ASPECTS OF
MOORING IN DEEP WATER

By

Niels P. Dahl

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Signed: ______________

Golden, Colorado

Date: May 7, 1976

Approved: Bill Mitchell
Dr. B.J. Mitchell
Thesis Advisor

D. M. Bass
Dr. D.M. Bass
Head of Department
Petroleum Engineering

Golden, Colorado

Date: May 7, 1976

ABSTRACT

The purpose of this thesis is to cover various aspects of deep water mooring with specific application for oil and gas drilling and production from ships and semisubmersibles. The theoretical aspect is presented and the work is illustrated by example calculations.

Throughout the work, emphasis has been placed on mooring in deep water - i.e., to 1500 ft of water.

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INTRODUCTION

Offshore drilling activity for oil and gas has been on a steady increase since the early 50's and has only temporarily leveled out in recent years. For offshore drilling operations various drilling vessel configurations have been employed, e.g., jack-up's, drill ships and barges, and semisubmersibles. Jack-up's are in contact with the seafloor while drilling and therefore, station-keeping is not a problem; however, they have a limited water depth in which they can operate - namely less than 300 ft.

For many years offshore drilling has been conducted in water depth of more than 300 ft using drillships and semisubmersibles. Station-keeping for these floating vessels is handled with mooring systems and more recently, dynamic positioning. The combination of vessel-type and station-keeping systems will give four combinations, each with its application as determined from operational and economical considerations.

This thesis deals with mooring of ships and semisubmersibles and treats the special problems encountered in deep water (1500 ft) mooring systems design.

Drilling operations conducted from floating vessels are dependent upon the mooring system to keep the vessel within certain horizontal limits of the entry in the seafloor, entitled excursion, as measured in feet or in percent of total water depth. They are further dependent upon the system to maintain the position in such a fashion that drilling operations can be successfully carried out.

The distance of excursion is usually kept to within 6 to 10% of total water depth[1-3] even under the most severe environmental conditions. For normal operations the excursions should not amount to more than 2 to 3%[1-3] provided that the mooring system is designed to give maximum restoring force, which is the sum of the horizontal forces from the mooring system on the vessel as defined later in this thesis. Only in rare occasions should the excursion be more than 5 to 6%. Depending on the marine riser design, drilling will normally be suspended for excursions of a magnitude of 5 to 6%. Even though the marine riser normally can sustain these imposed stresses, the drill-pipe will cause excessive wear on the riser at these excursions.

Survival conditions exist for excursions beyond 8 to 10%[1-3] again depending on the marine riser design, and in this mode the riser is normally disconnected from the blowout preventer at the seafloor. During survival conditions, the excursion is only secondary to relieving the high mooring line tension.

ENVIRONMENTAL FORCES

The first parameters to be considered in a mooring systems design are the environmental forces acting on the vessel and the vessel's response to these forces, in order to establish the vessel's environmental resistance characteristics. The vessel's response will differ depending on the angle of attack of the environmental forces, and each of the attack angles causing large vessel movements must be studied.

The environmental forces to be studied are wind force, wave drift force, and current force. In obtaining data on these forces, the direction and occurrence frequency should be determined in addition to the amplitude.

The environmental forces will induce static forces to the vessel, however, due to the oscillatory changes in the wave drift force, and the gusty nature of the wind force, a certain amount of dynamic force are transferred to the mooring system.

The above mentioned forces will cause horizontal motion of the vessel. In addition hereto the waves will cause a heave motion which is the vertical up and down motion of the vessel and at the same time rolling motions around the three axis, respectively yaw, pitch, and roll as shown in Figure 1. These motions of the vessel will again cause dynamic forces to be transferred to the mooring system. Each of the forces will be dealt with separately and both the static and the dynamic forces will be treated. Equations are given for an approximate calculation of the load on the vessel from the static forces.

In most cases, the forces and the vessel response is obtained in connection with model tank tests in order to give a higher degree of accuracy, since one the greatest uncertainties in analyzing a mooring system is in determining the static and dynamic forces. This is especially true where more complicated vessel shapes are involved, as in the case of most semisubmersibles.

For mooring in deep water the effect of the dynamic forces is much less important than the static forces[1], since the vessel's heave and rolling motions for a given type of sea as a percent of total water depth becomes relatively smaller with increased water depth. For this reason emphasis in this thesis is placed on the static forces.

Wind Force

The wind force is a result of a change in direction of an air mass and thereby its momentum as it contacts a surface. A part of the total force is due to the drag of the air as it slips past a surface.

A propeller-type instrument is used to measure the wind velocity and is simultaneously measuring the wind direction. The wind velocity is reported as an effective velocity measured in knots and equal to 1.096 times a 5 min. mean reading[1].

The force induced onto a surface is a function of the wind velocity, and for simple shapes the force can be calculated. Below are listed equations for calculating the static wind force as published by The American Bureau of Shipping[8]:

$$F = 0.00338 \cdot A \cdot V_k^2 \cdot C_h \cdot C_s \qquad (1)$$

where F = wind force, lbf

A = the projected area of all exposed surfaces in either the upright or the tilted position, sq ft

V_k = wind velocity, knots

C_h = height coefficient (see Table 1)

C_s = shape coefficient (see Table 2)

Consideration should be given to the mean wind velocity as well as the maximum gust velocity. Harris[3] suggest calculation of the wind velocity from equation (2):

$$V_k = 0.6 \cdot V_a + 0.4 \cdot V_g \qquad (2)$$

where V_a = average wind velocity, knots

V_g = gust wind velocity, knots

In most cases, for mooring system design, only the static wind forces are considered, based upon the wind force calculated using equation (1).

An example relationship between the wind velocity and force on the vessel is given in Figure 2.

/

Wave Drift Force

In order to find the wave drift force, the significant wave height and wave period must be known. As described by Bascom[18], the significant wave height is defined as the average of the highest one-third of the waves (H_3), and the wave period is defined as the time, in seconds, for a wave crest to traverse a distance equal to one wave length where the wave length again is the horizontal distance between adjacent crests.

Wave action will cause horizontal motion of the vessel involving both a direct wave induced short period motion and a gradual long period oscillation[6-7]. This motion is caused by the wave drift force resulting from the change in wave momentum as part of the wave is reflected from the vessel. In regular seas the reflected waves causes a steady drift force resulting in a static force applied to the vessel. American Bureau of Shipping[8] has published equations for calculation of the static forces. For ship-shaped vessels the equations are:

Bow forces:

$$F_{bow} = (0.273 \cdot H^2 \cdot B^2 \cdot L)/T^4 \tag{3}$$

$$\text{where } T \geq 0.332 \cdot \sqrt{L}$$

$$F_{bow} = (0.273 \cdot H^2 \cdot B^2 \cdot L)/(0.664 \cdot \sqrt{L} - T)^4 \tag{4}$$

$$\text{where } T < 0.332 \cdot \sqrt{L}$$

Beam forces:

$$F_{beam} = (2.10 \cdot H^2 \cdot B^2 \cdot L)/T^4 \qquad (5)$$

$$\text{where } T \geq 0.642(B + 2D)^{1/2}$$

$$F_{beam} = (2.10 \cdot H^2 \cdot B^2 \cdot L)/(1.28(B + 2D)^{1/2} - T)^4 \qquad (6)$$

$$\text{where } T < 0.642(B + 2D)^{1/2}$$

where F = wave force, lbf

T = wave period, sec

H = significant wave height, ft

B = beam of vessel, ft

D = draft of vessel, ft

L = length of vessel, ft

Due to the complex shape of semisubmersible vessels, the wave drift force are normally determined by model tank tests.

Irregular waves cause a varying sequence of drift forces because of the changes in wave height and period. Investigations[6-7] have shown that the long period oscillations of the vessel can be of dominating influence in determining mooring line tension.

In determining the peak mooring forces from slow oscillatory motions, Hsu et al.[6] describe the basic method of calculating wave drift forces based on the concept of "Radiation Stress"[9] as explained with the following quotation: "It is well known that surface waves possess momentum which is directed parallel to the direction of propagation and is proportional to the squares of wave amplitude. Now if a wave train is reflected from an obstacle its momentum must be reserved. Conservation of momentum requires that there be a force exerted on the obstacle equal to the rate of change of a wave momentum." They found that the resulting average drift force per unit length as a function of incident wave height and the vessel's heave and sway motion for a ship-shaped vessel based on beam attack, is given by:

$$F = \frac{1}{2} \cdot \rho \cdot g \cdot a^2 \left[2(Q-1) \left(1 + \frac{A_s}{a} \cos(\theta_s + k\,x_1) \right) - Q \cdot \frac{A_h}{s} \left(\cos(\theta_h + k\,x_1) + \frac{A_s}{a} \cos(\theta_h - \theta_s) \right) \right] \tag{7}$$

where a = amplitude of incident wave

$Q = 2 \cdot \cosh(k(h-D))/\cosh(k \cdot h)$

A_h, A_s = amplitude of vessel heave and sway, respectively

θ_h, θ_s = phase angle of vessel heave and sway motion with respect to incident wave train surface elevation at the average position of the center line of the vessel, i.e., $x = 0$

h = water depth

k = wave number $= \frac{2\pi}{\lambda}$

λ = wave length

ρ = water density

g = acceleration of gravity

D = vessel draft

In setting up a mathematical model to describe the vessels motion in irregular seas Hsu <u>et al.</u>[6] combine the above equation (7) with a time-dependent wave drift force on a mass and non-linear spring system to illustrate the moored vessel, further assuming that "each of the waves of an irregular sea will impart to the moored vessel the same wave drift force which it would were it merely one of a sequence of regular waves," as follows:

$$m \cdot x'' + c \cdot x' + f(x) = g(t) \tag{8}$$

where m = virtual mass

c = damping

$f(x)$ = non-linear spring function

$g(t)$ = the wave drift force function that gives the average wave force over each wave cycle

The application of this model, however, must be used in connection with comprehensive testing in a model tank to obtain amplitudes of vessel heave and sway, and phase angles for different types of sea or knowledge of the vessel's response must be known.

The above model was developed for ship-shaped vessels. The slow drift oscillation force can be expected to have much less influence for open constructions, as is the case with semisubmersibles[6].

Static induced wave drift force is shown in Figure 2 for an example vessel as a function of significant wave height.

Current Force

The current force is a result of the change in the velocity of a mass of water and thereby its momentum as it contacts a surface. The drag force of water is a much greater part of the total water force than is air drag with respect to total wind force.

Measurement of the current velocity is made in a fashion similar to the wind measurement. The current velocity is expressed in knots. Ocean currents are normally fairly stable within a given water depth, however, they will change direction and velocity with increased water depth[10]. Current velocity profiles are often constant in a region, but can differ widely from region to region[10].

The current force constitutes a combination of the current as it affects the vessel, the marine riser, and the mooring system, mathematically represented by equation (9):

$$F_t = F_{ves} + F_{ris} + F_{mor} \tag{9}$$

The following equations can be used to calculate current forces for ship-shaped vessels[12]:

$$F_{beam} = 0.30 \cdot A \cdot V_c^2 \tag{10}$$

$$F_{bow} = 0.016 \cdot A \cdot V_c^2 \tag{11}$$

For semisubmersibles current forces on the bow or beam can be calculated from[12]:

$$F = (2.4 \cdot A_c + 5.7 \cdot A_f) \cdot V_c^2 \tag{12}$$

where F = current force, lbf

A = the wetted area, sq ft

A_c = total projected area of all cylindrical members below the surface, sq ft

A_f = total projected area of all other members below the surface, sq ft

V_c = current velocity, knots

The current force on the marine riser can be calculated from the following hydrodynamic equation[4,10]:

$$F_{ris} = 0.0457 \cdot C \cdot A_c \cdot \rho \cdot V_c^2 \tag{13}$$

where C = drag coefficient

ρ = fluid density, lbm/ft^3

For a linear current distribution of 2 knots at the surface and 1 knot at the seabottom, and a drag coefficient of 1[4,10], the horizontal reaction force at the vessel is no more than 12,800 lbf for a 24" diameter riser. This force is small compared to the other environmental forces and therefore normally disregarded.

Current forces acting on the mooring system are normally very small and hence they are disregarded in most mooring systems design.

An example relationship between the load on a vessel and the magnitude of the current velocity is shown in Figure 2.

