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STUDY OF VAPS MOORING CABLE FAILURE AND ALTERNATIVE DESIGNS

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by

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ABSTRACT

During the 1980 summer operation of the Vertical Automatic Profiling System (VAPS), the centre strength member type mooring cable suffered failure of electrical conductors on two separate occasions. This incapacitated the system.

Circumstances of these failures are described.

A method for estimating stress in the conductor is developed and applied to the cable.

It is concluded that the conductor failure was due to tensile fatigue stress in the conductors exceeding the endurance limit stress of copper. This stress was induced by the combination of conductor lay direction and centre core torque characteristic being such that tension on the cable core produced twist which tightened the conductor lay; thus magnifying the stress in the conductors. This stress would be considerably reduced if the lay was opposite in direction, and increased from 5% to 17% take-up.

Alternative cable configurations are considered, and it is recommended that the external braid configuration is the most likely candidate for success.

1. INTRODUCTION

The first deployment trials of the Vertical Automatic Profiling System (VAPS) in 1979 used a mooring cable of the external braid strength member type. This cable failed prematurely, in our opinion, due to a defect in the outer jacket. This allowed the cable to flood, with subsequent failure of conductors by corrosion through pinholes in the conductor jacket. A claim for warranty replacement was made. A replacement cable, along with a 5 m length for test sample was eventually received in December 1980.

To provide for the 1980 season, a mooring cable of local manufacture was purchased. This was of the centre core strength member type, evolved from the cable design developed by NWRI for use in Fixed Temperature Profilers.

During trials in Lake Ontario on 5-18 June, 1980, this centre core type mooring cable suffered a failure of electrical conductors after exposure to a wave climate, not exceeding 1.5 m in height. Following the cable repair, and on operation at station C-11 in Lake Erie on 19-25 August, the cable again failed in a similar fashion, following exposure to a similar wave climate.

In view of the intention to have the VAPS capable of operation in more severe sea states, these failures call into question the viability of the system.

This report presents an analysis of these cable failures in some detail in order to establish a rational explanation for them, and a basis for corrective action.

2. INSTALLATION CONFIGURATION

The installation configuration in both cases was generally as shown in Figure 1. However, detail changes in end terminations of the cable were made between the Lake Ontario and the Lake Erie incidents. The changes made were directed towards improving the bending strain relief at the cable ends by forcing, through the use of heavy hydraulic hose sections, a larger bend radius at the bow of the surface buoy, and at the anchor point.

The system was moored in a depth of 23 ±1 m, and the cable length from the buoy to the anchor was 40 m. The cable was fitted with a floatation jacket for 20 m from the anchor up, to provide support and avoid tangle during calm weather. A slip-ring assembly at the surface buoy attachment made the cable free to twist under load without hockling.

The anchoring arrangements consisted of a strength member fitting on the cable, and a 2.5 m long steel rod bridle connecting this to a 2 axis swivel on the anchor. This allowed the cable to swivel in a conical fashion about the anchor point, but did not allow the cable to twist more than ±75°. The mass of the strength member fitting, including the 2.5 m of cable between it and the anchor was 14.4 kg, and that of the bridle was 11.1 kg. A set of floats was attached to the strength member fitting to make the whole assembly near neutral. However, the virtual mass of the assembly in the water could not be avoided.

On recovery, after some 14 days at Lake Erie Stn. C-11, it was found that the anchor had sunk into the bottom to a depth of 3 m, thus negating the value of the swivel bridle. This is not considered a contributing factor to the cable failure, but has implications for long term moorings on this type of bottom. It had been previously estimated (Zeman, 1978) that the anchor would sink up to 21 cm in the lake bottom, assuming the steady weight of the anchor only as the bearing load. Although the implication may be drawn that the cyclic mooring loads caused the anchor to work in, discussion with A. Zeman suggested that the shear strength of the bottom soil was probably the more significant factor, and that anchor bearing area should be increased on this type of bottom.

3.0 CABLE DESCRIPTION 1980 VERSION

The cable was a centre core strength member type evolved from the basic design developed by N.W.R.I. and Boston Insulated Wire and Cable (BIW) of Hamilton for Fixed Temperature Profiler (F.T.P.) applications. This cable was chosen based on:

a) good F.T.P. cable reliability in recent years indicated the manufacturer's learning period was over;
b) source close to hand;
c) use of moulding tools common to F.T.P. meant quicker delivery and some reduction in cost;
d) torque balanced centre core configuration was expected to induce less stress on conductors than squeeze or core pressure induced by external strength member type.

The essential features of the cable are summarized as follows:

a) Strength member - 19 x 7 wire strands, improved plow steel, 45kN breaking strength - 9.5 mm dia. Eight strand right hand lay core, and eleven strand left hand lay over core, with 2 mm thick neoprene jacket over all.
b) Conductors - Ten strands of conductor sets as shown in Figure 2, wound left hand lay with 5% take up, which gives a conductor helix pitch of approximately 17.4 cm, and a lay angle of 18.25°. A lubricant of talcum powder is used between the conductors and core.
c) Finish and Jacket - The conductor lay is wrapped with 25 mm wide cotton tape with 6 mm overlap, followed by a basket weave yarn braid. A 3 mm thick neoprene jacket completes the cable.

4.0 CABLE PROPERTIES

For the purpose of all calculations herein, the following values are used, based on data sources as noted.

a) Unstrained Conductor Helix

Circumference through conductor centroid	57.5 mm (measured)
Pitch length	174.0 mm "
Lay length	183.1 mm (calculated)
Lay angle	18.25° "
Helix radius through conductor centroid	9.2 mm "
Modulus of elasticity	19.5×10^9 Pa (Appendix 2)

b) Wire Rope Core

Steel area (based on 19 x 7 strands, .64 mm wire)	42.1 mm^2
Core dia. over sheath	13.5 mm
Modulus of elasticity (tension)	81.4×10^9 Pa (Appendix 1)
Twist modulus	24.4×10^{-6} rad-$N^{-1}m^{-1}$ (Appendix 1)

c) Cable

Overall dia.	31.0 mm

5. DESCRIPTION OF FAILURE IN 1980 VERSION

After exposure to a wave climate estimated to average 1.5 m in height in a depth of 23 ±1 m for a period of 8 to 10 hours, cable failure occurred by progressive deterioration of the conductors carrying the digital data. These are the #22 shielded duplex sets. Some 30 hours after the initial signs of failure, the signal conductors controlling the winch failed. These are the #20 triplex sets.

Examination of the cable showed the failures to be very localized in the termination mouldings, and generally in the same sectional plane through the cable.

Examination of failed conductor ends with a 4X microscope showed the majority of wires in the strand to be fatigued, and the remainder to be necked down characteristic of failure due to ultimate tensile load. Some of the fatigued wires show evidence of electrical arcing. In the case of the winch control signal which carries 230 volts, the jacket around the conductor was burned.

6.0 ESTIMATION OF FORCES ON CABLE

No means for measurement of the mooring cable tension were provided for in the 1980 field operations.

Data describing the wave climate typical of the region was obtained for MEDS Station 66, Point Pelee, approximately 22 km N.W. of the VAPS mooring (Appendix 6).

It was reported (Miners, 1980) that the average wave heights during the period over which the failure occurred were 1.5 m. From the MEDS data this suggests a severe storm with only a 5% probability of being exceeded. It also suggests maximum wave heights to 2.4 metres could be encountered.

The generation of tension load in the mooring cable of a freely floating hull is quite complex. In simplistic terms, the interaction of the wave excitation forces with the hull mass results in hull motion about six degrees of freedom. Because these motions may be coupled, a detailed analysis may have to deal with 12 degrees of freedom. This hull motion is then imposed on the surface end of the mooring cable. With a slack mooring, the major generator of dynamic tension in the cable is induced by the lateral drag of the cable through the water. This also produces strumming in the cable. Furthermore, as the whole system is analogous to a damped spring-mass system, resonances between wave frequencies and hull natural frequencies in each degree of freedom may occur, resulting in shock loads well in excess of average maximum forces.

For these reasons, it is obvious that in any future application, it would be highly desirable to place a force transducer in the mooring line. Instrumentation to record hull motion would also be valuable.

Estimations of cable tension are derived in Appendix 6, by assuming the buoy to be a fixed structure in the surface wave, and equating the horizontal and vertical components of wave force to the cable tension. It is recognized that this is a gross simplification, but should result in at least an upper limit of cable force.

In addition, a second estimate of tension forces is made by extrapolation from data collected on a similar yacht hull by the Bedford Institute of Oceanography (Dessureault, 1980).

These estimated load environments are depicted in Figure A-6.4 as described in Appendix 6.

The two estimates are arrived at independantly, but they are similar in magnitude. As noted in Appendix 6, the estimate from BIO data is probably low, due to the difference in scope of the mooring systems.

7.0 CONDUCTOR STRESS IN CENTRE-CORE CABLE

Stress in the conductors can be estimated on the basis of helix unit strain induced by tension or bending loads applied to the cable.

For tension loads applied to the cable core, the core deforms by elongation and rotation.

The cable elongation deforms the conductor helix by reduction of lay angle. This may occur due to elongation of lay length (incompressible core), reduction of helix circumference (compressible core), or something in between.

The cable core rotation also deforms the conductor helix by a change of lay angle. If the core rotation is in the same direction as the conductor helix, then the conductor strain increases. If the core rotation is opposite in direction to the conductor helix, the axial strain on the conductors is relieved, as shown in Appendix 4.

It is of interest to note, that increased tension in the conductor helix increases the friction between the core and conductors, like a self-locking band brake, and reduces conductor slip relative to the core.

8.0 STRESS CALCULATION

An HP System 45 calculator program (CABLE 1) was arranged to evaluate stress in the conductor helix of the cable. The basic variant of the program estimates conductor stress for a range of values of tension force on the wire rope core, and conductro lay direction.

The second variant (CABLE 2) estimates conductor stress vs. conductor helix diameter. This represents the adjustment of lay angle by increasing the helix diameter for a fixed pitch length.

The third variant (CABLE 3) estimates conductor stress vs. pitch length. This represents the adjustment of lay angle by decreasing the pitch length for a fixed helix diameter.

Program derivations and listings are shown in Appendix 4.

Conductor stress against load for left and right hand lay conductors are plotted in Figure 3.

Typical materials properties for annealed oxygen-free copper taken from the Materials Selector (1978) are:

Ultimate tensile stress	220.6 M Pa
Tensile yield stress	68.9 M Pa
Endurance limit	75.8 M Pa @ 10^8 cyc.

Fatigue properties for annealed copper taken from Mark's (1958), page 5-11 are:

Endurance Limit - M Pa	Cycles
75.2	10^7
78	10^6
90	10^5
106	2.5×10^4
130	10^4

According to Faires, 1955, varying axial and torsional loads reduce the endurance limit, giving an endurance strength of 42% of the limit.

Thus the stress calculation predicts a fatigue failure of the conductors under cycling loads as follows:

Cycles	Endurance Stress (M Pa)	Equivalent Cable Load (kN)	
		Left Lay	Right Lay
10^7	31.6	4.9	8.3
10^6	32.8	5.1	8.6
10^5	37.8	5.9	9.9
2.5×10^4	44.5	6.9	11.6
10^4	54.6	8.5	14.3

A fatigue test (Appendix 2) was conducted on a previously unstressed piece of mooring cable.

The results are shown against the predicted fatigue failure curve in Figure 4.

Although the test data is limited, this demonstrates that the conductor stressing calculation is reasonable.

Figure 5 shows this calculated cable fatigue life in relation to the estimated wave forces on the cable, as derived in section 6 and Appendix 6.

9.0 CAUSE OF CABLE FAILURE

As depicted in Figure 5, and discussed in Appendix 6, the results of the stress calculation and the estimation of tension load in the cable are considered in terms of a load-cycle environment

It is evident from this presentation that there is coincidence between the estimated loading environment generated by the storm, and the calculated fatigue failure characteristic of the cable.

It is to be appreciated, as discussed in Appendix 6, that the WAV FOR estimate of tension force is pessimistic. However, it is also to be appreciated that the stress calculation and fatigue test of the cable are based simply on straight cyclic tension loads on the cable. It would be quite reasonable engineering practice to derate this result by a factor of at least 2 for a field condition, recognizing the unknown additional contributions to cable fatigue due to strumming, and periodic bending and shock loads.

On this basis, the failure of the cable conductors can be explained in terms of fatigue due to cyclic tension loads imposed on the mooring cable.

It should be noted that had the conductor lay been opposite to the centre core twist characteristic, a significantly better performance might be expected in the specific conditions on this occasion, but it is still not adequate for confident long term use.

10.0 REDUCTION OF CONDUCTOR STRESS

The conductor stress in the preceeding calculation derives from the axial and torsional strain of the wire rope core, and the lay length of the unstrained helix.

As calculated by CABLE I, the conductor stress for right hand lay is 60% of the stress for left hand lay.

As shown in Section 9 this improvement is not really adequate to ensure a reliable cable fatigue life.

Increasing the lay length by increasing the helix diameter, assuming also that the conductor lay is opposite the cable core twist, results in further conductor stress reduction. Indeed, if the cable core torque characteristic were linear over the full load range as assumed, it should be possible by adjustment of helix diameter to obtain a design which resulted in a conductor stress which is within fatigue limits up to the rated breaking strength of the cable. For example, calculation with CABLE 2 shows a conductor helix diameter of 33 mm with a pitch length of 174 mm, yields a conductor stress of 32 M Pa with a cable tension of 44 kN. To obtain this helix diameter a 10 mm thick cushion would be required over the cable core. This suggests the possibility of having a neutrally buoyant cable if sufficiently low density materials can be found. The finished cable would be about 50 mm diameter, as compared to approximately 80 mm diameter over the floatation jacket of the present cable.

