NATIONAL INSTITUTE OF OCEANOGRAPHY

WORMLEY, GODALMING, SURREY

Model Tests of a Data Buoy Hull

by

R. M. CARSON

N.I.O. Internal Report No. A. 59

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1. Introduction

This report gives the results of a short series of tests carried out at the National Institute of Oceanography in support of the DB1 Data Buoy design study. This buoy is to be used as a general purpose sensor platform, primarily in the North Sea. The choice of hull type open to us is restricted by the job the buoy has to do; in particular the requirement to measure waves has led us to propose a surface following discus buoy. The mooring is likewise restricted by the need for a sea-bottom unit, with a cable connection to the buoy: this makes a three point mooring obligatory. The full discussion leading to this choice of system is given in the Final Report on the design study, submitted to the Committee on Marine Technology.

The buoy size is mainly fixed by the required endurance of the buoy, and the resulting weight of the power supply. Also the ability of the buoy to carry a 10m meteorological mast, and to support two or three maintenance men, influences the choice of size. These considerations have led us to propose a buoy of 6.1m diameter and 2.15m thickness.

While the hull shape and size were more or less fixed by these practical considerations, we still had certain reservations about the buoy's dynamic behaviour in combinations of current and waves. The published work on buoy/mooring dynamics is concerned with the deep-water, single-point, elastic mooring; this is basically a linear system, in which the wave excitation amplitude is small compared to the mooring dimensions. By contrast, we are concerned with a mooring where the wave amplitude may be a significant fraction of the depth, and where the cable catenary introduces a strongly non-linear spring to the system. This problem could be solved by numerical simulation, or by an analogue computer simulation. Both of these would require some gross assumptions about the hydrodynamic forces acting on the buoy. Alternatively, the whole system could be modelled in the wave tank, the only assumptions being those of conventional ship model testing.

2. The Objectives

The model tests can be divided into four sections, each aimed at a particular facet of the buoy behaviour.

(i) The maximum towing speed is of interest, as it affects the efficiency of buoy deployment.

(ii) We wish to know whether the buoy and its mooring can survive in North Sea conditions, and in particular the maximum load that the mooring must sustain.

(iii) The three-point mooring has an effect on the ability of the buoy to follow the wave surface; it is important to quantify this effect, because the buoy motion is to be used as a measure of wave height and slope.

(iv) The buoy motion in short waves may make servicing operations difficult. The magnitude of this motion is of interest, as is the effectiveness of various proposals for damping the motion.

3. Model Scaling

(i) The buoy hull

The model scale factor is something of a compromise, controlled by the available wavemaker. This is capable of a 25cm maximum waveheight, and of a 39cm minimum wavelength. We would like to model the highest expected wave - 18m - which would lead to a scale of

$$\frac{0.25}{18} = \frac{1}{72}$$

This gives a model diameter of 8.5cm. Equally we would like to see the performance of the buoy in wavelengths comparable to its own diameter - this suggests a model diameter of 39cm. The compromise we chose was 25.4cm, or a scale factor of 24:1. We were thus able to test the buoy in waves up to 6m in height, and in wavelengths down to $1\frac{1}{2}$ times the buoy diameter.

Other factors of course influence the choice of scale. Firstly, if the model is too small, it becomes difficult to construct with the correct mass distribution. Secondly, the mooring forces become very small for a small model, with corresponding problems of accurate measurement. Finally, the water depth is limited by the tank depth, in this case 1.7m. This is equivalent to 41m full-scale, a reasonable depth for a North Sea mooring.

(ii) The mooring chain

The model should match the full-scale chain in mass, weight-in-water (i.e. density), lateral and longitudinal drag, and in elasticity. Elasticity is the least important in a long-scope mooring, which will probably drag its anchor before coming taut. If the model and the full size chain are made of the same material (steel in the present case), then the mass per unit length must scale as $(\text{length})^2$. The model chain used weighed 42.5g/metre, equivalent to 24.5kg/metre full-scale (16.4 lb/ft) which is an average value for $1\frac{1}{4}''$ chain, breaking load C.42 tonnes.

Modelling the chain drag is more difficult. Since Froude scaling must be followed in the model tests to give the correct wake and wave conditions, the model velocities must be less than full-scale by $(24)^{-\frac{1}{2}}$. As a result the model Reynolds Number, which is a function of velocity x length, is $(24)^{1\frac{1}{2}}$ times too small; this might have a significant effect on the chain drag coefficient.

The actual values of Reynolds Number are in the range 2×10^2 on the model to 10^5 full-scale. In this range the drag coefficient of a circular cylinder is practically constant. We must assume that a chain will behave similarly.

A second deviation from true scaling arises from the geometric dissimilarity of the model and the full-scale chains; the link of the model being round and open, while the full-scale link is elongated. Thus while the frontal area in lateral flow is scaled correctly, the link width is about 25% too great, giving a proportional increase in longitudinal drag.

4. The Model Hull

The model was constructed from perspex, the bulkheads and base being of $\frac{1}{8}$" thickness, and the curved skin of $\frac{1}{16}$". The general arrangement is shown in Fig.1. The weight of the basic model was 556gr; this was brought up to 870gr by the addition of 6 steel bolts as shown, and a central lead weight. This total weight is equivalent to a full size displacement of 12 tonnes.

The centre of gravity was 3.30cm below deck level; the measured radius of gyration was 7.75cm.

5. Metacentric Height

Because of the difficulty of calculating the metacentric height of the buoy hull, an inclining test was performed on the model. At 5° inclination, the full-scale metacentric height deduced was 3.2m; at 10° it became 2.73m.

6. Towing Performance

(i) Hull drag

The buoy was towed on a light nylon filament from a point just above the water surface. The towing drag was measured on the towing carriage dynamometer.

In the first case the towline was attached to the top of the chine (A in Fig.1). This tended to lift the buoy nose, so that the buoy planed without difficulty at the higher speeds. The measured drag is given in Table 1, with conversion to full-scale values.

