FILE

INTERNAL DOCUMENT 165

I.O.S.

DB2 theoretical mooring study

A.R. Packwood

August 1982

Internal Document No. 165

INSTITUTE OF OCEANOGRAPHIC SCIENCES

NATURAL ENVIRONMENT RESEARCH COUNCIL

INSTITUTE OF OCEANOGRAPHIC SCIENCES

Wormley, Godalming,
Surrey GU8 5UB
(042-879-4141)

(Director: Dr. A. S. Laughton, FRS)

Bidston Observatory,
Birkenhead,
Merseyside L43 7RA
(051-653-8633)
(Assistant Director: Dr. D. E. Cartwright)

Crossway,
Taunton,
Somerset TA1 2DW
(0823-86211)
(Assistant Director: M. J. Tucker)

DB2 theoretical mooring study

A.R. Packwood

August 1982

Internal Document No. 165

Institute of Oceanographic Sciences,
Brook Road, Wormley,
Godalming, Surrey, GU8 5UB.

CONTENTS

DB2 THEORETICAL MOORING STUDY

1. INTRODUCTION

A $\frac{4}{5}$ scale version of the data buoy DB1, henceforth referred to as DB2, has been proposed for operation on the Porcupine Bank off the west coast of Ireland in 400 m of water.

The survivability of the DB1 mooring concept - a 3 point mooring with ground chain and compliant braidline in mid-water, is assumed acceptable having proven itself over the last 4 year deployment in the S.W. Approaches. A similar three point mooring is therefore envisaged and the purpose of this report is to suggest what might be a suitable mooring specification and to try and evaluate the buoy/mooring system performance in adverse conditions.

Extreme wave conditions for this area are estimated as 33-35 m for the 50 year return wave height and 30 m for the 10 year return value. Typical periods for these waves may be 16 s. Typical mean currents are of order 0.5 kts peaking to 1 → 2 kts in directions predominantly from the west and south-west. January winds are s-sw-w and are 30% of the time greater than 28 kts. Most of this data is obtained from the W. Atlantic tables of wind and waves.

Numerical models are used in the analysis to evaluate first the steady forces on the buoy-mooring system and the effective stiffness of the ground chain catenary and then the dynamic loads in the mooring. Several simplifications are made to enable a very simple one degree of freedom model of the buoy motion to be used. This model is used to estimate the mooring tensions in the extreme wave conditions, however this does not cover breaking wave events, the significance of which is discussed later (see section 8). Having previously determined the effective stiffnesses of the mooring, section 6 examines the various natural frequencies of the mooring system.

The results of the DB1 model trials in breaking waves performed at NMI in 1977 are discussed and compared with the results obtained numerically. Two sizes of ground chain are considered and the merits of each are presented.

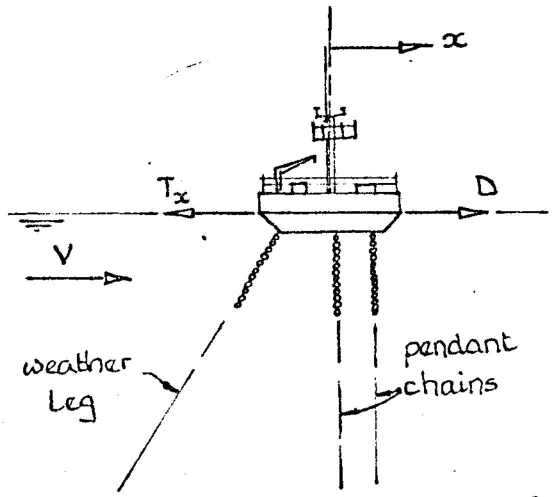
Overall, no problems are found in choosing the mooring materials. It also appears that certain resonant conditions may be acceptable in view of the high damping in the mooring system.

2. DESCRIPTION OF THE NUMERICAL MODELS

The basis for the steady force calculations is the IOS cable/mooring program SHAPE. The program is described in more detail in Carson (1975) but basically it will calculate the shape of a cable catenary in a current which may vary with depth. The cable is divided into sections which may have different properties, weight, diameter, drag or local current. The water depth is fixed and the program can be made to determine the necessary buoyancy required to keep a surface buoy afloat. The program was modified so that the bottom section would automatically, by an iterative procedure, be altered in length such that the cable formed a catenary with an angle of less than 5° to the horizontal at the sea bed. This was to simulate the ground chain catenary.

The results obtained by running the steady state program for a variety of water depths and currents are discussed in detail in the following sections. The results suggest that a simple dynamic model might be used to estimate wave forces on the buoy/mooring system. It was found that the vertical displacement of the buoy had only a small effect on the mooring load when compared with horizontal displacements. This is borne out by a comment made by Carson (1977) commenting on the results of the DB1 deployment off Lowestoft. He concluded that with respect to mooring loads "tidal height appears to be much less important than current". The comment related to a much shallower mooring but the same result is indicated by the numerical model results of section 4. Hence the major wave force component comes from the drift of the buoy in the wave velocity field. A simple one degree of freedom system is devised to give the unsteady drift and horizontal force component which can then be related back to the steady state results to give the total mooring force including the vertical component. In this simplified calculation the drag of the buoy and upper chain are allowed for in the horizontal but vertical drag is ignored as are chain stiction forces in the bottom mud. Wind force has also been ignored at this stage.

The simple dynamic model is depicted below. The equation of motion is then



$$M\ddot{x} = D - T_x \qquad (1)$$

where

$$D = \tfrac{1}{2}\rho\,(SC_D)\,(V-\dot{x})\,|V-\dot{x}|$$

$$T_x = T_x(x)$$

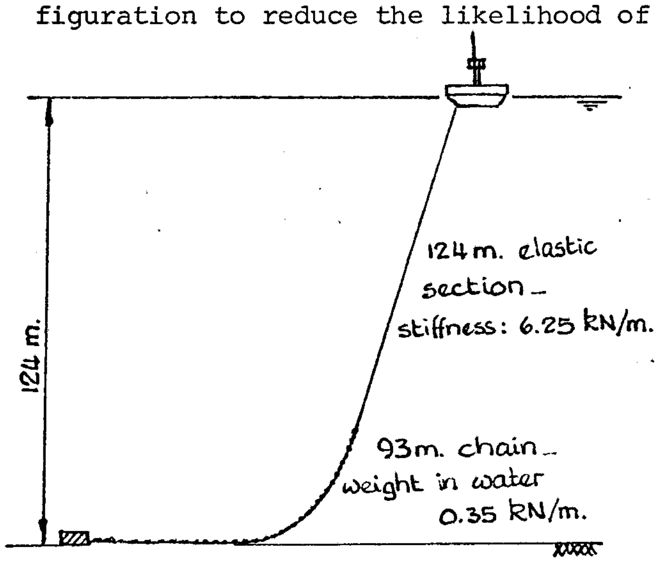
$$V(t) = V_o + V_w(t)$$

$T_x(x)$ is a non-linear restoring function due to the "weather" mooring leg and is determined by the steady flow calculations, D is the drag force and (SC_D) represents the summed (projected area x drag coefficients) for the hull and upper parts of the 3 leg mooring in the wave velocity field, M is the effective mass i.e. mass plus added mass of the buoy plus upper pendant chains, V_o is the steady current and $V_w(t)$ is the imposed wave particle velocities. Eq.(1) is a non-linear ordinary differential equation which is solved numerically using standard NAG library routines. $V_w(t)$ is the main forcing function and is chosen to represent the velocity field of a suitable wave train.

3. DB1 RESULTS

3.1 SCALE MODEL TESTS

A summary of the model tests carried out at NMI in January 1977 is reported in Carson (1982). The purpose of the tests was to test the survivability of DB1 in breaking waves and determine a mooring configuration to reduce the likelihood of the buoy being overturned.



A sketch of the best mooring and that originally proposed for DB1 in the S.W. Approaches is sketched below. The numbers are scaled up to full DB1 size from the $\frac{1}{31}$ scale model test results. Maximum forces in 25 m, 13.2s waves are 7 – 8.5 tonnes. With this arrangement the buoy capsized 5 times in 30 breaking waves of about this size.

DB2 is $\frac{4}{5}$ the scale of DB1 so, ignoring the difference in mooring depth for the moment, these forces under Froude scaling scale as $(\frac{4}{5})^3 = 0.512$ of the DB1 values. So the mooring force scaled for DB2 from these DB1 model tests is of order 3.5 – 4.3 tonnes. The braidline stiffness scales as $(\frac{4}{5})^2 = 0.64$ as does the chain weight giving 4 kN/m braidline stiffness and 0.224 kN/m chain weight in water. However the scaled water depth is only $\frac{1}{4}$ that of the proposed DB2 site and the scaled model test waves are only 19 m high compared with the 35 m predicted maximum wave. These figures then can only be used as a guide giving data which may be compared with actual DB1 data.

3.2 FULL SCALE DB1 MEASUREMENTS

The largest loads measured on DB1 while in the S.W. Approaches were ≈ 13 tonnes which was measured in 20 m high waves, see Rusby & Waites (1980). This is a considerably higher load than predicted in the model tests with the arrangement described above but may be due to the reduced compliance of the braidline used on DB1 and a larger pre-tension, 5 - 6 tonnes on lay. A 13 tonne load corresponds to a load of 6.7 tonnes at DB2 scale.

3.3 NUMERICAL MODELLING OF DB1

The DB1 mooring was modelled using the steady flow program to compare the numerical model with the actual model tests and full-scale measurements outlined above. A full description of the DB1 mooring and the data required to run the program is given in fig. 1. The drag of the buoy hull was measured by Carson (1972), his results give $(SC_D)_{HULL} \simeq 1.0\ m^2$ at current speeds of 1 - 2 m/s. The drag of the pendant chains I crudely estimate as $(SC_D)_{CHAIN} \simeq 3.2\ m^2/\text{leg}$ using $C_D = 1.2$ on the projected area of the chain and I include in the buoy drag 50 m of braidline on the two slack moorings which adds $(SC_D)_{SLACK\ ROPES} = 9.7\ m^2$. Thus the total buoy drag at the upper end of the weather mooring becomes $(SC_D)_{TOT} = 17.1\ m^2$. The velocity profile is an arbitrary choice, hopefully not unrealistic. Wind drag has not been accounted for in the total drag above. This is unimportant in the sense that the model will only be used to give the restoring force and catenary shape for given horizontal and vertical displacements of the buoy. A summary of the findings is given in table 1, the symbols used are defined in fig. 1, the results are shown plotted in figs 2 - 4. By plotting $\ell n(T_x)$ vs x it can be shown that the function T_x is exponential and is reasonably approximated by the relation

$$T_x = 0.057e^{x/22.7} \text{ tonnes} \qquad (2)$$
$$= 0.559e^{x/22.7} \text{ kN}$$

The surge stiffness which is just the differential of this is then

$$k_s = 24.6e^{x/22.7} \text{ N/m} \qquad (3)$$

As suspected the stiffness is highly non-linear.

In contrast, the heave stiffness, which is the slope of the lines of fig. 3, is linear in z and varies only a comparitively small amount with x. Since the restoring force is very much more dependant on x that z, it is justifiable to ignore this contribution and argue that if we know how T_x and x vary in large waves then we may infer T from the steady flow results of figs 2 - 4 and correct for the wave height.