11.0 ALTERNATIVE CONFIGURATIONS

Alternative configurations should be considered which improve reliability by removal of the cause of failure. Five examined briefly here are:

a) Same B.I.W. central core cable with the conductor lay right hand, with increased core diameter to allow the lay angle to be increased to 31°, and minimum conductor size to be #18 AWG.

b) Selection of an external strength member configuration.

c) Selection of a make-up cable of in-house assembly.

d) Modification of electronics to reduce the number of conductors.

e) Optimization of mooring.

11.1 CENTRAL CORE CABLE

Accepting that the primary cause of failure of the present cable configuration is due to the magnification of conductor stress brought on by the torque response of the strength core of the cable, then change to the cable design is a reasonable developmental step. As calculated by CABLE 2, for right hand lay, increasing the helix diameter to 33 mm increases the lay take-up to 18% and results in a conductor stress of 32 M Pa, when the cable load is 44 kN. This would ensure conductor stress of one half the endurance limit over the full range of load. Increasing the minimum conductor dimension from #22 to #18 AWG will not reduce stress but will reduce stress concentrations on smaller members.

The cable diameter would require an increase from 30.0 mm to about 50 mm. Low density materials could be incorporated in the core jacket to reduce the cable weight in water.

The increased cable diameter has cost implications in that moulding tools for upper and lower moulds, which are in fact

FTP cable moulds, will no longer fit. The increased diameter and increased lay take-up also have material cost implications.

The main reasons for adopting the B.I.W. cable were:

a) Existing technology base in F.T.P. cables;

b) Close to hand and convenient;

c) Use of existing F.T.P. tooling.

The experience with the VAPS has demonstrated that the VAPS cable must absorb cycling tension loads while the F.T.P. load is more bending. Thus the centre core configuration which has advantages in terms of cable flexibility and access to conductors, is not required or even desirable in this case.

Further, it is clear that the cable diameter must be increased, so that the advantage of using existing tooling is lost.

Consultations by telephone (see Appendix 7) in general tend to avoid centre stress core type cables for this type of application, because of the torque behavior.

In summary, the continuing development of the VAPS cable along the route of a centre-core cable is reasonable, but not the best route to take.

11.2 <u>EXTERNAL STRENGTH MEMBER CABLE</u>

A second model shipped as a replacement for the original VAPS cable supplied by Romor Equipment Ltd., arrived as an external strength member cable complete, as well as a 5 m test piece. The original failure of this cable in 1979 was the corrosion of the #20 AWG wires in a triplex set. The cable was flooded due to a small leak in the jacket. The individual conductors were supposed to be water tight. The jacket of the failed conductor was in fact open. One conclusion was that the jacket was pin-holed. Another was that the jacket was extruded due to pressure from adjacent conductors. The replacement cable has been slightly modified by placing the #20 AWG triplex set in a soft vinyl jacket, thus reducing hazard from core pressure loads. In addition, the supplier has given assurance that all conductors have been hydrostatically tested for pin-hole leaks prior to cable assembly.

One source of concern with this cable is the relative modulus of elasticity of the electrical core relative to the braided strength member. It is difficult to assess what portion of applied load is carried by the core, and what by the braid.

Another concern is the amount of core pressure or squeeze on the conductor core that develops as a consequence of tension load on the braid. This is what will produce extrusion or abrasion of conductor jacket material. It is also difficult to assess analytically.

These matters could be somewhat resolved by doing tensile fatigue tests of the cable sample, and further study by analytical methods.

The consultations (Appendix 7), in general recommended this configuration of cable as that with which most success has been had in their experience, although in detail this particular cable falls short of the preferred construction, due mainly to its short mooring scope and in having the floatation at the bottom rather than on the top part of the cable.

In summary, because the cable is available, and because sample fatigue testing is relatively easily done, thereby accumulating sufficient confidence to justify using this cable in a field situation, it is reasonable to try this cable, This appears more likely to yield early success than continuing with development of a centre strength core cable.

11.3 MAKE-UP CABLE ASSEMBLY

One concept which has been considered is that of a make-up cable comprised of commercially available multiple conductor wiring sets, loosely grouped around a steel or Kevlar strand cable, the whole enclosed in a suitable retaining hose.

Superficially, for shallow moorings, such an arrangement has some advantage. It may be shop repairable, it may concentrate 100% of the tension load in the strength members, it may result in lower cost than a specially moulded cable.

There are however, a number of developments needed to bring the idea to practical fruition in VAPS. The arrangement of connections, the question of abrasion of wiring sets on one another or against the strength cable when confined within the hose, provision for swivels at top or bottom to prevent hockling of the strength member, provisions for cable buoyancy, the physical task of threading cable through hose 60 to 100 m long.

These questions indicate a need for much experimental work, since their resolution is based more on experience than analysis. The method has been used for short term relatively static conditions, but no experience with long periods of mooring in large wave conditions has been found.

In summary, the deceptive simplicity of this idea makes one cautious. If, in fact, it would work, why is it not more widely used in practice already? Yet, it seems reasonable that it should be tried.

11.4 REDUCTION OF CONDUCTORS

The objective of this approach would be by electronic redesign, to reduce the requirement for conductors down to a number, size and arrangement which could be satisfied from, for example, U.S. Steel Amergraph warehouse stock.

This approach is feasible, but not necessarily highly rewarding. Certainly, the fewer conductors in the cable, the higher should be its reliability. But conductors are still required, and the problem of cable selection and demonstration still remains, arrangements for connection, swivelling, flotation and so on.

For these reasons, this idea was not pursued here, although it obviously would be the starting point in the next evolution of a future VAPS.

11.5 OPTIMIZATION OF MOORING

Several alternative mooring configurations have been considered, however none appears to offer great advantages one way or another. The dynamical analysis of mooring systems is sufficiently complex that a separate study proposal was made aimed at establishing an optimal mooring configuration.

12.0 CONCLUSIONS

1. The B.I.W. cable failed due to tensile fatigue stress in the conductors exceeding the endurance limit stress of copper in this configuration.
2. This stress was aggravated by the conductor lay direction being made the same as the wire rope core twist direction (i.e., both left hand). A conductor lay in opposition to the core twist direction would tend to reduce conductor stress to 60% of the original value.
3. The centre core strength member type cable is inherently less appropriate to this application and should be set aside in favour of the external braid type.

13.0 RECOMMENDATIONS

1. Fatigue tests at the 9.0 to 0 kN force level should be conducted on a sample of externally braided cable to accumulate some confidence in its construction. Tight radius bend and twist tests have already shown its superiority in these areas (Ref. Appendix 2).

2. Unless otherwise determined from the above fatigue test, the externally braided cable should be used in a confirming field test early in the 1981 season. A tension force transducer should be used at the bow of the buoy for this field test. Such transducers are available in-house, and can be easily accommodated on the VAPS buoy.

3. The procurement of an additional VAPS mooring cable should be predicated on the results of the above field test, any conclusions that may arise from a further study of mooring configurations, as well as further consideration of future system needs.

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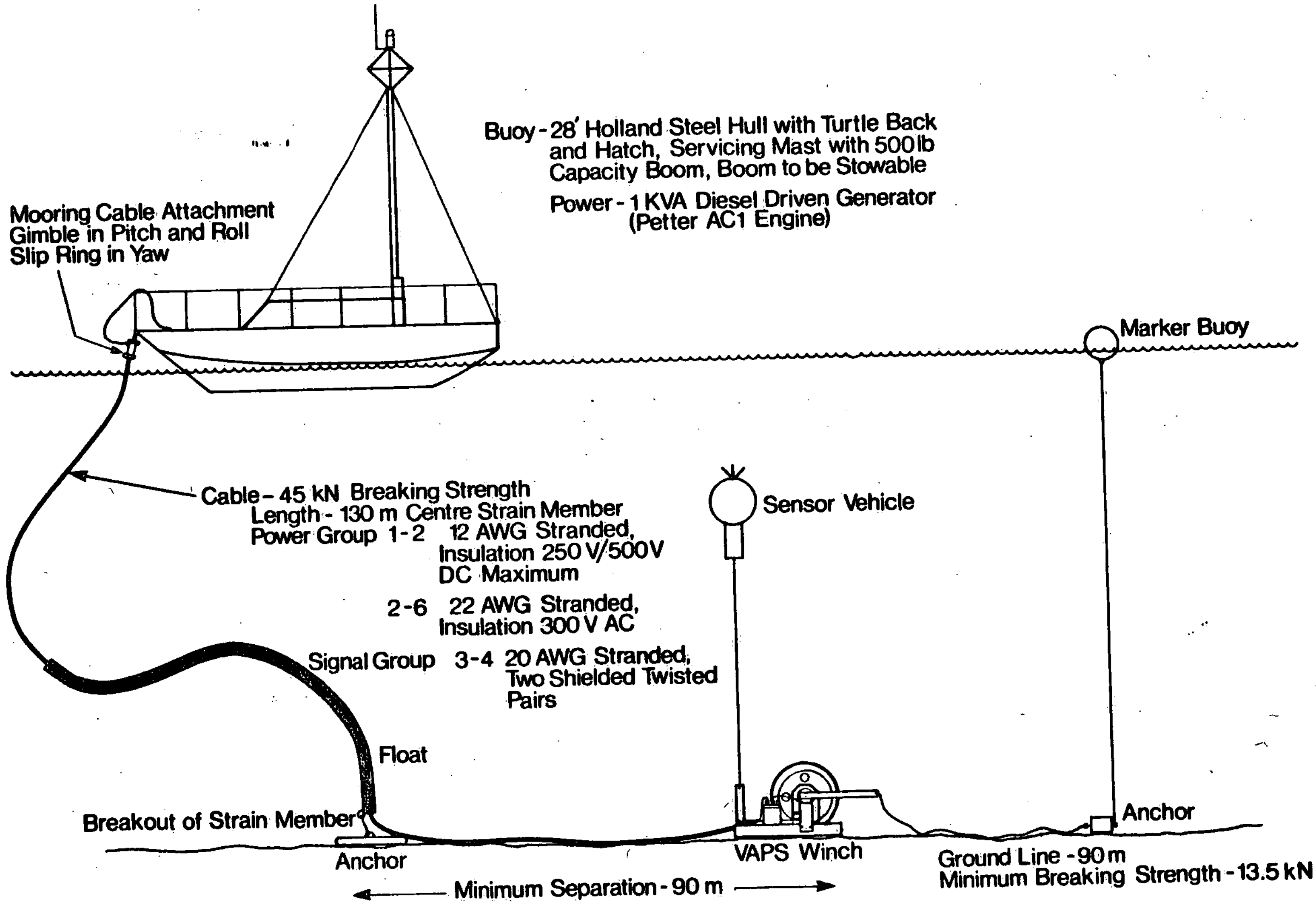
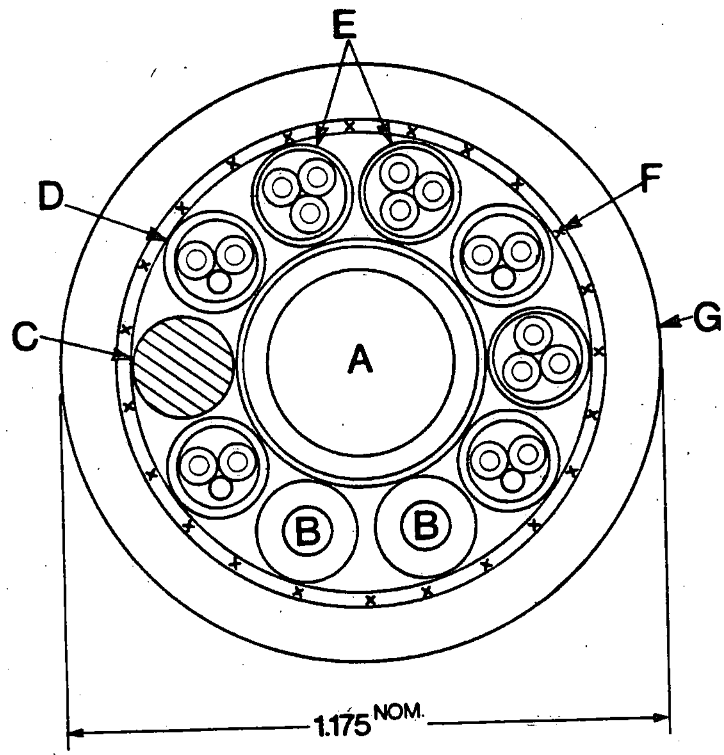


Figure 1. Installation Configuration



A) 3/8" non rotating strain relief - breaking strength 10,000 lbs.
B) 2 No. 12 A.W.G. power conductors
C) 1 rubber filler
D) 4 pair No. 22 A.W.G. shielded
E) 3 groups of 3 No. 20 A.W.G. conductors
F) Basket weave reinforcing yarn braid
G) B.I.W. GN 336 neoprene jacket

Figure 2 19-conductor mooring power cable

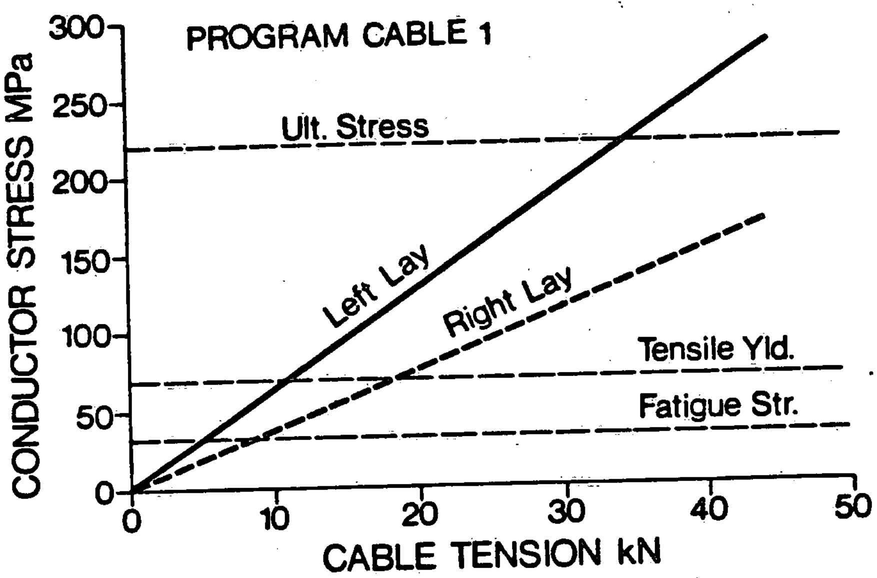


Figure 3. Conductor Stress against Core Load.

