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The analysis of the forces on seaplane tank models into hydrostatic pressure, hydrodynamic pressure and skin friction

- by -

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SUMMARY

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Reasons for enquiry

The investigation originated in the search for a "Basic Curve" for the water resistance of seaplane hulls.

Range of investigation

The physical processes associated with planing are discussed in an elementary way and a new method of analysis, based on this discussion, is applied to existing tank tests. New tank tests are used to investigate particular details.

Conclusions

The new method of analysis has given satisfactory results in all cases to which it has been applied. The results can be put into a non-dimensional form. In the case of a geometrically simple planing form the forces can be separated into components due to hydrostatic pressure, hydrodynamic pressure and skin friction. The analysis applies throughout almost the whole speed range. It ceases to apply only at very low speeds which are of little importance in seaplane tank testing.

Further developments

It is proposed to apply the new method of analysis to the investigation of scale effect in tank testing.

1.. Introduction

The work described in this report originated in the search for a "Basic Curve" for the water resistance of seaplane hulls. In former reports[1] attempts have been made to find a non-dimensional method of plotting resistance measurements on seaplane models which would represent the measurements for all loads and speeds at one attitude on a single "Basic Curve". Formulae are known which will reduce the measurements to one curve at high speeds or to one curve at low speeds but no formula is known which is satisfactory throughout the whole speed range. Search was made for an empirical formula which would converge to the known forms at high and low speeds and would also be satisfactory at the "hump speed". A large measure of success was achieved in plotting the results for two flying boats but no formula of general application to a number of hulls was found.

It appeared to the present writer that little success was likely to be achieved in the search for a basic curve without a better understanding of the physical processes of planing at the hump speed. Such an understanding should lead to the most satisfactory method of plotting resistance measurements. The investigation which will now be described has resulted in a greater simplification than was originally hoped. The theoretical work and such new tank measurements as have been made have been done at various times between February and October, 1937.

2. Preliminary theoretical considerations

The forces acting on a seaplane hull are composed of hydrostatic and hydrodynamic pressures acting normal to the surface of the hull, and tangential forces due to skin friction. The resultant force acting on the surface of the hull is equal to the surface integral of these forces taken over the whole of the wetted surface. This surface integral may be separated into three parts

(1) The integral of the forces due to hydrostatic pressure.

(2) The integral of the forces due to hydrodynamic pressure.

(3) The integral of the forces due to skin friction.

These integrals are in all cases the integrals of vector quantities. We will consider the horizontal and vertical components of the resultants.

At very low speeds the integral of the hydrostatic pressures has a vertical component equal to the weight of the seaplane, and the integral has no horizontal component. The integral of the hydrodynamic pressures has a small or negligible vertical component but a finite horizontal component which produces a resistance opposed to the direction of motion. The hydrodynamic pressures which produce this resistance also produce waves on the surface of the water and for this reason this resistance is referred to as a wavemaking resistance. In addition there is resistance due to skin friction. These are the conditions obtaining in a ship. The weight is supported by buoyancy and the resistance is due to wavemaking and skin friction.

As the speed of the seaplane increases these conditions break down and planing commences. In practice, effectively the whole of the tank testing of seaplane models is concerned with planing conditions. The characteristic of planing is that the water breaks away from the hull at the step instead of flowing round it, and, from the present point of view, the back of the step is no longer a part of the wetted surface over which the integrals have to be taken. In addition, the hydrodynamic pressure on the forward part of the hull throws up a sheet of water over the surface of the hull to form the so-called blister, so that the wetted surface of the hull now extends above the level of the undisturbed water surface.

Consider the hull at rest and the water flowing past it. We may calculate the pressure at any point on the wetted surface of the hull by applying Bernoulli's equation to a stream tube passing just outside the boundary layer. Consider a stream tube passing through a point on the wetted surface at a depth z below the undisturbed water surface. At this point let the velocity be v and the pressure p. At infinity upstream the velocity in this stream tube will be equal to V, the velocity of the hull, and let h denote its depth below the undisturbed water surface. The pressure in the tube will then be ρgh (ρ = density of water, g = gravity; strictly, terms containing the barometric pressure and the density of air should be included. These may be omitted without error.) Applying Bernoulli's equation we get :-

$$p + \rho g\,(-z) + \tfrac{1}{2}\rho v^2 = \rho gh + \rho g\,(-h) + \tfrac{1}{2}\,\rho V^2$$