MOORING PATTERN

Mooring patterns refers to the layout of the mooring lines, their number, and their position in terms of the vessel and in terms of each other (see Figure 11). The most common type of mooring system is the spread system with from one to twelve lines. These lines can be laid out in many different fashions and a great number of mooring patterns do exist. The reason for the diversity of patterns stems from an effort to gain the maximum restoring force from the mooring system in combination with the vessel's environmental resistance characteristics.

Some patterns are uni-directional where the mooring system is designed to take the biggest load in one given direction. This pattern is preferred in areas with a prevailing environmental force direction. Other patterns are omni-directional, constituting an often symmetrical pattern able to withstand loads from any direction.

Normally the vessel is moored with the bow toward the direction of the predominant environmental force. The mooring pattern selection is influenced by the magnitude, direction and occurrence frequency of the design forces and by the design of the vessel deck machinery.

Design of the optimum pattern is a very important factor in the total mooring system design, partly in reducing mooring line tension, and partly in order to minimize horizontal displacement and thus to stay within given excursion tolerances. The stiffer the system the more optimal it is in absorbing dynamic forces and thus reducing the vessel's potential for gaining momentum which can result in peak mooring forces, as the momentum must be absorbed in the mooring system[6]. If the system, however, becomes too stiff, it will cause excessive mooring line tension, even for small offsets, and the life of the mooring line will be severely impaired because of fatigue characteristics[1,15].

The optimum pattern is found by evaluating the vessel offset and the maximum tension in the mooring lines for different patterns for the environmental forces acting. Eventually, however, it will be a matter of economic "trade-off" where additional expenditure are not warrented by increase in mooring system efficiency.

MOORING LINES

The mooring line is the tie between the vessel and the anchor. There are several mooring line types and configurations, all employing chains, cables or combinations thereof, as listed below (see Figure 3):

1. All wirerope or all chain,
2. Clumb weight system; where a secondary anchor is placed at the end of the chain and the primary anchor attached to the secondary anchor by wirerope (not "piggy-back"),
3. Combination all chain; where one type of chain is used for the main portion of line from the vessel and a heavier chain used along the sea bottom and attached to the anchor,
4. Combination wirerope-chain; where wirerope is used from the vessel to the seafloor and chain is used to tie into the anchor.

Presently the two most common configurations are (a) all-wirerope or (b) all-chain. These systems are suitable in water depth to 1500 ft. The actual choice between wirerope and chain depends on expected mooring line load, water depth, environmental forces, handling equipment, storage facilities on board the vessel, and economics.

For low water depth applications wirerope mooring lines result in too stiff of a mooring system[1] and the all-chain mooring line system is generally preferred. However, with increased water depth the all-chain system is in the most cases too loose and requires very high pretensioning.

Beyond 1500 ft water depth - in what is normally called ultra deep water - problems arises with the all-wirerope system as well as the all-chain system. This is mainly due to problems in the manufacturing of these long lines and in handling. Of the four mooring line systems listed above, the fourth - combination wirerope-chain system - seems to be the most suited as reported by Childers[1]. Drawbacks with this system is due to the necessity of a new design of the deck handling equipment to give reasonable deployment and retrieving of the mooring line. In addition to the handling problems Atwood, et al.[13], reported that the varying vibration characteristics of the wirerope and the chain can result in severe connection problems between the two.

Working load of wirerope and chain are normally one-third of their rated breaking strengths[1-2]. Fatigue characteristics[2,14] is a major problem of the wirerope as well as the chain mooring lines, necessitating that the working load be kept low, as it will reduce the strength and the life of the lines. The higher the peak load and the longer the spread between high and low tension the shorter the life. Fatigue of the lines is one of the biggest reasons for line breakage[2,13]. For reasons of fatigue most mooring systems are designed for a maximum tension of one-half the break strength.

The correct pretensioning of the mooring lines is very important in the total mooring line design. Optimum pretensioning load has been reported[1-2] to be such that the maximum working load (one-third of the breaking strength) occurs at the maximum allowable excursion for continued drilling, normally 5 to 6% of total water depth. Hsu *et al.*[6] shows in connection with his development of the peak forces from oscillatory drift how the optimum pretensioning can be obtained; however, this procedure requires model tank tests. If the pretensioning is too high, it will result in excessive tension in the mooring lines even for small vessel offsets and causes the wirerope or chain life to be severely impaired due to their fatigue characteristics. If the pretensioning is too small, the mooring system will be too loose and this results in large excursions before sufficient restoring force is obtained. This could cause undue drilling stoppage and it could result in an increase in peak mooring line tension since the vessel would be allowed to obtain momentum, which eventually must be absorbed in the mooring lines.

ANCHORS

The anchor will supply the main holding power for the mooring system. The most common anchors used are one of the following light weight type anchors[1-3]: (see Figure 4)

1. The U.S. Navy Light Weight Type Anchor (LWT)
2. The Danforth Anchor
3. The Stockless Anchor

Beck[14] reports on testing with an even later design entitled "Boss" (see Figure 4) which generally outperformes the others by digging in faster in sand as well as mud bottoms, by giving increased pulling power and by avoiding ball-up (see Figure 5).

All of the anchors are of the dynamic type which will increase their holding power with increased pull. It should be pointed out that this is true only if there is no uplifting force on the anchor. Even at a pull of 6° between the force and the sea bottom the holding power will decrease rapidly[1-2]. For this reason, it is important that sufficient mooring line is deployed at all times to insure that the end of the mooring line is parallel with the ocean floor at or before the anchor.

The anchor sizes normally used are in the range of 20,000 - 30,000 lbf dry weight[1-3]. The maximum holding power will among other things vary with the anchor weight. For small anchors to 15,000 lbf the holding power is in the range of 12 to 17 times[2] their dry weight. For larger anchors to 30,000 lbf the holding power will decline and be around 8 to 11 times[2] their dry weight. For even larger anchors the holding power will generally be below 10 times[2] their dry weight. The holding power will vary with the type of sea bottom depending on whether it is sand or mud. However, the above indicated holding powers seem to be good average values.

The type of sea bottom will affect the anchors tendency to dig in. Here it is important to adjust the fluke angle - which is the angle between the anchor shaft and blade as seen from Figure 5 - to correct value[1-3]. Even though the correct fluke angle will vary for different types of anchors, 50° seems to be a good value in mud and 30° to 35° best in sand[3]. For unknown or mixed sea bottom, a fluke angle of 35° to 40° should be used[3].

As seen from above, an increase in anchor dry weight does not significantly increase holding power because the power factor will decrease. For very large semisubmersibles and a combination of severe environmental conditions and deep water operation, single anchors will not give sufficient holding power. Very often therefore "piggy-backing" is necessary, which is two anchors used in series[1].

In addition to the common type anchors other anchor types are used. Of interest is anchor piles specially used in areas where hard rock bottom precludes the use of conventional anchors[3]. A more recent innovation is explosive-set anchors. This anchor type is embedded into the seafloor by the aid of an explosive charge. The advantage of these anchors is a very large holding power; however, the anchor is not recoverable.

MOORING

Mooring is here meant in a practical sense to constitute all the operations necessary from the time the vessel is on location to the time when the spudding for the drilling operation can take place.

In practice the mooring of a large drilling vessel is aided by work boats or anchor handling boats. It is necessary that the proper size boat be used; one that can handle the weight of anchor(s) and mooring line during deployment of the anchor and at the same time output sufficient amount of bollard pull to overcome the drag from the mooring line through the water and along the sea bottom. These drag forces are especially severe if chain mooring lines are being deployed. In Figure 6 is shown the normal deployment geometry (ABCD).

Sufficient length of mooring line must be deployed. As previously stated, enough line must be deployed to insure that the mooring line is tangent to the seafloor at or before the anchor(s), even at maximum offset.

The cable length required for mooring is determined by the calculated mooring line length, plus a length for setting of the anchor and a length for vessel positioning. The amount of drag while setting the anchor can be as much as 300 ft in soft mud bottom[13].

The solution of the mooring line configuration equations requires knowledge of the amount of mooring line remaining deployed after reel-in during anchor setting operation, the pretensioning of the line and the final positioning of the vessel; thus it is necessary to keep track of the amount of line. If the balance of line remaining deployed is not sufficient to fulfill the requirement of some line at the seafloor even for maximum offset, new deployment of the anchor must be attempted.

If the anchor will not dig in, it could be an indication of faulty fluke angle setting. However, additional information could be necessary in terms of the specific anchor used and in terms of the nature of the sea bottom in order to define the correct fluke angle setting.

MATHEMATICAL DEVELOPMENT

A segment of a cable system is shown in Figure 7 with the static forces to be considered: namely, line tensions, gravity force, and hydrodynamic forces induced by a constant or slowly varying current. Under the assumed condition of co-planarity between the cable and the current, the problem becomes two dimensional, as shown in Figure 7.

Equilibrium conditions applied to the system leads to:

$$dT = \left[w \cdot \sin\phi - F(R,\phi)\left(1 + \frac{T}{A \cdot E}\right)\right] dS \qquad (14)$$

$$d\phi = (1/T)\left[D(R,\phi)\left(1 + \frac{T}{A \cdot E}\right) + w \cdot \cos\phi\right] dS \qquad (15)$$

$$dX = \left(1 + \frac{T}{A \cdot E}\right)\cos\phi \cdot dS \qquad (16)$$

$$dY = \left(1 + \frac{T}{A \cdot E}\right)\sin\phi \cdot dS \qquad (17)$$

These equations are non-linear and a general explicit solution can not be derived; thus, in order to solve the equations various simplifications are necessary. If the mooring cable is considered heavy and stiff the stretch can be neglected and the equations reduce to:

$$dT = (w \cdot \sin\phi - F(R,\phi))\ dS \qquad (18)$$

$$d\phi = (1/T)(D(R,\phi) + w \cdot \cos\phi)\quad dS \qquad (19)$$

$$dX = \cos\phi \cdot dS \tag{20}$$

$$dY = \sin\phi \cdot dS \tag{21}$$

Solution for this equation set by explicit solution would yield:

$$dS = \frac{dT}{w \cdot \sin\phi - F(R,\phi)} \tag{22}$$

$$dS = \frac{T \cdot d\phi}{D(R,\phi) + w \cdot \cos\phi}$$

and

$$T(\phi) = T_o \cdot \exp\left[\int_{\phi_o}^{\phi} \frac{P(\psi)}{Q(\psi)}\, d\psi\right] \tag{23}$$

where $P(\phi) = w \cdot \sin\phi - F(R,\phi)$

$Q(\phi) = D(R,\phi) + w \cdot \cos\phi$

Further $dS = \frac{T(\phi) \cdot d\phi}{Q(\phi)}$

$$S = \int_{\phi_o}^{\phi} \frac{T_o}{Q(\theta)} \cdot \exp\left[\int_{\phi_o}^{\theta} \frac{P(\psi)}{Q(\psi)}\, d\psi\right] d\theta \tag{24}$$

and for X and Y

$$X = \int_{\phi_o}^{\phi} \frac{T_o}{Q(\theta)} \cdot \exp\left[\int_{\phi_o}^{\theta} \frac{P(\psi)}{Q(\psi)}\, d\psi\right] \cos\theta \cdot d\theta \tag{25}$$

$$Y = \int_{\phi_o}^{\phi} \frac{T_o}{Q(\theta)} \cdot \exp\left[\int_{\phi_o}^{\theta} \frac{P(\psi)}{Q(\psi)}\, d\psi\right] \sin\theta \cdot d\theta \tag{26}$$

Special form of $F(R,\phi)$ and $D(R,\phi)$ can be evaluated, however, the current forces are relatively very small in the case considered and thus can be neglected giving:

$$T = T_o \cdot \frac{\cos\phi_o}{\cos\phi} \tag{27}$$

$$S = T_o \cdot \frac{\cos\phi_o}{w} (\tan\phi - \tan\phi_o) \tag{28}$$

$$X = T_o \frac{\cos \phi_o}{w} \left[\ln\left(\frac{1}{\cos \phi} + \frac{\sin \phi}{\cos \phi}\right) - \ln\left(\frac{1}{\cos \phi_o} + \frac{\sin \phi_o}{\cos \phi_o}\right) \right] + X_o \tag{29}$$

$$Y = T_o \frac{\cos \phi_o}{w} \left(\frac{1}{\cos \phi} - \frac{1}{\cos \phi_o}\right) + Y_o \tag{30}$$

$$T = \left[T_o^2 \cdot \cos^2 \phi_o + (S \cdot w + T_o \cdot \sin \phi_o)^2 \right]^{1/2} \tag{31}$$

For the particular case of $X_o = Y_o = \phi_o = 0$ the equations for a catenary will be obtained, since:

$$\exp \left[\frac{X \cdot w}{T_o} \right] = \frac{1}{\cos \phi} + \frac{\sin \phi}{\cos \phi} = \cosh \frac{X \cdot w}{T_o} + \sinh \frac{X \cdot w}{T_o}$$

and therefore:

$$\frac{1}{\cos \phi} = \cosh \frac{X \cdot w}{T_o} \qquad \text{and} \qquad \frac{\sin \phi}{\cos \phi} = \sinh \frac{X \cdot w}{T_o}$$

giving the equations as follows:

$$S = \frac{T_D}{w} \cdot \sinh \frac{X \cdot w}{T_D} \tag{32}$$

$$Y = \frac{T_D}{w} \cdot \left(\cosh \frac{X \cdot w}{T_D} - 1\right) \tag{33}$$

$$T = \left[T_D^2 + (S \cdot w)^2 \right]^{1/2} \tag{34}$$

In the development of the caternary curve and its solutions the following will be defined (see Figure 8):

$$Ya = Y + C \qquad \text{where } C = \frac{T_D}{w} \tag{35}$$

$$Ya = \frac{T_D}{w} \cdot \cosh \frac{X \cdot w}{T_D} \tag{36}$$

and further

$$Ya = C \frac{1}{\cos \phi} \tag{37}$$

$$\phi = \cos^{-1} \frac{C}{Ya} \tag{38}$$

and

$$T = T_D / \cos \phi \tag{39}$$

$$T = w \cdot C \cdot \cosh \frac{X}{C} \tag{40}$$

In Appendix A the catenary equations are used in the solution of the catenary-shaped mooring line to find line tension, catenary length, anchor pull, and cable angle with horizontal at the vessel; subsequently the pretensioning and reel-up are determined.