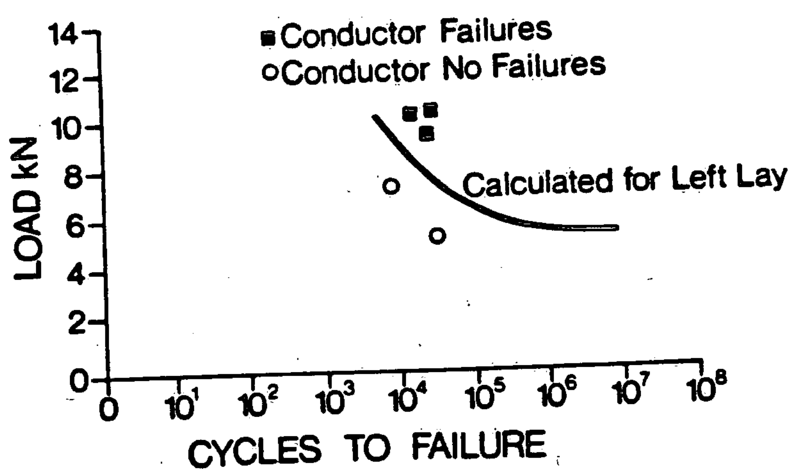


Figure 4. Lab Test Load - Cycle Diagram

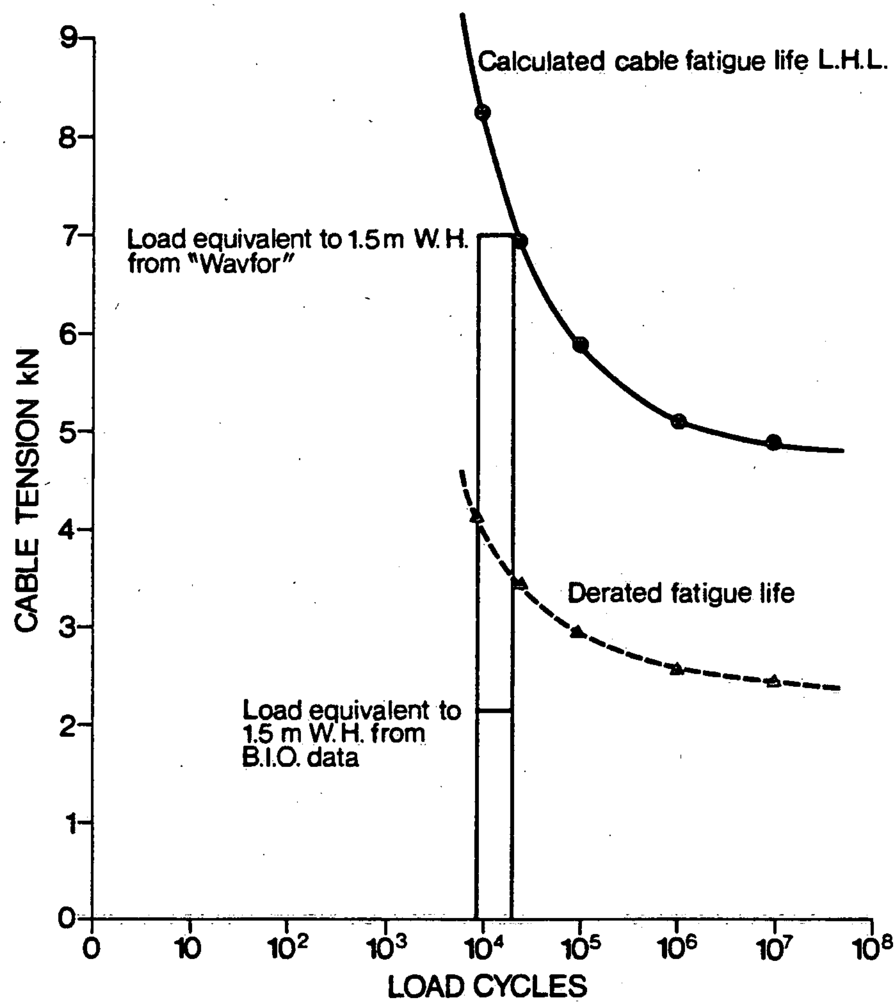


Figure 5 Cable Failure Condition

APPENDIX I

Estimation of Wire Rope Core Properties

Method

A 4 m length of cable was loaded in tension by attachments to the wire rope core with a force dynometer at one end. A gauge length of 1 m was marked on the cable. The cable was then subjected to load in increments over the range 0 to 22.5 kN.

Axial and angular strains of the wire rope core were measured at each load increment.

From the data obtained, the modulus of elasticity based on the area of wire in the core, and the modulus of twist were calculated.

Result

$$Ec = 81.4 \times 10^{9} \text{ Pa}$$

$$Gc = 24.4 \times 10^{-6} \text{ rad. } N^{-1}m^{-1} \text{ Left hand}$$

The value of Ec compares favourably with 82.7 x 10^9 Pa, given as a typical value for plow steel wire rope in Faires (1955).

APPENDIX 2

16 January, 1981 - F. Roy

Interim Test Report - G VAPS Mooring Cables

1. Method:

   a) Bend - B.I.W. Bend test machine - ±90° bend over 7.6 cm (3 in.) mandril, with 111.2 N (25 lb.) tensile load on the sample, at the rate of 1.5 cycles/minute.

   b) Twist - B.I.W. Twist test machine - 180° right hand twist over a length of 1 m, with 356 N (80 lb.) tensile load on the sample, at the rate of 1.5 cycles/minute.

   c) Tensile Fatigue- C.C.I.W. test. Axial tension force varying as simple harmonic motion from eccentric cam. Force adjustable from 0 to 10 kN (0 to 2500 lb.). Speed 13.6 cycles/minute (20,000 cy/24 hrs.)

2. Results:

		Cycles to Failure	
a) Bend Test	B.I.W. Cable	8*	30
	Kintec Cable	593	
b) Twist Test	B.I.W. Cable	16*	26
	Kintec Cable	30,000 cycles - no failure	

* B.I.W. test piece from upper portion of mooring cable which may have been fatigued. Test was repeated with sample from bottom portion.

   c) Fatigue Test — B.I.W. Cable

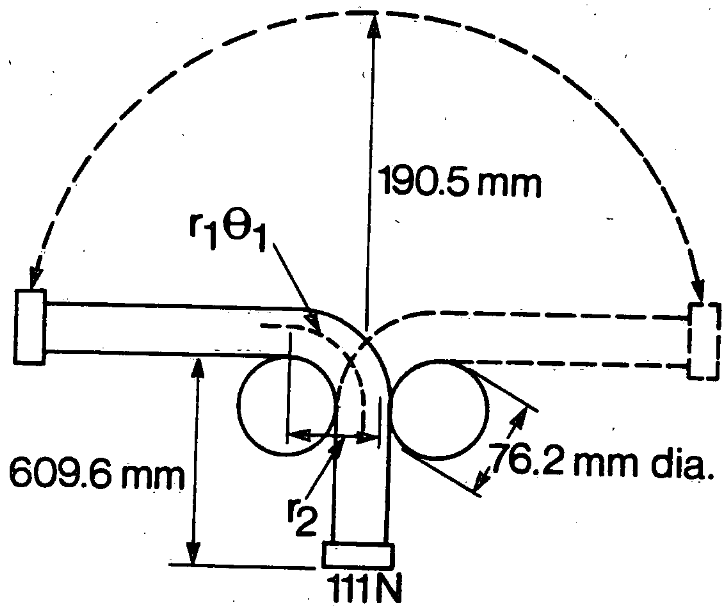
Load kN	Cycles x 10^3	Condition
4.4	25.7	No faults
6.7	6.5	No faults
8.9	25.0	#22 AWG opened
9.8	17.1	#22 AWG opened
9.8	27.0	#22 AWG opened

APPENDIX 3

Estimation of Conductor Modulus of Elasticity

A. From Bend Test

The cable is flexed over a 76.2 mm diameter mandril as shown.



An estimate of the axial strain of a conductor may be made by consideration of its arc length relative to the arc length of the neutral axis of the cable over the bend.

1. Neutral axis arc length $= r_1\theta = (38.1 + 15.5)\frac{\pi}{2} = 84.19$ mm
2. Conductor arc length $= r_2\theta_1 = (38.1 + 15.5 + 9.2)\frac{\pi}{2} = 98.65$ mm
3. Strain due to bending - 98.65 - 84.19 = 14.46 mm
4. Gauge Length $= \dfrac{190.5 + 609.6}{\text{Cos } 18°25} = 842.5$ mm
5. Unit Strain $= \dfrac{14.46}{842.5} = .0172$

6. For ultimate tensile stress of copper of 241.3 M Pa

$$\text{Modulus of Elasticity} = \frac{241.3}{.0172} = 14.03 \times 10^9 \text{ Pa}$$

B. <u>From Twist Test</u>

1. Cable is twisted 180° in a length of 1.0 m

2. Rotation per pitch, $\theta = \frac{180}{1 \text{ m}} \times .174 \times \frac{\pi}{180} = 0.55^r$

3. Elongation of helix circumference = $r\theta$ = .0092 x .55 = 5.06×10^{-3} m

4. Elongation of lay = $((.0575 + .00506)^2 + .174^2)^{\frac{1}{2}} - .183 = 1.905 \times 10^{-3}$ m

5. Unit strain of conductor $= \frac{1.905 \times 10^{-3}}{.183} = 1.04 \times 10^{-2}$

6. For ultimate tensile stress of 241.3 M Pa

$$\text{Modulus of Elasticity} = \frac{241.3}{1.04 \times 10^{-2}} = 23.2 \times 10^9 \text{ Pa}$$

C. The mean value from the above is 18.62×10^9 Pa

Due to the tightness of both the bend and the twist, it is reasonable to allow some compression of sheathing materials surrounding the copper.

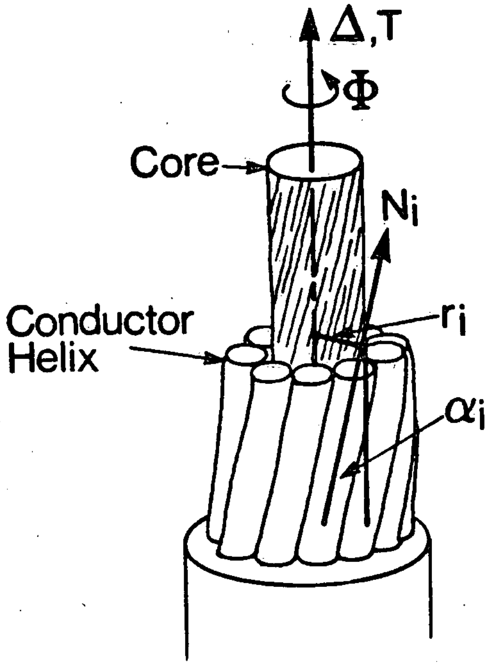
To account for this, the Modulus is increased by 5%.

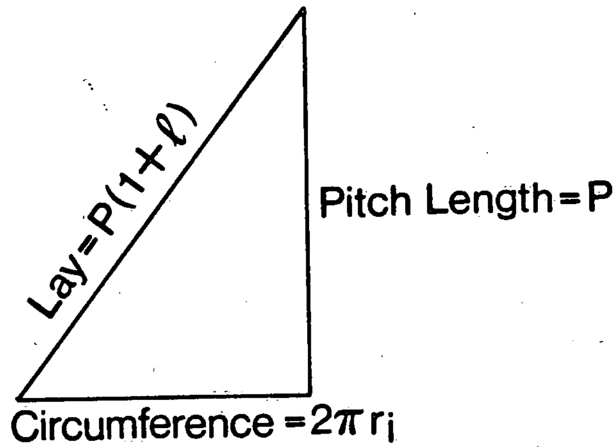
Hence - Estimated Modulus of Elasticity for Copper Conductor

$$Ei = 19.5 \times 10^9 \text{ Pa}$$

Calculation of Conductor Stress

The relaxed conductor helix may be described in terms of the lay angle and the radius of the centroid of the conductor to the centroid of the cable.