In (1) T_x is now known, it is assumed that (SC_D), in the expression for D, is the same as for the steady flow case since no better assumption is available. DB1 weighs 40 tonnes in air, assuming the added mass of the buoy hull is equal to the displaced volume this adds another 40 tonnes and adding some extra for the pendant chains and their added mass, say in total M = 83 tonnes. It only remains to determine the forcing function V(t). It was decided that the breaking wave groups used in the NMI experiments would be scaled up thus again providing a useful test of the numerical model with experiment. In the experiment, (F) in Carson (1982), the waves came in groups of six. Four smaller waves were followed by two larger ones the first of which usually broke near to the model. Using Froude scaling to scale the pen recorder traces of wave height the full scale DB1 waves were 4 @ H = 11.3 m, T_p = 14.4s period followed by 2 @ H = 24 m, T_p = 12.5s period. The maximum particle velocity is taken as $H\pi/T_p$ and V_w is then assumed sinusoidal. V_o was chosen to be 1 m/s, a typical surface velocity at the DB1 site is 0.7 m/s, so V_o probably never exceeds 1 m/s. In the model tests there was no tidal flow but some tidal drift is required to make the model representative for the exponential function for T_x is invalid for small x. Some back tension was employed in the model test, sufficient to give the weather leg a load of 1 - 2 tonnes at full scale. A 1 m/s current gives a pretension of 3.6 tonnes according to the numerical model so it may be expected that the numerical results will give tensions slightly larger than those predicted from the tests.

The calculation was started from the steady state with $V(t) = V_o$, $\dot{x} = \ddot{x} = 0$. The initial value of x was determined by solving (1) with these conditions using (2) and the assumed drag coefficient and effective mass. The results of this calculation are shown in fig. 5. The maximum value of T_x is 7.9 tonnes and x_{max} = 112 m. The greatest tension occurs not at the peak of the first big wave but at the peak of the first smaller wave following the two larger ones. This is brought about by the large trough in the wave particle velocity preceeding the leading big wave. The buoy response, shown on the bottom graph, indicates the fast response to the initial drop in velocity and the slower build up to the peak tension as the big waves push the buoy along the surface. The mean tension then decreases as the buoy gradually drifts back through the next three waves. The response indicates that the system is very heavily damped, the buoy velocity never exceeds the magnitude of the forcing velocity.

Returning to the steady flow results, it can be deduced that if x = 112 m then from fig. 2, $T \simeq 12$ tonnes @ $z = 0$ and $\ell \simeq 170$ m @ $z = 0$. The results of table 1 also indicate that ℓ increases as z thus in a 24 m wave the total chain lifted may be $\simeq$ 195 m. T is also increased slightly, from fig. 3, $T_z \simeq 9.6$ tonnes in a 24 m wave, with $T_x \simeq 8$ tonnes this increases the total tension at the buoy to T = 12.5 tonnes.

The force on the anchor $T_A \simeq 8.6$ tonnes under these conditions.

These forces are larger than those measured at model scale but this is due to the higher pretension and reduced compliance of the braidline. However the numerical model does give tensions similar to those measured on DB1 on site in 20 m waves which is very encouraging. It is also sobering to think that this force is sufficient to lift nearly all the 210 m anchor chain that lies on the bottom. It is therefore not surprising that the loads of 17 tonnes measured shortly after the initial mooring lay were sufficient to relax the mooring pretension by dragging the anchor (see Carson (1982)).

4. DB2 TRIAL MOORING CONFIGURATION ($DB2_{(1)}$)

For typical design mooring forces one may take the measured DB1 maximum load of 13 tonnes and scale by $(\frac{4}{5})^3$ to get an equivalent DB2 load of 6.7 tonnes. A minimum proof load for the chain would then be say 15 tonnes. This would correspond to 19 mm high strength stud link chain. But it would be unwise to go for the minimum specification since at the DB2 site the water depth is much greater and the 50 year wave somewhat higher than at the DB1 site. So for a first trial mooring try 25 mm chain, high strength stud link, at 27 tonnes proof load weighing 146 N/m in air $\equiv$ 127 N/m in sea water.

The braidline should not be loaded to more than 20% of its breaking load if it is not to be permanently deformed thus losing some of its compliance. The 27 tonne proof chain suggests a maximum S.W.L. of 16.5 tonnes so to be consistent with this initial choice of chain a braidline with a minimum breaking load of 82.5 tonnes would be appropriate. The 64 mm Viking, nylon braidline of British Ropes has a quoted break load of 90 tonnes and therefore seems suitable as an initial choice. Suppose 25 m of chain is pendant at the buoy and 50 m of bottom chain are lifted as pretensioning chain in zero current conditions. This leaves 325 m to be taken up by the braidline. The 64 mm braidline stretches 10% for a 10 tonne applied load, this gives a braidline stiffness of 3.02 kN/m. The pretension is $\simeq$ 6.35 kN therefore static stretch is 2.1 m. The length of ground chain will be determined by the calculations as will a suitable anchor size.

The details of the trial DB2 mooring are given in summary in fig. 6 together with the assumed velocity profile and drag assumptions necessary for running the steady flow program. The buoy drag was obtained by scaling the DB1 data and the drag of pendant chains and moorings was found as described in section 3.3. The results of running the steady flow program using this data with a range of surface currents and water depths are given in table 2. These results are shown graphically in figs 7 - 10. Again the restoring function T_x is found to be exponential and may be reasonably fitted by the curve

$$\begin{aligned} T_x &= 0.0236e^{x/48.8} \text{ tonnes} \\ &= 0.232e^{x/48.8} \text{ kN} \end{aligned} \qquad (4)$$

Consequently the surge stiffness on the one weather mooring leg is given by

$$K_s = 4.75e^{x/48.8} \quad \text{N/m} \qquad (5)$$

Comparing (5) with (3) the DB2 surge stiffness is very much less than DB1. This one might have expected since DB2 is in much deeper water. Similarly from fig. 8 the heave stiffness is also much reduced compared to the DB1 mooring, this being a consequence of the lighter chain. Hence the buoy can drift 160 m in a 2 kt current cf. DB1: 76 m drift in the same steady current. This means that the DB2 watch circle radius will be approximately twice that of the DB1 mooring in the S.W. Approaches in a similar surface current.

Eq. (4) is used to give the restoring force in the simplified equation of motion (1) and an effective mass of M = 51.3 tonnes made up as for the DB1 calculation, see section 3.3, is assumed.

A similar wave group pattern as for the DB1 experiments is used as a forcing function. A wave train of four 16.5 m, 18s waves lead the group and are followed by two 33 m, 16s waves. These have peak particle velocities of 2.88 m/s and 6.48 m/s respectively. An initial steady current of 1 m/s is again assumed and the calculation is started from rest. The results are shown in fig. 11. It is noticeable that the buoy takes longer to reach its maximum excursion, requiring two wave groups to pass before the motion becomes periodic. Once more the motion appears heavily damped.

$T_{x\,max}$ = 2.74 tonnes and x_{max} = 232 m. The steady flow calculations indicate that at this drift the full tension in the mooring allowing for an additional 33 m lift due to the wave is approximately 5.9 tonnes. The length of chain lifted is 265 - 270 m and the force on the anchor is approximately 3.5 tonnes.

This result is encouraging in that the specified chain and braidline are very adequate for these forces. Some over specification is desirable since from DB1 experience it is known that larger forces can be induced at the time of laying the mooring and in the shake-down period that follows.

5. 2ND TRIAL MOORING ($DB2_{(2)}$)

It was felt that possibly the 25 mm chain might suffer heavy wear in the thrash zone on the sea bed where it is constantly being pulled in and out of the mud. So a slightly heavier chain was substituted for the ground chain in the calculations. The 25 mm chain was retained at the buoy but 31.75 mm chain was used for the entire length of ground chain. This has a weight in air of 230 N/m and 200 N/m in sea-water and has a proof load of 42 tonnes. Re-running some of the steady flow calculations of section 4 with this data gives the results tabulated in table 3. The mooring tension T, T_x and T_A are shown plotted against the drift in fig. 12. The restoring force with the heavier chain can be approximated by

$$T_x = 0.387e^{x/50} \text{ kN} \qquad (6)$$

giving

$$\dot{k}_s = 7.75e^{x/50} \text{ N/m} \qquad (7)$$

The buoy dynamic response shown in fig. 13 is very similar to the first DB2 trial mooring giving a peak restoring force T_x = 2.7 tonnes. The only noticeable difference is that x is reduced throughout by approximately 20 m so that x_{max} = 211 m. Because the chain is heavier however T_z is larger giving T ≃ 7 tonnes allowing for 35 m additional chain lifted on passing through a 33 m wave. The total length of chain lifted is ≃ 210 m and the anchor force is of order 4 tonnes. Summaries of all these maximum load estimates obtained for DB1 and the two DB2 trial moorings from the numerical solutions are given in table 4.

6. NATURAL PERIODS OF THE BUOY/MOORING SYSTEM

The stiffness of the various systems discussed have already been calculated using the steady flow program. So in summary on a single mooring leg -

	DB1 (41.3mm chain)	DB2 (25mm chain)	DB2 (31.75mm chain)
braidline elasticity) k_b (kN/m)	40	3.02	3.02
surge 1 leg) k_s (N/m)	$24.6e^{x/22.7}$	$4.75e^{x/48.8}$	$7.75e^{x/50}$
heave 1 leg) k_H (N/m) @ V=1m/s	324	107	169
weight of chain) W_c (N/m)	307	127	200
Buoy mass (kg) Added mass (kg) (estimated)	40×10^3 43×10^3.. → 22×10^3	25×10^3 26×10^3... → 13×10^3	25×10^3 26×10^3.. low freq. → 13×10^3 high freq.

The natural period of oscillation is given by

$$T_p = 2\pi \left(\frac{M}{k}\right)^{\frac{1}{2}} \qquad (8)$$

where M = effective mass and k is the appropriate stiffness for the mode of oscillation. Clearly in surge where the buoy is effectively moored on one leg, the other two pendant, k_s is the appropriate stiffness since the pendant legs will contribute very little to the restoring force. However in heave the buoy must lift not only the chain on the weather leg but also the slack chain on the two pendant legs. Hence in heave the appropriate "stiffness" is $(k_H + 2W_c)$ in the table above. Note the chain itself acts as a spring in providing a restoring force which is proportional to the length lifted. So its effective stiffness is just its weight in water - when the chain is slack. As V decreases it is expected that $k_H \rightarrow W_c$ as $V \rightarrow 0$. We note that k_H is not very different to W_c in the cases studies so a reasonable approximation to the total stiffness in heave is $3W_c$.

The added mass is a function of the wave frequency, the added mass coefficient being approximately 1.0 at the low frequency end of the spectrum ranging to approximately 0.5 at the high frequency limit, see Newman (1977). The natural periods of the system are tabulated, see table 5, for both high (ω_H) and low (ω_L) frequency limits for the three buoy configurations considered (DB1 and DB2 with two chain sizes). Three modes of mooring oscillation are considered

(i) buoy surge $k = k_s$

(ii) buoy heave $k = 3W_c$

(iii) braidline natural frequency $k = k_b$

The results for DB1 are for its mooring in the S.W. Approaches and are not therefore for direct comparison with the DB2 mooring off Ireland, they are included for information only and to compare performance of the systems at their different locations.

The surge stiffness is a function of x and therefore the natural period in surge is shown plotted against x in fig. 14. The surge periods shown on table 5 are for typical excursions in x in heavy sea conditions (see mean values of x in figs 5, 11 and 13), these values are also marked on fig. 14. The energetic part of the wave spectrum is contained within the period range 5 - 30s. DB1 surge periods approach this band but in heavy sea conditions the natural period is ≃ 40s at the low frequency limit keeping it just clear of the band. In the other configurations both heave and surge periods are well outside the energetic period band. The natural period given by the braidline elasticity does appear within the band however. The buoy has to be hard against the anchor before the braidline stiffness becomes smaller than the effective stiffness of the chain catenary. Therefore sufficient chain should be supplied on the DB2 mooring for this situation not to occur.

There remains the transverse vibrations of the braidline to be considered. There are two types of transverse vibration possible (i) vortex induced vibration and (ii) the stretched string modes of oscillation. The natural periods due to vortex shedding are given by

$$T_p = \frac{d}{0.2V} \tag{9}$$

where d is the braidline diameter and V the current speed which for simplicity is assumed constant. In the current range V = 0.5 - 1 m/s the vortex shedding period for the 64 mm braidline is very short, $T_p = 0.64 \rightarrow 0.32$ s.