In Appendix B the basic mathematical development is used to write the equation set for the solution of combination wirerope-chain mooring line configuration.

In the following mathematical development the stretch of the cable is considered. The current forces are neglected as in the above development since they are relatively small specially in the case of wirerope. Based on these assumptions, equations 14 to 17 are reduced to:

$$dT = w \cdot \sin \phi \cdot dS \tag{41}$$

$$d\phi = \frac{1}{T} \cdot w \cdot \cos\phi \cdot dS \qquad (42)$$

$$dX = (1 + \frac{T}{A \cdot E}) \cdot \cos\phi \cdot dS \qquad (43)$$

$$dY = (1 + \frac{T}{A \cdot E}) \cdot \sin\phi \cdot dS \qquad (44)$$

The above equation set must be solved by numerical methods and computer integration. The equations would be:

$$\phi_{j+1} = \phi_j + \frac{1}{T_j} \cdot w \cdot \cos\phi_j \cdot dS \qquad (45)$$

$$T_{j+1} = T_j + w \cdot \sin\phi_{j+1} \cdot dS \qquad (46)$$

$$X_{j+1} = X_j + (1 + \frac{T_j}{A \cdot E}) \cos\phi_{j+1} \cdot dS \qquad (47)$$

$$Y_{j+1} = Y_j + (1 + \frac{T_j}{A \cdot E}) \sin\phi_{j+1} \cdot dS \qquad (48)$$

and the boundry conditions (j = 0):

$T_o = T_D$

$\phi_o = 0$

$X_o = 0$

$Y_o = 0$

These equations are listed for completeness. Cable configurations are calculated for a wirerope and in Table 3 comparisons are made between the cable configurations based on the catenary development and the above development which includes stretch. As will be seen from the data the effect of the stretch is significant for the larger tensions (larger offsets).

For subsequent calculations, however, the catenary solution is used in all cases, as the writing and implementing of a comprehensive computer program for the solution including cable stretch is outside the scope of this thesis.

EXAMPLE CALCULATION

In this paragraph is presented an example to show the method of calculation. Of special interest is:

Line pretensioning,
High line tension,
Total cable length and maximum reel-up,
Restoring force.

The calculations will be made for two water depths - 1000 ft and 1500 ft. For each water depth the calculations will be made for two mooring line configurations - namely, all-wirerope and all-chain. This number of calculations are performed to illustrate the differences and characteristics of the two systems. Only the calculation for the all-wirerope configuration at 1500 ft of water depth is carried through in the following example; however, all calculated values are shown in graphs.

The data used for the example calculation are given in Appendix C.

Pretensioning

The equations used for calculating the pretensioning force at zero offset are those developed in the paragraph entitled "Mathematical Development". The solution procedure for the data set given is a trial and error procedure due to the complexity of the equations. The calculation procedure is explained in Appendix A.

The maximum working load for the mooring line cable or chain should be one-third its break strength[1-3] given in the data, Appendix C. For the case of the wirerope this would be 350,000 lbf.

From the text the maximum working load in the mooring line should occur at a maximum offset for continued drilling, which is given in the data as 6% offset, and the data set at this offset then:

Line tension	350,000 lbf
Cable buoyant weight	17.0 lbf/ft
Water depth	1,500 ft
Cable length at the sea bottom	3,450 ft

The length of cable at the sea bottom must initially be estimated, and later calculations will show whether or not the amount of cable is sufficient to fulfill the requirement of some amount of cable at the sea bottom even at maximum offset. For each of the cases calculated, the total line length is selected so that between 50 and 100 ft remains on the sea bottom at maximum offset.

Solving the equation set for the catenary with the data given - as described in Appendix A - yielding:

$$S_{rem} = 11{,}165 \text{ ft}$$

and the distance from the entry in the seafloor to the anchor (zero offset):

$$L = 10{,}879 \text{ ft}$$

At zero offset the solution to the catenary can be calculated by trial and error, yielding:

$C = 8{,}727$ ft

and other data are at zero offset:

$Ya = 10{,}227$ ft

$X = 5{,}046$ ft

$S_{cat} = 5{,}332$ ft

$S_{bot} = 5{,}833$ ft

$T_D = 148{,}359$ lbf

$\phi = 31.4$ deg

Finally the pretensioning at zero offset is:

$T_{pre} = 173{,}859$ lbf

High Line Tension

The high line is defined as the line in the mooring system with the most tension for any given amount of offset. Any one line will have the highest tension if the displacement of the vessel is in the plane of the mooring line away from the anchor.

The calculation procedure used to obtain the high line tension for various displacements is outlined in Appendix A. For this example the known data for each vessel offset would be; w lbf/ft, Y ft, S_{rem} ft and L + d ft where d is the additional length due to offset. The solution is found by trial and error and explained in Appendix A.

For this example, values of line tension, anchor pull, and bottom line length are calculated for various vessel offsets. The data are listed in Table 4 and graphs are shown in Figure 9. In Table 5 the data for the other three cases are listed, and the data for these cases are shown in Figure 10.

Total Cable Length and Maximum Reel-Up

The total amount of cable to be deployed is calculated from the deployment geometry (Figure 6) and the catenary data for zero vessel offset, as follows:

$$S = Y + X + S_{bot} + \text{Anchor setting} + \text{Vessel positioning} \tag{49}$$

$$= 1{,}500 \text{ ft} + 5{,}046 \text{ ft} + 5{,}833 \text{ ft} + 300 \text{ ft} + 200 \text{ ft}$$

$$S = 12{,}880 \text{ ft}$$

The maximum cable reel-up is calculated from equation (50):

$$\text{Cable reel-up} = Y + X - S_{cat} + \text{Anchor setting} + \text{Vessel positioning} \tag{50}$$

$$= 1{,}500 \text{ ft} + 5{,}046 \text{ ft} - 5{,}332 \text{ ft} + 300 \text{ ft} + 200 \text{ ft}$$

$$\text{Cable reel-up} = 1{,}714 \text{ ft}$$

As stated previously it is necessary to observe and keep track of the amount of cable reel-up. Should the reel-up for any line exceed the above amount a new deployment of that line should be attempted.

Restoring Force

The restoring force is defined as the resulting force acting on the vessel from all mooring lines for a given offset in a given direction.

Vessel offset in one direction will cause stretching and increased tension in the lines away from the direction of the offset and slacking and decreased tension in the lines in the direction of the offset; this is shown in Figure 11. The method of calculation for each line is the same as used for the high line tension calculation above, except in this case L + a is calculated from the mooring pattern geometry, direction of movement and amount of offset: (see Figure 11)

$$L + a = \left[(L \cdot \cos \alpha + \text{Offs} \cdot D)^2 + (L \cdot \sin \alpha)^2 \right]^{1/2} \tag{51}$$

where L = the distance between the entry in the seafloor and the anchor, ft

α = the angle between the offset plane and the mooring line, deg

Offs = vessel offset

D = water depth, ft

a = additional length due to offset, ft

For movements away from the cable, a will be positive, and for movements in the direction of the cable, a is negative.

From the above length and the data at zero offset the line tension and anchor pull for each line can be calculated and the restoring force then is the summation of the line tension forces as projected on the horizontal plane (same as anchor pull) and subsequently projected in the plane of the movement (offset):

$$\text{Restoring force} = \sum_{j=1}^{n} T_{Dj} \cdot \cos \alpha_j$$

The leeward lines are working against the restoring force. Under very severe weather conditions it can be necessary therefore to slack off the leeward lines to increase the restoring force and decrease the offset.

For the example calculation, the restoring force is calculated for vessel offsets in the beam direction (see Figure 11). Also calculations are made of the restoring force for the two leeward lines completely slacked. The calculations were performed on computer and the results are listed in Table 6 and graphs shown in Figure 12. In Table 7, the data for the other three cases are listed and the data for these cases are graphed in Figure 13.

Example Summary

The example mooring system has been designed and the high line tension and restoring force determined for vessel offsets in the beam direction. The data are listed respectively in Table 4 and Table 6 and graphed in respectively Figure 9 and Figure 12.

The maximum tension in the mooring line should be no more than one-half the rated break strength. Based on this limitation the vessel should have no more than 128 ft offset or 8 1/2% of water depth as determined from Figure 9. This is provided that the offset takes place in the plane of one of the mooring lines away from the anchor. Somewhat greater amount of offset can be tolerated in the beam or bow direction for the mooring pattern in the example because a mooring line is not in the plane of these movements. For offset determination, however, the maximum allowed offset for the high line should be used for offsets in all directions.

For the example environmental forces given in the data in Appendix C, the load on the vessel can be determined in the beam direction from Figure 2. Assuming that all the forces are acting in the same direction, the load is:

Wind force	186,000 lbf
Wave drift force	58,000 lbf
Current force	199,000 lbf
Total force	443,000 lbf

From Figure 12 the offset due to this load (which is a severe environmental load) can be determined as 90 ft or 6.0% of water depth. This offset is well below the maximum allowed, and the mooring system under this static load would be able to absorb significant oscillations due to dynamic forces around the static offset and would further be able to sustain additional environmental conditions.

If any condition should cause nearly maximum vessel offset as listed above, the slacking of two leeward lines will add significant additional amount of restoring force as seen in Figure 12. The restoring force for two leeward lines completely slacked at 8 1/2% offset is 855,000 lbf (from Figure 12). Thus the slacking of leeward lines allows for additional safety margin.

Other angles of attack of the environmental forces and other mooring system designs should be studied in order to determine the optimum system to match the vessel's environmental characteristics; however, the procedure is similar to the one outlined in this example.

DISCUSSION OF DATA

Calculation of high line tension, high line anchor pull and restoring force have been performed for all-wirerope and all-chain mooring line configuration for water depth of 1000 ft and 1500 ft for comparative purposes and the calculated values are listed in Table 5 and Table 7 and they are graphed in Figure 11 and Figure 13.

As is seen from these data, the two different mooring line configurations result in significantly different mooring systems. The all-chain system requires large pretensioning in order to meet the design criteria of a line tension of one-third the break strength at maximum offset for continued drilling and yet this system is rather loose as seen from the slope in Figure 10 and Figure 13.

The all-wirerope system requires low pretensioning but will give rapid increase in restoring force, as seen from the steeper slope of these graphs. This fact makes the wirerope system a much more desirable system for deep water application; however, for low water application this system is much too stiff as previously stated.

For ultra-deep water a combination wirerope-chain system should be selected.

APPENDIX A

Procedure for Pretensioning Calculation

The mooring line geometry for pretensioning is shown in Figure 14 where the line pretensioning would take place in position ABC. The line tension, however, would be known in position A'B'C indicating the offset at which the maximum working load in the mooring line should take place.