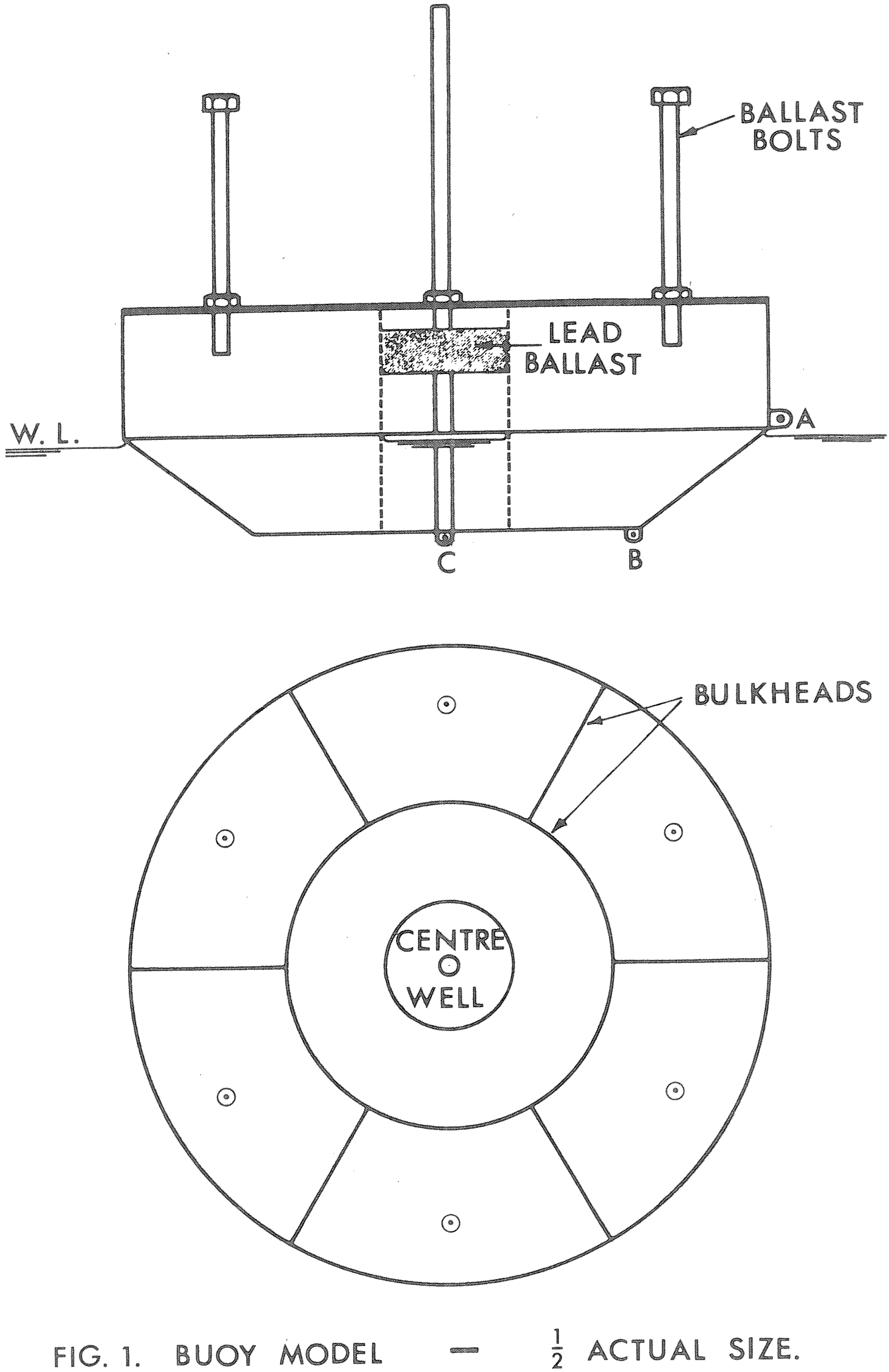


FIG. 1. BUOY MODEL — $\frac{1}{2}$ ACTUAL SIZE.

TABLE 1

Model speed cm/sec	Model drag gm	Full-scale speed kts	Full-scale drag tonnes
27.1	7	2.6	0.10
49.2	22	4.7	0.30
76.2	111	7.2	1.52
100.4	304	9.5	4.20

In an attempt to simulate the maximum drag of the buoy as it passes through the crest of a wave, the buoy was canted nose-down by the addition of 300gm of ballast on the forward pair of bolts. Under this condition the buoy deck was half submerged in the bow wave at 76cm/sec, while at 100cm/sec the entire deck was awash. The buoy remained approximately level.

The maximum measured drag was some 33% greater than before. (Table 2)

TABLE 2

Model speed cm/sec	Model drag gm	Full-scale speed kts	Full-scale drag tonnes
27.7	7	2.6	0.10
48.2	39	4.6	0.54
76.2	240	7.2	3.31
100.6	402	9.6	5.55

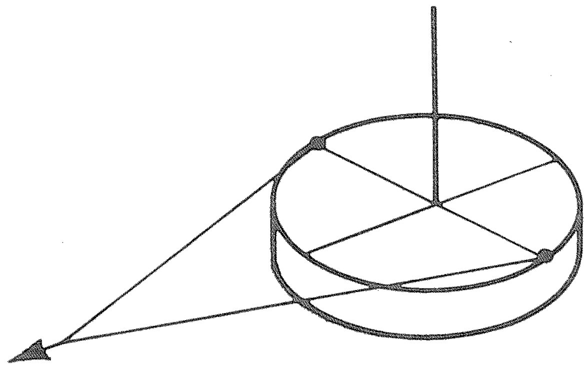


FIG. 2.

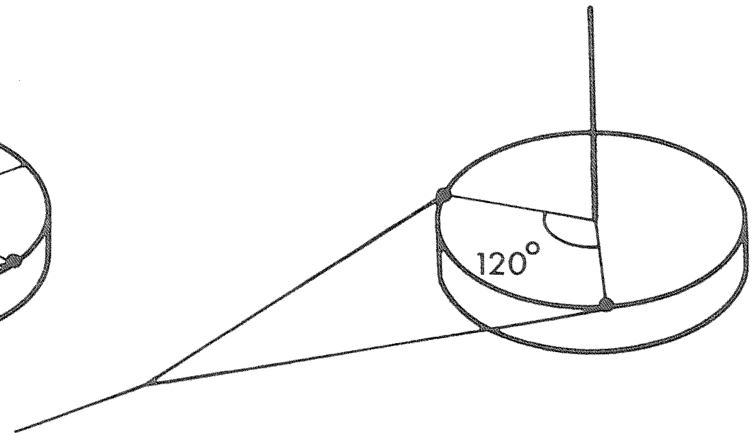


FIG. 3.

A single towing test was made in short waves. The model wave (0.6sec period, 1.8cm height) scales to a wave of 2.94secs period, and 0.43m height. The buoy was towed successfully at 76cm/sec (7.2kts full-scale) with a drag of 138gm (= 1.9t). This is 25% greater than the still water drag. The tow point in this test was the chine top, point A in Fig.1.

(ii) The effect of towing bridles

Trinity House practice is to use a towing bridle, made on to the buoy deck, the object being to prevent buoy yaw while under tow. This system was briefly investigated. With a bridle attached to the buoy diameter (Fig.2) the buoy capsized nose down at about 8 knots full-scale. On moving the bridle to 120^{o} points (Fig.3), the capsizing speed was 9 kts full-scale. Both tests were in still water.

The model showed little tendency to yaw when towed on a single line. We therefore recommend that a single line be used in preference to a bridle, even at lower speeds. However, if the full-scale buoy should prove troublesome in yaw, we would prefer to use a bridle attached to the chine mooring points rather than to the deck.