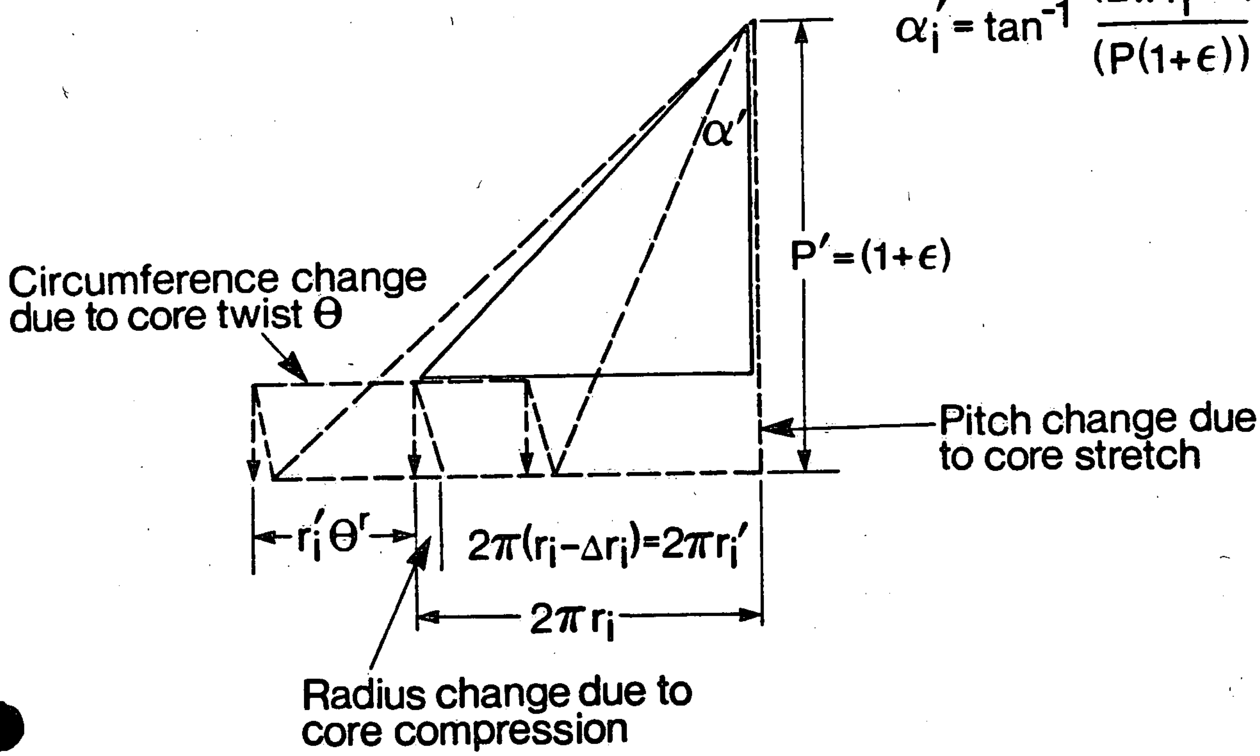




$$\alpha_i = \tan^{-1}\frac{2\pi r_i}{P}$$

The strained conductor helix is also described in terms of the strained lay angle and the strained radius of the conductor centroid to the cable centroid.

$$\alpha_i' = \tan^{-1}\frac{(2\pi r_i' \pm r_i'\Theta)}{(P(1+\epsilon))}$$



As illustrated, distortions of lay angle result from stretch of the cable core (ξ_c), compression of the cable core (ΔRi), and twist of the cable core (θ).

The stress in the helical conductors can be determined from the axial strain and deformed lay angle (Knapp, 1975) as.

Axial stress

$$\sigma_i^a = E_i \left| \frac{\cos\alpha_i}{\cos\alpha_i'} (1+\epsilon_c) - 1 \right|$$

Bending stress

the bending stress

$$\sigma_i^b = E_i \left| \frac{d_i}{2R_i} \sin\alpha_i \left[\sin\alpha_i' - \frac{\sin\alpha_i \cos\alpha_i (1+\epsilon_c)}{\cos\alpha_i'} \right] \right|$$

Shear stress due to twist

$$\tau_i = \frac{E_i}{2(1+\nu_i)} \left| \frac{d_i \sin\alpha_i \cos\alpha_i}{2R_i} \left[\frac{\cos\alpha_i'}{\cos\alpha_i} - \frac{\cos\alpha_i}{\cos\alpha_i'} (1+\epsilon_c) \right] \right|$$

in which di = wire diameter, Vi Poissons ratio

For ductile material, total stress σ_i is

$$\left[(\sigma_i^a + \sigma_i^b)^2 + 3\tau_i^2 \right]^{1/2} = \sigma_i$$

In this case, the wire diameter for #22 AWG is .07 mm in the cable diameter of 18.2 mm, hence bending and shear stress are of order 10^{-3} times axial stress and may be neglected.

Furthermore, because the jacket over the steel core is only 2 mm of neoprene, the core compression ΔRi will be small compared to the effect of core twist, so it will be assumed that the core is incompressible and $\Delta Ri = 0$.

Measurement of the Modulus of Elasticity (Ec) of the wire rope core of the cable established that:

$E_c = 81.4 \times 10^9$ Pa

Similarly, a twist modulus for the wire rope core of the cable was found to be:

$G = 24.4 \times 10^{-6}$ rad $N^{-1}m^{-1}$

If it is assumed that all of the applied load is carried by the wire rope core, then values for axial and angular strain of the core (and hence of the conductor helix) may be stated in terms of applied tension force T.

$$\varepsilon_C = \frac{T}{Ac.Ec}$$

and

$$\theta^r = G.T.P$$

The other factor required is the modulus of elasticity of the copper wire. As shown in Appendices 2 & 3, bend and twist test results indicate this to be

$$Ei = 19.5 \times 10^9 \text{ kPa}$$

The HP System 45 calculator program CABLE I attached, then calculates conductor stress versus cable tension.

A second variant of this program (CABLE 2) estimates conductor stress for conductor helix angle. This represents the adjustment of lay angle by increasing the helix diameter for a fixed pitch length and fixed cable tension.