From the mathematical development the following equations are obtained:

$$Ya = C \cdot \cosh \frac{X}{C} \tag{A-1}$$

$$S_{cat} = C \cdot \sinh \frac{X}{C} \tag{A-2}$$

$$T = w \cdot C \cdot \cosh \frac{X}{C} = Ya \cdot w \tag{A-3}$$

$$Y = Ya - C \tag{A-4}$$

$$C = \frac{T_D}{w} \tag{A-5}$$

$$\phi = \cos^{-1} \frac{C}{Ya} \tag{A-6}$$

and from the geometry A'B'C in Figure 14:

$$L + d = X + S_{bot} \tag{A-7}$$

$$S_{rem} = S_{cat} + S_{bot} \tag{A-8}$$

For the problem at hand the following data at A'B'C would be known:

T = tension which is the maximum working cable load, lbf

w = cable weight (buoyant), lbf/ft

Y = water depth, ft

S_{bot} = line laying on seafloor (selected), ft

From equation (A-3)

$$Ya = T/w$$

Now:

$$C = Ya - Y = \frac{T}{w} - Y$$

$$X = (\frac{T}{w} - Y) \cdot \cosh^{-1} \left[\frac{\frac{T}{w}}{\frac{T}{w} - Y} \right]$$

$$S_{cat} = (\frac{T}{w} - Y) \cdot \sinh \left[\frac{X}{\frac{T}{w} - Y} \right] \tag{A-9}$$

and from equation (A-7) and (A-8)

$$L = X + S_{bot} - d$$

$$S_{rem} = S_{cat} + S_{bot}$$

The pretensioning of the mooring line cables would take place in the geometry ABC, indicating zero offset. For this geometry the following data would be known:

w = cable weight (buoyant), lbf/ft

Y = water depth, ft

S_{rem} = total amount of cable out after pretensioning, ft

L = distance between entry in seafloor and anchor, ft

The solution to this problem is found by a trial and error calculation procedure using equations (A-1) thru (A-8), except that equation (A-7) would be:

$$L = X + S_{bot} \tag{A-10}$$

Guessing a value for C the following can be calculated:

$$Ya = Y + C$$

$$X = C \cdot \cosh^{-1} \frac{Ya}{C}$$

$$S_{cat} = C \cdot \sinh \frac{X}{C}$$

and from equation (A-10)

$$S_{bot} = L - X$$

and

$$S''_{rem} = S_{cat} + S_{bot}$$

This value of S''_{rem} must equal the S_{rem} given in the data. New value of C must be guessed until the equality $S''_{rem} = S_{rem}$ holds.

When the correct value of C is found, the catenary at geometry ABC is known and all necessary data can be calculated.

In specific the pretensioning of the mooring line at zero offset is:

$$T_{pre} = Ya \cdot w$$

APPENDIX B

Calculation Procedure for Combination Wirerope-Chain Mooring Line

The equation set for mooring line calculation of a combination line of wirerope-chain is listed below. The mooring line geometry is shown in Figure 15.

The equations are those developed in the paragraph entitled "Mathematical Development", and for the wirerope portion of the mooring line the following equations can be written:

$$T = T_o \cdot \frac{\cos \phi_o}{\cos \phi} = \left[T_o^2 \cdot \cos^2 \phi_o + (S_{wr} \cdot w_{wr} + T_o \cdot \sin \phi_o)^2 \right]^{1/2} \qquad \text{(B-1)}$$

$$S_{wr} = T_o \cdot \frac{\cos \phi_o}{w_{wr}} (\tan \phi - \tan \phi_o) \qquad \text{(B-2)}$$

$$X_1 = \frac{T_o \cdot \cos \phi_o}{w_{wr}} \left[\ln(\frac{1}{\cos \phi} + \frac{\sin \phi}{\cos \phi}) - \ln(\frac{1}{\cos \phi_o} + \frac{\sin \phi_o}{\cos \phi_o}) \right] + X_o \qquad \text{(B-3)}$$

$$Y_1 = \frac{T_o \cdot \cos \phi_o}{w_{wr}} (\frac{1}{\cos \phi} - \frac{1}{\cos \phi_o}) + Y_o \qquad \text{(B-4)}$$

and for the chain part:

$$T_o = w_{ch} \cdot Ya = w_{ch} \cdot \frac{T_D}{w_{ch}} \cdot \cosh \frac{w_{ch}}{T_D} X_2 \qquad \text{(B-5)}$$

$$S_{ch} = \frac{T_D}{w_{ch}} \cdot \sinh \frac{w_{ch}}{T_D} X_2 \tag{B-6}$$

$$Y_2 = Ya - \frac{T_D}{w_{ch}} = \frac{T_D}{w_{ch}} \cdot \cosh \frac{w_{ch}}{T_D} X_2 - \frac{T_D}{w_{ch}} \tag{B-7}$$

$$Ya = \frac{T_D}{w_{ch}} \cdot \cosh \frac{w_{ch}}{T_D} X_2 \tag{B-8}$$

$$\phi_o = \cos^{-1} \frac{T_D}{w \cdot Ya} \tag{B-9}$$

and from the geometry in Figure 15 the following equations are derived:

$$X = X_1 + X_2 \tag{B-10}$$

$$Y = Y_1 + Y_2 \tag{B-11}$$

$$S_{rem} = S_{bot} + S_{ch} + S_{wr} \tag{B-12}$$

$$L = S_{bot} + X_1 + X_2 \tag{B-13}$$

$$S_{chtot} = S_{ch} + S_{bot} \tag{B-14}$$

For problem solving - finding pretensioning and line configuration - sufficient data would not be known for either the wirerope portion or the chain portion to solve any one separately, since X_1, X_2, Y_1, and Y_2 remain unknown for any one problem.

The solution is done graphically as a trial and error procedure on the entire system of equations, starting with the chain portion (catenary) for estimated values in order to find X_1'', X_2'', Y_1'', and Y_2''. The sought solution would be one where:

$$Y'' = Y_1'' + Y_2'' = Y$$

$$L'' = X_1'' + X_2'' + S_{bot} = L \quad (\text{or } L + d)$$

and

$$S_{rem}'' = S_{rem}$$

APPENDIX C

Data for Example Calculation

Environmental data - maximum expected forces:

Wind velocity (V_k)	59 knots
Wave height (significant)	35 ft
Current velocity	2.0 knots

Mooring pattern:

8 lines

30° - 60° configuration as measured from the bow (see Figure 11)

Water depth:

1500 ft and 1000 ft

Mooring line:

	WIREROPE	CHAIN
Size	3 1/4"	3"
Dry weight, lbf/ft	19.5	89.3
Buoyant weight, lbf/ft	17.0	78.0
Break strength, lbf	1,050,000	1,045,000

Offset:

Maximum, drilling	6% of water depth
Maximum	10% of water depth

APPENDIX D

Nomenclature

ENGLISH SYMBOLS			UNIT
A	-	Area	in^2
A_c	-	Projected area	ft^2
A_f	-	Projected area	ft^2
A_h	-	Vessel heave amplitude	ft
A_s	-	Vessel surge amplitude	ft
a	-	Wave amplitude	ft
a	-	Length due to vessel offset	ft
B	-	Beam of vessel	ft
C	-	Coefficient	
C	-	Calculation length	ft
C_h	-	Height ciefficient	
C_s	-	Shape coefficient	
c	-	Damping	
D	-	Draft of vessel	ft
d	-	Length due to vessel offset	ft
E	-	Modulus of elasticity	lb/in^2
F	-	Force	lbf
g	-	Acceleration of gravity	ft/sec^2
H	-	Wave height significant	ft

ENGLISH SYMBOLS			UNIT
h	-	Water depth	ft
k	-	Wave number = $\frac{2\pi}{\lambda}$	
L	-	Length	ft
L	-	Length of vessel	ft
m	-	Virtual mass	lbm
Offs	-	Offset (fraction)	
R	-	Radius	ft
S	-	Length (cable)	ft
T	-	Tension force	lbf
T	-	Wave period	sec
T_D	-	Anchor pull	lbf
V	-	Velocity	ft/sec
V_a	-	Velocity, average	knots
V_c	-	Velocity, current	knots
V_g	-	Velocity	knots
V_k	-	Velocity	knots
w	-	Weight per foot	lbf/ft
X	-	Length in x-direction	ft
x	-	Coordinant	
Y	-	Water depth	ft
Y	-	Length in y-direction	ft
Ya	-	Calculation length (catenary)	ft

GREEK SYMBOLS			UNIT
α	-	Angle	deg
ρ	-	Density	g/cm^3
θ	-	Angle	deg
θ_s	-	Phase angle	deg
θ_h	-	Phase angle	deg
ϕ	-	Angle	deg

SUBSCRIPT		
beam	-	Vessel beam
bot	-	Sea bottom
bow	-	Vessel bow
cat	-	Catenary
ch	-	Chain
chtot	-	Chain total
mor	-	Mooring
o	-	Initial condition
pre	-	Pretensioning
rem	-	Remaining
ris	-	Riser
T	-	Total
ves	-	Vessel
wr	-	Wirerope

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TABLE 1

Height Coefficient (C_h) for Wind Force Calculation[8]

Height, ft	Coefficient (C_h)
0 - 50	1.0
50 - 100	1.1
100 - 150	1.2
150 - 200	1.3
200 - 250	1.4

The height is here defined as the vertical distance from the design water surface to the center of area, as defined.

TABLE 2

Shape Coefficient (C_s) for Wind Force Calculation[8]

Shape	Coefficient (C_s)
Cylindrical shape	0.5
Hull (surface type)	1.0
Deck house	1.0
Insulated structural shape (cranes, angles, channels, etc.)	1.5
Under deck areas (smooth surface)	1.3
Under deck areas (exposed beams and girders)	1.3
Rig derrick (each face)	1.25

TABLE 3

Comparative Data of Wirerope Configuration

Data:		Catenary Solution	Solution Incl. Stretch	Catenary Solution	Solution Incl. Stretch
Cable type		Wirerope		Wirerope	
Size		$3\frac{1}{4}$"		$3\frac{1}{4}$"	
Buoyant weight	lbf/ft	17.0		17.0	
Break strength	lbf	1,050,000		1,050,000	
Modulus of elasticity	lbf/in^2	20,000,000		20,000,000	
Area of steel	in^2	3.91		3.91	
Water depth	ft	1,500		1,500	
Horizontal force	lbf	148,360		455,415	
Calculated Values:					
Line tension	lbf	173,860	173,810	480,915	480,776
Anchor pull	lbf	148,360	148,360	455,415	455,415
Hanging cable length	ft	5,332	5,336	9,089	9,114
Unstretched cable lg.	ft	5,332	5,325	9,089	9,060
x-coordinant	ft	5,046	5,050	8,923	8,948
Angle with horizontal	deg	31.4	31.4	18.7	18.7
Approximate offset	% of W.D.	0.0	0.0	8.0	9.7

TABLE 4

High Line Tension, Anchor Pull and Bottom Line Amount

Data:

Cable Type	Wirerope
Size	$3\frac{1}{4}$"
Buoyant weight, lbf/ft	17.0
Break strength, lbf	1,050,000
Water depth, ft	1,500

Offset % of W.D.	Line Tension kips	Anchor Pull kips	Bottom Line ft
0	173.9	148.4	5,833
1	191.6	166.1	5,547
2	212.5	187.0	5,227
3	237.5	212.0	4,866
4	267.6	242.2	4,458
5	304.4	278.9	3,990
6	350.0	324.5	3,450
7	407.3	381.8	2,820
8	480.9	455.4	2,075
9	577.5	552.0	1,181
10	707.8	682.3	89

TABLE 5

High Line Tension, Anchor Pull, and Bottom Line Amount

Data:

Cable Type	Wirerope	Chain	Chain
Size	$3\frac{1}{4}$"	3"	3"
Buoyant weight, lbf/ft	17.0	78.0	78.0
Break strength, lbf	1,050,000	1,045,000	1,045,000
Water depth, ft	1,000	1,500	1,000