7. Mooring Loads

(i) Introduction

The problem of load prediction in a structure subject to wave forces has been most fully studied in the case of ships. The same techniques have been applied to offshore structures such as oil drilling rigs.

The first step in the general method is the calculation of the motion of the structure in response to regular sinusoidal waves. The hydrodynamic forces are calculated on the basis of strip theory (two-dimensional flow) assumptions. The resulting equations of motion are linear, so that the response amplitude is proportional to wave height. Defining the Response Amplitude Operator (RAO) as response amplitude per unit wave amplitude, a curve of RAO versus frequency can be found by solving the equations of motion for a number of frequencies. Similarly, RAOs of load, bending moment, etc may be defined and calculated.

The second step is to determine the response to irregular waves. These waves will generally be defined by an assumed wave spectrum, though in some cases a measured spectrum may be available. This wave spectrum is multiplied by the $(RAO)^2$ to give a response spectrum, of motion or of load.

Finally, the load spectrum is used to calculate the probability of a given peak load occuring during the life of the structure.

Two difficulties arise in applying this approach to the buoy mooring. The first lies in the calculation of the hydrodynamic forces on the buoy. Intuitively, one expects the two-dimensionsl strip to be less accurate when applied to a buoy rather than to the relatively slender shape of a ship hull. This difficulty is avoided if the RAO is measured directly in model tests.

The second, more fundamental difficulty is the assumption of linearity inherent in the use of an RAO. The buoy mooring, however, is strongly non-linear, since the mass, damping and stiffness of the cable catenary all vary with buoy displacement in both heave and surge. The results given later in this report, though not conclusive, do show a non-linear effect.

There are, of course, other methods of using model tests to predict the full-scale mooring load, which do not assume linearity. The most obvious is to generate the expected wave spectrum in the wave tank, and measure the resulting load spectrum. The probability of a particular load occuring in the buoy lifetime can be derived from this. This approach is not open to us, since our wavemaker can only generate regular waves.

Alternatively, we may take measured values of maximum waveheight from existing records, with an estimate of the period of these maximum waves, and then test the model in regular waves of this height and period. This is the approach used in the present report. The necessary data for points in both the northern and southern sectors of the North Sea are available in Bell (1972).

Both these latter methods demand that the maximum design waveheight be available from the wavemaker. As already mentioned in Section 3, this would lead to a prohibitively small model. Since most other wave tanks are equally limited in their available waveheight, there is little to be gained by going to another facility.

We are driven, therefore, to extrapolate our test results to larger wave amplitudes. In the case of the RAO technique, this extrapolation is inherent in the method; it is of course a linear extrapolation. Our wavemaker becomes inefficient at long wavelengths, and cannot reproduce the longest waves at all; hence we must also attempt to extrapolate in frequency as well as waveheight.

In order to guide these extrapolations, it is tempting to devise a simplified theory. One such simplification which has been used is to ignore the surge motion of the buoy. First the steady-state position of the buoy is determined. It is assumed that the wave lifts the buoy vertically, with no lateral motion. The static mooring force in this new position is then calculated. This approach may be valid for a deep-water single point mooring, where the lateral surge excursions of the buoy barely alter the mooring geometry, but it is incorrect when applied to a shallow water mooring where the lateral motion may be a significant fraction of the water depth.

An alternative assumption ignores the vertical motion of the buoy, and considers only the horizontal drag force. This drag force is computed from the peak water velocity, taken as the sum of the wave particle velocity and the prevailing current. This is again unsatisfactory, since it ignores the surge velocity of the buoy.

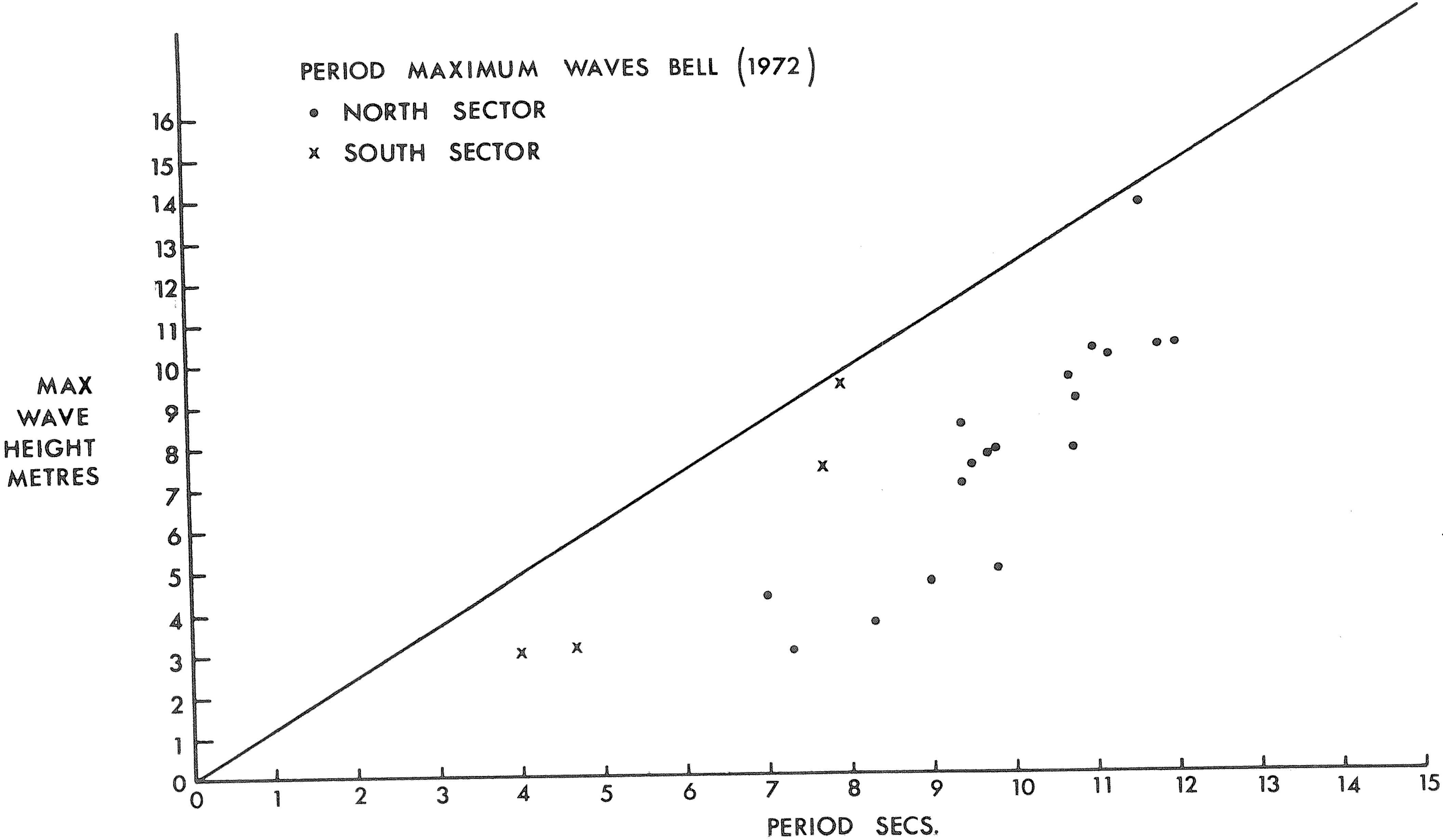
The importance of this may be clearer if we recollect that the buoy/mooring system has a natural surge period of its own. For example, the model mooring used in our tests has a full-scale period of 38secs in the absence of a current. Thus for a quasi-static drag calculation to be valid, the assumed velocity must act for a period long by comparison with 38secs.