A third variant (CABLE 3) estimates conductor stress against pitch length of the conductor helix. This represents the adjustment of lay angle by decreasing the pitch length for a fixed helix diameter.

```
10   ! Program CABLE1,Version 1.0,Updated 81/1/21.
20   ! Stored on F.Roy File1.
30   !
40   !
50   ! Program CABLE1,for estimating the stress in the conductors
60   ! of an electro-mechanical cable having a wire rope core with
70   ! the conductors helically wound outside this core.
80   ! This varient of CABLE estimates conductor stress vs. cable
90   ! tension for given cable characteristics.
100  ! Units are metric.
110  !
120  !
130  ! List of Variables
140  !
150  !     P  = Measured pitch length of conductor helix
160  !     Ec = Modulus of elasticity of wire rope core
170  !     Ei = Modulus of elasticity of conductors
180  !     Gc = Modulus of twist of wire rope core
190  !     Ac = Sectional area of wire rope core
200  !     Ri = Measured mean radius through conductors
210  !     T  = Load on wire rope core
220  !     Tm = Maximum load on wire rope core
230  !     Sl = Stress in conductor;LEFT LAY
240  !     Sr = Stress in conductor;RIGHT LAY
250  !
260  !
270 Main: GOSUB Init
280 Loop: GOSUB Input
300       GOSUB Calc
310       GOSUB List
311       PAUSE
315       GOSUB Plotsheet
320       GOSUB Graph
330       PAUSE
340       GOTO Loop
350       END
360 Init: DIM T(20),Sl(20),Sr(20)
370         DATA 42.1E-6,81.4E9,24.4E-6,.174,9.2E-3,4.448E4,19.3E9
380         READ Ac,Ec,Gc,P,Ri,Tm,Ei
390       RETURN
400 Input:  RETURN
410 Plotsheet: PLOTTER IS "9872A"
420            LINE TYPE 1
430            CSIZE 3,.5
440            SCALE -10,53,-60,310
450            CLIP 0,50,0,300
460            AXES 10,50,0,0
470            UNCLIP
480            LORG 5
490            LDIR 0
500            FOR I=0 TO 50 STEP 10
510                MOVE I,-20
520                LABEL USING "K";I
530            NEXT I
540            MOVE 25,-40
550            LABEL USING "K";"Cable Tension   kN"
560            MOVE 15,290
570            LABEL USING "K";"Prog.CABLE1"
580            LABEL USING "K";"Solid line is LEFT LAY"
590            LABEL USING "K";"Dotted line is RIGHT LAY"
600            MOVE 0,220.6
610            LINE TYPE 5
620            DRAW 50,220.6
630            MOVE 0,68.9
640            DRAW 50,68.9
650            MOVE 0,31.85
```

```
660             DRAW 50,31.85
670             LINE TYPE 1
680             MOVE 15,227
690             LABEL USING "K";"ULT. STRESS"
700             MOVE 40,75
710             LABEL USING "K";"TENSILE YLD."
720             MOVE 40,39
730             LABEL USING "K";"FATIGUE STR."
740             LDIR PI/2
750             FOR I=0 TO 300 STEP 50
760                 MOVE -2,I
770                 LABEL USING "K";I
780             NEXT I
790             MOVE -6,150
800             LABEL USING "K";"Conductor Stress  MPa"
810             RETURN
820 Calc:       T=0
830             Ci=2*PI*Ri
840             Alf=ATN(Ci/P)
850             FOR N=0 TO 20
860             Dc=T/(Ac*Ec)
870             Thet=Gc*T*P
880             Pd=P*(1+Dc)
890             Cdl=Ci+Ri*Thet
900             Cdr=Ci-Ri*Thet
910             Alfl=ATN(Cdl/Pd)
920             Alfr=ATN(Cdr/Pd)
930             Sl=Ei*ABS(COS(Alf)/COS(Alfl)*(1+Dc)-1)      ! Pa
940             Sr=Ei*ABS(COS(Alf)/COS(Alfr)*(1+Dc)-1)      ! Pa
950             Sl(N)=Sl/1E6
960             Sr(N)=Sr/1E6
970             T(N)=T/1000
980             T=T+Tm/20
990             NEXT N
1000            RETURN
1010 List:      INPUT "PRINTER IS 0 (Hardcopy) or 16 (CRT)?",A
1020            PRINTER IS A
1030            PRINT "Program CABLE1";LIN(2)
1040            IMAGE "    Cable Tension        Left Lay Stress        Right Lay St
ress"
1050            IMAGE "          kN                       MPa                     MPa
"
1060            PRINT USING 1040
1070            PRINT USING 1050
1080            PRINT LIN(2)
1090            FOR I=0 TO 20
1100               PRINT USING "5X,DDDDD.D,15X,DDDDD.D,15X,DDDDD.D ";T(I),Sl(I),S
r(I)
1105            NEXT I
1110            IF A=0 THEN PRINT PAGE
1120            PRINTER IS 16
1130            PRINT "If you want a graph of this data press CONT."
1150            RETURN
1160 Graph:    GRAPHICS
1170           PDIR 0
1180           LINE TYPE 1
1190           MOVE T(0),Sl(0)
1200           FOR I=1 TO 20
1210           DRAW T(I),Sl(I)
1220           NEXT I
1230           LINE TYPE 3
1240           MOVE T(0),Sr(0)
1250           FOR N=1 TO 20
1260           DRAW T(N),Sr(N)
1270           NEXT N
1280           PAUSE
1290           RETURN
```

```
10   ! Program CABLE2,Version 1.0, Updated 81/2/11
20   ! Stored on F. Roy File 1
30   !
40   !
50   ! Program CABLE2,for estimating the stress in the conductors
60   ! of an electro-mechanical cable having a wire rope core with
70   ! the conductors helically wound outside this core.
80   ! This version of CABLE estimates conductor stress vs. helix
90   ! diameter,thus representing the adjustment of lay angle by
100  ! increasing helix diameter for a fixed pitch length.
110  ! Units are metric.
120  !
130  !
140  ! List of Variables
150  !
160  !     Pi = Measured pitch length of conductor helix
170  !     Ec = Modulus of elasticity of wire rope core
180  !     Ei = Modulus of elasticity of conductor bundle
190  !     Gc = Modulus of twist of wire rope core
200  !     Ac = Sectional area of wire rope core
210  !     Ai = Sectional area of metal conductor bundle
220  !     Di = Measured mean diameter through conductors
230  !     Fc = Load on wire rope core
240  !     Fi = Load carried by conductor bundle
250  !     F =  Total load on cable
260  !     Si = Stress in conductor bundle
270  !
280  !
290 Main: GOSUB Init
300 Loop: GOSUB Input
310       GOSUB Calc
320       GOSUB List
330       PAUSE
340       GOSUB Plotsheet
350       GOSUB Graph
360       PAUSE
370       GOTO Loop
380       END
390 !
400 !
410 Init: DIM Fl(20),Fr(20),Sl(20),Sr(20),D(20),Lp(20),Alf(20)
420        DATA .174,81.3E+9,19.3E+9,24.4E-6,42.1E-6,16.0E-6,.0183,4450
430        READ Pi,Ec,Ei,Gc,Ac,Ai,Di,Fc
440       RETURN
450 !
460 Input:RETURN
470 !
480 Plotsheet: GCLEAR
490            LINE TYPE 1
500            CSIZE 3,.5
510            SCALE 10,36,-10,41
520            CLIP 15,35,0,40
530            AXES 5,5,15,0
540            UNCLIP
550            LORG 5
560            LDIR 0
570            FOR I=15 TO 35 STEP 5
580              MOVE I,-1
590              LABEL USING "K";I
600            NEXT I
610            MOVE 25,-4
620            LABEL USING "K";"Lay Angle - Deg."
630            MOVE 28,25
640            LABEL USING "K";"Prog.CABLE2"
650            MOVE 28,23
660            LABEL USING "K";"Nominal Cable Load is ";Fc/1000;" kN"
```

```
670            MOVE 28,20
680            LABEL USING "K";"Solid Line is LEFT LAY"
690            MOVE 28,18
700            LABEL USING "K";"Dotted Line is RIGHT LAY"
710            MOVE 15,31.85
720            LINE TYPE 5
730            DRAW 35,31.85
740            LINE TYPE 1
750            MOVE 32,32.5
760            LABEL USING "K";"LIMIT STRESS"
770            LDIR PI/2
780            FOR I=0 TO 40 STEP 5
790               MOVE 14.5,I
800               LABEL USING "K";I
810            NEXT I
820            MOVE 13.5,20
830            LABEL USING "K";"Conductor Stress   MPa "
840            RETURN
850 Calc:     FOR I=1 TO 15
860           D(I)=Di*1000
870           Ci=PI*Di
880           Alfa=ATN(Ci/Pi)
890           Alf(I)=Alfa*180/PI
900           L=SQR(Pi^2+Ci^2)
910           Lp(I)=L/Pi
920           Dc=Fc/(Ac*Ec)
930           Thet=Gc*Fc*Pi
940           Pd=Pi*(1+Dc)
950           Cdl=Ci+Di/2*Thet
960           Cdr=Ci-Di/2*Thet
970           Alfl=ATN(Cdl/Pd)
980           Alfr=ATN(Cdr/Pd)
990           Sl=Ei*ABS(COS(Alfa)/COS(Alfl)*(1+Dc)-1)
1000          Sr=Ei*ABS(COS(Alfa)/COS(Alfr)*(1+Dc)-1)
1010          Sl(I)=Sl/1E6
1020          Sr(I)=Sr/1E6
1030          Fil=Sl*Ai*COS(Alf)
1040          Fir=Sr*Ai*COS(Alf)
1050          Fl(I)=Fil+Fc
1060          Fr(I)=Fir+Fc
1070          Di=Di+.05*Di
1080          NEXT I
1090        RETURN
1100 !
1110 List:  DEG
1120        INPUT "PRINTER IS 0 (Hardcopy),or 16(CRT)?",A
1130        PRINTER IS A
1140        PRINT PAGE
1150        PRINT "Program CABLE2";LIN(2)
1160        PRINT SPA(2);"Initial Values";LIN(1)
1170        PRINT SPA(4);"Mean diameter thru conductors",D(1),"mm."
1180        PRINT SPA(4);"Load on wire rope core",Fc,"Newton"
1190        PRINT LIN(2)
1200        PRINT SPA(2);"Output";LIN(2)
1210        PRINT SPA(1);"LEFT LAY";LIN(1)
1220        IMAGE "Cable Load   Conductor Stress  Helix Dia.  Lay Takeup  Lay An
gle"
1230        IMAGE "   kN                   MPa             mm           %             De
g."
1240        PRINT USING 1220
1250        PRINT USING 1230
1260      FOR J=1 TO 15
1270        PRINT USING "DDDDD.DD,10X,DDDDD.DD,5X,DDD.DD,7X,DDD.DD,7X,DDD.DD";Fl
(J)/1000,Sl(J),D(J),Lp(J),Alf(J)
1280      NEXT J
1290        PRINT LIN(3)
```

```
1300         PRINT SPA(1);"RIGHT LAY";LIN(1)
1310         PRINT USING 1220
1320         PRINT USING 1230
1330       FOR K=1 TO 15
1340         PRINT USING "DDDDD.DD,10X,DDDDD.DD,5X,DDD.DD,7X,DDD.DD,7X,DDD.DD";Fr
(K)/1000,Sr(K),D(K),Lp(K),Alf(K)
1350       NEXT K
1360         RAD
1370         PRINTER IS 16
1380         PRINT "If you want a graph of this data press CONT."
1390     RETURN
1400 Graph:  PRINT PAGE
1410         GRAPHICS
1420         PDIR 0
1430         LINE TYPE 1
1440         MOVE Alf(1),Sl(1)
1450         FOR I=1 TO 15
1460         DRAW Alf(I),Sl(I)
1470         NEXT I
1480         LINE TYPE 3
1490         MOVE Alf(1),Sr(1)
1500         FOR N=1 TO 15
1510         DRAW Alf(N),Sr(N)
1520         NEXT N
1530         PAUSE
1540       RETURN
```

```
10   ! Program CABLE3,Version 1.0, Updated 81/2/13
20   ! Stored on F. Roy File 1
30   !
40   !
50   ! Program CABLE3,for estimating the stress in the conductors
60   ! of an electro-mechanical cable having a wire rope core with
70   ! the conductors helically wound outside this core.
80   ! This version of CABLE estimates conductor stress vs. pitch
90   ! length,thus representing the adjustment of lay angle by
100  ! decreasing pitch length for a fixed helix diameter.
110  ! Units are metric.
120  !
130  !
140  ! List of Variables
150  !
160  !     Pi = Measured pitch length of conductor helix
170  !     Ec = Modulus of elasticity of wire rope core
180  !     Ei = Modulus of elasticity of conductor bundle
190  !     Gc = Modulus of twist of wire rope core
200  !     Ac = Sectional area of wire rope core
210  !     Ai = Sectional area of metal conductor bundle
220  !     Di = Measured mean diameter through conductors
230  !     Fc = Load on wire rope core
240  !     Fi = Load carried by conductor bundle
250  !     F =  Total load on cable
260  !     Si = Stress in conductor bundle
270  !
280  !
290 Main: GOSUB Init
300 Loop: GOSUB Input
310       GOSUB Calc
320       GOSUB List
330       PAUSE
340       GOSUB Plotsheet
350       GOSUB Graph
360       PAUSE
370       GOTO Loop
380       END
390 !
400 !
410 Init: DIM F1(20),Fr(20),S1(20),Sr(20),P(20),Lp(20),Alf(20)
420        DATA .174,81.3E+9,19.3E+9,24.4E-6,42.1E-6,16.0E-6,.0183,4450
430        READ Pi,Ec,Ei,Gc,Ac,Ai,Di,Fc
440       RETURN
450 !
460 Input:RETURN
470 !
480 Plotsheet: PLOTTER IS "9872A"
490            LINE TYPE 1
500            CSIZE 3,.5
510            SCALE 10,36,-10,41
520            CLIP 15,35,0,40
530            AXES 5,5,15,0
540            UNCLIP
550            LORG 5
560            LDIR 0
570            FOR I=15 TO 35 STEP 5
580              MOVE I,-1
590              LABEL USING "K";I
600            NEXT I
610            MOVE 25,-4
620            LABEL USING "K";"Lay Angle - Deg."
630            MOVE 28,25
640            LABEL USING "K";"Prog.CABLE3"
650            MOVE 28,23
660            LABEL USING "K";"Nominal Cable Load is ";Fc/1000;" kN"
```

```
670             MOVE 28,20
680             LABEL USING "K";"Solid Line is LEFT LAY"
690             MOVE 28,18
700             LABEL USING "K";"Dotted Line is RIGHT LAY"
710             MOVE 15,31.85
720             LINE TYPE 5
730             DRAW 35,31.85
740             LINE TYPE 1
750             MOVE 32,32.5
760             LABEL USING "K";"LIMIT STRESS"
770             LDIR PI/2
780             FOR I=0 TO 40 STEP 5
790               MOVE 14.5,I
800               LABEL USING "K";I
810             NEXT I
820             MOVE 13.5,20
830             LABEL USING "K";"Conductor Stress   MPa "
840             RETURN
850 Calc:      FOR I=1 TO 15
860             P(I)=Pi*1000
870             Ci=PI*Di
880             Alfa=ATN(Ci/Pi)
890             Alf(I)=Alfa*180/PI
900             L=SQR(Pi^2+Ci^2)
910             Lp(I)=L/Pi
920             Dc=Fc/(Ac*Ec)
930             Thet=Gc*Fc*Pi
940             Pd=Pi*(1+Dc)
950             Cdl=Ci+Di/2*Thet
960             Cdr=Ci-Di/2*Thet
970             Alfl=ATN(Cdl/Pd)
980             Alfr=ATN(Cdr/Pd)
990             Sl=Ei*ABS(COS(Alfa)/COS(Alfl)*(1+Dc)-1)
1000            Sr=Ei*ABS(COS(Alfa)/COS(Alfr)*(1+Dc)-1)
1010            Sl(I)=Sl/1E6
1020            Sr(I)=Sr/1E6
1030            Fil=Sl*Ai*COS(Alf)
1040            Fir=Sr*Ai*COS(Alf)
1050            Fl(I)=Fil+Fc
1060            Fr(I)=Fir+Fc
1070            Pi=Pi-.05*Pi
1080            NEXT I
1090          RETURN
1100 !
1110 List:    DEG
1120          INPUT "PRINTER IS 0 (Hardcopy),or 16(CRT)?",A
1130          PRINTER IS A
1140          PRINT "Program CABLE3";LIN(2)
1150          PRINT SPA(2);"Initial Values";LIN(1)
1160          PRINT SPA(4);"Pitch Length ";P(1);" mm."
1170          PRINT SPA(4);"Load on wire rope core ";Fc;" Newton"
1180          PRINT LIN(2)
1190          PRINT SPA(2);"Output";LIN(2)
1200          PRINT SPA(1);"LEFT LAY";LIN(1)
1210          IMAGE "Cable Load   Conductor Stress  Pitch Len.  Lay Takeup  Lay An
gle"
1220          IMAGE "   kN                 MPa           mm            %            De
g."
1230          PRINT USING 1210
1240          PRINT USING 1220
1250        FOR J=1 TO 15
1260          PRINT USING "DDDDD.DD,10X,DDDDD.DD,5X,DDD.DD,7X,DDD.DD,7X,DDD.DD";Fl
(J)/1000,Sl(J),P(J),Lp(J),Alf(J)
1270        NEXT J
1280          PRINT LIN(3)
1290          PRINT SPA(1);"RIGHT LAY";LIN(1)
```

```
1300        PRINT USING 1210
1310        PRINT USING 1220
1320      FOR K=1 TO 15
1330        PRINT USING "DDDDD.DD,10X,DDDDD.DD,5X,DDD.DD,7X,DDD.DD,7X,DDD.DD";Fr
(K)/1000,Sr(K),P(K),Lp(K),Alf(K)
1340      NEXT K
1350        RAD
1351        IF A=0 THEN PRINT PAGE
1360        PRINTER IS 16
1370        PRINT "If you want a graph of this data press CONT."
1380    RETURN
1390 Graph:  GRAPHICS
1400         PDIR 0
1410         LINE TYPE 1
1420         MOVE Alf(1),Sl(1)
1430         FOR I=1 TO 15
1440         DRAW Alf(I),Sl(I)
1450         NEXT I
1460         LINE TYPE 3
1470         MOVE Alf(1),Sr(1)
1480         FOR N=1 TO 15
1490         DRAW Alf(N),Sr(N)
1500         NEXT N
1510         PAUSE
1520      RETURN
```

Program CABLE1

Cable Tension kN	Left Lay Stress MPa	Right Lay Stress MPa
0.0	0.0	0.0
2.2	14.2	8.4
4.4	28.3	16.8
6.7	42.5	25.2
8.9	56.7	33.7
11.1	70.8	42.1
13.3	85.0	50.5
15.6	99.2	59.0
17.8	113.3	67.4
20.0	127.5	75.9
22.2	141.7	84.4
24.5	155.9	92.9
26.7	170.0	101.3
28.9	184.2	109.8
31.1	198.4	118.3
33.4	212.6	126.9
35.6	226.8	135.4
37.8	241.0	143.9
40.0	255.1	152.4
42.3	269.3	161.0
44.5	283.5	169.5

Program CABLE2

Initial Values

Mean diameter thru conductors	18.3	mm.
Load on wire rope core	4450	Newton

Output

LEFT LAY

Cable Load kN	Conductor Stress MPa	Helix Dia. mm	Lay Takeup %	Lay Angle Deg.
4.90	28.34	18.30	1.05	18.28
4.91	28.63	19.22	1.06	19.13
4.91	28.95	20.18	1.06	20.02
4.92	29.30	21.18	1.07	20.93
4.92	29.67	22.24	1.08	21.88
4.93	30.07	23.36	1.09	22.86
4.94	30.50	24.52	1.09	23.88
4.95	30.95	25.75	1.10	24.93
4.95	31.44	27.04	1.11	26.02
4.96	31.95	28.39	1.12	27.14
4.97	32.50	29.81	1.14	28.29
4.98	33.07	31.30	1.15	29.47
4.99	33.68	32.86	1.16	30.68
5.00	34.31	34.51	1.18	31.92
5.01	34.97	36.23	1.19	33.19