Offset % of W.D.	Line Tension kips	Anchor Pull kips	Bottom Line ft	Line Tension kips	Anchor Pull kips	Bottom Line ft	Line Tension kips	Anchor Pull kips	Bottom Line ft
0	149.5	132.5	6,165	269.9	152.9	987	243.8	165.8	1,125
1	167.7	150.7	5,910	280.3	163.3	918	256.8	178.8	1,053
2	189.9	172.9	5,619	291.6	174.6	845	271.2	193.2	976
3	217.0	200.0	5,285	303.9	186.0	767	287.3	209.3	893
4	251.0	234.0	4,897	317.3	200.3	684	305.3	227.2	803
5	294.1	277.1	4,442	332.2	215.2	595	325.4	247.4	706
6	350.0	333.0	3,900	348.3	231.3	500	348.1	270.0	601
7	424.3	407.3	3,244	366.1	249.1	399	373.8	295.8	486
8	526.1	509.1	2,435	385.8	268.8	291	403.0	325.0	361
9	670.9	653.9	1,410	407.6	290.6	175	436.4	358.4	224
10	886.7	869.7	74	431.8	314.8	50	474.9	396.9	73

TABLE 6

Restoring Force - Beam Attack

Data:

Cable Type	Wirerope
Size	$3\frac{1}{4}$"
Buoyant weight, lbf/ft	17.0
Break strength, lbf	1,050,000
Water depth, ft	1,500
Mooring pattern	8 lines - 30°-60°

Offset % of W.D.	Restoring Force kips	Restoring Force for Two Leeward Lines Comp. Slacked kips
0	0.0	-
1	65.6	-
2	132.5	-
3	202.4	-
4	276.7	-
5	357.5	523.8
6	446.9	600.6
7	548.4	690.9
8	665.6	797.9
9	804.1	927.2
10	971.0	1,085.8

TABLE 7

Restoring Force - Beam Attack

Data:

Cable type	Wirerope	Chain	Chain
Size	$3\frac{1}{4}$"	3"	3"
Buoyant weight, lbf/ft	17.0	78.0	78.0
Break strength, lbf	1,050,000	1,045,000	1,045,000
Water depth, ft	1,000	1,500	1,000
Mooring pattern	8 line - 30°-60°	8 line - 30°-60°	8 line - 30°-60°

Offset % of W.D.	Restoring Force kips	Restoring for Slacked Lines* kips	Restoring Force kips	Restoring for Slacked Lines* kips	Restoring Force kips	Restoring for Slacked Lines* kips
0	0.0	-	0.0	-	0.0	-
1	66.5	-	39.9	-	49.7	-
2	134.9	-	80.1	-	99.9	-
3	207.4	-	120.8	-	150.9	-
4	285.9	-	162.2	-	203.2	-
5	373.5	514.6	204.5	406.2	257.6	468.5
6	473.8	603.3	248.1	439.4	314.0	513.0
7	592.3	711.4	293.3	474.8	373.5	561.4
8	735.7	845.6	340.2	512.6	436.6	614.1
9	914.5	1,016.1	389.5	553.3	503.9	671.8
10	1,145.6	1,239.8	441.2	596.9	576.7	735.6

* Two leeward lines completly slacked

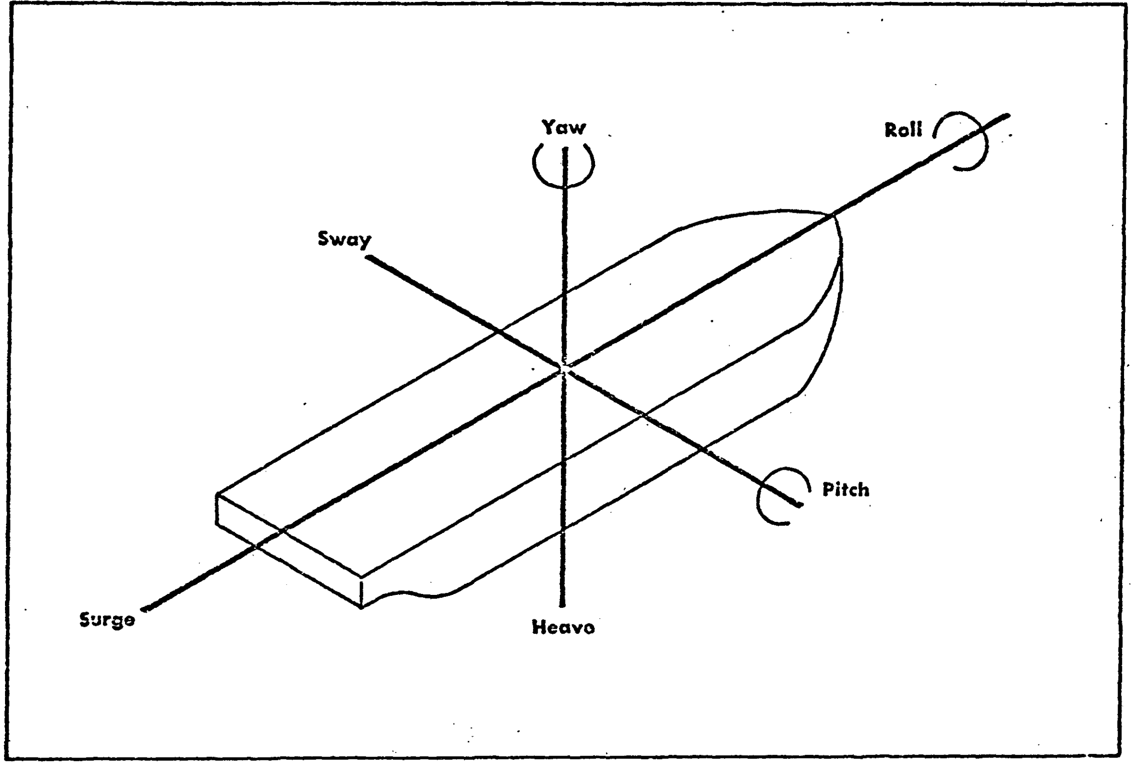


FIGURE 1 - Types of Vessel Movements Defined. (From Reference 3)

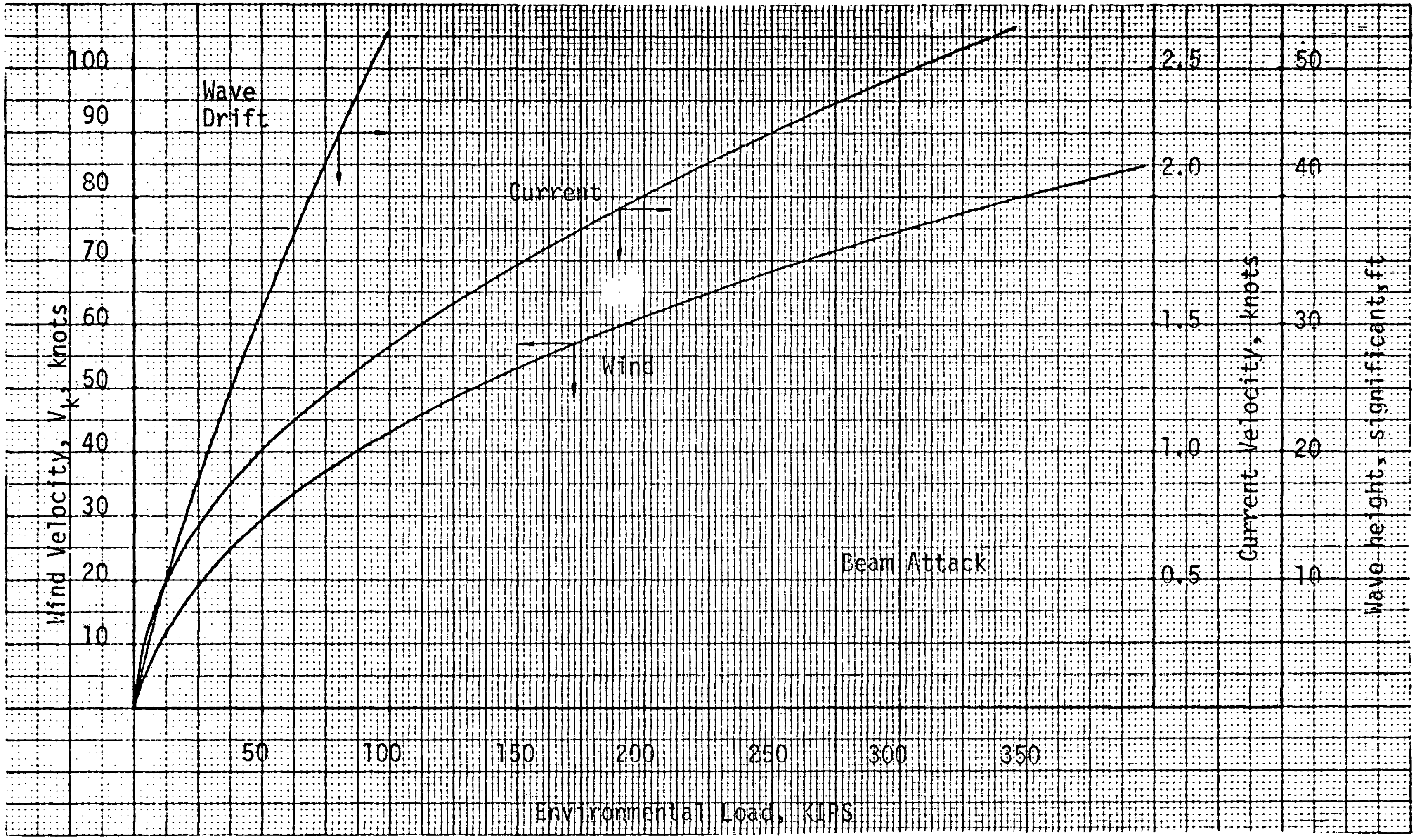


FIGURE 2 - Wind, Wave Drift and Current Load on Vessel for Beam Attack and Specific Draft