A final simplification which should be mentioned is that used by Wilson and Garbaccio (1967) to describe the mooring of ships. Their assumption is that the ship motion is unimpeded by the cable, and can be calculated from the wave record; they then take this motion as the upper boundary condition of the cable, and calculate the cable motion and peak load. This method cannot be applied to a buoy, whose motion is markedly influenced by its cable.

We must conclude that, for the present, there is no satisfactory simple theory for the shallow, chain catenary mooring. In the future it may be worth developing an approximate non-linear model of the mooring for analogue solution. This would have to be verified either by model or full-scale experimental results.

(ii) Model tests

The primary purpose of the tests is the prediction of the maximum mooring force, using the maximum waveheights taken from Bell (1972) in combination with a 5kt current. These waveheights are plotted in Fig.4 against wave period, this being the estimated period of the five waves adjacent to the maximum wave. A straight line exceeding all these measured points is rather arbitrarily taken as defining the design height of the maximum regular wave at each period.


PERIOD MAXIMUM WAVES BELL (1972)
• NORTH SECTOR
x SOUTH SECTOR
MAX
WAVE
HEIGHT
METRES
0
1
2
3
4
5
6
7
8
9
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15
16
0
1
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4
5
6
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8
9
10
11
12
13
14
15
PERIOD SECS.

FIG. 4.

The majority of the tests were made with the mooring attached to the bottom of the buoy chine, since this position gave the best wave-following action (see Section 9). Limited results with other mooring points and in 2 kt and zero currents were also made; the significance of these is discussed later.

Only one mooring depth and scope was used; we should perhaps emphasise that the present poverty of theory makes it very difficult to deduce the mooring forces for other configurations.

For zero current, the mooring can be laid out to clump anchors in the tank. The mooring geometry is shown in Fig.5. Because the tank width is restricted to 1.83m it is not possible to model the full extent of the trailing legs. This does not matter greatly, because the buoy takes up on the leading leg of the mooring even in the smallest waves, and the trailing legs lie slack and vertical. It would not be possible to model a very taut pretensioned mooring in this way. However, this type of mooring is not recommended unless the watch circle of the buoy has to be kept to a minimum; in high waves and tides it applies an unnecessarily high load to the buoy, and moreover it is difficult to lay.

The tests in waves and current were modelled by towing the buoy through waves. It was no longer possible to anchor each leg, but a fair model was obtained by taking the leading leg to a clump, hanging from the carriage, just above the bottom of the tank. The trailing legs were, in fact, left to trail; the shape they take up is very similar to their full-size, anchored shape, for under the combined effect of wave and current they will be quite slack.

It will be pointed out that all the tests have been carried out with the current along the line of one leg of the mooring; the current could equally act between two legs, so that two legs are taut, and one trailing. The main reason for neglecting this case is that it cannot be satisfactorily modelled in a tank of restricted width; but we may argue that the maximum mooring load will not occur in this case, since a similar drag force is carried by two legs rather than one.

The simplest possible force measuring device was used. This was a miniature spring-balance (range 200-1300gr), 0.6cm in diameter and 7cm long, and weighing 3.3gr in air. The maximum deflection was registered by a sliding nylon marker. This spring-balance was placed in the leading leg of the mooring, adjacent to the buoy. It may be objected that the additional elasticity introduced by the spring-balance would alter the peak mooring loads; but the maximum spring deflection (2cm) is not very significant when compared with the overall surge of the buoy in waves (C.20cm).