RIGHT LAY

Cable Load kN	Conductor Stress MPa	Helix Dia. mm	Lay Takeup %	Lay Angle Deg.
4.72	16.93	18.30	1.05	18.28
4.71	16.18	19.22	1.06	19.13
4.70	15.37	20.18	1.06	20.02
4.68	14.50	21.18	1.07	20.93
4.67	13.57	22.24	1.08	21.88
4.65	12.57	23.36	1.09	22.86
4.63	11.49	24.52	1.09	23.88
4.62	10.34	25.75	1.10	24.93
4.60	9.12	27.04	1.11	26.02
4.58	7.83	28.39	1.12	27.14
4.55	6.45	29.81	1.14	28.29
4.53	5.00	31.30	1.15	29.47
4.51	3.48	32.86	1.16	30.68
4.48	1.88	34.51	1.18	31.92
4.45	.22	36.23	1.19	33.19

Program CABLE3

Initial Values

Pitch Length 174 mm.
Load on wire rope core 4450 Newton

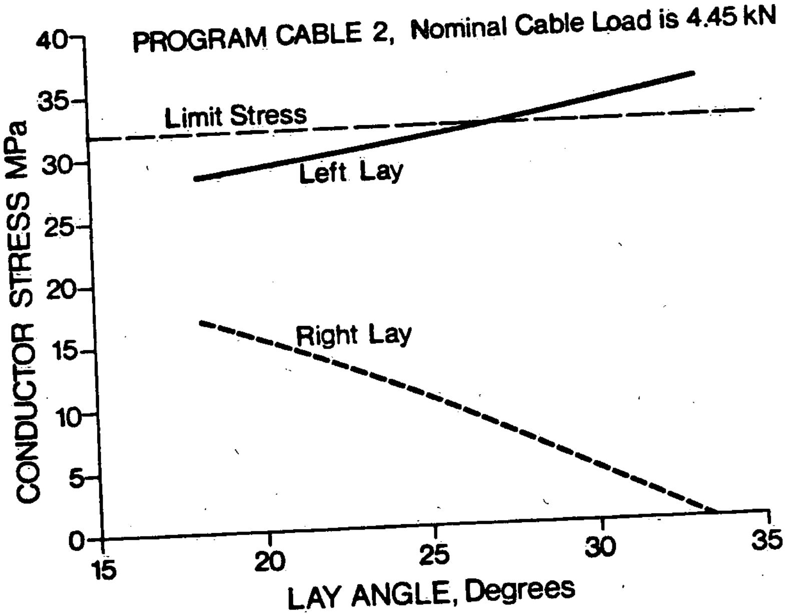
Output

LEFT LAY

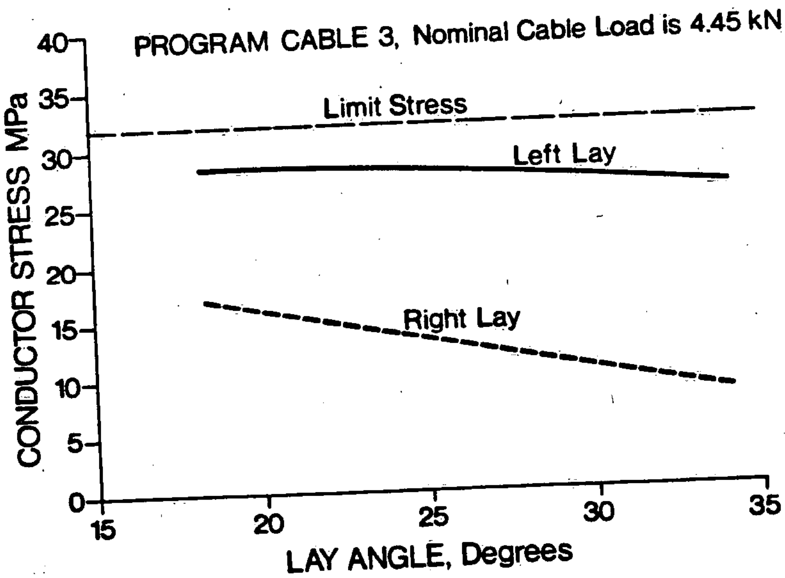
Cable Load kN	Conductor Stress MPa	Pitch Len. mm	Lay Takeup %	Lay Angle Deg.
4.90	28.34	174.00	1.05	18.28
4.90	28.34	165.30	1.06	19.18
4.90	28.32	157.04	1.06	20.11
4.90	28.28	149.18	1.07	21.08
4.90	28.23	141.72	1.08	22.08
4.90	28.15	134.64	1.09	23.12
4.90	28.05	127.91	1.10	24.20
4.90	27.92	121.51	1.11	25.32
4.89	27.76	115.44	1.12	26.48
4.89	27.57	109.66	1.13	27.67
4.89	27.35	104.18	1.14	28.89
4.88	27.09	98.97	1.16	30.15
4.88	26.80	94.02	1.17	31.44
4.87	26.47	89.32	1.19	32.77
4.87	26.10	84.86	1.21	34.12

RIGHT LAY

Cable Load kN	Conductor Stress MPa	Pitch Len. mm	Lay Takeup %	Lay Angle Deg.
4.72	16.93	174.00	1.05	18.28
4.71	16.45	165.30	1.06	19.18
4.71	15.95	157.04	1.06	20.11
4.70	15.43	149.18	1.07	21.08
4.69	14.88	141.72	1.08	22.08
4.68	14.31	134.64	1.09	23.12
4.67	13.72	127.91	1.10	24.20
4.66	13.11	121.51	1.11	25.32
4.65	12.47	115.44	1.12	26.48
4.64	11.81	109.66	1.13	27.67
4.63	11.14	104.18	1.14	28.89
4.62	10.45	98.97	1.16	30.15
4.61	9.75	94.02	1.17	31.44
4.59	9.03	89.32	1.19	32.77
4.58	8.31	84.86	1.21	34.12



PROGRAM CABLE 2, Nominal Cable Load is 4.45 kN
Limit Stress
Left Lay
Right Lay
CONDUCTOR STRESS MPa
0
5
10
15
20
25
30
35
40
15
20
25
30
35
LAY ANGLE, Degrees



PROGRAM CABLE 3, Nominal Cable Load is 4.45 kN
Limit Stress
Left Lay
Right Lay
CONDUCTOR STRESS MPa
0
5
10
15
20
25
30
35
40
15
20
25
30
35
LAY ANGLE, Degrees

APPENDIX 5

Buoy Hull Description

1. General - The buoy hull is a modified Holland '28 sail boat hull The modification comprises changes to top side and house and does not affect hull lines.

   The hull is double chine, welded steel with the following major dimensions:

Length between perpendiculars	8.5 m (LOA)
Length on water line	7.5 m L
Beam	2.8 m BM
Water line beam	2.5 m B
Draft (over keel)	1.6 m H
Keel depth	0.7 m

   Lines of the hull were not available from the manufacturer except in the form of advertising brochure data.

   From these, estimates of the following properties were made:

   Area of water line plane 10.7 m (Aw)

   Displacement = Hull Volume x P 3.3 tonnes Vol. Disp. ∇ or Δ

   Area of mid ship section below water line $1.5\ m^2$ (Ax)

   Block co efficient = $\frac{\nabla}{LBH} = .11 \equiv C_b$

   Vertical co efficient = $\frac{\nabla}{AW.H} = .19 \equiv C\nu$

   Waterplane co efficient = $\frac{\nabla}{LBHC} = .58$ $C\omega$

   Midship section co efficient = $\frac{Ax}{BH} = .38 \equiv C$

APPENDIX 6

Estimation of Cable Loads

The analytical method for estimating forces on a mooring cable is based on the derivation of equations of dynamic equilibrium of the hull. Assuming no cross-coupling, there are at least six degrees of freedom, i.e. heave, surge, sway linear motions and yaw, roll, pitch angular motions, thus requiring six equations.

The equation of dynamic equilibrium is of the form

$$m\ddot{x}_\iota = F_1 + F_2 + F_3 + F_4 + F_5$$

where $F_1 \equiv$ hull motion induced force, i.e. $F_1 \alpha\ a\ddot{x}_\iota$

$F_2 \equiv$ hull damping force, i.e. $F_2 \alpha\ b\dot{x}_\iota$

$F_3 \equiv$ hull hyrostatic restoring force, i.e. $F_2 \alpha\ cx_\iota$

F_4 wave excitation force, i.e. $F_4 \alpha\ F_0 \cos (et + \emptyset)$

F_5 cable restoring force, i.e. $F_5 \alpha\ d\dot{x}_\iota$

The method involves solving the equation in each degree of freedom for hull motion x_ι. This motion would then be applied to the buoy end of the mooring cable, and from equations of dynamic equilibrium at this point on the cable, taking the anchor end as fixed, the tension in the cable induced by cable normal velocity through the water would result.

Thus even assuming only three degrees of freedom, i.e. heave, surge and pitch, as significant, it can be seen that this is a major calculation. It is also much influenced by various characteristics and co efficients associated with hull shape and mass distribution. It is concluded therefore, that estimates of cable load by this method would be no more reliable than those from less sophisticated approaches.

A less realistic method for estimating the cable tension is to assume the buoy remains fixed in space, and the cable tension maintains the buoy in static equilibrium.

The inertial force on a fixed structure is defined as

$$F_\iota = m_v a_\iota$$

where m_v is the virtual mass of the fluid, and a_ι is the acceleration of the fluid past the structure. The virtual mass is the mass of displaced fluid plus the added mass of entrained fluid. That is

$$m_v = \rho Vol. (1 + Cm).$$

The acceleration is the time derivative of the velocity field at the fixed point in space

$$F_\iota = \rho Vol. (1+Cm). \frac{Dv}{Dt}$$

where ρ is fluid density

Vol is displacement volume of buoy.

Cm. is the added mass co efficient characteristic of the buoy shape.

In addition to the inertial force, the fixed structure is also subject to drag forces. These are parameterized as

$$F_d = \tfrac{1}{2} C_D \rho . S . /V/V$$

Here C_D and S are the drag force co efficient and characteristic drag force area.

The horizontal and vertical components of wave induced forces on the fixed buoy would thus be:

$$F_H = \rho \, C_{i_h} \, Vol \, \frac{Du}{Dt} + \tfrac{1}{2} C_{D_H} \, S_h /u/u$$

$$F_V = \rho \, C_{\iota_V} \, Vol \, \frac{Dw}{Dt} + \tfrac{1}{2} C_{D_V} \, S_V /w/w$$

For a gravity wave in water, the velocity field is defined as.

$$u = \frac{Ag}{\omega} \frac{\cosh(kz + Kh)}{\cosh(Kh)} \cdot \cos(Kx-wt)$$

$$w = \frac{Ag}{\omega} \frac{\cosh(Kz + Kh)}{\cosh(Kh)} \cdot \sin(Kx-wt).$$

$$\frac{Du}{Dt} \simeq \frac{du}{dt} = - Ag \frac{\cosh(Kz + KL)}{\cosh(KL)} \cdot \sin(Kx-wt).$$

$$\frac{Dw}{Dt} \simeq \frac{dw}{dt} = Ag \frac{\cosh(Kz + KL)}{\cosh(KL)} \cdot \cos(Kx-wt).$$

Maxima occur when sin (Kt-wt) = cos (Kx-wt) = 1, that is when x=o and wt=o or wt = $\frac{\pi}{2}$, which is at wave crest (or trough) and at wave node.

Hence at wave crest, wt = o ∴ sin wt = o, cos wt = 1

$$F_{H_C} = \rho \; \tfrac{1}{2} C_{D_H} S_H |U_{max}| U_{max}$$

$$F_{V_C} = \rho \; C_{i_V} \text{Vol.} \frac{dw}{dt} max$$

while at wave node, wt = $\frac{\pi}{2}$, sin wt = 1, cos wt = o

$$F_{H_n} = \rho \; C_{i_H} \cdot \text{Vol.} \frac{du}{dt} max$$

$$F_{V_n} = \rho \; \tfrac{1}{2} C D_V \cdot S_V |W_{max}| W_{max}$$

An HP-45 Program "WAVFOR" was written to do these calculations, using the following input information:

$M_f p$	= mass of water =	1 tonne/m^3
Ci_v	= virtual mass co efficient for heave motions	= 1.8
Ci_H	= virtual mass co efficient for surge motions	= 1.1
Vol	= hull volume	= 3.3 m^3
C_{d_v}	= drag co efficient for heave motions	= 0.6
C_{d_h}	= drag co-efficients for surge motions	= 0.05
S_v	= horizontal projection of hull area in water = Aw	= 10.7 m^2
S_h	= vertical projection of hull area in water = ½ B.H.	= 1.26 m^2
G	= acceleration of gravity	= 9.806 m/sec^2
H	= water depth	= 22 m
K	= wave number	= 2Π/wave length
WL	= wave length	= $gT^2/2\Pi$
T	= wave period	

The wave height and period data for this calculation were taken from Marine Environment Data Service publications for the 1973 season at Station 66, Point Pelee, Ontario, which site was 22 km NW of the VAPS mooring in 18 m depth (10 fa.) and 21 km off shore, ESE of Point Pelee.

From the Percentage Exceedance graph, (Figure A6.1) wave heights in feet were taken, and converted to metres. A linear relation between wave height and peak period was drawn from the scatter plot of this data (Figure A6.2) and a period was assigned to each wave height as:

$$T = \frac{W.H.}{1.82} + 2.5$$

Wave length was then calculated from

$$WL = \frac{gT^2}{2\pi} \tanh \left(\frac{2\pi h}{WL}\right)$$

for a depth h of 22 m.