$$\text{or}\quad p = \rho gz + \tfrac{1}{2}\,\rho(V^2 - v^2).$$

The first term in this expression for the pressure is the term to be integrated in the hydrostatic integral, while the second goes into the hydrodynamic integral. Provided the shape of the wetted surface is known the hydrostatic integral can be evaluated since it depends only on z which can be determined from the hull form. The shape of the wetted surface can only be determined by experiment since its calculation would involve a complete solution of the hydrodynamic problem. As will be shown later, it is possible to analyse model measurements in such a manner that the wetted surface does not change with the velocity and under these conditions the hydrostatic integral is a constant. Hence the lift or resistance may be separated into a constant part due to hydrostatic pressure and a part depending on the velocity, which is due to the combined action of hydrodynamic pressure and skin friction.

The shape of the wetted surface, when the seaplane is in the planing condition, leads to important conclusions. The wetted surface is very unsymmetrical fore and aft since it extends above the level of the undisturbed water surface on the fore part of the hull while the back of the step is dry. From this it follows that in general, the hydrostatic integral has both vertical and horizontal components. Thus there is a hydrostatic lift which supports part of the load on water and there is also a hydrostatic resistance. For those parts of the wetted surface below the undisturbed water surface, z in the expression for p, is positive and the hydrostatic lift obtained from integration over this part of the wetted surface is equal to the weight of the water which could be contained in the volume included by the intersection of the following three surfaces.

(1) The plane of the undisturbed water surface.

(2) The wetted surface below the undisturbed water surface.

(3) A surface generated by vertical lines through the boundary of this wetted surface.

For a simple planing form without an afterbody, this integral differs by a small amount, due to absence of pressure over the back of the step, from the static displacement at the same draught. To this integral must be added the integral taken over the wetted surface which is above the undisturbed water surface and this integral is negative since here z is negative. Hence the hydrostatic lift is diminished. The effect is the same as if the volume included by

(1) the undisturbed water surface

(2) the wetted surface above the undisturbed water surface

(3) a surface generated by vertical lines through the boundary of this wetted surface,

was filled with water which was suspended from the hull. These considerations will be shown to lead to numerical agreement in one case in which they have been checked. A difficulty which arises under certain circumstances is considered later.

Fig.26 has been added to illustrate the general shape of the wetted surface above the undisturbed water level. It is a view from directly ahead of a large model. The undisturbed water surface in the foreground of the picture should be followed back until it meets the model in two diagonal lines which meet on the keel. The wetted surface covered by the thin sheet of water forming the blister can be seen just above these lines. There is a hollow space between this sheet of water and the undisturbed water surface. The view point makes the whole picture appear very much fore shortened.

The hydrodynamic pressure acts over the same wetted surface as the hydrostatic pressure and gives lift and drag in the same way. At high speeds the hydrostatic pressure becomes negligible and only the hydrodynamic pressure remains. The hydrodynamic pressure produces waves on the surface of the water and hence the resistance is a wave-making resistance. It is often referred to as a resistance due to planing forces.

Consider now the method of analysing the results of resistance measurements on seaplane models, with the object of separating them into hydrostatic pressures, hydrodynamic pressures and skin friction forces. Resistance measurements on tank models are usually made with the model free to rise and fall, the mechanism of the balance being arranged to maintain a fixed attitude and a constant load on water. Resistance and pitching moments are measured under these conditions. In addition, provision is made for measuring the height of a suitable datum point above the undisturbed water level so that draughts may be deduced but, as little use has so far been made of draught measurements, they are usually not given in reports. Resistance is plotted against speed for constant values of the load on water and draught does not appear in the results. Pitching moments are treated similarly. It is clear, however, that load on water, that is lift, and resistance are each components of the resultant force acting on the model and that in any fundamental investigation this resultant force, or its components, should be regarded as a function of the speed, the attitude and the draught. Hence, model measurements have been cross plotted to obtain load-on-water and resistance for constant values of the draught and the results have been plotted against the square of the speed.

3. Analysis of Singapore IIc model tests

The analysis was first applied to existing Royal Aircraft Establishment tank tests of the 1/12th scale Singapore IIc model hull. These tests were made for a report on comparative tank tests[2] and were unusually extensive. In particular, by combining results given in two figures of the former report resistance measurements at an attitude of 7° are obtained for eight different values of load-on-water. For each load, measurements are given at speeds between 6 and 32 ft./sec. These measurements are given in Fig.1. (Full scale values were given in the original report. In the present report all measurements refer to the model. The results of Fig.1 have been recalculated using the air drag correction obtained by the routine method used in the Royal Aircraft Establishment tank. The results given in the original report included the air drag of the hull.) The draughts corresponding to these resistance measurements are given in Fig.2. The draught was measured from the undisturbed water level to the lowest point of the v step of the model.