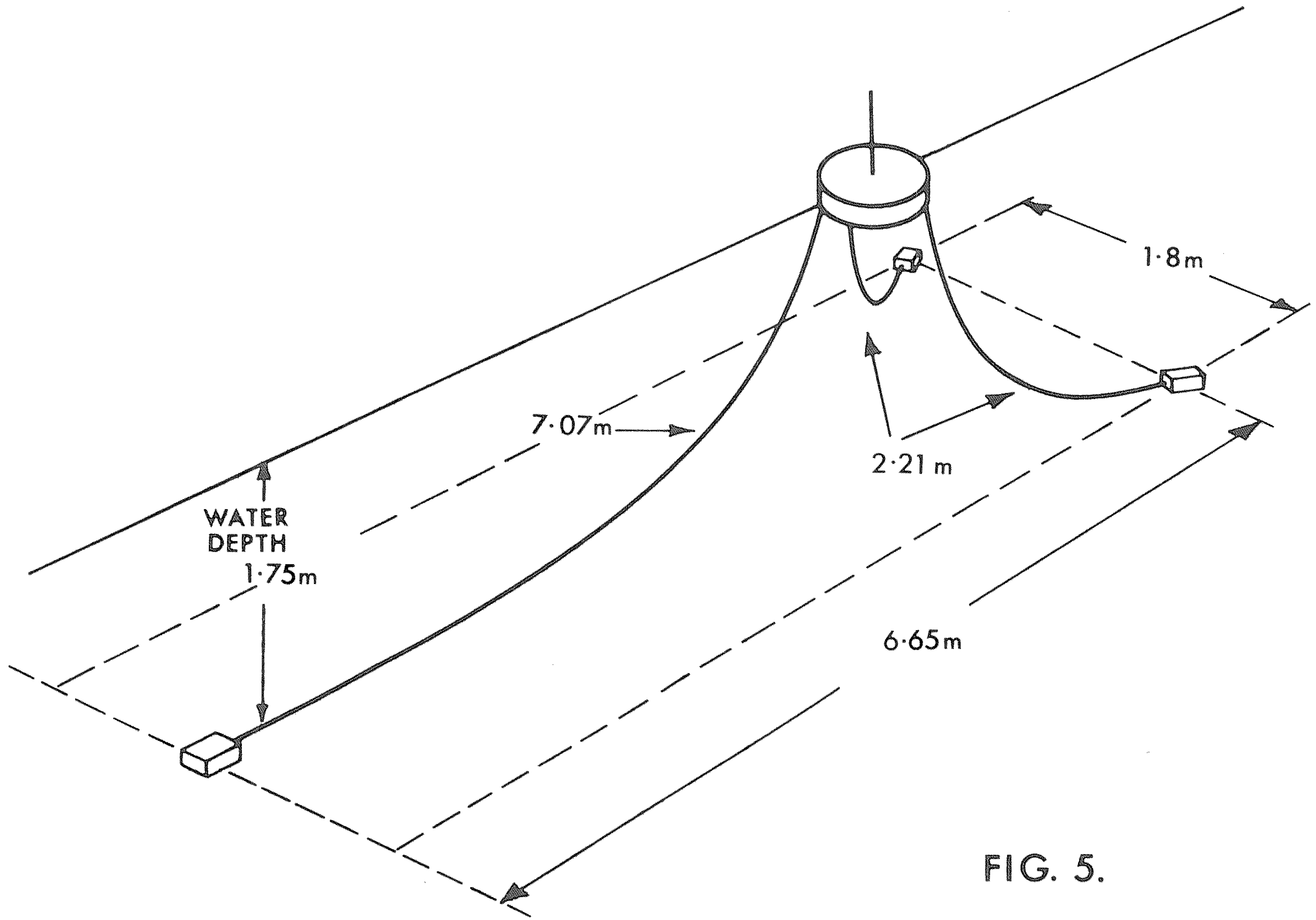


FIG. 5.

To obtain the peak load in given conditions, the buoy was lowered gently into an established wave-train, brought gradually up to speed and held there for about 10 wave encounters, then stopped and recovered before closing down the wavemaker. This procedure avoided the exceptional first and last waves of the train, which give spuriously large forces.

The mooring load could be read to the nearest ±10gr. The repeatability was ±20gr in the same wave-train; but if the wavemaker was reset in the interim, small differences in waveheight could cause a larger spread of the results. The main possible source of error is a jerk on the mooring while launching the buoy; this could be avoided with care, but nevertheless every reading was repeated until a consistent answer was obtained.

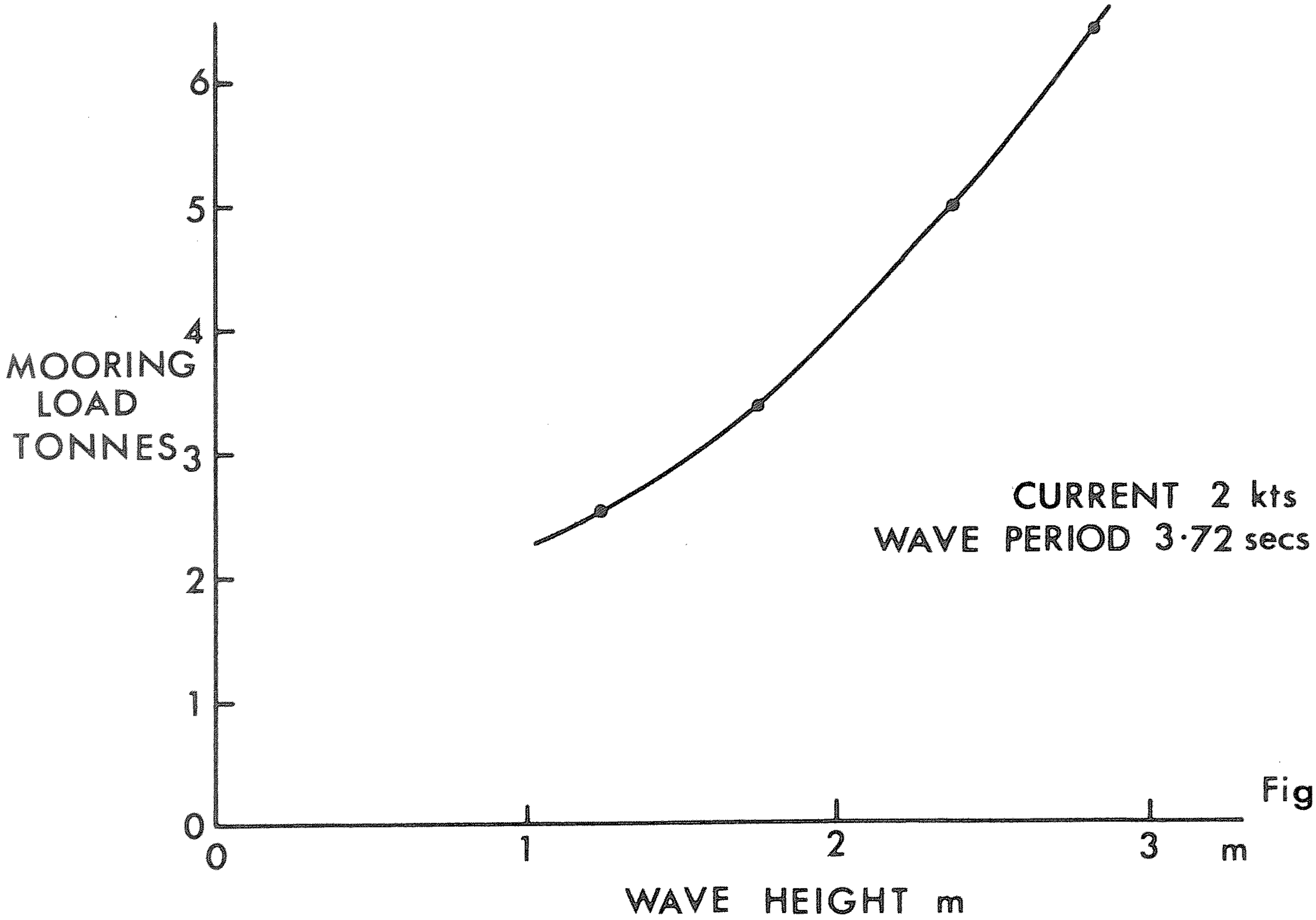
The full results are given in Table 3, in full-scale units. The wave period given is the wave encounter period of the buoy, rather than the actual generated wave period.

(iii) Maximum Mooring Forces

The model test data, scaled to full-size, are plotted in Fig.7 as load against waveheight. The current acting on the system was 5kts throughout. Useful sets of data are available for these wave periods, 3.72, 6.05, and 8.47 secs. Of these the 3.72 sec data is the most satisfactory, since it covers virtually the full range of waveheight demanded by Bell i.e. 4.5m (see Fig.4); the resulting peak load is 19tonnes. The 6.05sec data goes up to a waveheight of 6m; it must be extrapolated to 7.5m to cover the desired waveheight. This can reasonably be done, suggesting a peak load of 22 tonnes. The 8.47sec data is less satisfactory. At this period the wavemaker is much less effective, giving only a 4m waveheight, and this has to be extrapolated to 10.4m. This extrapolation is somewhat conjectural, but if the curve is akin to those of the smaller periods, we might suggest an upper limit of 25tonnes.