The natural periods of the stretched string modes are given by the relation

$$T_{Pn} = \frac{2L}{n}\left(\frac{M_c}{T}\right)^{\frac{1}{2}} \tag{10}$$

where L = length of the string, n is the mode number, M_c the (mass + added mass) per unit length of cable and T is the mean tension. Eq.(10) assumes that the ends of the cable are fixed. The fact that the ends are flexible, i.e. the chain can move, and that there is a considerable amount of free hanging chain on the end of the braidline will increase the period of the fundamental since L is not just the braidline length but includes the free chain also. The tension varies with the buoy drift, wave conditions and also down the length of the mooring. By averaging the tension and obtaining an average mass per unit length for the entire cable and chain lifted a rough approximation to the natural period may be obtained. For each mooring configuration the high and low load limits are considered where the low load is just the static weight of the minimum length of the mooring lifted, as under zero current conditions. The results are given in table 6 where (10) has been used to give T_{P1}. It is clear that DB1 has fundamental natural periods that fall within the high energy band of wave periods. $DB2_{(1)}$ and $DB2_{(2)}$ move the low tension fundamental outside the band but the high tension fundamental falls within the band as do the second modal periods T_{P2}. This appears to be something of a problem, especially since there does not seem to be a simple way of shifting these fundamental periods below the lower limit of the band where all of the modes would then be outside the high energy part of the wave spectrum. This difficulty of maintaining a high frequency tether response as water depth is increased is mentioned by Bowers & Standing (1982). Their conclusion is that an increase in T_p may have to be accepted in the hope that fluid damping will reduce the dangers of dynamic response and fatigue problems.

7. BUOY PITCH RESONANCE

A first approximation of DB2 pitch resonance may be determined by scaling the DB1 pitch resonance period. This assumes that the buoy loading and distribution of weight may all be scaled down in the same manner as the geometry. The natural frequency in pitch may be defined as

$$\omega = \left(\frac{Fr}{I}\right)^{\frac{1}{2}} \text{ rad/s} \qquad (11)$$

where F is some restoring force, r the moment arm of F from the pitch axis and I is the 2nd moment of inertia in pitch. Now I may be defined as

$$I = \Sigma\ Ma^2 \qquad (12)$$

where M is an element of mass of the buoy or payload, a is its distance from the pitch axis and Σ signifies summation over the whole structure and payload.

If s represents the linear scale factor between DB1 and DB2 such that $\ell' = s\ell$, where all dashed quantities will refer to DB2 and undashed to DB1, then by Froude scaling force and mass scale as s^3. Hence

$$\frac{I'}{I} = \frac{\Sigma M'a'^2}{\Sigma Ma^2} = \frac{\Sigma s^3 Ms^2 a^2}{\Sigma Ma^2} = s^5 \qquad (13)$$

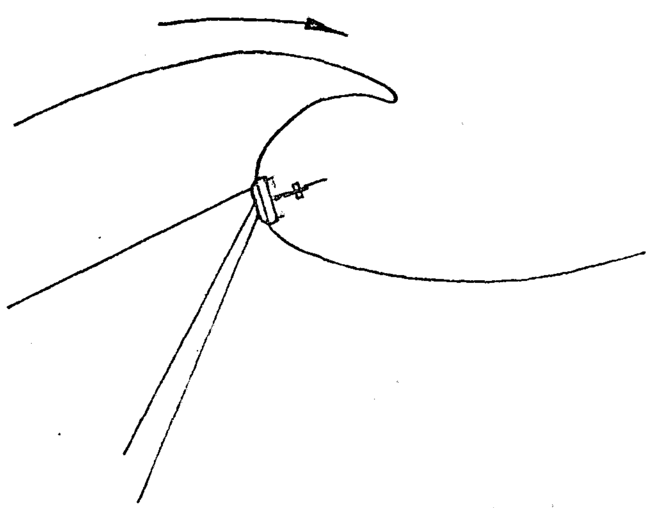
Using (13) and (11) it is then easy to show that

$$\frac{\omega'}{\omega} = \left(\frac{F'r'}{I} \times \frac{I}{Fr}\right)^{\frac{1}{2}} = \left(\frac{s^3.s}{s^5}\right)^{\frac{1}{2}} = s^{-\frac{1}{2}} \qquad (14)$$

It is known that $s \simeq 0.8$ therefore $(\omega'/\omega) = 1.118$. Carson (1982) quotes the DB1 period of pitch resonance as 2.2s, i.e. $\omega = 2.856$ rad/s, this gives $\omega' = 3.193$ rad/s which is equivalent to a period of 1.97s.

8. PERFORMANCE IN BREAKING WAVES

The performance of the DB1 mooring system in breaking waves was studied at NMI in model trials carried out in 1977 as already described. The buoy is essentially a surface following device and in a breaking wave the buoy will track around the concave face of a large breaker as depicted below. In order to invert the buoy the wave must be at least two buoy diameters high. Particle velocities and wave speed in a breaker are substantially higher than in a linear wave and the buoy can be carried along with the wave for a considerable distance.



Carson (1982) found that peak mooring loads in breaking waves with a non-compliant mooring could be very high, up to 86 tonnes at DB1 scale. The best mooring was found to be a compliant one with the lower chine attachment point. With this system loads were reduced by a factor of 10. The chine attachment gives a strong righting moment which aids survivability in breaking and spilling breakers and helps to pull the buoy through the crest of the wave. It is thought that the load reduction is mainly brought about by the compliance in the mooring. The wave sketched above evolves very quickly and rapidly dissipates as the jet forms a torrent of white water. The compliance allows the buoy to move with the wave even after all of the ground chain has been taken up. This allows some time for the wave to break so that the buoy does not have to be pulled through the solid wall of water, as it inevitably would with non-compliant mooring. Instead the buoy may ride through the cascading white water as the wave evolves and breaks over it. The white water being much aerated is much less dense which reduces the drag considerably. The fact that the DB2 mooring is very much more compliant than DB1 and of approximately the same compliance as that of the scaled up model mooring should give it a better survivability than DB1.

The probability of meeting a plunging breaker 12 - 15 m high in deep water at any one given location such that the breaker face is just becoming vertical as it approaches the buoy must be very remote. Carson (1982) argues that the majority of ocean breakers are of the spilling type, which are much less damaging. It is almost certain from the undamaged state of the relatively delicate meteorological sensors on the DB1 mast that DB1 has never encountered such a wave in its 4 year deployment in the S.W. Approaches.

In summary, the forces in a big breaking wave are potentially high enough to break a non-compliant mooring of the DB1 or DB2 type specification, although it would probably lift an anchor first. The degree of compliance of the $DB2_{(1)}$ or $DB2_{(2)}$ moorings however enable the buoy to ride with the wave as it breaks which reduces the forces by an order of magnitude. Under such circumstances the mooring loads may not be much different from those predicted for the extreme non-breaking waves. However, the likelihood of such a wave hitting the buoy are very slight. The chine attachment gives a righting moment which improves the buoy survivability in both spilling and plunging breakers making it superior to centre point moored discus buoys.

9. DISCUSSION

It is encouraging to note that in surge and heave the moorings for both $DB2_{(1)}$ and $DB2_{(2)}$ are more compliant and therefore have longer natural periods than DB1. The mooring forces are significantly reduced by a factor between 0.5 and 0.67 for the smaller buoy in the deeper water. Either of the DB2 moorings considered appear to be suitable from consideration of mooring forces and natural periods. The choice may therefore be made from wear and corrosion considerations. The 32 mm chain of the $DB2_{(2)}$ mooring is the more substantial and hence more appealing. The heavier chain increases the tension in the mooring slightly when compared with $DB2_{(1)}$ but this has the beneficial effect of reducing the drift by approximately 20 m, roughly a 10% improvement. The increased water depth and compliance of the DB2 system means that the watch circle radius, i.e. the circle the buoy describes through a typical tidal cycle, is approximately twice that of DB1. The braidline compliance for the chosen 325 m length of 64 mm diameter braidline is more than 10 times that of the DB1 braidline compliance. This figure is nearer that originally proposed by Carson, see Carson (1982), for the DB1 system when appropriately scaled for the DB2 system, following the model trials in breaking waves at NMI. There is therefore every hope that the DB2 system may fair equally as well as in the original model tests which showed good survivability characteristics and low mooring loads in breaking waves. This was by virtue of the chine mounted mooring attachment point and the high degree of compliance in the elastic mooring. The probability of the buoy meeting a large breaking wave just at the point when the front face becomes vertical is considered small. It is thought that DB1 on its 4 year deployment in the S.W. Approaches has not encountered such an occurence.

The simple dynamic numerical model has proved very useful in predicting peak mooring loads in extreme non-breaking wave conditions. The predicted tensions for DB1 are in reasonable agreement with those measured on site in the S.W. Approaches. There must be some uncertainty in this deterministic approach however since only one wave group has been examined. It would therefore be prudent to be conservative in making the final choices of materials and chain lengths for the system. A linear spectral model which might hope to cover a wider range of wave amplitudes and frequencies is very clearly inappropriate for the mooring systems examined here which are highly nonlinear both in damping and stiffness.

On the basis of the results of the numerical model, see table 4, it would seem that for $DB2_{(1)}$ at least 400 m of chain should make up the bottom section between braidline and anchor. For $DB2_{(2)}$ with the heavier chain 350 m may be sufficient, remember that ℓ + 50 m is the minimum required by the calculation for this length, since 50 m is used to pretension the mooring. In either mooring a 1 tonne Bruce anchor, quoted as having a holding power of 40:1 in good ground, should be sufficient to withstand these anchor loads.

A number of possible modes of the mooring vibration appear to have periods that fall within the high energy band of the wave spectrum. These are the elastic natural period of the braidline and the first two modes of the transverse oscillation of the whole mooring as a stretched string, see tables 5 and 6. With regard to the first of these the compliance of the chain catenary is much greater than that of the braidline even at large values of x, the drift. The braidline only becomes the most compliant section of the mooring when the buoy is hard against the anchor having lifted all of the ground chain. If such a condition can be avoided, by laying adequate lengths of ground chain, the elastic natural frequency of the braidline should not excite a large or damaging response of the system. It is thought that after the initial lay of the DB1 moorings in the S.W. Approaches the tensions recorded in the first significantly high waves (17 tonnes in 14 m waves) were sufficient to lift the entire length of ground chain. The outcome appears to have been that the anchor was dragged and the pretension relaxed. If the calculations here are correct then subsequent peak loads ($\simeq$ 13 tonnes) have not quite managed to lift the chain and the mooring seems to have functioned as designed.

The second set of natural modes that appear potentially problematical are the transverse modes. There is evidence that these modes do not cause any problem on the DB1 mooring system. If it were a problem then it might be expected to show itself in excessive chain wear between links. Examination of recovered DB1 mooring chains suggests that inter-link wear is not significant. Of much greater significance is corrosion of unprotected links and shackles, damage due to fishing warps and abrasion in the ground chain thrash zone. It is thought that the fluid damping, especially over the chain sections, is more than adequate to damp these modes of vibration. It is considered that the same will be true of the DB2 mooring in deeper water. The remaining transverse vibration due to vortex shedding has a much higher frequency than any of the natural modes discussed and so is not likely to excite any large response of the system.

The buoy pitch response is very similar to that of DB1, the scaled natural period being slightly less at approximately 2 s. It is interesting to note from the dynamic response calculations of figs. 5, 11 and 13 that the buoy will always under-read the wave particle velocity because of the large mooring motion which allows the buoy to drift with each wave. The mean velocity, or the current underlying the wave motion, is correctly averaged however so that $\overline{V - \dot{x}}$ is correctly given as V_o in each case.

All of these results with the great benefit of the DB1 experience indicate no particular difficulty in choosing materials or a mooring configuration that gives promising performance on paper. In particular the DB1 experience should be used to guard the new mooring against corrosion, handling and fishing activity problems which still probably present the gravest dangers to the integrity of the mooring.

10. REFERENCES

Bowers E.C. and Standing R.G. (1982) Environmental loading and response. NMI R135 March 1982.