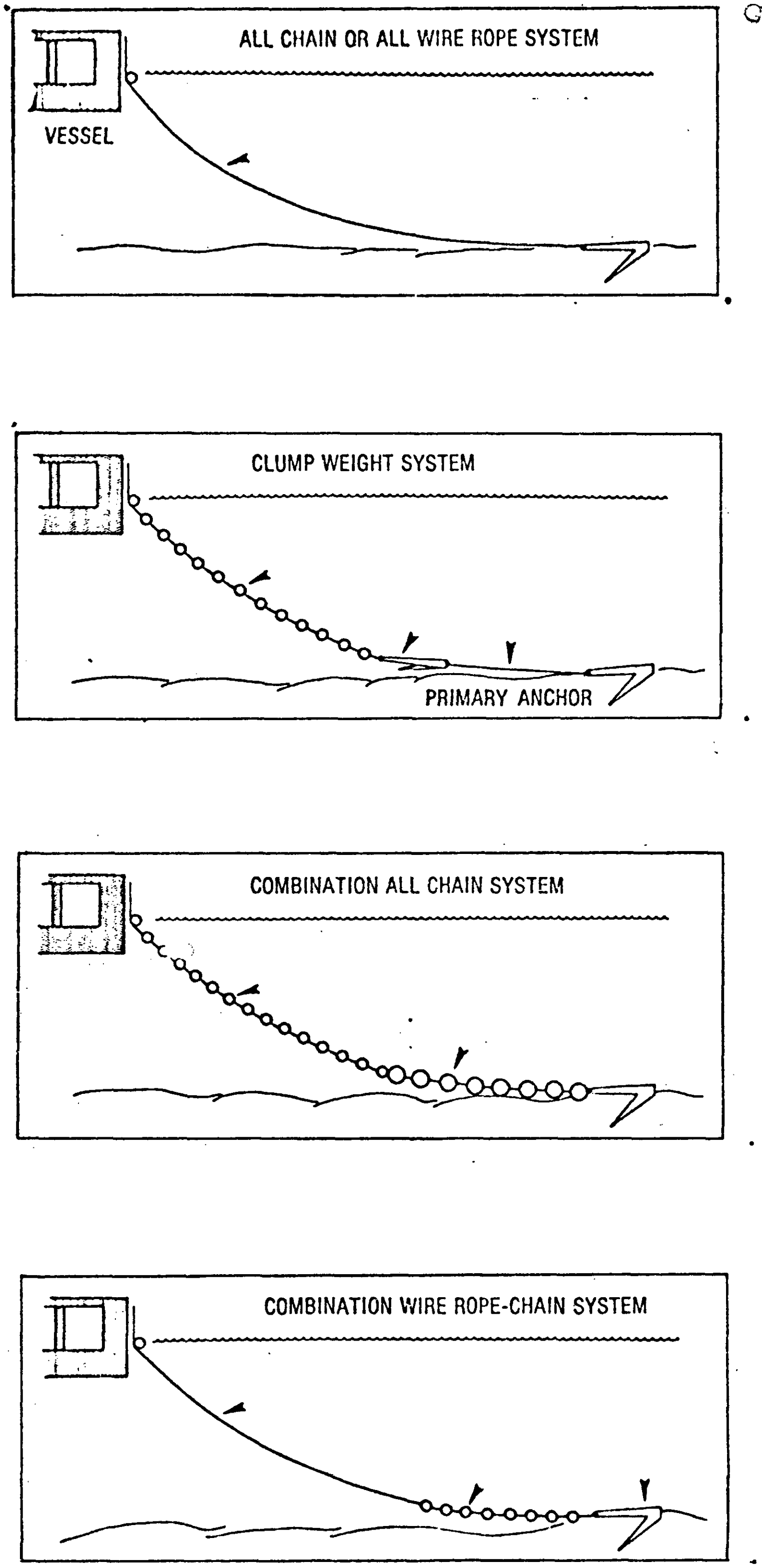
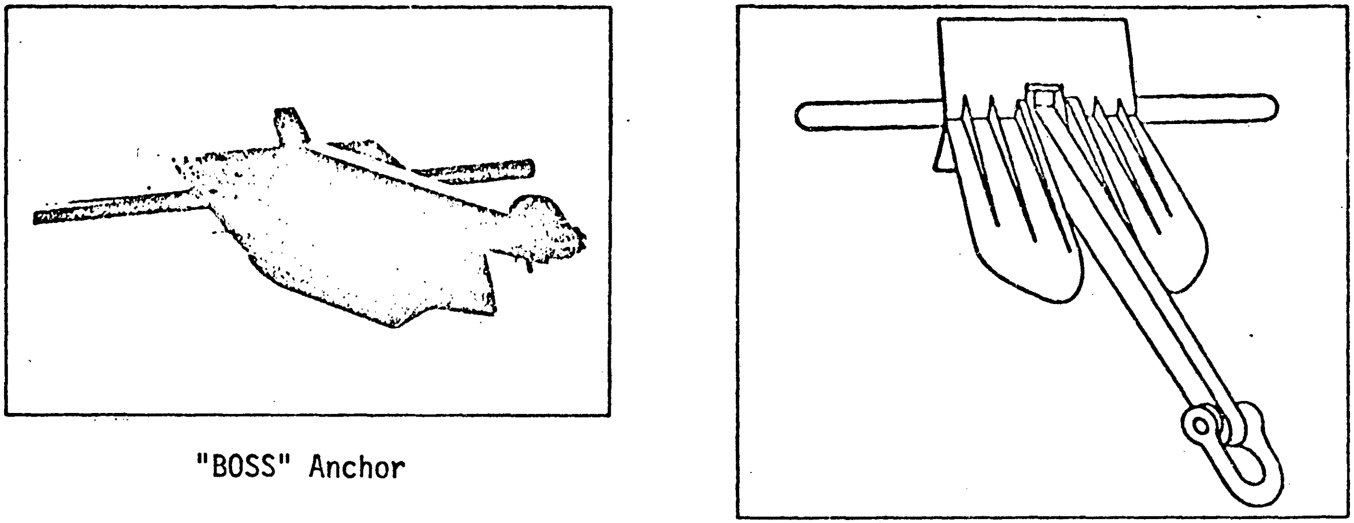


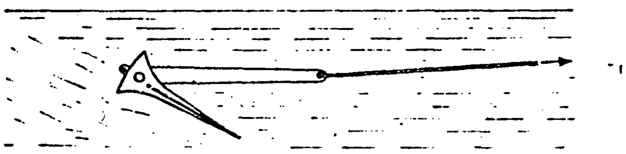
FIGURE 3 - Mooring Line Configuration for Deep Water Spread Mooring System. (From Reference 1).



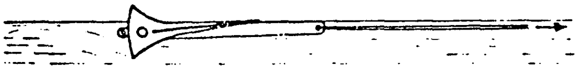
"BOSS" Anchor

General Type Anchor

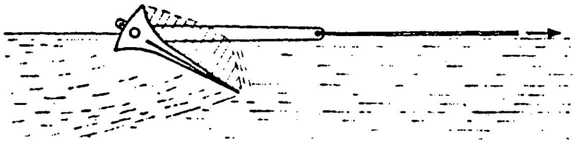
FIGURE 4 - Anchor Types (From Reference 14).



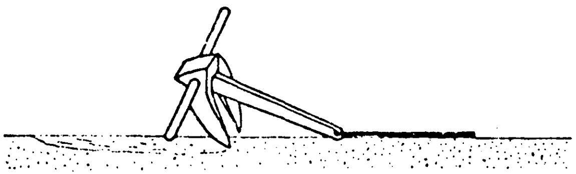
(A) ANCHOR PERFORMING PROPERLY'



(B) FLUKES NOT TRIPPED IN MUD



(C) ANCHOR BALLING UP AND PULLING OUT



(D) USE OF EXCESSIVE FLUKE ANGLE IN SAND

FIGURE 5 - Anchor Behavior (From Reference 14).

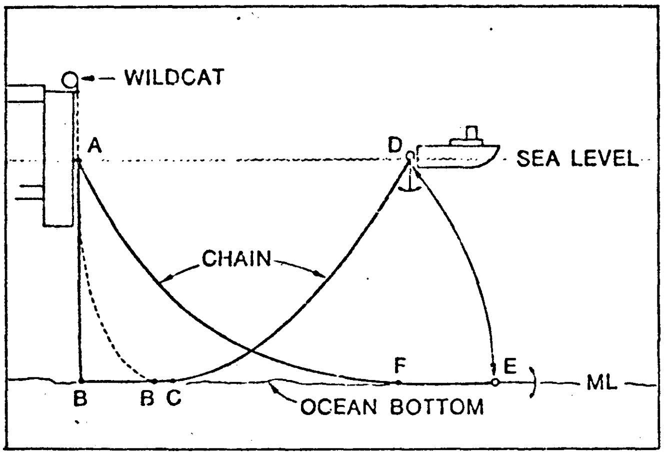


FIGURE 6 - Cable Deployment Geometry (From Reference 2).

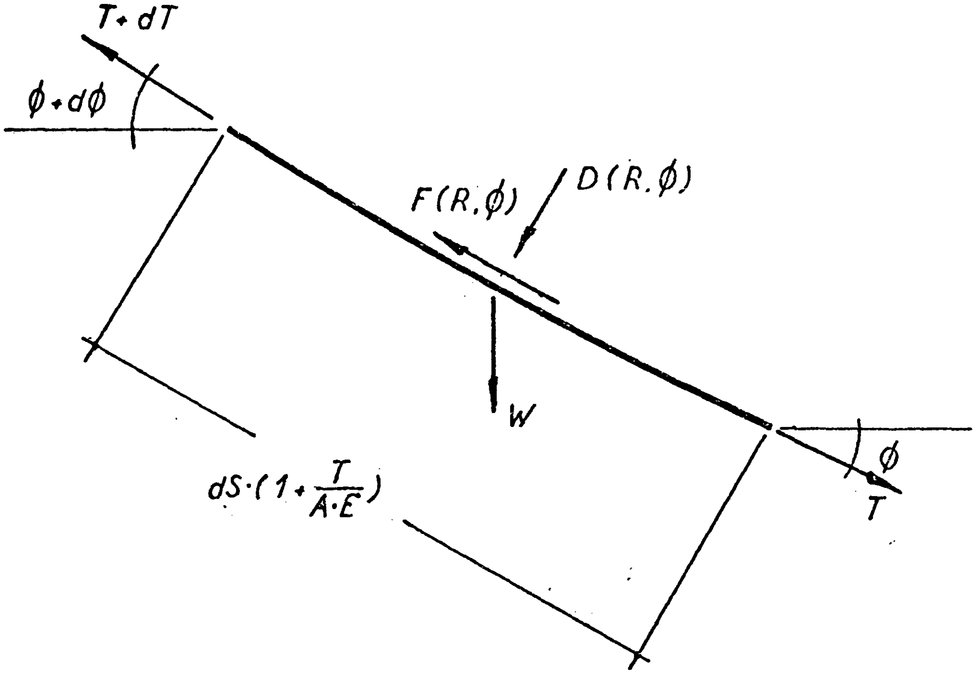


FIGURE 7 - Cable Segment with Static Forces.

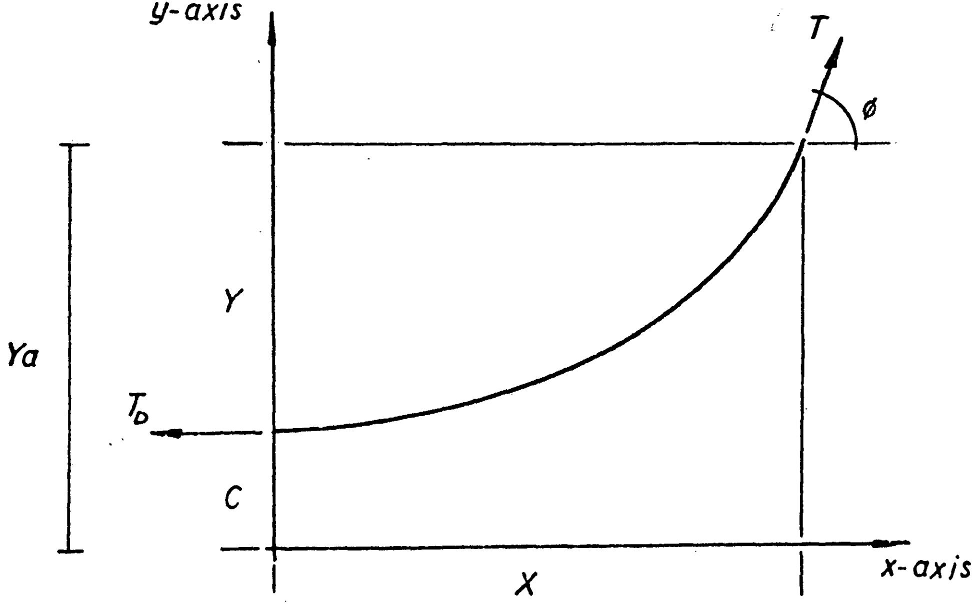
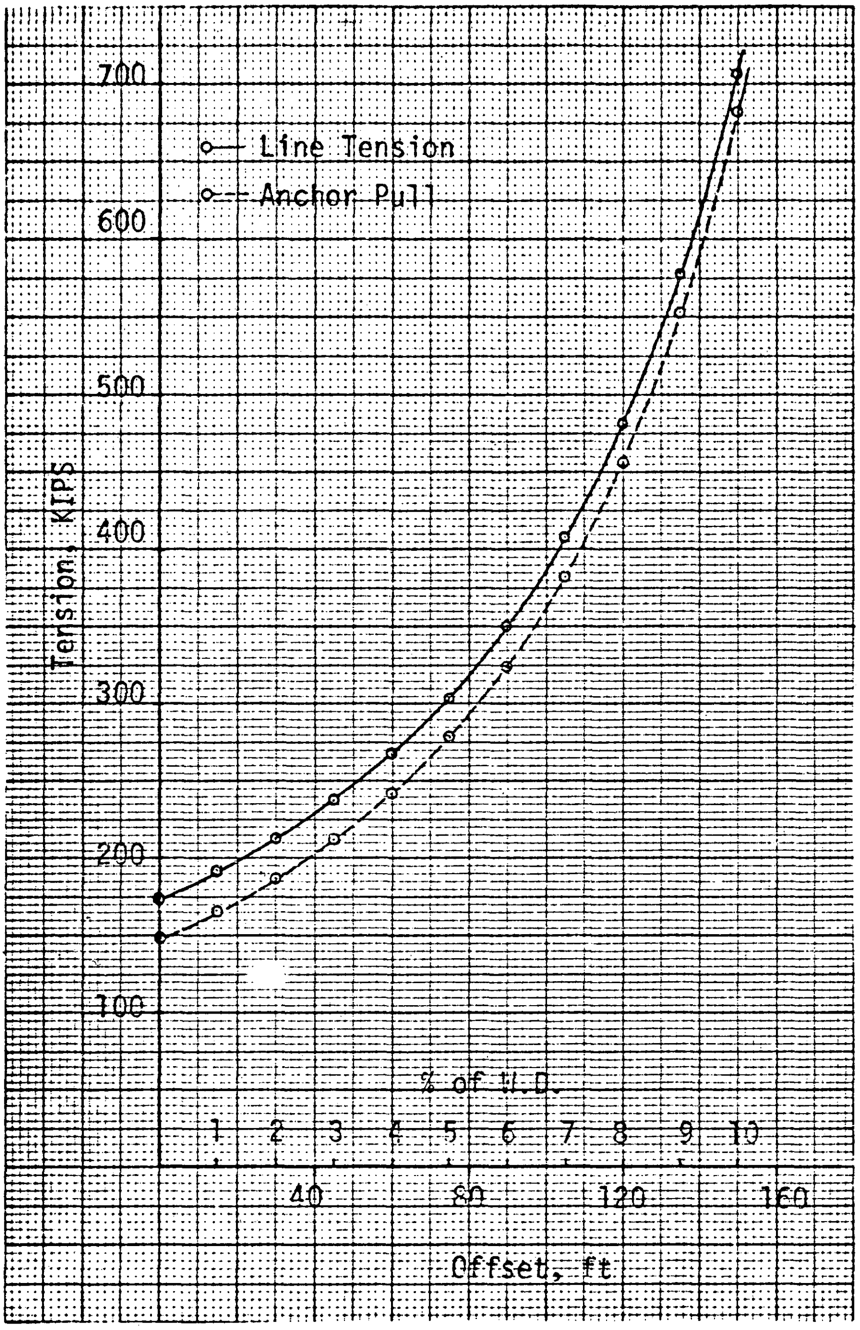


FIGURE 8 - Catenary Geometry.