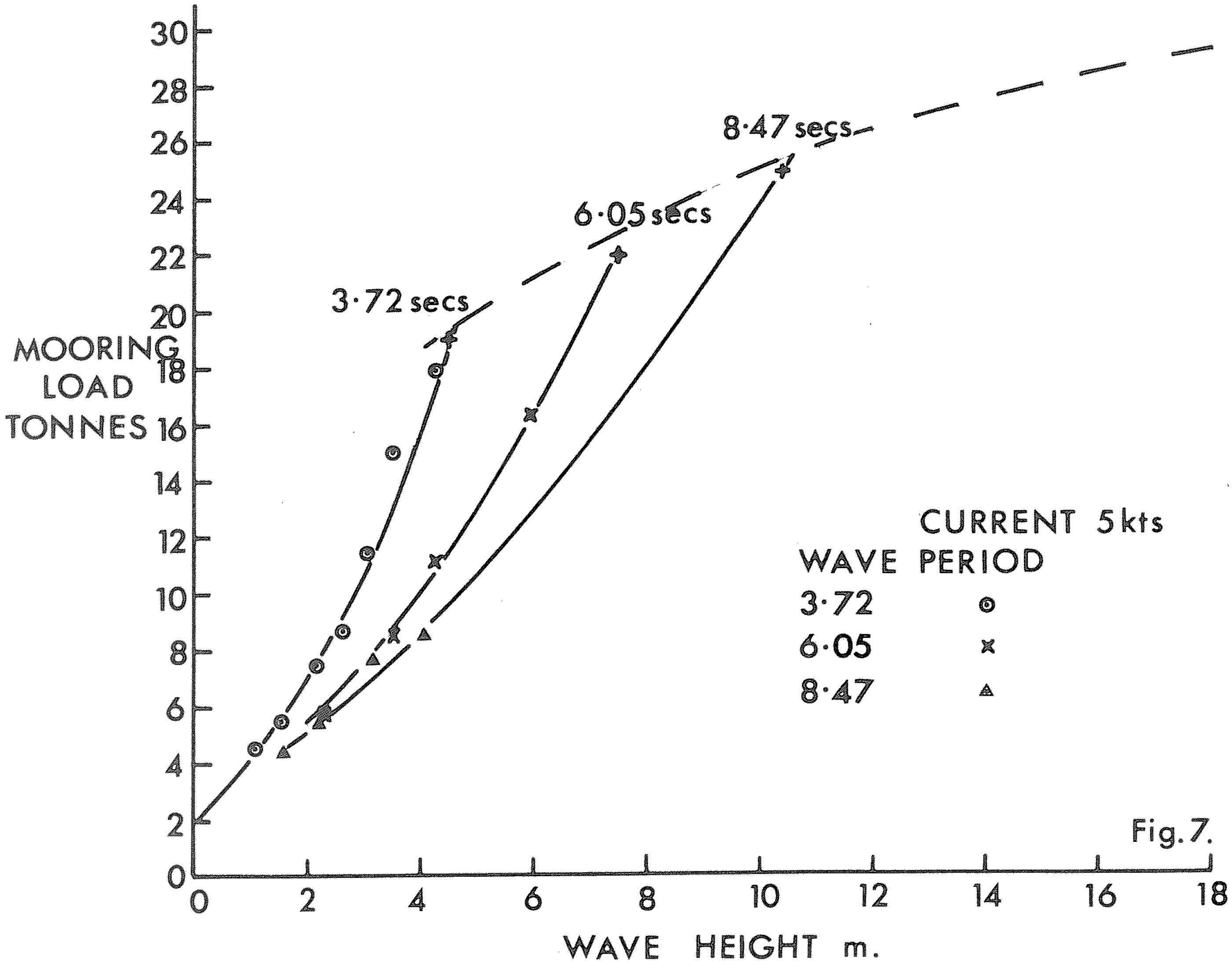
Finally, we must try to predict the peak load due to an 18m wave, of about 12 or 15sec period. We would obviously like to have more data on which to base this; nevertheless it is possible to draw an "envelope" as shown by the dashed line, indicating a maximum load of 28-30tonnes.

There is no published work with which to compare this result. However, we are aware that our measured loads are substantially higher than those predicted in two commercial designs. One of these is based on superposition of model measurements, which we will show leads to an underestimate of load; the second is based on an analysis taking the mooring



MOORING LOAD TONNES
CURRENT 2 kts
WAVE PERIOD 3·72 secs
WAVE HEIGHT m

Fig. 6.



MOORING LOAD TONNES
3·72 secs
6·05 secs
8·47 secs
CURRENT 5kts
WAVE PERIOD
3·72
6·05
8·47
WAVE HEIGHT m.

Fig. 7.

TABLE 3

Mooring attachment points	Current (kts)	Wave Period (secs)	Wave Height (m)	Tension (tonnes)
3 point Bottom of Chine	5	1.47	0.53	5.94
		1.91	1.07	9.95
		2.60	1.52	11.68
		3.72	1.07	4.56
			1.52	5.53
			2.13	7.53
			2.59	8.71
			3.05	11.47
			3.50	15.00
			4.27	17.97
		6.05	2.28	5.81
			3.50	8.29
			4.27	11.06
			5.94	16.24
		8.47	1.52	4.42
			2.21	5.53
			3.12	7.33
			4.04	8.57
	2	3.72	1.22	2.49
			1.67	3.32
			2.28	4.98
			2.82	6.36
	0	2.45	0.53	1.94
		2.94	1.07	2.21
		3.67	1.52	2.49
		4.90	1.07	1.66
			2.13	2.76
			3.05	3.32
			3.96	4.84
			4.27	6.50
		7.35	3.66	2.49

TABLE 3 (cont.)

Mooring attachment points	Current (kts)	Wave Period (secs)	Wave Height (m)	Tension (tonnes)
3 point	5	1.91	1.07	9.19
Top of Chine		3.72	3.05	12.72
		6.05	3.50	7.88
Single point	5	1.91	1.07	5.53
Buoy Centre		3.72	3.05	7.19
		6.05	3.50	5.67

cables to be attached to the buoy axis, which again we will show to give a misleadingly small load. It is of little help to point out that moorings based on these analyses have been laid, and have survived, since (a) they are generally designed with a safety factor of 4 on the chain breaking load, and (b) the maximum design conditions may never have been sustained.

(iv) Non-linearity

The results in Fig.7 for 3.72sec and 6.05sec waves show a distinctly non-linear trend. A similar effect is shown by the 2kt results (Fig.6). It would be possible, nevertheless, to fit a straight line to these results without great error in the range of measurement. The RAO method could then be used. However, this is ignoring the difficulty of fitting a straight line to non-linear data, which has then to be extrapolated. It also means that a set of data must be measured for each wave period, for various waveheights, rather than the single measurement which suffices for a truly linear system. Moreover, this procedure must be repeated for each current condition, since the buoy response depends on the mooring stiffness, and hence on the prevailing current. The simplicity of the RAO method is thus lost.