Taking any value of the draught, say 1.25 in., each curve of Fig.2 gives a load and speed corresponding to this draught. Using these values for load and speed the corresponding resistance is obtained from Fig.1. The loads and resistances are then plotted against the squares of the speeds and curves corresponding to a constant draught are obtained. In Fig.3 loads are plotted in this way for a series of values of the draught and Fig.4 gives the resistances. In these figures the points lie, within the limits of experimental error, on a series of straight lines, each line corresponding to a definite value of the draught. For the Singapore IIc model the hump speed is about 12 ft./sec. and planing commences at 6 - 8 ft./sec. All the observations from speeds of about 6 ft./sec. upwards fit the lines of Fig.3 and 4, so that this method of plotting is satisfactory from well below the hump speed up to the highest speeds.

Consider now the physical significance of Fig.3. The straight lines for small draughts pass through the origin but in general the lines pass above the origin giving a finite lift at zero speed. This does not imply that a lift of this magnitude could be observed at zero speed but it is the constant part of the lift function which applies for all speeds greater than about 6 ft./sec. Any given line corresponds to a wetted surface of constant shape and area and the lift at zero speed gives the value of the vertical component of the hydrostatic integral which was considered in the preceding section of this report. This quantity will be called the hydrostatic lift. It is the part of the load on water which is supported by buoyancy. When this hydrostatic lift is subtracted from the load on water the residue is the part of the lift which is proportional to V^2. This includes the vertical components of the hydrodynamic pressure integral and a small vertical component of the skin friction integral, which may be negative. That a constant draught gives a constant wetted surface (for all speeds greater than about 6 ft./sec.) is a fairly obvious deduction from Fig.3 in the light of the theoretical considerations which have been given. It has been verified by running a model at a fixed draught and observing the wetted surface. This provides sufficient information for calculating the hydrostatic integral but such a calculation would be very laborious for the Singapore IIc model owing to the complicated hull form. The calculation has therefore been made for a simple wedge form and is given later.

In Fig.4 some of the lines pass above the origin giving a finite resistance which is independent of the speed. This is the horizontal component of the hydrostatic integral and will be called the hydrostatic resistance. Subtracting this hydrostatic resistance gives the part of the resistance which is proportional to V^2. This consists of the horizontal components of the integrals of hydrodynamic pressure and skin friction.

The same method of analysis may be used for the pitching moments. Fig.5 gives the pitching moments for the Singapore IIc model. When these moments are cross plotted to obtain moments at constant draughts, the straight lines of Fig.6 are obtained. For any line the negative moment at zero speed is a hydrostatic moment which could be calculated from the hydrostatic integral if the position of the centre of pressure was calculated. The part of the moment which is proportional to V^2 is caused by hydrodynamic pressure and skin friction. Fig.6 implies that the centre of pressure of the hydrodynamic pressures and the line of action of the resultant of the skin friction forces are fixed when the wetted surface is fixed.

The information contained in Fig.3, 4 and 6 can be expressed in a much more concise form. Any straight line in Fig.3 is completely defined by the hydrostatic lift and the slope of the line. Similarly any line in Fig.4 is defined by the hydrostatic resistance and the slope of the line. Fig.7 gives the hydrostatic lift and resistance as functions of the draught. These quantities vanish for draughts of less than 1.5 in. - a point which is discussed later. Fig.8 and 9 give the slopes of the lift and resistance lines as functions of the draught. The moments in Fig.6 reduce to the two curves in Fig.10 and 11 giving hydrostatic moment and slope of the moment lines as functions of the draught. Thus the whole of the information about resistance, moment and draught at a fixed attitude of 7°, all loads on water and all speeds greater than about 6 ft./sec., is contained in the six curves of Fig.7 - 11. The original measurements are given in 23 curves in a form which provides no theoretical basis for cross plotting.

4. Discussion of Singapore IIc analysis

The investigation which has been described can be continued in two different ways according to the object in view. First we may use the method of analysis as a means of recording model tests and second we may use it in theoretical investigation as, for instance, in scale effect.