Data: Wirerope
$3\frac{1}{4}$" size
Buoyant Weight, 17.0 lbf/ft
Water Depth, 1,500 ft

FIGURE 9 - High Line Tension and Anchor Pull

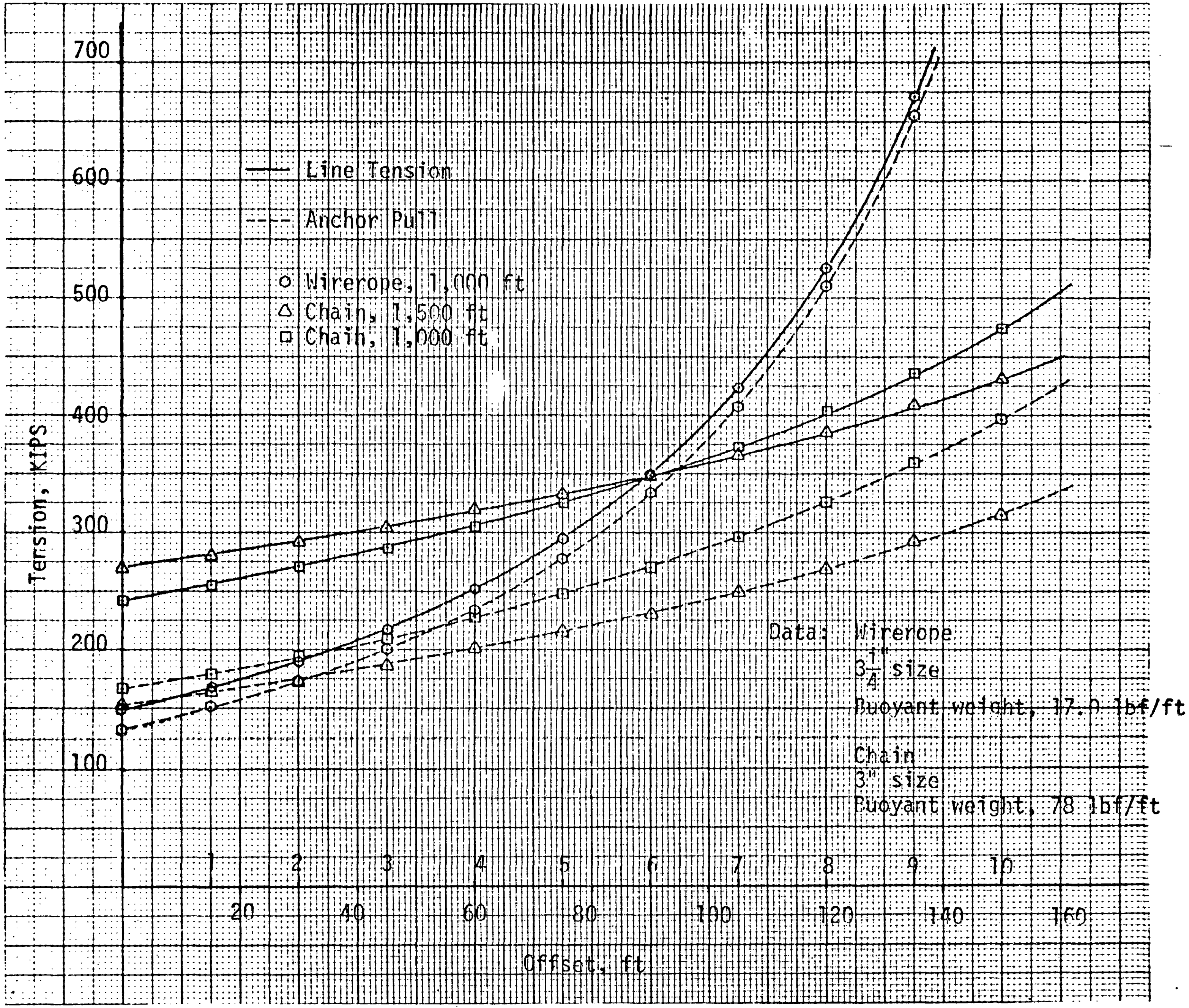


FIGURE 10 - High Line Tension and Anchor Pull.

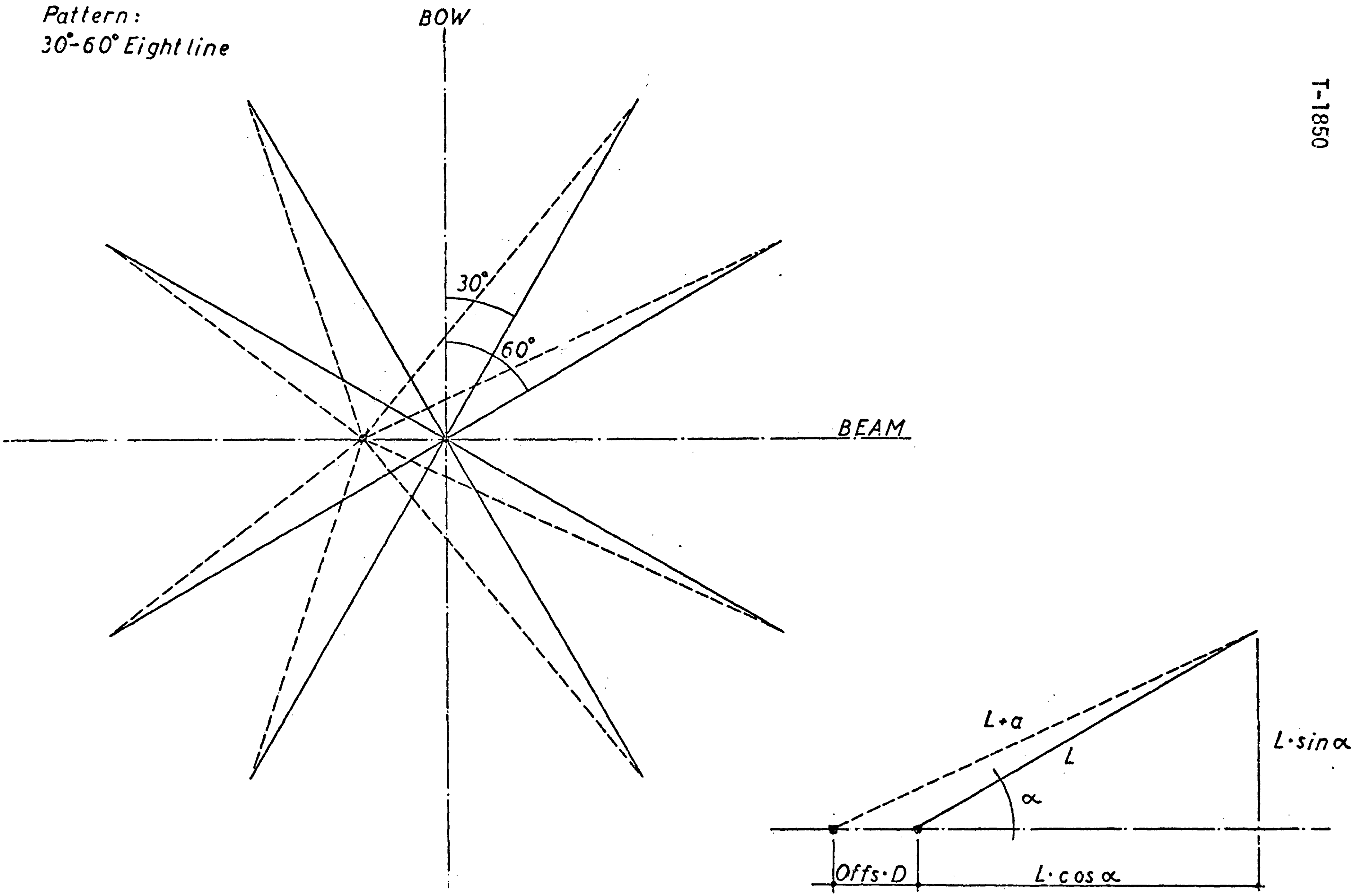
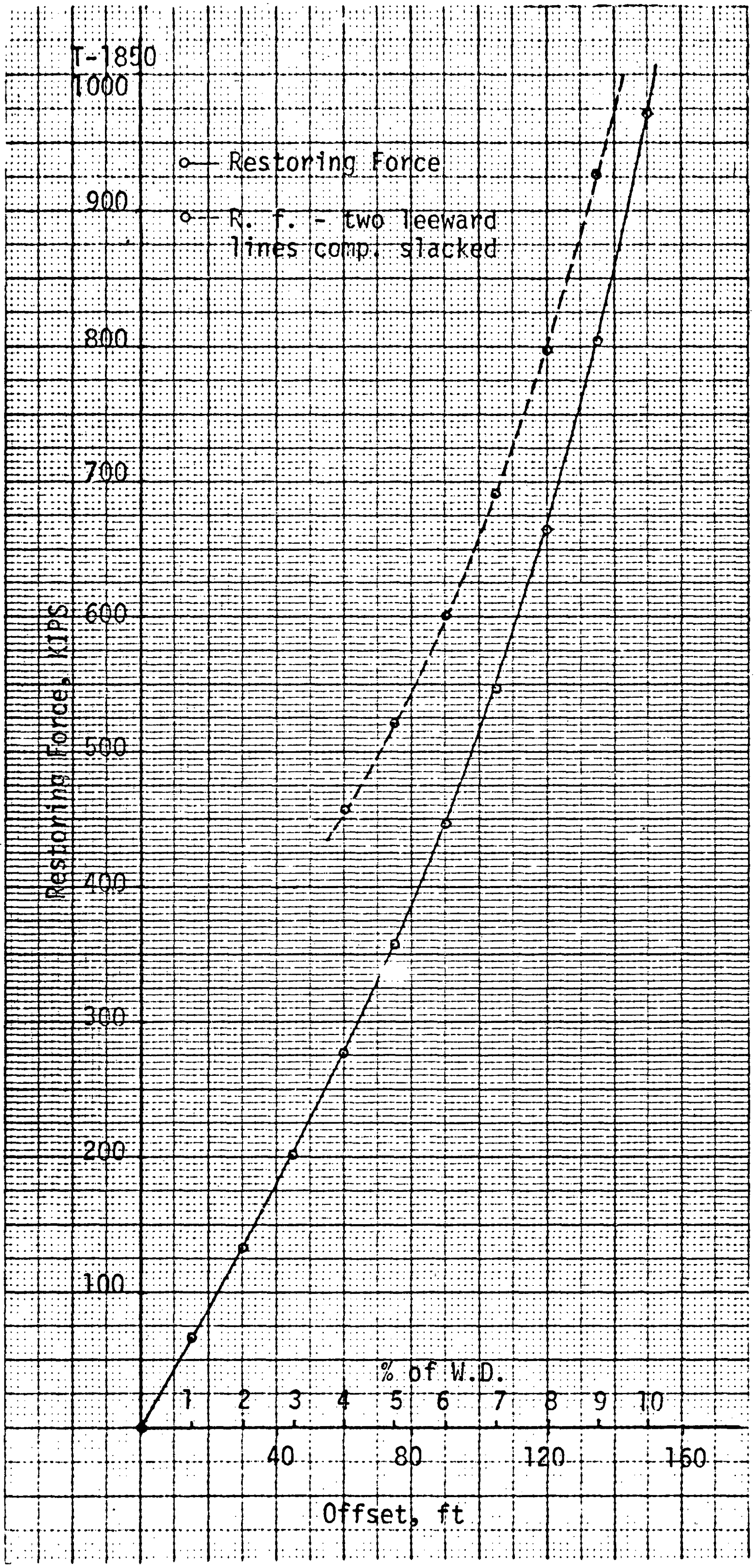


FIGURE 11 - Mooring Pattern and Offset Configuration.