(v) Effect of Wind Force

The specified 100m.p.h. wind produces a superstructure drag of 1.6tonnes. This has an effect similar to the water current, in that it alters the catenary shape; the effect is equivalent to increasing the current to C.6kts.

We do not expect this to increase the measured cable forces in this proportion, however. This is because the wind force tends to lift the buoy nose, partly counteracting the downward force of the cable on the leading edge of the buoy. This reduces the buoy drag, and the consequent cable tension.

We have not been able to confirm this reasoning, since we lack blowing arrangements in the wave tank. The effect can be partly simulated by ballasting the buoy nose-up, but this does not take account of the sheltering effect of waves which may be important.

(vi) Different Mooring Points

The mooring loads were compared for three different mooring arrangements; to the chine top (A), to the chine bottom (B), and finally with all three legs taken to the centre point of the buoy (C) (see Fig.1). Three "standard waves" were used for the comparison; the current in every case was 52cm/sec (= 5kts full-scale). The results are shown in Table 4 (full-scale values).

TABLE 4

Wave Encounter Period (secs)	Wave Height (m)	3-point Mooring Load Tonnes		
		Top of Chine	Botton of Chine	Centre Point
1.91	1.07	9.19	9.95	5.53
3.72	3.05	12.72	11.47	7.19
6.05	3.50	7.88	8.29	5.67

The load is very similar for both top and bottom chine attachments. This is slightly surprising, as the buoy does appear to ride more easily, with less deck wetness, when the mooring is to the chine bottom. The centre point mooring load, by contrast, is only 60-70% of the chine load. This is certainly explained by the freedom to plane which the centre point mooring permits to the buoy. This result is interesting, because it shows that a valid analysis of the system cannot ignore either the effect of the mooring force on the buoy motion, or the effect of the resulting buoy motion on the forces applied to the mooring. In particular, to assume that the mooring is attached to the buoy centre point when it is not, will lead to an underestimate of the mooring force. This assumption is made in a recent commercial study of a three-point mooring system.

(vii) Superposition

The dynamic load in a mooring due to a given wave is strongly influenced by the prevailing current. This is because the current alters the mean position of the buoy, and hence of the cable catenary; and because the mooring is strongly non-linear, this alters the mooring stiffness. As a result the buoy response to a given wave is changed, and the mooring force is consequently changed also. Superposition breaks down as a result of this non-linearity; it is not correct to measure the force in waves without current, and in current without waves, and to expect the sum of these to be the force in waves plus current. This has nevertheless been done in certain buoy mooring studies.

To illustrate the error involved, Table 5 shows the forces measured in a scaled wave of 3.72sec period, 1.52m. height, with currents of 0, 2, and 5kts. The values of drag at 2 and 5 kts in still water are derived from Table 1.

Adding these to the zero-current wave force we obtain the "superposition" mooring force; it is clearly erroneous at the higher current, when the mooring has significantly changed configuration.

TABLE 5

Current Speed (kts) (Full-scale)	Drag in Still Water (tonnes)	Measured Wave Force (tonnes)	Erroneous Wave Force by Superposition (tonnes)
0	0	2.49	-
2	0.057 ≁	2.63 *	2.55
5	0.344	5.53	2.83

≁ Value interpolated by assuming square law drag

* Obtained by linear interpolation of measured values

The conclusion that superposition does not hold is supported by Van Sluys (1971), who measured mooring forces on a model of the catamaran "DUPLUS". He found that the mooring force in current plus waves was considerably higher than the sum of the individual forces produced by current and waves acting alone. On the other hand, he found that wind and waves could be superposed. There is no obvious reason why this should be possible - after all, wind alters the mooring catenary in much the same way that current does. The explanation may be that wind also changes the hull attitude, and hence the hull wave drag, compensating for the effect on the mooring catenary stiffness. This perhaps serves to underline the complexity of the problem.

8. Buoy Survival

In all the tests we conducted, the buoy showed no signs of capsizing or foundering. In sharp-crested waves, especially in combination with a current, the buoy went through the wave-crest rather than riding over it. The deck was consequently awash, but waves did not break heavily on the deck.

9. Surface Following Performance

(i) *Zero current conditions*

The ability of the buoy to follow the wave surface is of interest, because it is proposed that buoy motion should be used as a measure of wave height and slope. Since the buoy model was rather small for carrying instruments, the data was obtained by filming the model through the windows in the wave tank wall, with the camera at water-level. This technique was necessarily restricted to zero current conditions. Three mooring attachment points were used, at the top of the chine, at the bottom of the chine, and at the centre point.

Each film record lasted 25 seconds. From this record a single wave cycle was selected at random. The film speed was 24 frames/second, so there were between 12 and 24 frames per cycle, giving good resolution of the buoy motion. From each frame the buoy angle and the wave slope at the buoy were measured; the difference between them is the "error angle", a measure of the buoy's inability to follow the wave surface.

The results are given in Table 6. The maximum wave slope, maximum buoy angle, and maximum error angle are shown. These are the maxima during the cycle, and do not of course occur simultaneously. The error angle is then expressed as a percentage of the maximum wave slope. Also given is the mean error angle during the cycle.

At first sight these results are disappointing. The maximum error angle is never less than 27% of the wave slope, and is sometimes greater than 100%. This result is in part due to a regretable choice of experimental conditions. By using the largest possible wave at each frequency, we obtained poorly-shaped waves from the wavemaker, with very sharp crests. The maximum error angle always occurs as the buoy flops over the sharp crest, and for the remainder of the cycle the buoy motion is marred by the pitch oscillation iniated by the crest. Our visual observations, not recorded on film, suggest that the surface following performance of the buoy is much better in waves with more rounded crests, i.e. without a high-frequency component.

The results show that the effect of the 3-point chain mooring is to damp the buoy resonance; the bottom of the chine appears to be the best in this respect. As mentioned previously, the longitudinal drag of the model chain may be too high, so that resonance may still be evident on the full-size buoy. Note that a fibre mooring rope will have a very different effect on this type of buoy motion, having less mass and damping and greater elasticity.