These numbers for wave height, period and wave length are recorded in a short data file in the sub routine INIT. in Program WAVFOR.

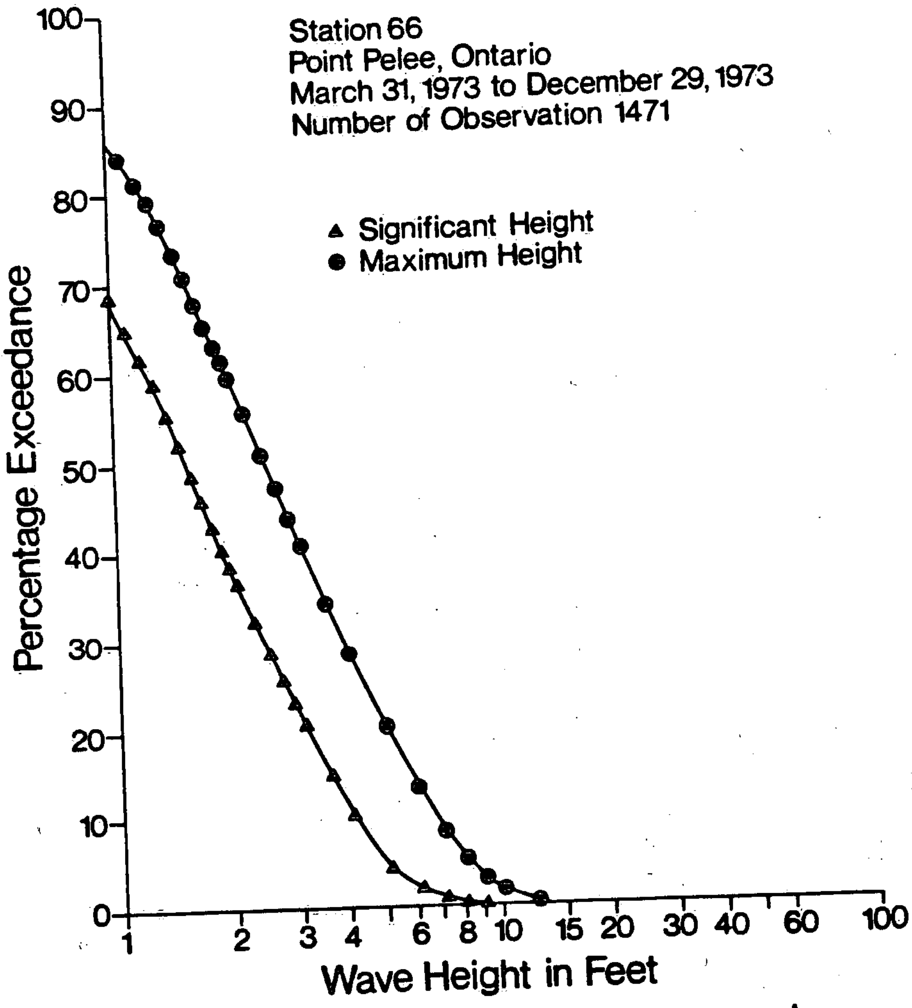


Figure A6-1 Percentage Exceedance graph

Station 66
Point Pelee, Ontario
March 31, 1973 to December 29, 1973
Number of Observation 1471