Data: Wirerope
$3\frac{1}{4}$"
Buoyant weight,
17.0 lbf/ft
Water depth,
1,500 ft
30°-60° eight line

FIGURE 12 - Restoring Force Beam Attack

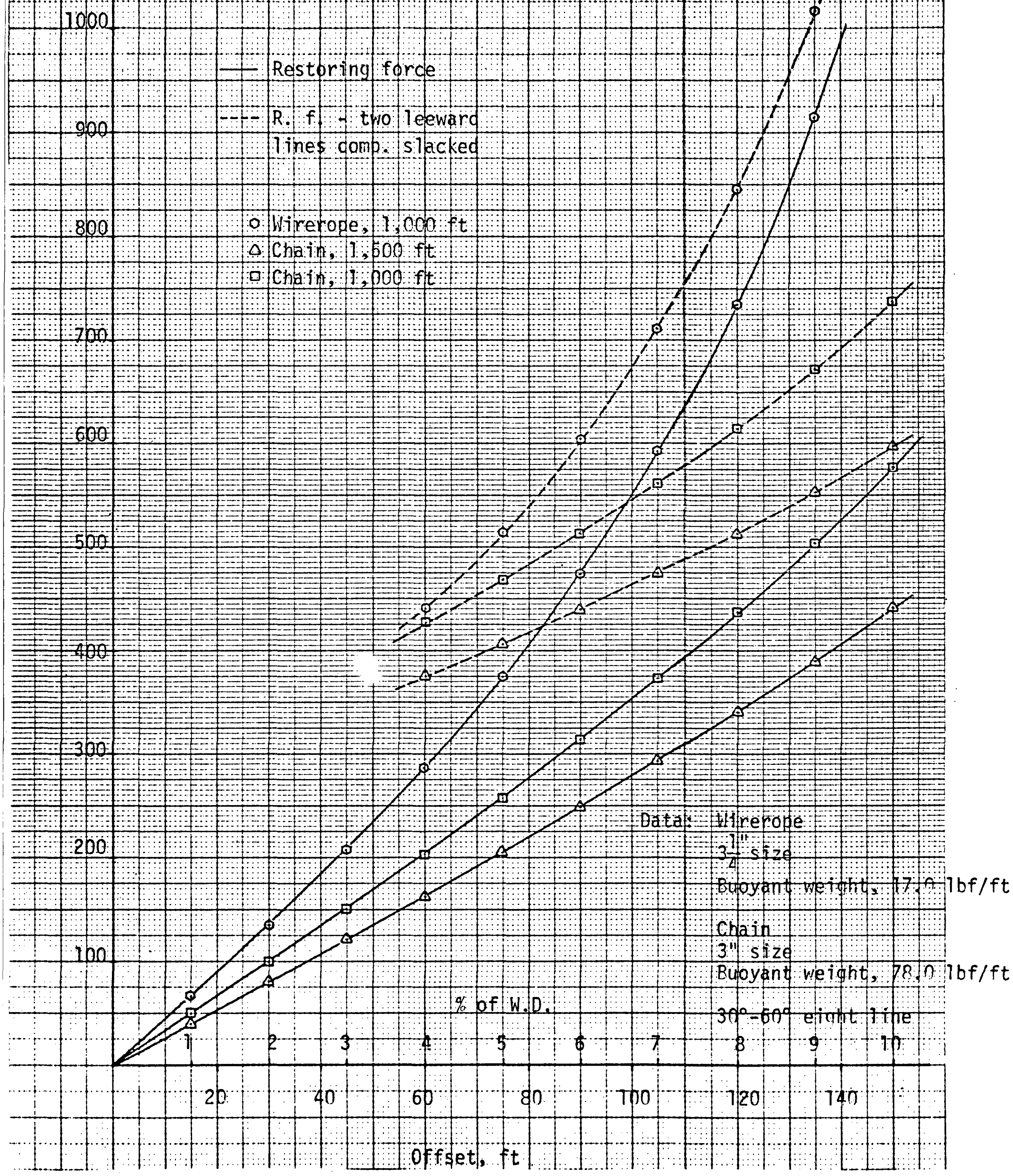


FIGURE 13 - Restoring Force Beam Attack

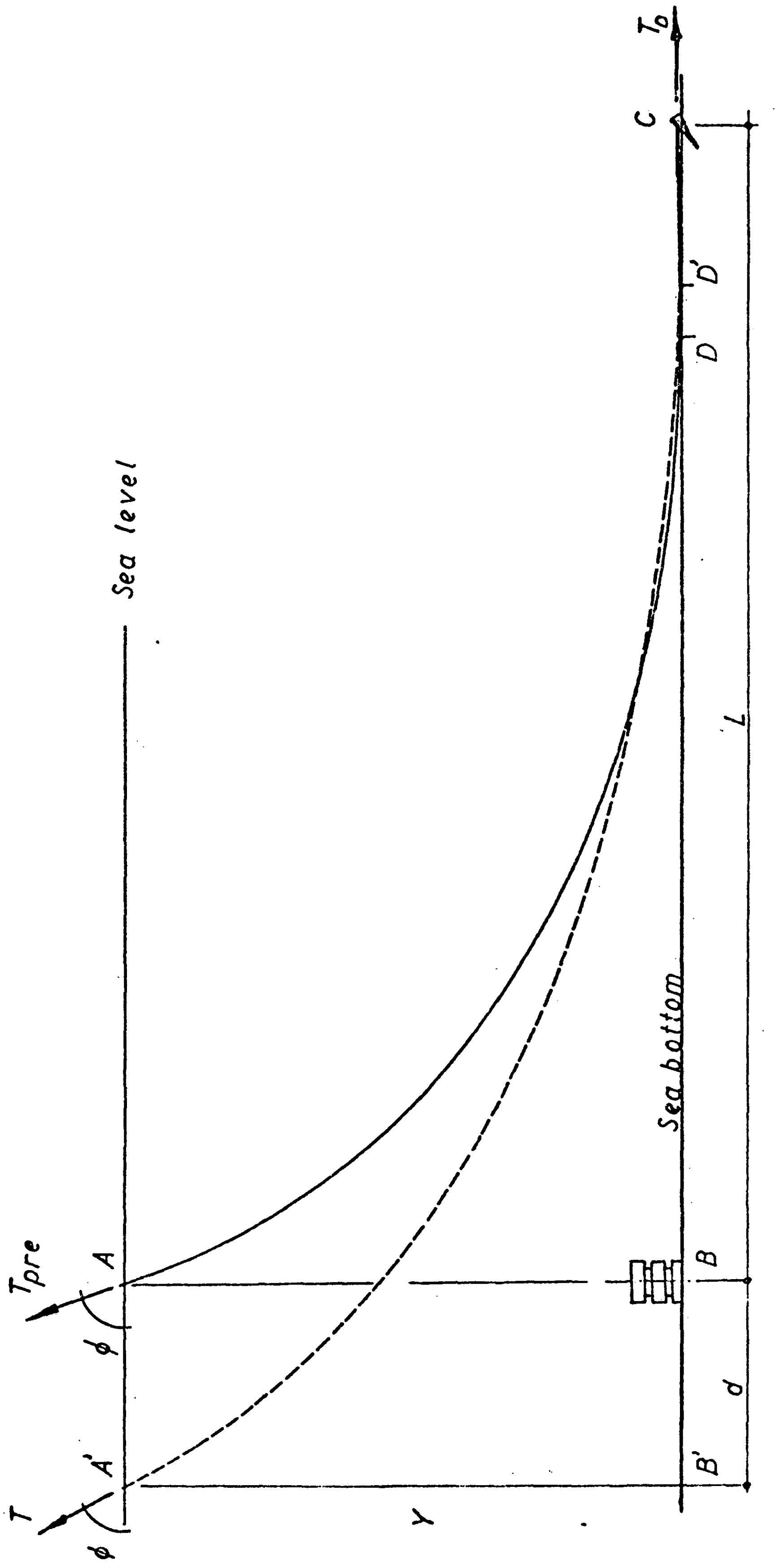


FIGURE 14 - Pretensioning Geometry.

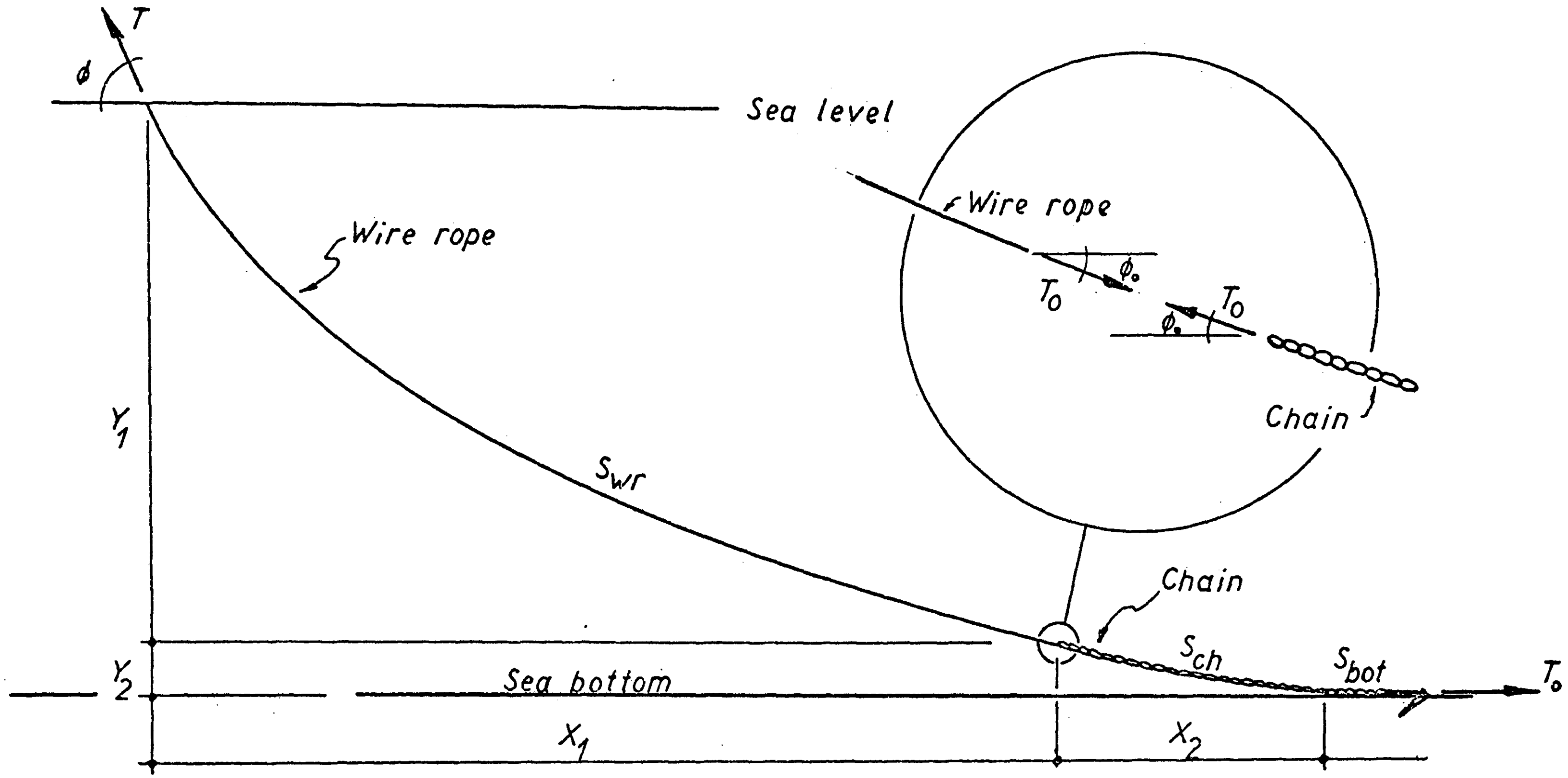


FIGURE 15 - Combination Wirerope-Chain Geometry.