Carson R.M. (1972) Model tests on a data buoy hull NIO internal report no. A59, September 1972.

Carson R.M. (1977) Motions and mooring forces of the data buoy. In: Proc. of the U.K. data buoy symposium. IOS Report 44.

Carson R.M. (1975) Mooring hydrodynamics. Technology of Buoy Mooring Systems, 55-63, pub. S.U.T. London.

Carson R.M. (1982) On the capsize performance of a discus buoy in deep sea breakers. (submitted Ocean Eng. 1982).

Newman J.N. (1977) Marine Hydrodynamics. pub. MIT press.

Rusby J.S.M. and Waites S.P. (1980) The deployment and operational performance of the DB1 data buoy system in the South-West Approaches to the British Isles. Oceans '80.

Table 1

DB1 steady flow results

V (m/s)	z (m)	T (tonnes)	T_x (tonnes)	T_z (tonnes)	ℓ (m)	x (m)	ϕ (deg)	T_A (tonnes)
0.25	0	2.15	0.06	2.15	2.5	15	88.5	0.075
0.5	0	2.4	0.22	2.4	10	33	84.7	0.3
1	0	3.55	0.9	3.44	40	66	75.4	1.2
1	2	3.6	0.9	3.49	40	64	75.7	1.2
1	4	3.67	0.9	3.56	45	62	75.9	1.2
1	14	3.95	0.9	3.86	55	53	76.9	1.23
1.5	0	4.85	2.0	4.41	65	84	65.5	2.28
2	0	6.75	3.58	5.72	100	97	58.0	3.96
3	0	11.74	8.05	8.5	170	113	46.7	8.59
3	5	11.89	8.05	8.75	175	111	47.4	8.6
3	10	12.0	8.05	8.94	180	109	48.0	8.6
3.5	0	14.8	10.9	10.0	205	119	42.4	11.5

Table 2

$DB2_{(1)}$ steady flow results

V (m/s)	z (m)	T (tonnes)	T_x (tonnes)	T_z (tonnes)	ℓ (m)	x (m)	ϕ (deg)	T_A (tonnes)
0.5	0	1.4	0.15	1.39	25	88	83.7	0.24
1	0	2.36	0.61	2.28	80	159	75.0	0.92
1	10	2.47	0.61	2.39	90	148	75.6	0.92
1	20	2.57	0.61	2.5	105	138	76.2	0.93
1	30	2.68	0.61	2.61	115	128	76.8	0.93
1	40	2.79	0.61	2.72	125	117	77.3	0.94
1.5	0	3.67	1.38	3.4	150	200	68.0	1.94
2	0	5.25	2.45	4.65	215	228	62.2	3.28
2	10	5.37	2.45	4.78	225	221	62.9	3.3
2	20	5.49	2.45	4.91	240	214	63.5	3.32
2	30	5.6	2.45	5.04	250	207	64.1	3.34
2	40	5.72	2.45	5.17	260	200	64.7	3.36
2.5	0	7.1	3.82	5.98	280	248	57.4	4.92
3	0	9.19	5.5	7.36	350	264	53.2	6.84

Table 3

$DB2_{(2)}$ steady flow results

V (m/s)	z (m)	T (tonnes)	T_X (tonnes)	T_Z (tonnes)	ℓ (m)	x (m)	ϕ (deg)	T_A (tonnes)
0.5	0	1.77	0.15	1.76	15	68	85.0	0.25
1	0	2.8	0.61	2.73	60	136	77.4	0.94
1	20	3.12	0.61	3.06	75	113	78.7	0.95
1	40	3.47	0.61	3.42	95	90	79.9	0.96
1.5	0	4.25	1.38	4.02	120	178	71.1	2.0
2	0	6.0	2.45	5.48	160	206	65.9	3.4
2	40	6.69	2.45	6.23	220	175	68.5	3.5

Table 4

Summary of results for extreme non-breaking waves taken from the combined dynamic and steady flow analyses

	max. wave		z = 0			Estimated for z = H			
	H (m)	T_p (s)	$T_{X_{max}}$ (tonnes)	x_{max}	ℓ (m)	T (tonnes)	T_z (tonnes)	T_A (tonnes)	ℓ (m)
DB1	24	12.5	7.9	112	170	12.5	9.6	8.6	195
	scaled from model tests								
$DB2_{(1)}$ (25mm chain)	33	16	2.74	232	230	5.9	5.2	3.5	270
$DB2_{(2)}$ (32mm chain)	33	16	2.7	211	176	7.0	6.5	3.7	211

Table 5

Natural periods of buoy/mooring system (sec.)

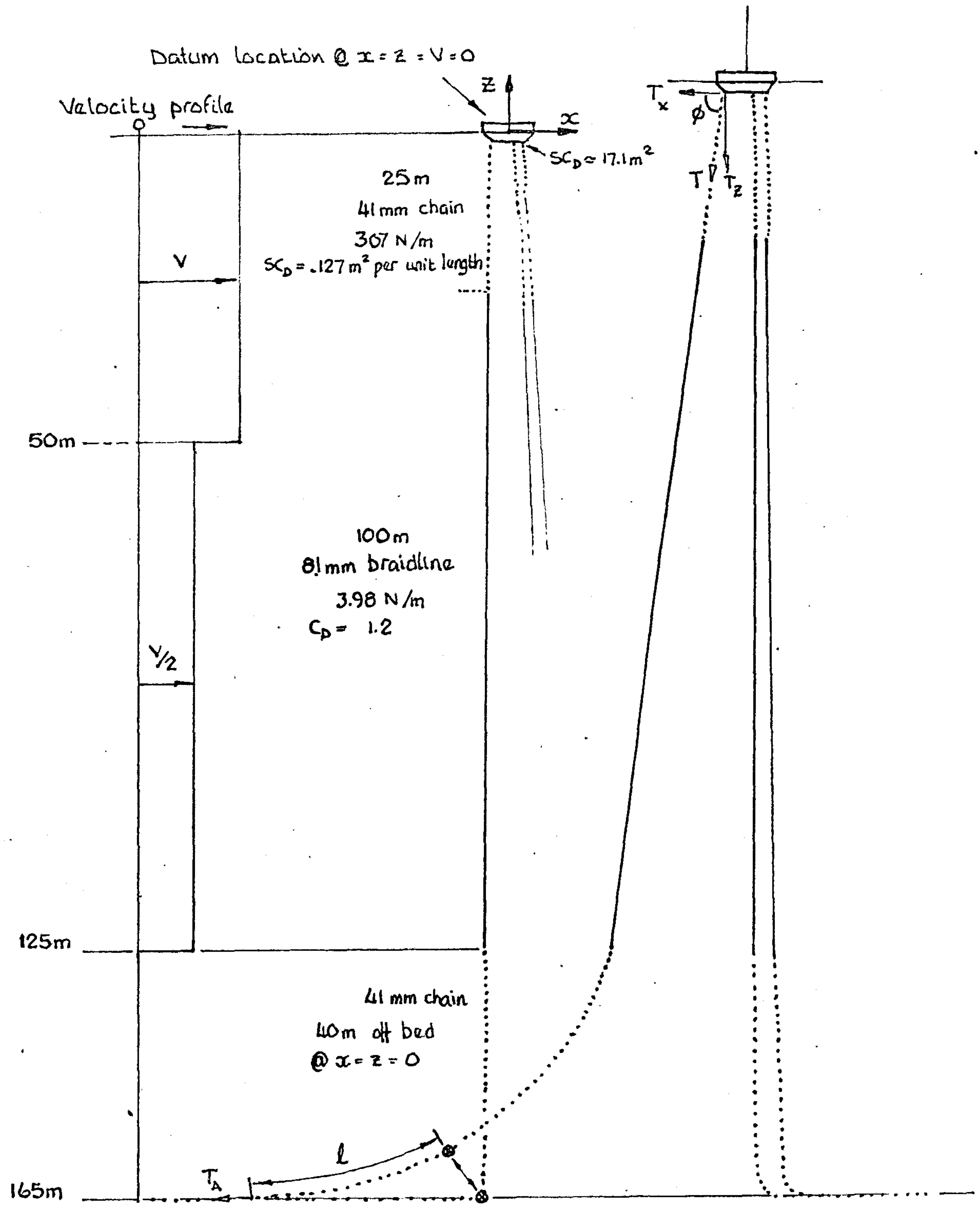
			DB1	$DB2_{(1)}$ (25mm chain)	$DB2_{(2)}$ (31.75mm chain)
(i)	surge	ω_H	35 } x = 100m	68 } x = 220m	77 } x = 190m
		ω_L	40	58	66
(ii)	heave	ω_H	51.6	62.7	50.0
		ω_L	59.6	72.7	57.9
(iii)	braidline elasticity	ω_H	7.8	22.3	22.3
		ω_L	9.1	25.8	25.8

Table 6

Mooring natural periods in transverse oscillations (as a stretched string)

	LOW LOAD					HIGH LOAD				
	L(m)	T_{ave} (N)	M_c (kg/m)	T_{P_1} (s)	T_{P_2} (s)	L(m)	T_{ave} (N)	M_c (kg/m)	T_{P1} (s)	T_{P2} (s)
DB1	165	10180	24.7	16.3	8.2	335	103500	32.8	11.9	5.9
$DB2_{(1)}$	400	4780	10.4	37.3	18.7	630	46107	12.8	21.0	10.5
$DB2_{(2)}$	400	7008	11.6	32.5	16.3	611	52680	16.7	21.8	10.9

FIG. 1



Schematic representation of the DBI mooring for the steady flow numerical model – shown at datum and steady state location for given V and z.