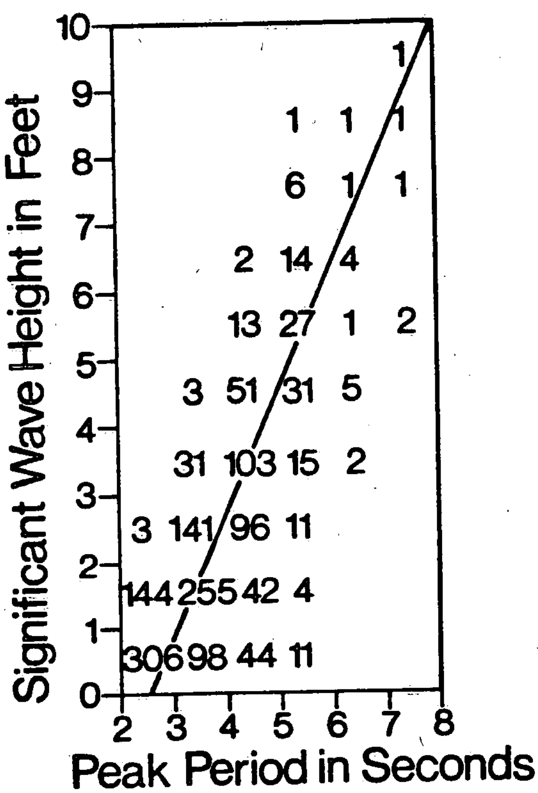


Figure A6-2 Wave-height / Period Scatter Diagram

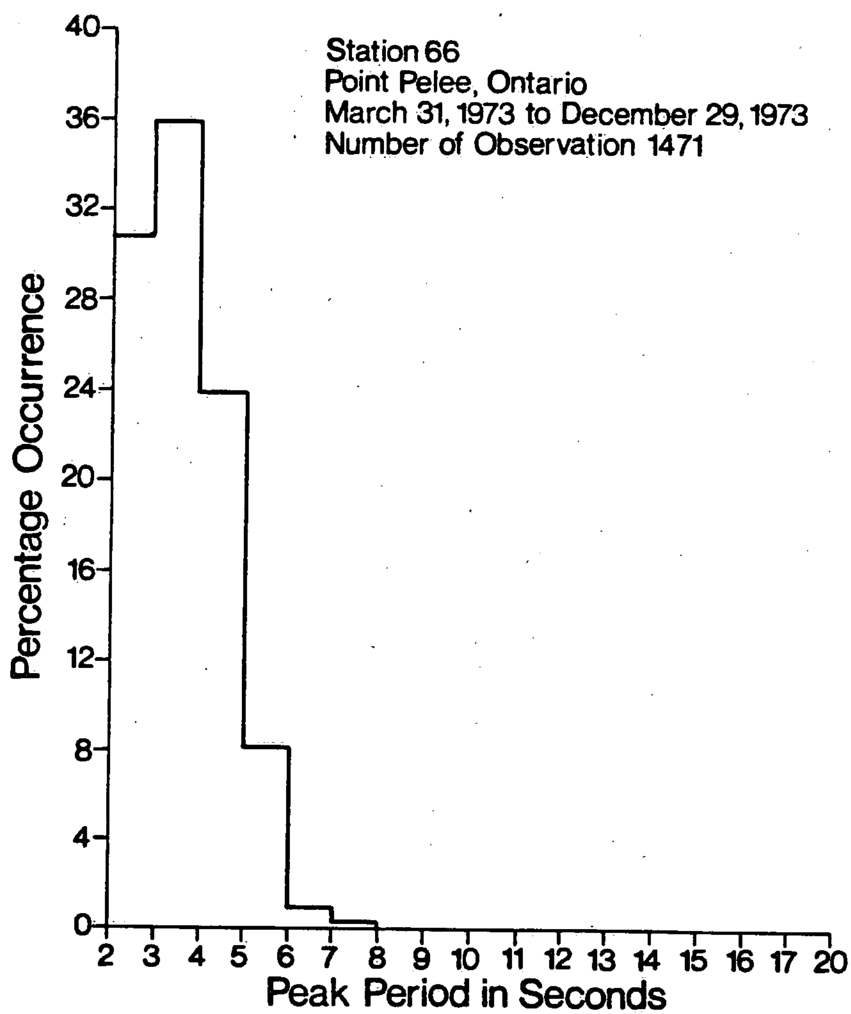


Figure A6.3 Wave Period Distribution

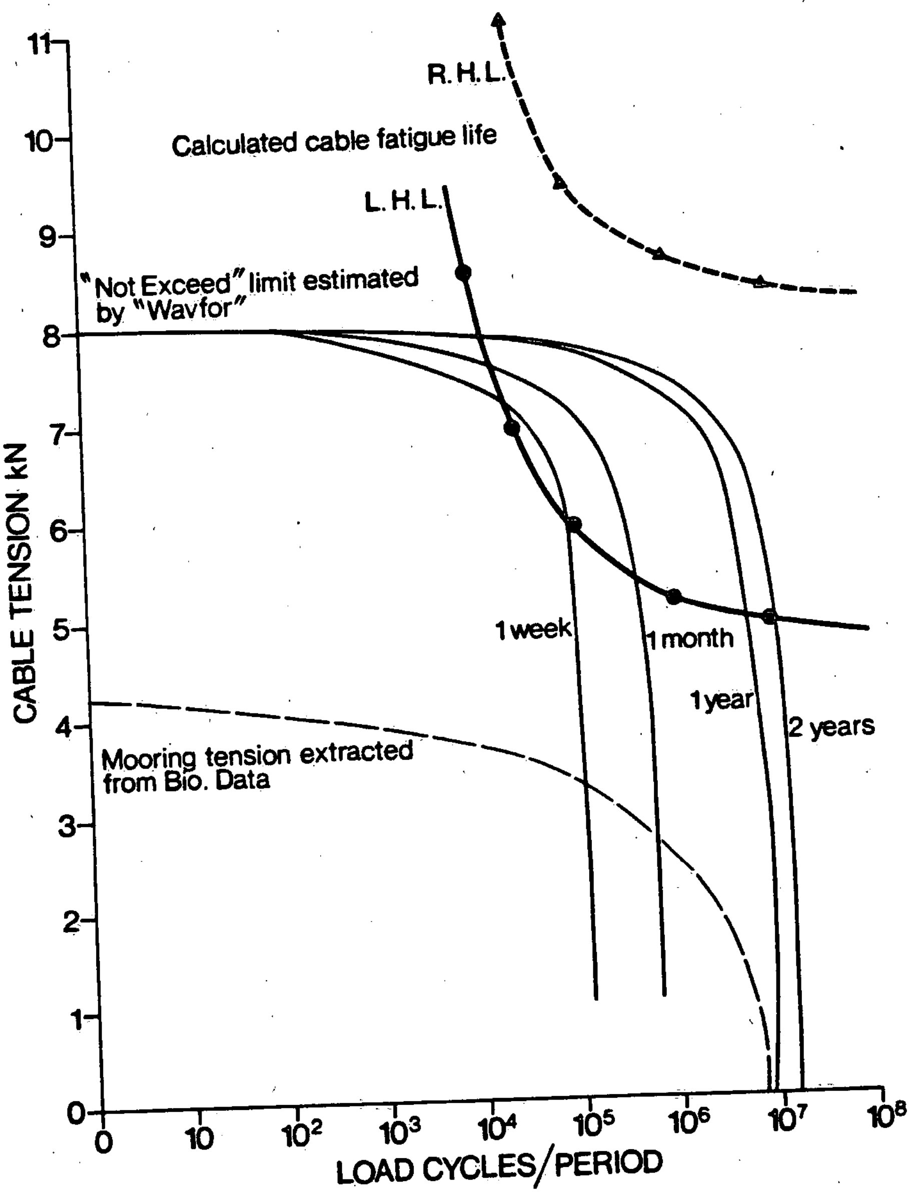


Figure A6.4 Fatigue Load Environment

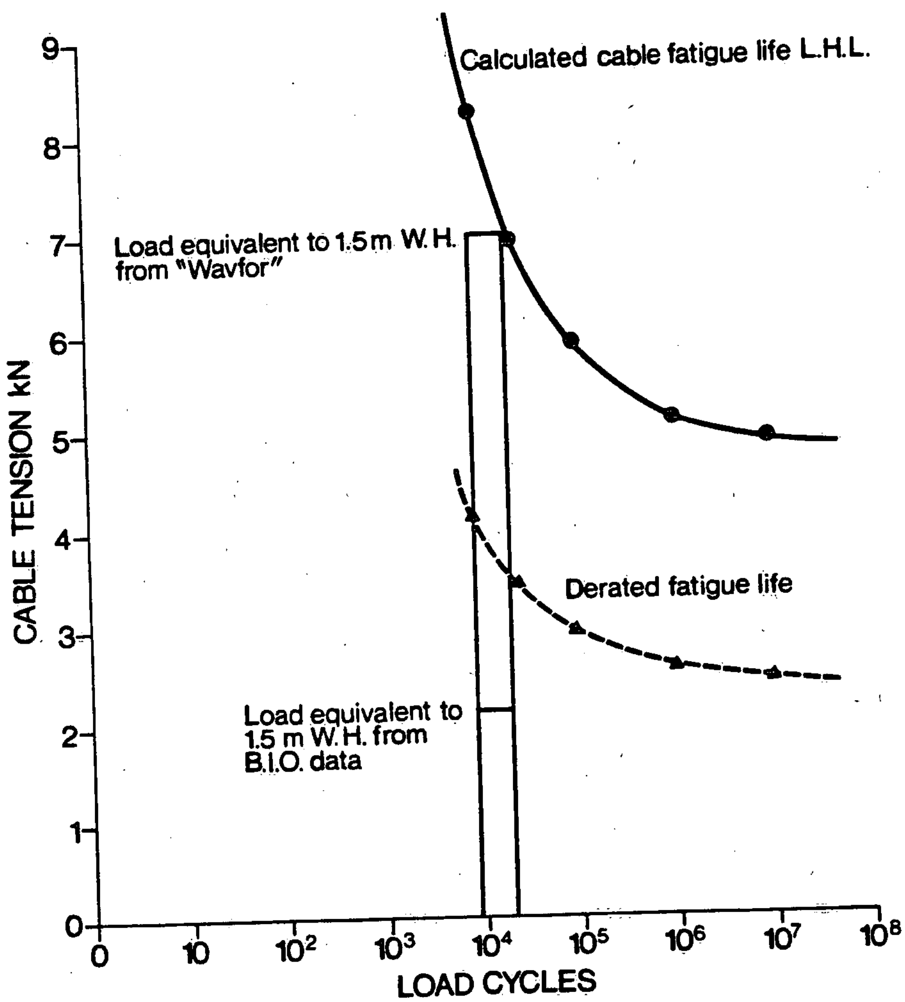


Figure A6.5 Cable Failure Condition

```
10 ! "WAVFOR";Version 1;Stored F.ROY File#1,5/3/81
20 ! Calculates maximum wave forces on GVAPS Buoy hull using equations
30 ! based on LINEAR waves.
40 !
50 ! Ref: Buoy Engineering,H.O.Berteaux,Wiley,1976; pg 78 ff.
60 !
70 !
80   GOSUB Init
90   GOSUB Calc
100  GOSUB Table
110  END
120 Init: DEG
130       OPTION BASE 1
140       DIM Hw(11),T(11),Lw(11),Fc(11),Dfc(11),Fhc(11),Fvc(11),Fhn(11),Fvn(11)
,Fn(11),Dfn(11)
150       DATA 4.5,12,120.,.61,3.6,20.23,.91,4.15,26.88,1.22,4.7,34.45,1.52,5.25
,42.88,1.83,5.8,51.98,2.13,6.35,61.53,2.44,6.9,71.26
160       DATA 2.74,7.45,81.05,3.05,8.0,90.75,3.96,9.65,119.75
170       FOR J=1 TO 11
180       READ Hw(J),T(J),Lw(J)
190       NEXT J
200        Mf=1
210        Ci=1.8
220        Vol=3.3
230        Cdv=.6
240        Cdh=.05
250        Sv=10.7
260        Sh=1.26
270        G=9.806
280        H=22
290        DEF FNSinh(I)=(EXP(I)-EXP(-I))/2
300        DEF FNCosh(I)=(EXP(I)+EXP(-I))/2
310        RETURN
320 !
330 !
340 Calc:    FOR N=1 TO 11
350          Z=T(N)/Lw(N)
360          K=2*PI/Lw(N)
370          A=Hw(N)/2
380          Umax=A*G*Z*FNCosh(K*(A+H))/FNCosh(K*H)
390          Wmax=A*G*Z*FNSinh(K*H)/FNCosh(K*H)
400          Dumax=A*G*K
410          Dwmax=A*G*K*FNSinh(K*(A+H))/FNCosh(K*H)
420          Fhc(N)=Mf*.5*Cdh*Sh*ABS(Umax)*Umax
430          Fvc(N)=Mf*Ci*Vol*Dwmax
440          Fc(N)=SQR(Fhc(N)^2+Fvc(N)^2)
450          Dfc(N)=ATN(Fvc(N)/Fhc(N))
460          Fhn(N)=Mf*Ci*Vol*Dumax
470          Fvn(N)=Mf*.5*Cdv*Sv*ABS(Wmax)*Wmax
480          Fn(N)=SQR(Fhn(N)^2+Fvn(N)^2)
490          Dfn(N)=ATN(Fvn(N)/Fhn(N))
500          NEXT N
510      RETURN
520 !
530 !
540 Table: IMAGE "     Wave Height  Period  Max.Force   Direction   Horz.    Vert.
"
550        IMAGE "          m            s         kN          Deg         kN       kN
"
560        IMAGE " Program WAVFOR -- Output"
570        IMAGE "     Force at wave crest "
580        IMAGE "     Force at wave node "
590        PRINT USING 560
600        PRINT LIN(2)
610        PRINT USING 570
620        PRINT LIN(1)
```

```
630          PRINT USING 540
640          PRINT USING 550
650          PRINT LIN(1)
660          FOR J=1 TO 11
670          PRINT USING "6X,DD.DD,5X,DD.DD,3X,DDDD.DD,6X,DDDD.DD ,2X,DDDD.DD,1X,D
DDD.DD";Hw(J),T(J),Fc(J),Dfc(J),Fhc(J),Fvc(J)
680          NEXT J
690          PRINT LIN(2)
700          PRINT USING 580
710          PRINT LIN(1)
720          PRINT USING 540
730          PRINT USING 550
740          PRINT LIN(1)
750          FOR J=1 TO 11
760          PRINT USING "6X,DD.DD,5X,DD.DD,3X,DDDD.DD,6X,DDDD.DD ,2X,DDDD.DD,1X,D
DDD.DD";Hw(J),T(J),Fn(J),Dfn(J),Fhn(J),Fvn(J)
770          NEXT J
780          RETURN
```

Program WAVFOR -- Output

Force at wave crest

Wave Height m	Period s	Max.Force kN	Direction Deg	Horz. kN	Vert. kN
4.50	12.00	6.47	88.35	.19	6.47
.61	3.60	6.07	89.90	.01	6.07
.91	4.15	6.89	89.85	.02	6.89
1.22	4.70	7.24	89.79	.03	7.24
1.52	5.25	7.23	89.74	.03	7.23
1.83	5.80	7.13	89.68	.04	7.13
2.13	6.35	6.92	89.63	.05	6.92
2.44	6.90	6.72	89.56	.05	6.72
2.74	7.45	6.48	89.48	.06	6.48
3.05	8.00	6.27	89.39	.07	6.27
3.96	9.65	5.61	89.06	.09	5.61

Force at wave node

Wave Height m	Period s	Max.Force kN	Direction Deg	Horz. kN	Vert. kN
4.50	12.00	12.51	56.75	6.86	10.47
.61	3.60	5.59	9.36	5.52	.91
.91	4.15	6.38	13.81	6.19	1.52
1.22	4.70	6.82	18.23	6.48	2.13
1.52	5.25	7.01	22.26	6.49	2.66
1.83	5.80	7.17	26.09	6.44	3.16
2.13	6.35	7.27	29.37	6.33	3.57
2.44	6.90	7.42	32.33	6.27	3.97
2.74	7.45	7.53	34.74	6.19	4.29
3.05	8.00	7.69	36.87	6.15	4.61
3.96	9.65	8.03	41.07	6.05	5.27

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MEMORANDUM · NOTE DE SERVICE

APPENDIX 7

F.E.Roy/NWRI/4311/ig

SECURITY - CLASSIFICATION - DE SÉCURITÉ	
OUR FILE /NOTRE RÉFÉRENCE	2242-4-80/81 ESO-31
YOUR FILE /VOTRE RÉFÉRENCE	
DATE	23 September, 1980

TO / À: A. Pashley
Engineering & Computing Support Group
National Water Research Institute

FROM / DE: F.E. Roy
Engineering & Computing Support Group
National Water Research Institute

SUBJECT / OBJET: Telephone Survey re VAPS Cable

As part of a broader examination of the VAPS Cable Failure Study, a telephone survey of identifiable experts and users of cables in lakes and seas was initiated.

The object of the survey was to identify anybody with relevant experience in the mooring of surface buoys in relatively shallow water with electro mechanical cable. The degree of success (duration) and cable design or construction reasons for success were then sought.

A set of 10 calls has been made to date, and the following is a preliminary report of the information obtained.

The definition of a successful mooring was one that survived exposure in its resident environment for more than six months.

To provide a perspective to this enquiry, it is necessary to review the VAPS configuration and the rationale for the design decisions that were taken.

The buoy size was based on a need to provide:

- diesel-electric plant, 1500 W output, greater than 60 day duration;
- accommodation for winch control and data recording panels;
- accommodation for operation/maintenance people for short periods on board;
- desire to have power source, control and data recording accessible for service.

An 8 metre sailboat hull was chosen as the most economic and readily available way to meet this need.

The single point slack mooring was chosen based on:

- relative ease of installation of a single anchor as opposed to three or more;
- vertical loads on the anchor due to heave in relatively shallow water are reduced by 2 to 1 scope in mooring, as opposed to taut mooring;
- single electro mechanical mooring cable was considered to have less risk of tangle, as opposed to separate mechanical mooring and electrical lines.

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The following people were contacted in this survey:

REF.		
1	RICK SWENSON	Naval Oceanographic R&D Administration (NORDA) Bay St. Louis Miss. 601-688-4702 Chairman I.E.E.E. - Cables & Connector Committee
2.	BILL LEWIS ALBERT PENCE	University of Washington - Applied Physics Lab. 206-543-1300
3.	ROD MESECAR	Oregon State University - School of Oceanography 503-754-2206
4.	GRAHAM SMITH	Mgr. of Engineering, Hermes Electronics, Halifax, N.S. 902-466-7491
5.	H. BERTEAUX	Woods Hole Oceanographic Institute of Ocean Engineering 617-548-2257
6.	BILL STANGE	Preformed Line Products, Marine Div., Cleveland 216-461-5200
7.	SIM WHITEHILL	Whitehill Manufacturing Ltd., Philadelphia, Pa. 215-494-2378
8.	MEREDITH SESSIONS	Scripps Institute of Oceanography, LaJolla, Calif. 714-452-3032
9.	RICK THOMPSON	I.O.S., Pat Bay 604-656-8363
10.	GEORGE FOWLER JOHN BROOKS J.G. DESSERAULT	Bedford Institute, Dartmouth, N.S. 902-426-3698

The following points were drawn from conversations with these people.

- Long term electro-mechanical (EM) single point moorings have been markedly unsuccessful, in that six months is the best duration. The problem is more difficult in shallow water where the length of the mooring is shorter for the amount of energy it must absorb.
- SWENSON has had good results with smaller, cylindrical telemeter buoys in 20 m depth, offshore in the Gulf of Mexico. These buoys are anchored with a three point mechanical mooring, and a separate electrical cable to a bottom mounted instrument.

...3

- SWENSON and WHITEHILL reported marginal success (six months) with smaller, cylindrical telemeter buoys on single point slack moorings, with the surface end of the cable buoyed with attached E&C floats. These moorings had EM connection to sub surface floats at 100 m depth. The subsurface floats were mechanical taut moorings to the bottom in >500 m.

- SESSIONS reported good success (9-12 months) with deep ocean single point moorings of catamaran (Bumblebee) buoys (Sessions & Brown , TNTS 1971, pg. 93). These moorings were in depths of 5000 m. However, the first 300 m of the mooring was a center core FTP sensor.

- In all successful systems, the mechanical and electrical terminations are separate. The PLP grips are examples. This is quite unlike the BIW moulded termination where conductors are rigidly moulded within the same frame as the mechanical strength member.

- MESECAR, SESSIONS, BERTEAUX all reported that the requirement for EM single point moorings has declined and studies now use smaller telemeter surface buoys, or drifter buoys with hanging sensor cables.

- Except where access to conductors along the cable length is required, as in FTP configurations, the preferred form of cable is with center core conductors and external helix or woven strength core. The major preference is for plow steel armor type strength members as experience with terminating and internal chaffing of Kevlar fiber types has not been good. However, for shorter, shallow moorings SWENSON preferred Kevlar, and recommended WHITEHILL on the basis of his good experience with Whitehill Manufacturing cables.

- Reasons for this preference were best articulated by MESECAR.
  - torque balance is better controlled in external strength member cables;
  - torque imbalance in strength member does not transfer load to conductors so effectively as torque imbalance in a center core;
  - center core conductors can be wound at shorter pitch;
  - conductors can be more easily protected from core pressure loads due to armour squeeze than from tension loads on external conductors due to center core twist and stretch;
  - tension loads on conductors due to bending are reduced, since conductors are near the neutral axis.

- MESECAR emphasized that it is often a more cost-effective approach to use "off-the-shelf" cable types standardized by the oil and offshore industry and invest money in making electronics match the cable, rather than design and procure a custom built cable.

- Desirable features of a cable for this application include:
  - all conductor jackets be pre-tested for water tight integrity, and absence of pinholes or jacket leaks;

...4

- conductors cabled around center core of the smallest conductors. Smallest conductor size should be not less than #18 AWG. Lay angle of this cabling should be greater than 20°. All conductors are stranded to obtain lowest modulus of elasticity compared to strength member.

- the cable core is water blocked with a viscous material to reduce flooding, but also to distribute core pressure loads from the strength member more evenly;

- the cable core is jacketed with a thin, but tough plastic, again to distribute core pressure loads evenly;

- the strength member is woven Kevlar, properly lubricated to prevent chafing, and of geometry chosen to ensure the modulus of the assembly is much larger than that of the conductor core;

- a tough abrasion resistant jacket is extruded over the Kevlar braid;

- there is a clear separation of the mechanical termination from the conductor core. A working loop of conductor core is provided between the mechanical termination and the electrical connector.

In summary, the impression gained was:-

- encouragement: Several design and construction shortcomings in both the BIW and ROMOR cables were identified. Deficiencies in the original mooring layout are also identified. Other people have had some success.

- caution: Such a mooring is a difficult job, as experience of others demonstrate. The G VAPS system is complex, and several areas in which this complexity can be reduced have been identified. The amount of data generated is large, and may be excessive for practical purposes. The investment required for improved mooring should be evaluated against the future need for the equipment and possible rationalization to reduced size and complexity, which may result in feasible internal power source, acoustic data link, or reduced cable complexity.

F.E. Roy

c.c. Head, ECSG