With the first object in view it is necessary to show by trial that the method can be applied to hulls of all forms. This is further considered in the next section. It is also necessary to show that the results can be used in their final form. If we choose a fixed attitude and a load on water corresponding to each speed it is easy to proceed by graphical methods, using Fig.7 and 8, to the draught and then, using Fig.7 and 9, to the resistance. If a curve taken from Fig.1 is reproduced in this way, fairly good agreement is obtained. It should be remembered that the original tests were not intended for this method of analysis and that considerable smoothing has been effected in drawing the straight lines in Fig.3 and 4. Again some latitude is possible in drawing the original curves in Fig.1 and this introduces errors in the cross plotting. Hence, exact agreement is not to be expected. It should be noted that if it is accepted that the points in Fig.3 and 4 should lie on straight lines, then a good mean value is obtained by drawing the best straight line through the points and the deviations of the points from the line give an indication of the accuracy of the measurements.

With the second object in view it is necessary to apply the method of analysis to tests on simple wedge forms and flat planing surfaces so that lifts and resistances can be analysed precisely into their component parts. Later sections of this report are concerned with this aspect of the work.

As explained in the introduction, the original object of the investigation was to find some non-dimensional method of plotting tank tests. The curves of Fig.7 - 11 can easily be made non-dimensional so that, in a sense, the object is achieved though in a form very different from that originally contemplated.

The best method of putting the results into non-dimensional form has not yet been decided but a simple method of doing so is as follows. Consider, for example, Fig.7, 8 and 9. Let b be any typical dimension of the model, for example, the maximum beam. The hydrostatic lift given in Fig.7 is divided by $\rho g b^3$ to give a non-dimensional coefficient which will be denoted by H_L. In the same way the hydrostatic resistance gives a resistance or drag coefficient H_D. The hydrodynamic lift gives a lift coefficient C_L on division by $\frac{1}{2}\rho b^2 V^2$. The slope of the lift lines, given in Fig.8 is a hydrodynamic lift divided by V^2. Hence this slope is divided by $\frac{1}{2}\rho b^2$ to obtain C_L. In the same way Fig.9 gives a resistance coefficient C_D. These coefficients all appear as functions of the draught h, which is expressed non-dimensionally as a fraction h/b of the beam. We now have for any given value of the non-dimensional draught :-

$$\text{Hydrostatic lift} = \rho g b^3 H_L$$

$$\text{Hydrodynamic lift} = \tfrac{1}{2}\rho b^2 V^2 C_L$$

These expressions effect the conversion to full scale values without explicit reference to Froude's number. The flow will be dynamically similar for model and full scale when the ratio

$$\frac{\text{Hydrodynamic lift}}{\text{Hydrostatic lift}} = \frac{V^2}{bg} \cdot \frac{C_L}{2H_L}$$

is the same for both. This requires that V^2/bg shall be the same for both, which is Froude's number based on the beam instead of the length as is more usual. If the speed is so small that planing has not commenced, these non-dimensional coefficients do not apply. For the 1/12th scale model, the minimum speed is 6 - 8 ft./sec. The corresponding minimum speed for the full scale must be calculated by the use of Froude's number. For very small draughts when the hydrostatic lift is negligible the forces are independent of Froude's number.

5. Analysis of other model tests

In order to try the method of analysis on other hull forms it was applied to tests of the Sikorsky S.40 for which the results of a N.A.C.A. general test[3] are available. It was soon found that the tests did not supply sufficient information for the analysis. Although the tests are very extensive they are restricted to heavy loads at low speeds and light loads at high speeds and the result of this is that usually only three and at most four points are obtained on each straight line in the final figures. The results are quite consistent with the method of plotting but it is not considered that they are worth reproducing here. It appears therefore that new series of tests will be required in order to check the applicability of this method of analysis to all types of hull.

The Singapore IIc tests, on which the analysis has so far been based, were all for an attitude of 7°, and at this attitude the model would, in general, be planing on the main step only. Under these conditions it was found that a constant draught gave a wetted surface which did not vary with the speed. It is not clear that this condition will still be satisfied when the model is planing on two steps, since the second step lies in the wake left by the first. The condition is probably satisfied approximately provided the speed is not too small. This is one of the most important points which require to be settled by further tests. As a first step, existing tests on the Singapore IIc at an attitude of 13° have been analysed. The final curves are given in Fig.12 and 13 for lift and resistance respectively. The number of points is not great; as the tests were not very extensive, but the agreement for these points is quite good. It is interesting to note that the points for 6 ft./sec. lie definitely above the lift lines in Fig.12 suggesting that planing has not commenced, but that the corresponding points for resistance lie well on the resistance lines in Fig.13.