Braidline : 81mm dia nylon Viking : 136 tonnes break : E ≃ 776 MN/m²

Chain : 41mm high strength stud link : 100 tonnes break : wt. in air 36 kg/m

FIG 2 Variations in mooring and restoring forces with steady drift - DB1

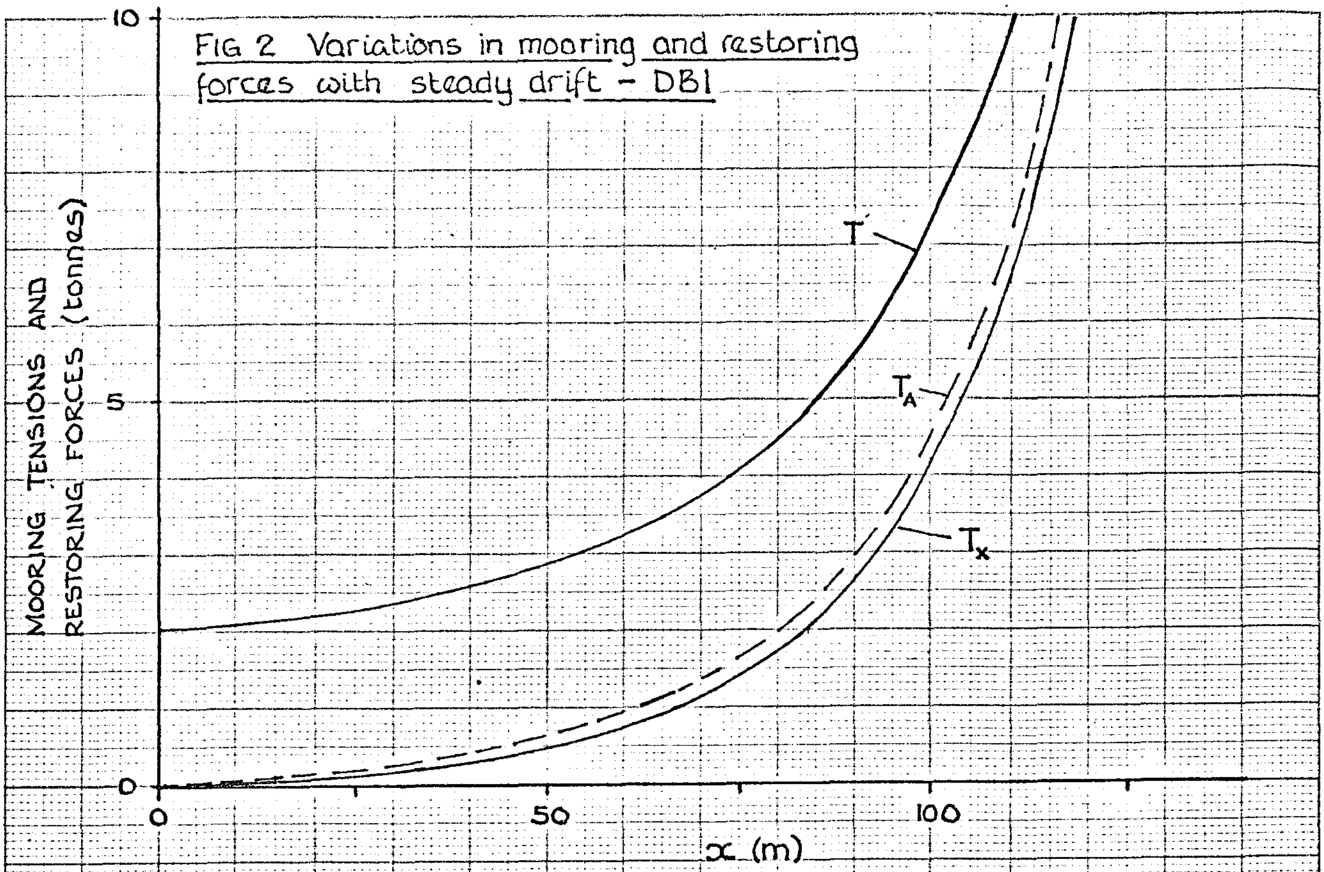


FIG. 3 Variation in vertical force component with heave DB1

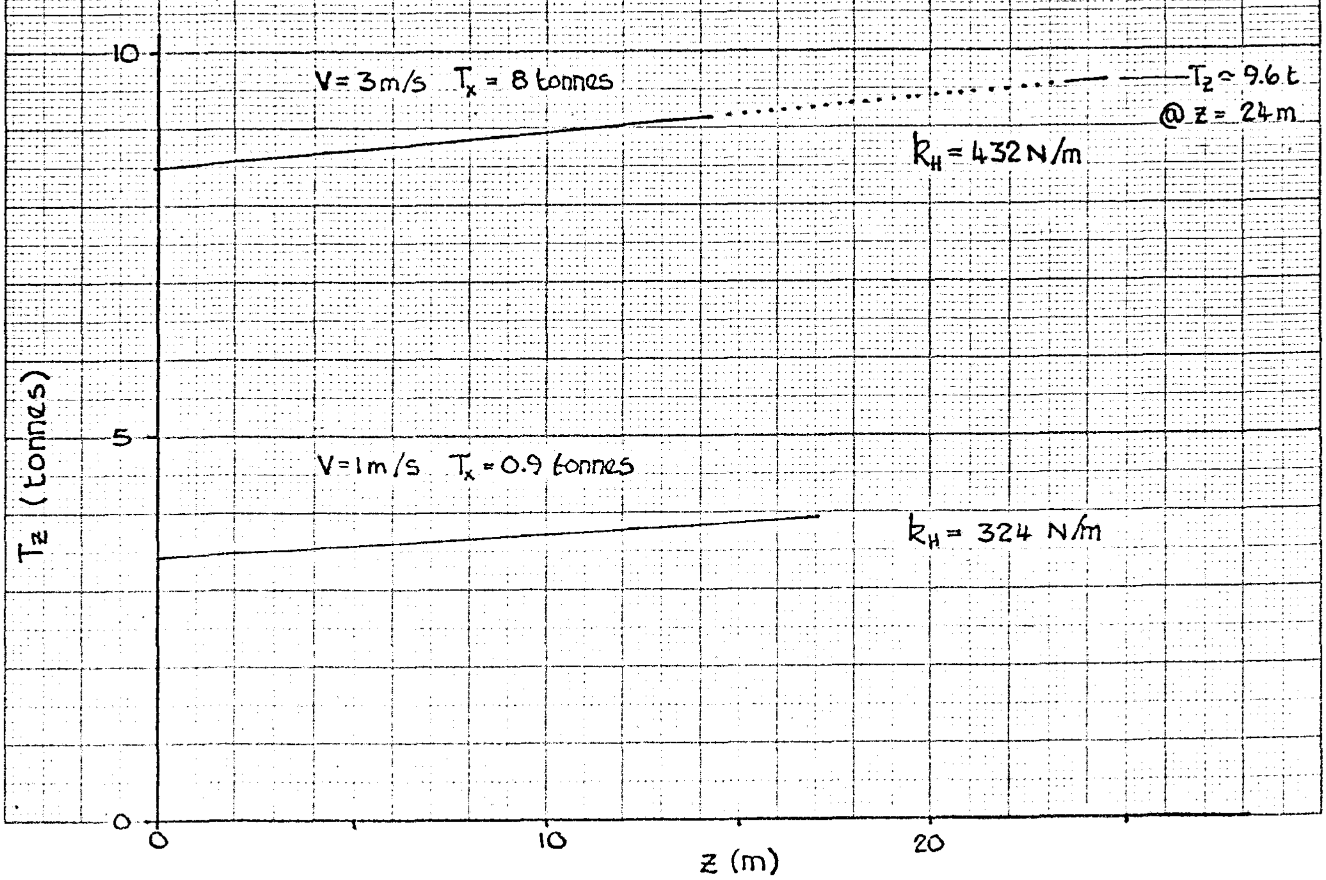
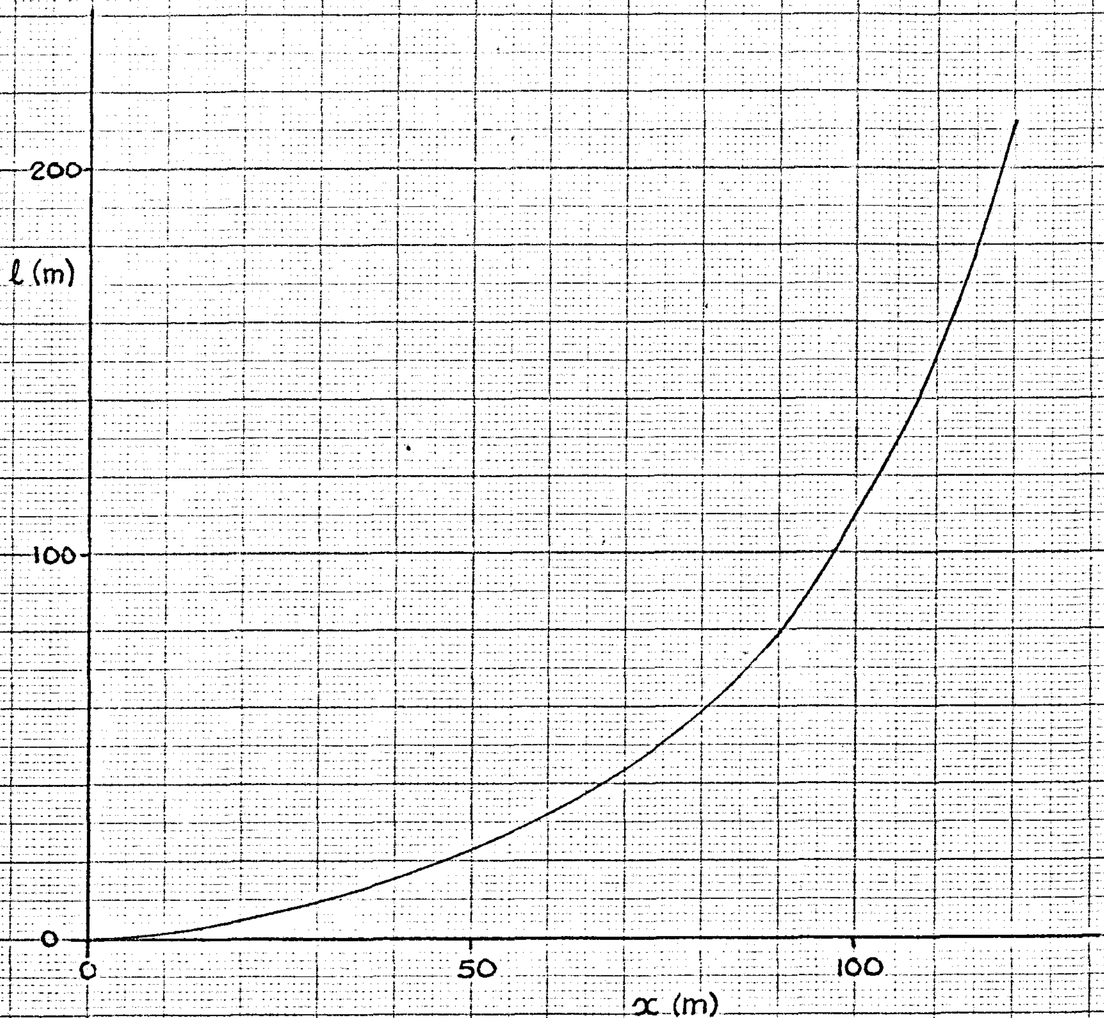