TABLE 6

Mooring Point	Full-scale Wave Period (secs)	Wave Height (m)	Maximum Wave Slope (degrees)	Maximum Buoy Slope (degrees)	Maximum Error Angle° (degrees)	Maximum Error %	Average Error Angle (degrees)	Average Error Angle %
Top of Chine	4.90	4.35	19	19	$5\frac{1}{2}$	29	3.28	15
	* 4.90	3.35	21	$20\frac{1}{2}$	12	57	5.38	24
	4.90	2.13	12	$11\frac{1}{2}$	$4\frac{1}{2}$	37	1.98	16
	2.94	0.36	9	8	$5\frac{1}{2}$	61	2.79	31
	2.45	0.26	6	5	7	116	3.14	52
Bottom of Chine	4.90	4.35	19	18	$5\frac{1}{2}$	29	2.75	14
	4.90	2.13	13	$9\frac{1}{2}$	5	38	2.47	19
	* 3.67	1.52	16	12	10	62	4.17	26
	2.94	1.06	15	$10\frac{1}{2}$	$5\frac{1}{2}$	36	3.3	22
	2.94	0.36	8	$7\frac{1}{2}$	$2\frac{1}{2}$	31	0.81	10
	2.45	0.26	$5\frac{1}{2}$	5	$1\frac{1}{2}$	27	0.92	17
Central Axis	4.90	4.35	22	30	24	109	9.7	44
	3.67	2.13	18	19	8	44	3.59	20
	2.94	0.36	20	22	15	75	6.94	34
	2.45	0.26	$8\frac{1}{2}$	8	$8\frac{1}{2}$	100	4.46	52

* Exceptionally sharp-crested waves

(ii) The effect of current

It was not possible to put the camera at water-level for tests in a current, because our tank windows do not extend along the tank. Film was taken from the towing carriage instead. At this oblique angle it is impossible to measure buoy angles; however, the qualitative effect of current can be seen.

The first effect of the current is to give the buoy a nose-down trim. At 2kts the buoy motion is more jerky, but it still follows the wave reasonably well. At 5kts the buoy slices through the wave crests, rather than flopping over the top. Even at 5 kts the effect of the mooring on the buoy heave motion can probably be neglected - a loss of 0.5m from a sharp crest is the maximum probable error.

(iii) Effect of buoy surge on wave measurement

A free wave buoy follows the surface water particle; in deep water the particle path is a circle, so that the buoy surges with an amplitude equal to the wave amplitude. It follows that the wave profile measured by the buoy is distorted, since it is not measured at a fixed point. The effect is to decrease the crest curvature, and to increase the trough curvature. It so happens that this exactly counterbalances the natural tendency of finite amplitude waves, which is to have a sharp crest and a rounded trough. Thus a free wave buoy measures a sinusoidal wave, removing the second harmonic component of the real wave.*

The buoy surge motion is modified in a complex way by the three-point mooring. In the absence of a current, the mooring is not very stiff in surge, and the buoy motion is close to that of the free buoy. As the current is increased, the mooring comes taut, restraining the buoy in surge, until at high currents the buoy is virtually fixed in space. It follows that the buoy will measure a percentage of the wave second harmonic component, but that this percentage will vary with the prevalent current.

10. Mooring Chain Motion

An acoustic current meter is planned for the buoy, which demands three legs, 2m long, protruding from the buoy hull bottom. We were concerned that the slack in the trailing mooring chains, in combination with the buoy motion, would result in the chains becoming snagged on the current meter legs. This fear is

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* It may be worth noting that in shallow water waves the particle path is elliptical, and the buoy surge amplitude is greater than the wave amplitude. This may introduce additional distortion to the wave record. This could apply to certain shallow mooring sites for the Data Buoy.

apparently groundless. The chains move more or less in phase with the buoy, since they are in the same wave velocity field, and do not interfere with the current meter legs. A slight reservation remains: if a strong wind brings the buoy taut on one mooring leg, and a tidal counter-current brings the trailing chains back under the buoy, then snagging could perhaps occur. We have not been able to simulate this in tank tests.

11. Servicing - Motion Damping

There was some concern that the buoy motion in short waves might be too severe to permit boarding and servicing. Since the buoy must follow the wave surface in normal operation, we require a damping device which can be "switched" on for servicing. Several proposals were studied.

(i) Free surface passive roll damping tanks.

These are used successfully on ships, with up to 50% reduction of roll amplitude. They have little effect on a buoy. This is because they are only activated by the difference in angle of the vessel and the wave slope. In a ship the resonant roll amplitude may be 6 times the wave slope, and the tanks may reduce this to 3 times. On the buoy the amplitude is never more than $1\frac{1}{2}$ times the wave slope, and the best tanks can only reduce this to $1\frac{1}{4}$ times; so they are not worth the additional space and cost.

(ii) Retractable bilge keels.

Since the buoy is basically a wave particle follower, there is no relative motion between the buoy and the adjacent water. Bilge keels therefore have no effect.

(iii) Retractable damping plate.

If a horizontal plate is attached to the buoy, sufficiently deep to escape wave particle velocity, it can have a marked damping effect on the buoy. Ideally it should be rigidly attached to the buoy on legs; since the plate must be retractable this is difficult to engineer. If the plate is suspended on cables, it may be more easily retracted; but in this case it must be very heavy, in order to keep the cables taut throughout the wave cycle. This, too, was reckoned impractical, especially since we require a cable-connection from the buoy to the sea-bottom.

12. Boarding the Buoy

We needed an estimate of the waveheight in which the buoy could be boarded, in order to predict the number of occasions per annum on which this could be achieved. The buoy motion in short waves (say 3-4secs period) is discouraging, in that the buoy pitch is such that the leading edge of the buoy is raised when over the on-coming wave trough. Thus the motion of a small boat relative to the buoy perimeter is greater than the waveheight, at least at the leading edge of the buoy. Of course, a small boat could be brought alongside the buoy, thus escaping much of this pitching motion, but in a cross sea the relative motion will still be quite severe.

The answer, we believe, will be to use a larger servicing craft, preferably flat-bottomed, with a motion characteristic similar to the buoy. Under these conditions we would expect to be able to board the buoy in waves of up to 1.2m waveheight, irrespective of wave period.

13. Conclusions

(i) We expect the buoy to survive in North Sea conditions.

(ii) We expect a peak mooring force of about 30 tonnes in a water depth of 40m. This will require a heavier chain than that used in the model tests.

(iii) We strongly urge that full-scale measurements of mooring tension be made on the buoy. These are badly needed to guide further work and future design of moorings.

(iv) The buoy motion will give adequate waveheight information, and a useful approximation to wave slope. The wave spectra measured by the buoy should be compared with an independent measurement by e.g. and NIO "Doughnut" pitch-roll buoy; this exercise should be done with and without a current, since the mooring tension affects the wave following ability.

(v) We expect to be able to board the buoy in 1.2m waves.

The results in this report must refer specifically to the buoy and mooring tested. In particular, any changes in:

(i) the buoy moment of inertia in pitch

(ii) the mooring depth

(iii) the mooring scope

(iv) the cable type e.g. chain to fibre

may have a significant effect on buoy motion and mooring load. The effect of changes are difficult to predict, in view of the present state of mooring theory.

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