6. Tests on a simple wedge form

A limited number of tests were made on a simple wedge or keeled form having an angle of dead rise of 20° and a straight keel throughout its whole length. It is illustrated in Fig.14A which gives the dimensions and shows the position of the centre of moments. This was chosen as a simple geometrical form for which the hydrostatic integral could be calculated after making observations of the wetted surface.

The tests were limited to an attitude of 7° and the results are given in Fig.15, 16 and 17. These give resistance, draught and pitching moment respectively. They are cross plotted in Fig.18, 19, 20 to give load on water, resistance and moment against V^2, for constant values of the draught. In these figures the points lie very well on straight lines. In Fig.19 the lines for small draughts (1 in., 1.5 in., and 2 in.) pass through a point above the origin instead of through the origin. The reason for this is not known but it suggests a systematic error in the resistance measurements.

The primary object in these measurements was to compare the experimental value for the hydrostatic lift with the value calculated from the dimensions of the wetted surface. To observe the wetted surface the model was run at fixed draughts of 1, 2 and 3 in. and the positions of the edge of the wetted surface at keel and chine were recorded. The edge of the wetted surface is almost straight between keel and chine. These observations were made at various speeds to check whether a constant draught did, in fact, give a wetted surface which was independent of the speed. The general result of these observations was that the area of the wetted surface above the undisturbed water level, increased from a small value at 4 ft./sec. to a limiting value at 8 ft./sec. which remained effectively unchanged at all greater speeds. At the higher speeds there were irregular variations in the keel and chine positions amounting to about 0.5 in. These were attributed to experimental error. This result shows that the wetted surface is independent of the speed when the draught is constant, only because it has reached a limiting value at a comparatively low speed and this result receives a ready explanation from elementary considerations. If V is the velocity of the water past the model, the height of a stagnation point above the undisturbed water level is $V^2/2g$. Consider the height of the chine at the highest point at which water leaves it. If this height is small compared with the height of the stagnation point, gravity will have a negligible effect on the path followed by the water between keel and chine and this path will then be independent of the speed. For the case of the wedge at 7° attitude the ratio: height of stagnation point to height of chine is 6 at 8 ft./sec. and this ratio increases as the square of the speed. Hence the condition is satisfied. It is in this sense of a limiting value that the wetted surface on an afterbody may be constant in the two step case.

Coming now to numerical values, the hydrostatic lift was calculated in two parts. First there is the positive part which depends only on the geometry of the wedge and the draught. This part differs very little from the static displacement and is shown in curve A of Fig.21. Curve B in Fig.21 is drawn through four points taken from Fig.18 and gives the observed hydrostatic lift. The difference between the two curves gives the negative part of the hydrostatic lift. For draughts greater than 2 in. this difference is roughly constant at 2 - 2½ lb. Calculation from observations of the wetted surface at draughts of 2 and 3 in. gave values of 2.2 and 1.9 lb. It is considered that this agreement is within the accuracy of the observations.

Under the conditions of the tests the corner of chine and step was level with the undisturbed water surface when the draught was 2 in. There is therefore a difference in the general shape of the wetted surface above the undisturbed water level depending on whether the draught is less or greater than 2 in. Fig.18 shows that the observed hydrostatic lift is negligibly small for all draughts less than 2 in.[x] If the negative part of the hydrostatic lift is calculated from the observed wetted surface, for a draught of 1 in., a value

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[x] In this connection see also Fig.7 where the hydrostatic lift is zero for draughts of less than 1.5 in.

of -1.8 lb. is obtained and if this is added to the positive part of the lift in Fig.21 a nett negative value is obtained. Thus the method of calculation appears to fail for draughts less than 2 in., that is when the corner of the chine and step is above the undisturbed water level. A probable explanation of this failure is that the pressure is zero over a portion of the apparent wetted surface above the undisturbed water level or in other words that the sheet of water forming the blister would follow the same path if a part of the wetted surface of the model were removed and the water was moving freely under gravity. Such part of the wetted surface should be excluded when calculating the negative part of the hydrostatic lift. Special experiments would be required to verify this supposition but it is interesting to note that roughly the correct result is obtained if all the wetted surface outside a certain beam is excluded. This beam is obtained if we imagine the sides of the model cut away until, for a given draught, the corner of the chine and step comes level with the undisturbed water surface.

For a simple form like the wedge the ratio of the hydrostatic resistance to the hydrostatic lift is equal to the tangent of the attitude. This condition is satisfied by the observations.