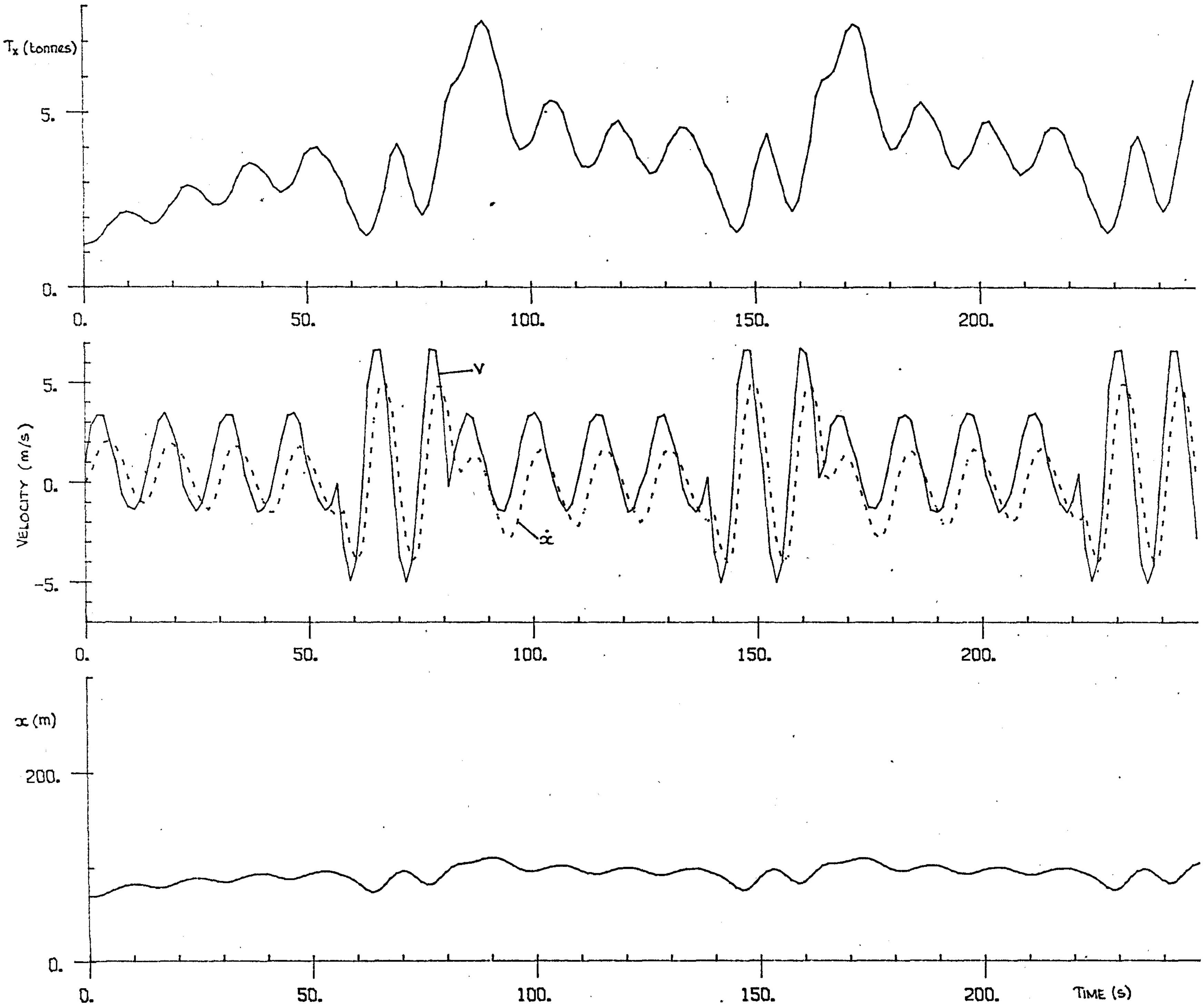
FIG. 4



Length of ground chain lifted plotted against drift for z = 0 – DBI

FIG. 5

DB1 dynamic response



Wave group period 82.6 s

4 waves @ 11.3 m, 14.4 s → $a\omega$ = 2.47 m/s

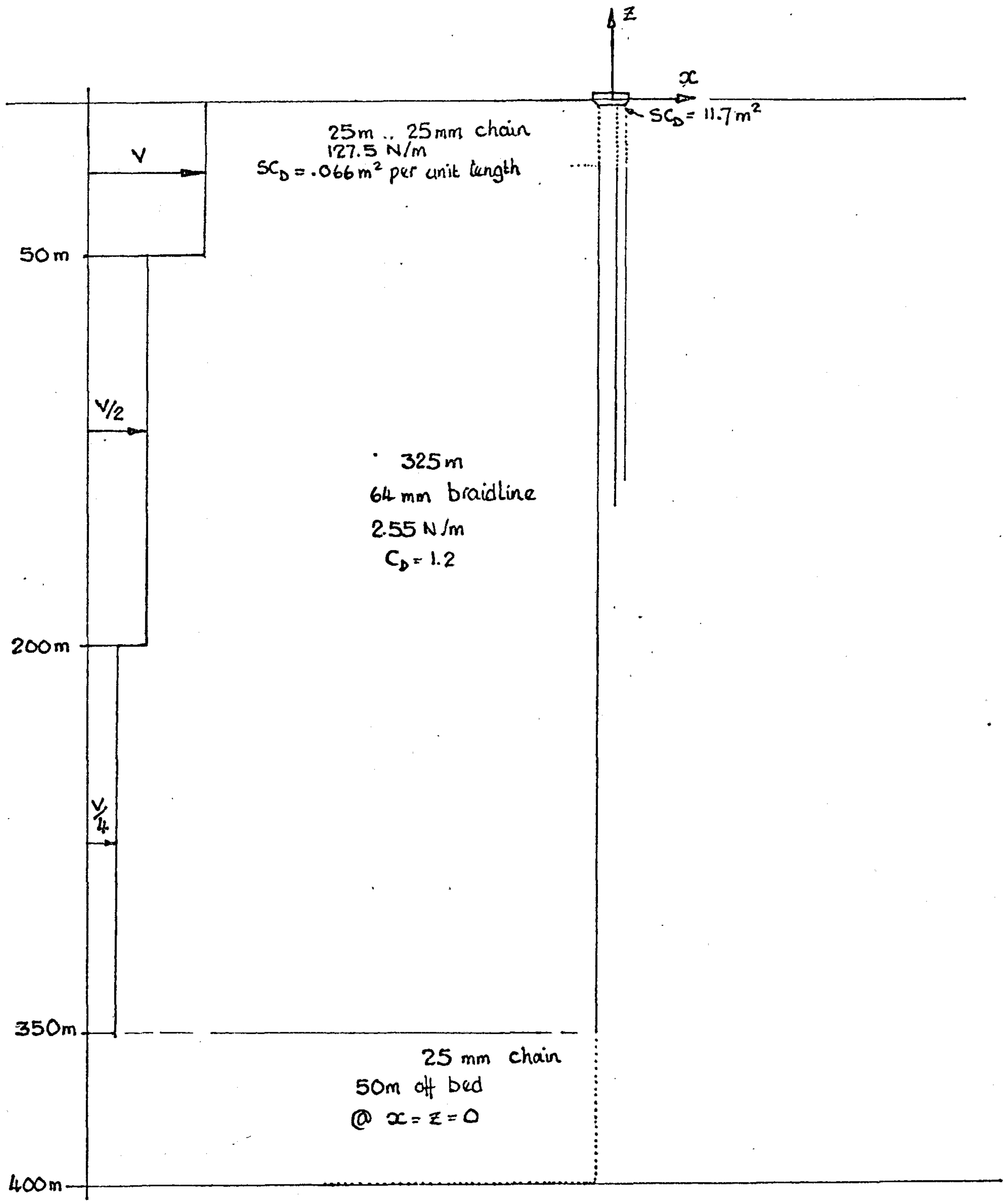
2 " " 24 m, 12.5 s → $a\omega$ = 6.03 m/s

V_o = 1 m/s

$T_{x_{max}}$ = 7.9 tonnes

x_{max} = 112 m

x_{mean} = 100m



Schematic representation of the DB2 (1) mooring in 400 m of water for the steady flow numerical model

Braidline : 64mm dia nylon Viking : 90 tonnes break : E = 305 MN/m²

Chain : 25mm high strength stud link : 38 tonnes break : wt. in air 15 kg/m.

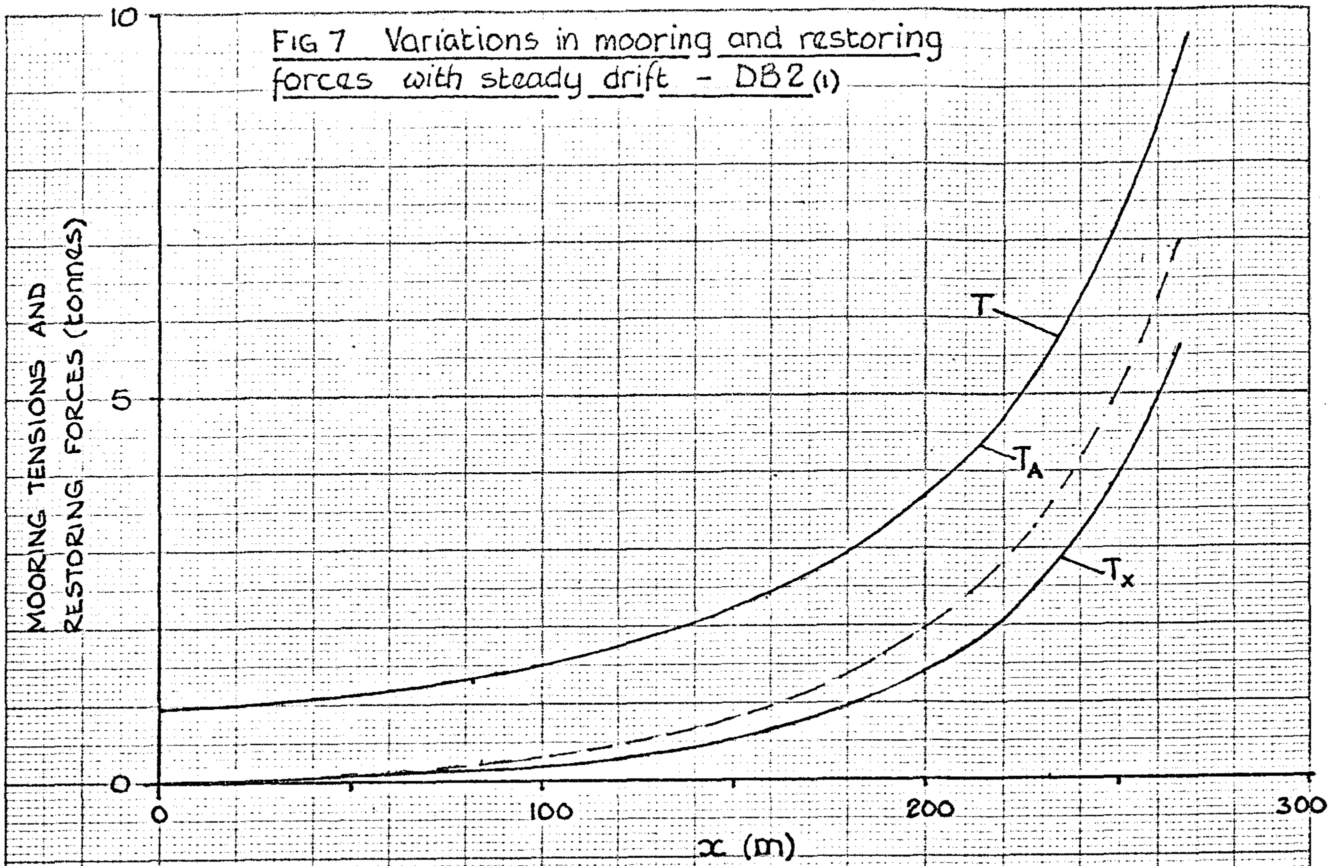


FIG 7 Variations in mooring and restoring forces with steady drift - DB2 (1)

