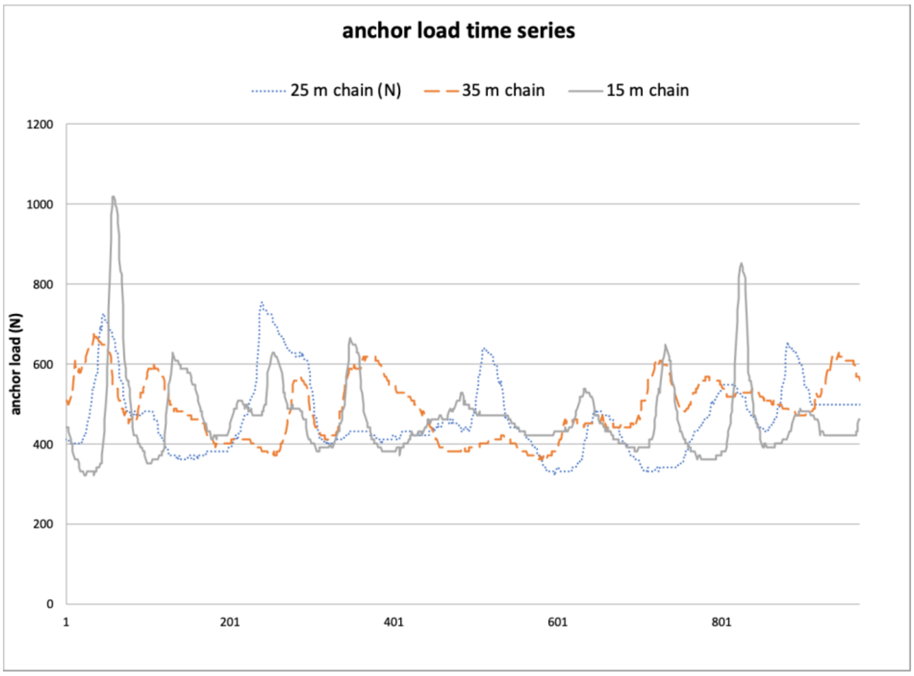

Figure A2 Anchor load time series

Table A2 Anchor loads v scope

cable length(m)	**scope ratio**	**average load (N)**	**max load (N)**	**standard deviation (N)**	**yaw range out-to-out (°)**
15	2.4	465	1020	101	35
25	4.0	461	755	95	40
35	5.6	489	677	7.7	45

As might be expected, the average load does not vary significantly with scope, but the standard deviation and the maximum load both increase as scope is reduced. This illustrates the benefit of using a long scope. There is a surprising and strong inverse correlation between the maximum load and the yaw range. This would suggest that the peak loads are caused by surge rather than yaw. However, the yaw range differences between the three different tests were only slightly greater than the estimated error range.

APPENDIX B

CATENARY EQUATION

A concise derivation of catenary equations can be found at
https://www.awelina.co.uk/anchor_rode/rode_length.html

The standard equation for a catenary with coordinates x (horizontal) and y (vertical) can be written as:

$$y = \lambda \cosh\left(\frac{x}{\lambda} - 1\right)$$

where:

$\lambda = \frac{F_x}{w_c}$

F_x = horizontal force
w_c = weight of chain in water per metre

Rewriting the above equation in terms of cable length L_c, and replacing y with water depth H, yields the quadratic equation:

$$H^2 + 2\lambda H - L_c^2 = 0$$

The solution to which is:

$$H = -\lambda \pm \sqrt{\lambda^2 + L_c^2}$$