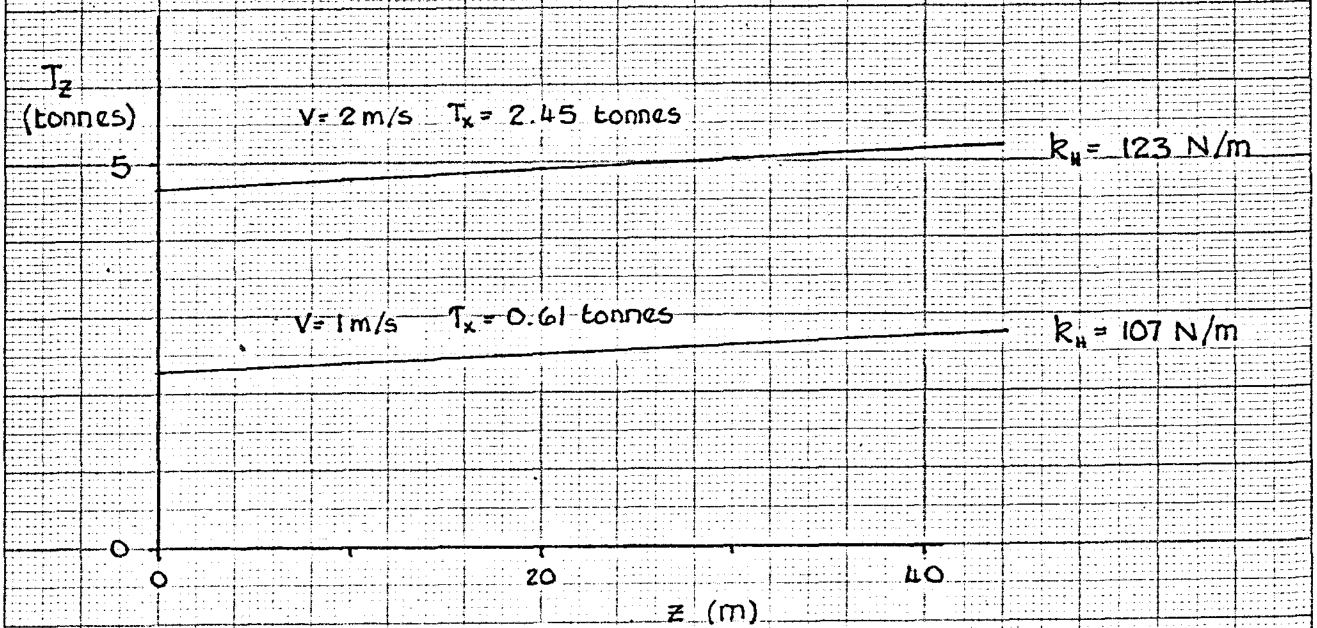
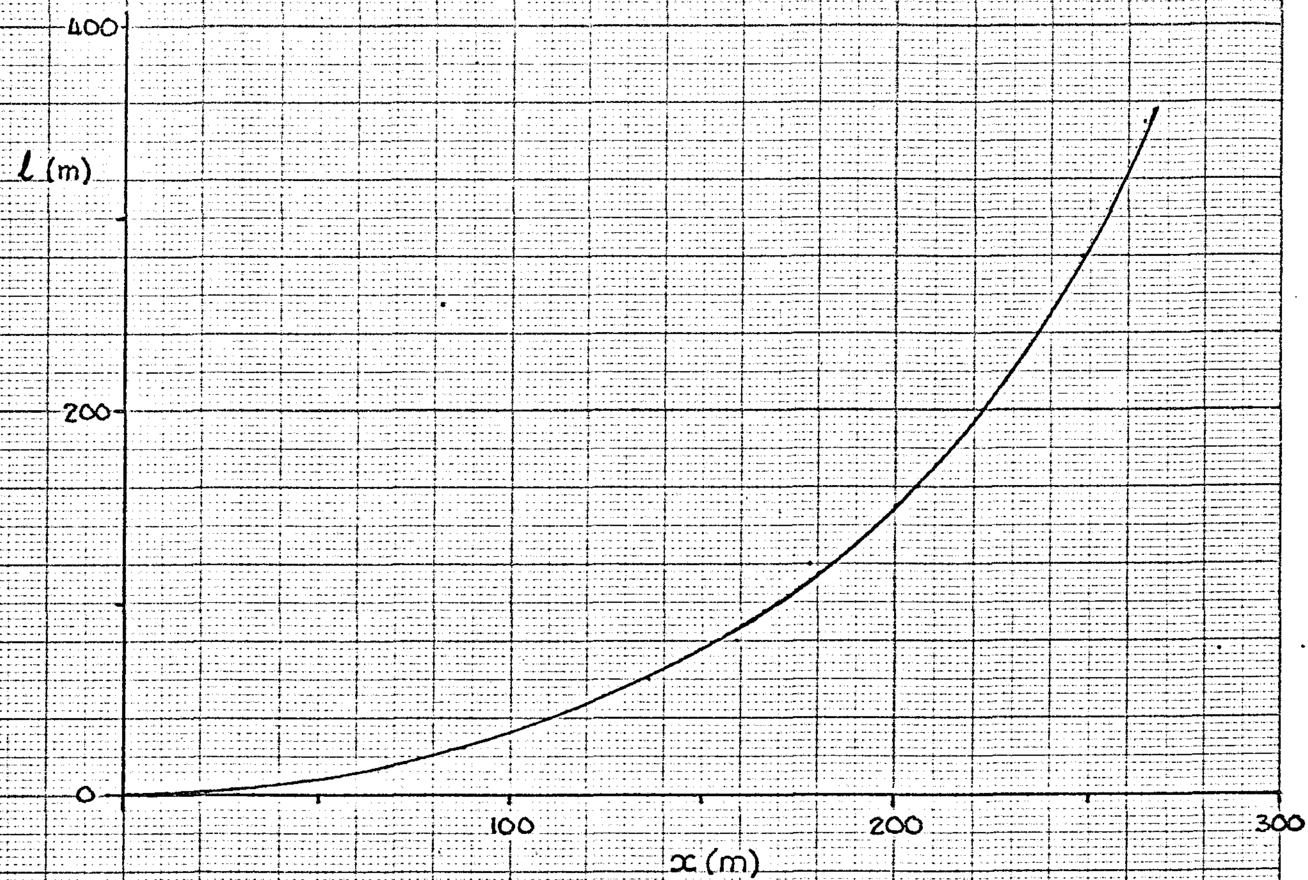


FIG 8 Variation in mooring vertical force component with heave DB2 (1)

FIG. 9



Length of ground chain lifted plotted against drift for $z = 0$ ... $DB2_{(1)}$ and $DB2_{(2)}$. (same for both.)

DB2(1) Variation in cable angle at the buoy with drift for z = 0.

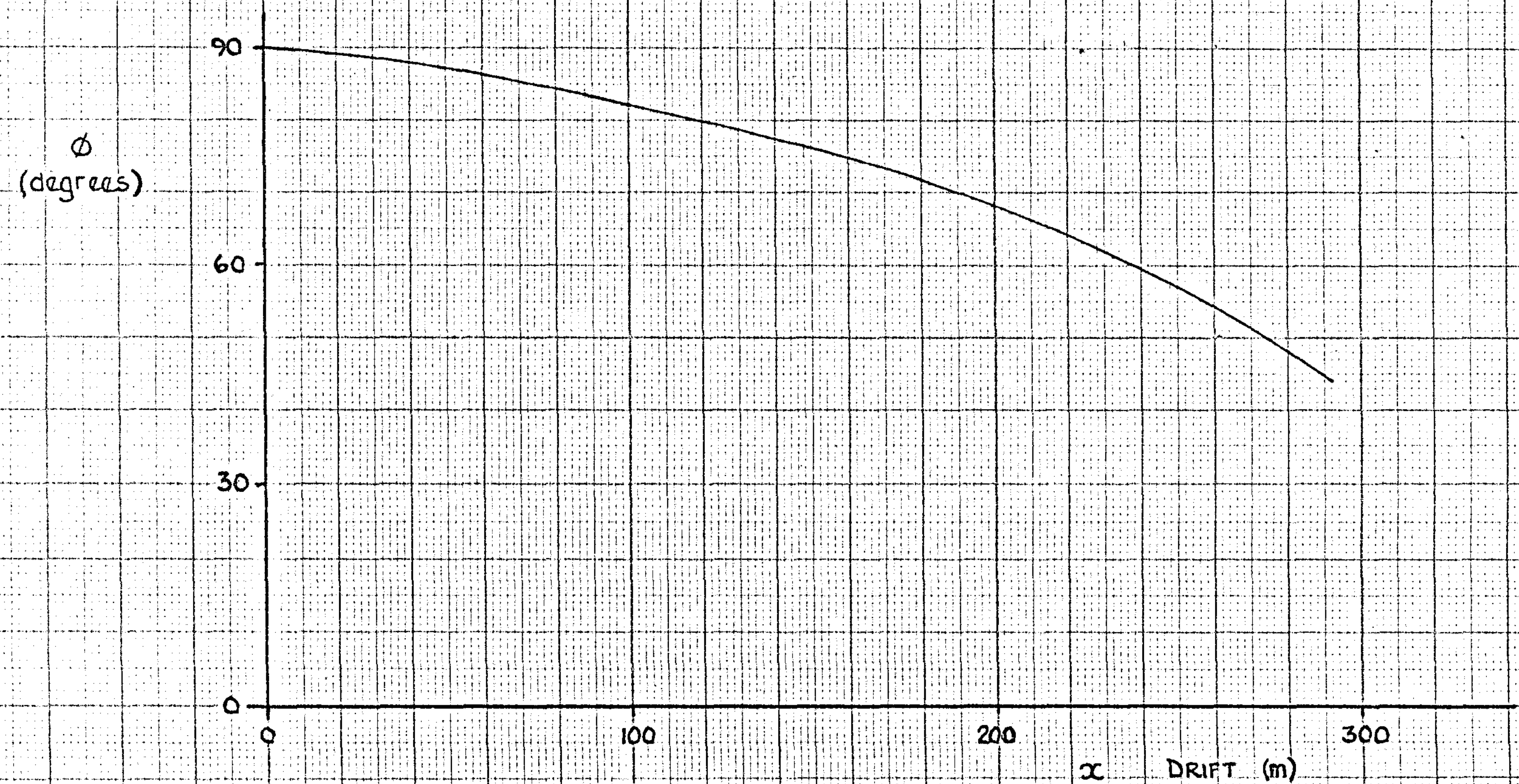
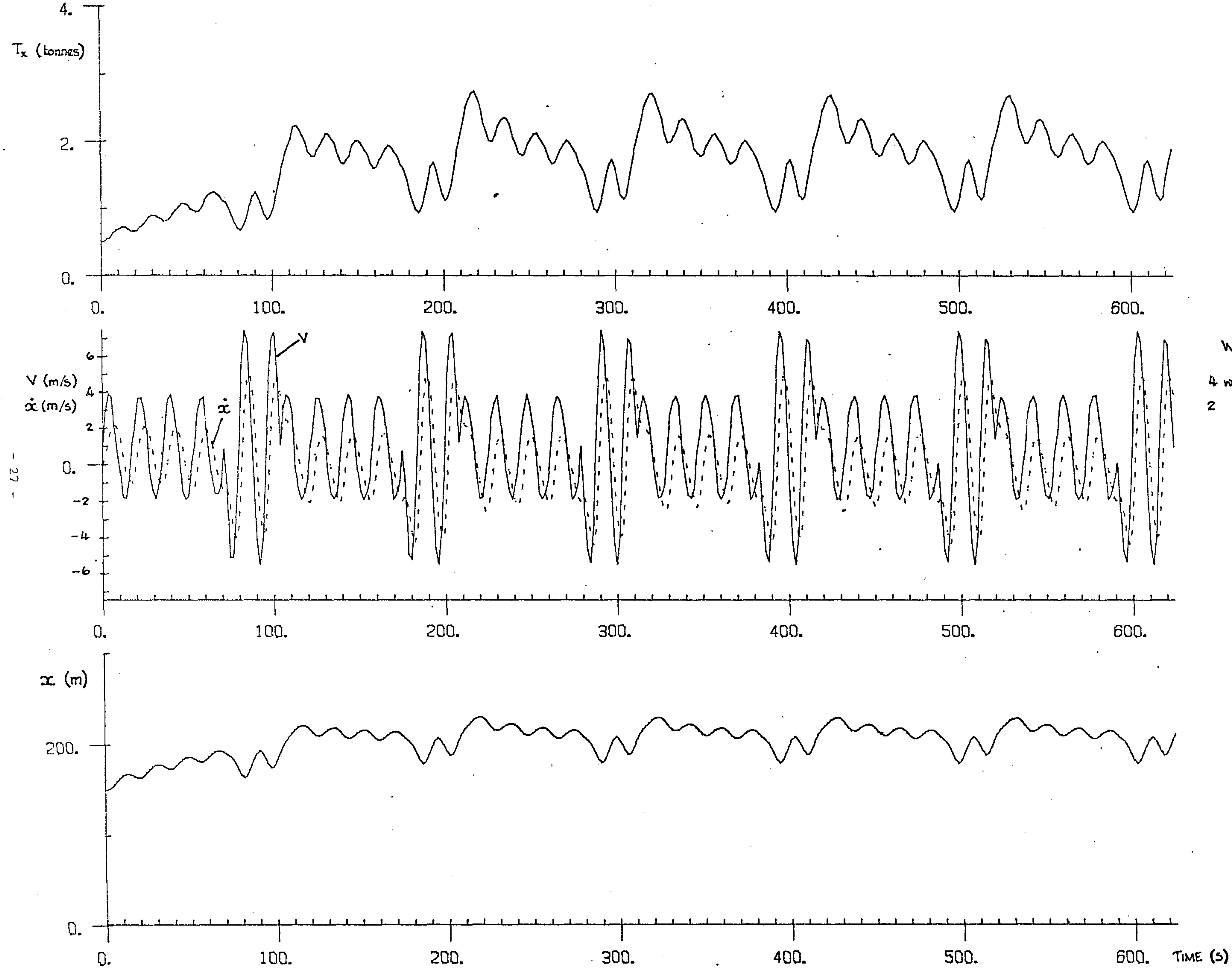


FIG 10



DB2(1) dynamic response

Wave group period 104 s

4 waves @ 16.5m, 18 s → $a\omega$ = 2.88 m/s

2 " " 33 m, 16 s → $a\omega$ = 6.48 m/s

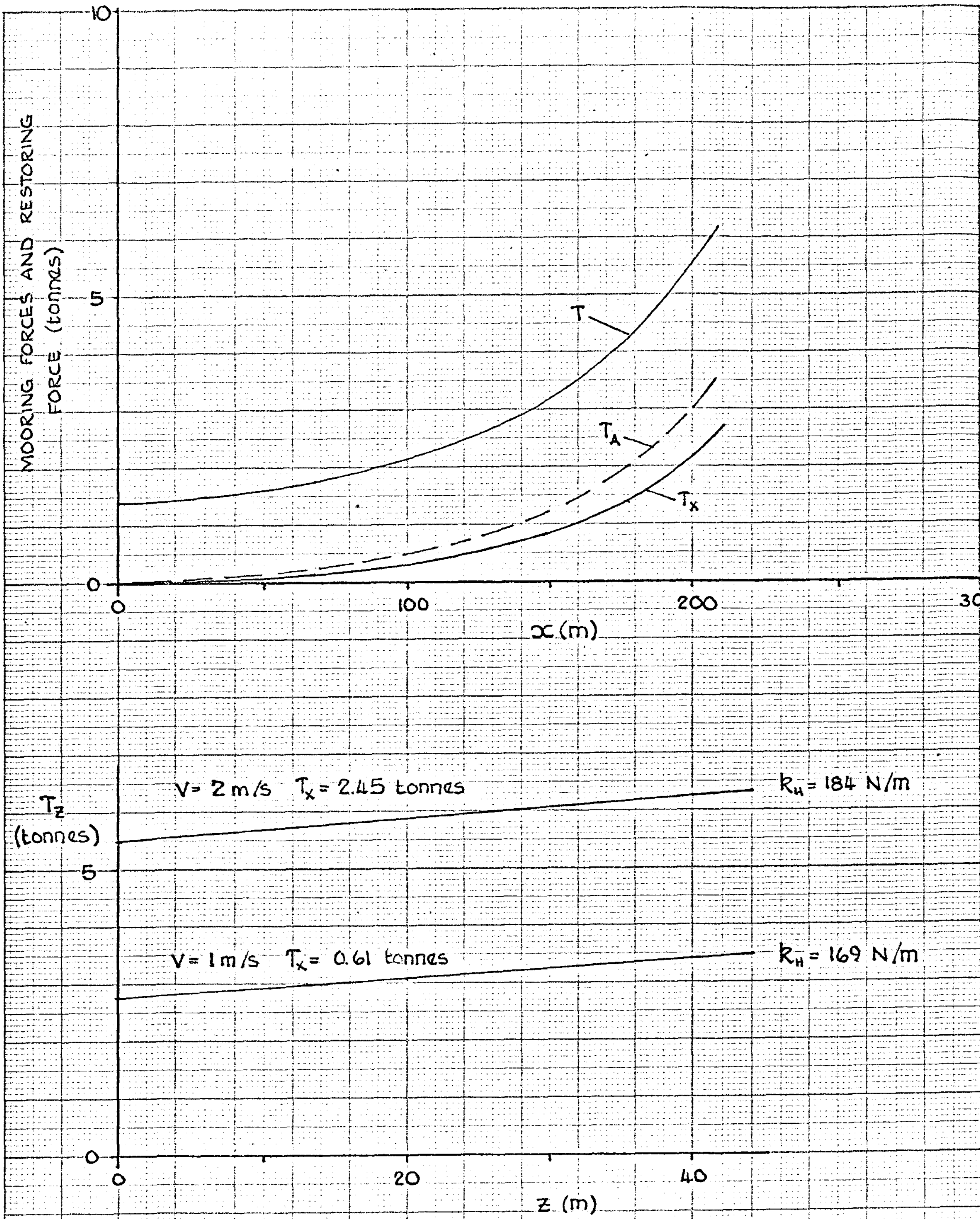
V_0 = 1 m/s

$T_{x\,max}$ = 2.74 tonnes

x_{max} = 232 m

x_{mean} = 220 m

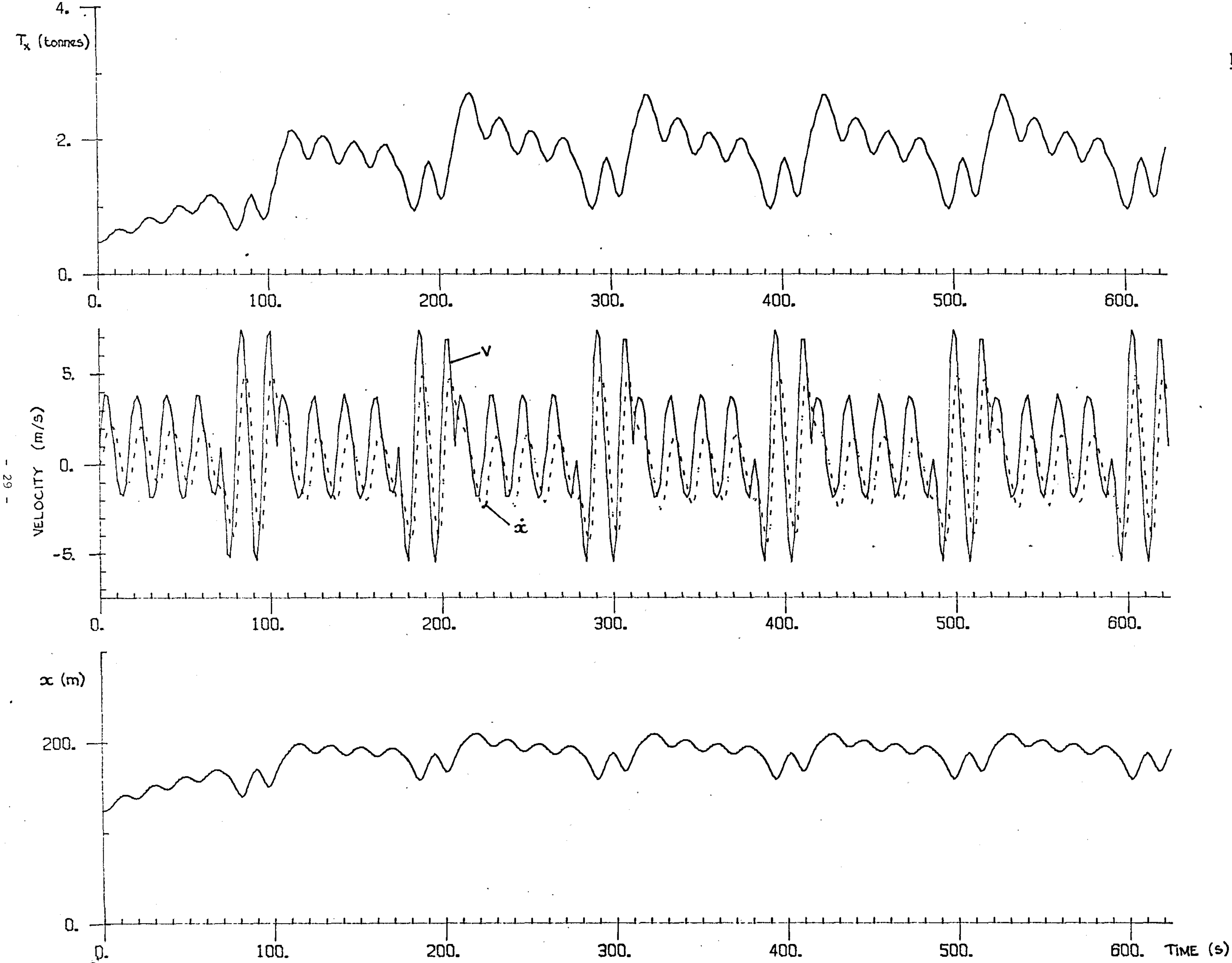
FIG. 12



Variations in mooring forces and restoring forces with drift and heave - DB2 (2)

FIG. 15

DB2(2) dynamic response



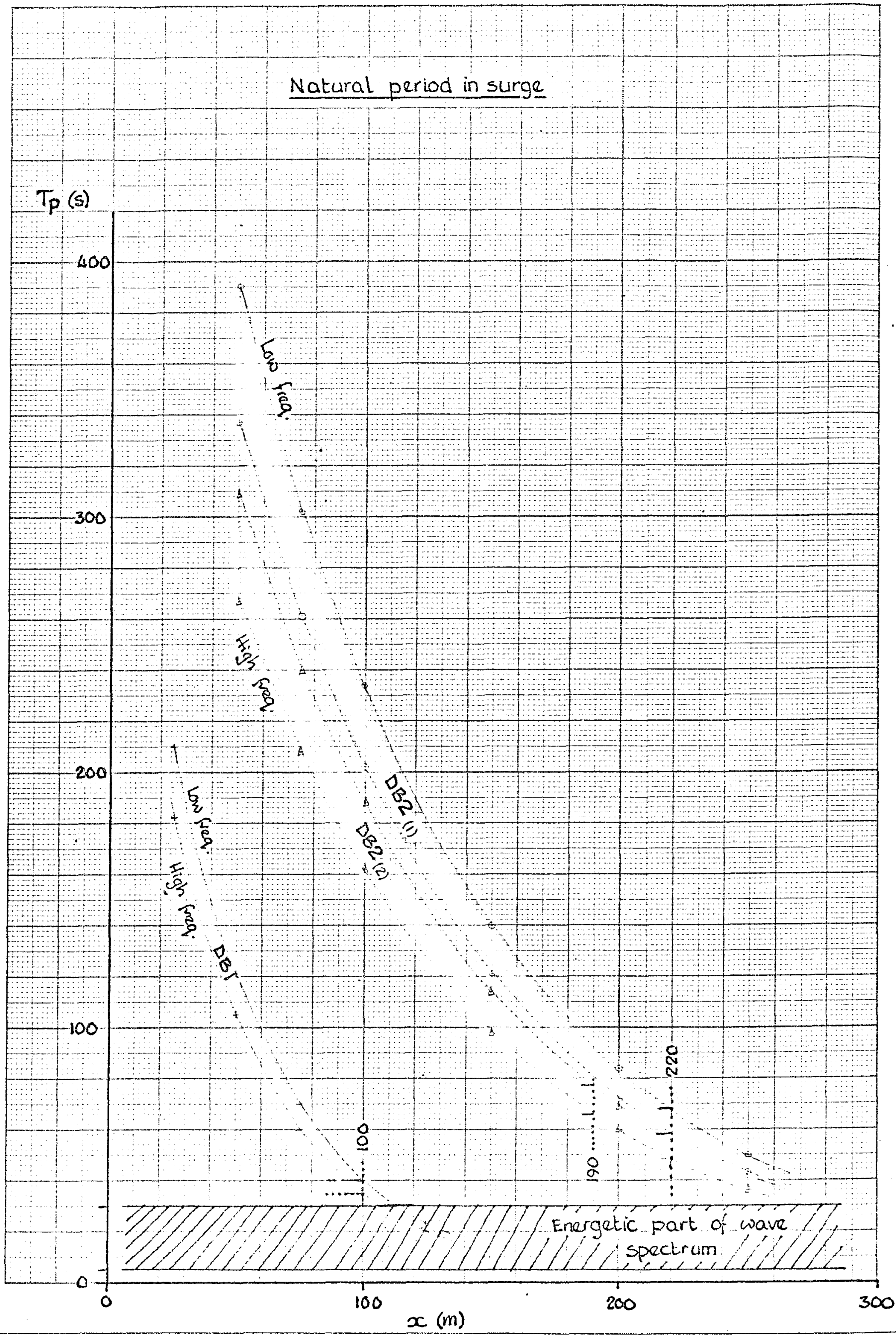
Velocity field as FIG 11

$T_{x_{max}}$ = 2.7 tonnes

x_{max} = 211 m

x_{mean} = 190 m

FIG. 14


Natural period in surge
Tp (s)
400
300
200
100
0
Low freq.
High freq.
DB2 (1)
DB2 (2)
Low freq.
High freq.
DB1
100
190
220
Energetic part of wave spectrum
0
100
200
300
x (m)