7. Tests on a flat planing surface

In any normal hull form or in any simple form like the wedge, the flow divides smoothly on each side of the keel, but in the case of a flat planing surface there is no definite position at which the flow must divide. General considerations such as these, suggested that the wetted surface might not be independent of the speed for a flat planing surface and hence that the method of analysis might fail. To settle this point tests were made on the flat planing surface which is illustrated in Fig.14B. This was almost the first occasion on which a flat planing surface had been tested in the Royal Aircraft Establishment tank and it was found to be a very unfavourable form for accurate work. The flow in the "blister" pulsates in a very irregular manner and as a result the model bounces on the water at light loads or high speeds and it was impossible to measure pitching moments under any conditions. Resistance measurements were possible for a limited range of speed though with less than the usual accuracy. It is possible that a smaller model or a different type of balance might give better results. The results of these tests are given in Fig.22-25. Fig.22 gives the resistance measurements and Fig.23 the corresponding draughts. In Fig.24 and 25 the lift and resistance are plotted against V^2 for constant values of the draught and it is seen that the points lie quite well on straight lines, so that the method of analysis is satisfactory in this case also. In Fig.22 there are some negative values for the hydrostatic lift. This did not occur for the keeled forms.

8. General discussion

It has already been indicated that measurements on planing surfaces of simple geometrical form, such as the 20° wedge or the flat planing surface, when analysed by the present method, provide precise data for fundamental investigations and it is hoped to investigate scale effect in tank testing in this way. To do this it is necessary to obtain the forces due to skin friction separate from other forces. The forces proportional to V^2, which can be expressed non-dimensionally in terms of C_L and C_D, are due to hydrodynamic pressures and skin friction. For a simple geometrical form they are easily transformed into other forces tangential and normal to the keel. The force tangential to the keel is due to skin friction only, since the normal pressures can produce no force in this direction, but on account of the complicated nature of the flow it is not a simple matter to calculate the skin friction coefficient. In the case of the flat planing surface the force normal to the surface is due to hydrodynamic pressure only. In the case of the wedge the force normal to the keel contains a small component due to skin friction. On account of the smoother flow and the more definite wetted surface the wedge seems the more favourable form with which to work.

The forces which have been expressed in terms of C_L and C_D are directly proportional to V^2 and it follows that the tangential and normal forces derived from them are also directly proportional to V^2. Since any straight line in any of the figures corresponds to a constant wetted surface, this requires a skin friction coefficient which does not vary with the speed. The speed range covered by any line may be as great as one to three, corresponding to an equal range of Reynolds number, and the observations should be sufficiently accurate to detect a variation of skin friction coefficient. Such a variation would change the resistance lines into slight curves but an examination of the figures shows that, although there are considerable deviations of individual points, there is no consistent indication of any curvature of the lines. This is the first point which requires closer investigation in future work. If a variation of skin friction coefficient with speed is detected, the analysis will be complicated, but it will still be possible.

The investigation of scale effect appears to be the most important further development of this work but the use of the method of analysis to record the results of a general test on a particular hull form should not be overlooked. The tests which have been analysed constitute a preliminary survey and make it reasonably certain that the method of analysis can be applied to any normal form of hull. A complete analysis for a particular hull is now required. This should cover all attitudes with particular reference to the two step case. The most satisfactory results would probably be obtained if the measurements could be made with a new type of balance in which the model would be fixed in draught, and lift and resistance measured. This would avoid the necessity of cross plotting the original observations and would also reduce the number of observations required to a minimum. Such a balance has been described in a Russian report[4]. Whatever method of measurement is adopted it is necessary to measure draughts with considerable care. It is possible to have a very shallow long wave in the tank which will so disturb the level of the water surface as to make measurements of the draught very inaccurate.

9. Conclusions

It will be convenient to summarise the main results obtained.

(1) The forces on a seaplane hull are the result of hydrostatic pressure, hydrodynamic pressure and skin friction. The resultant of the hydrostatic pressures can be calculated when the shape of the wetted surface is known.

(2) Consideration of the general shape of the wetted surface on a seaplane in the planing condition shows that there must be a hydrostatic resistance as well as a hydrostatic lift.

(3) It is found experimentally that the wetted surface is independent of the speed when the draught and attitude are constant provided the speed is not too small, and it is shown that this result might have been anticiptated from elementary considerations.

(4) It is found experimentally that the resultant force due to hydrodynamic pressure and skin friction is directly proportional to V^2 when the wetted surface is constant. This means that the skin friction coefficient does not vary with Reynolds number under the conditions of seaplane tank testing.

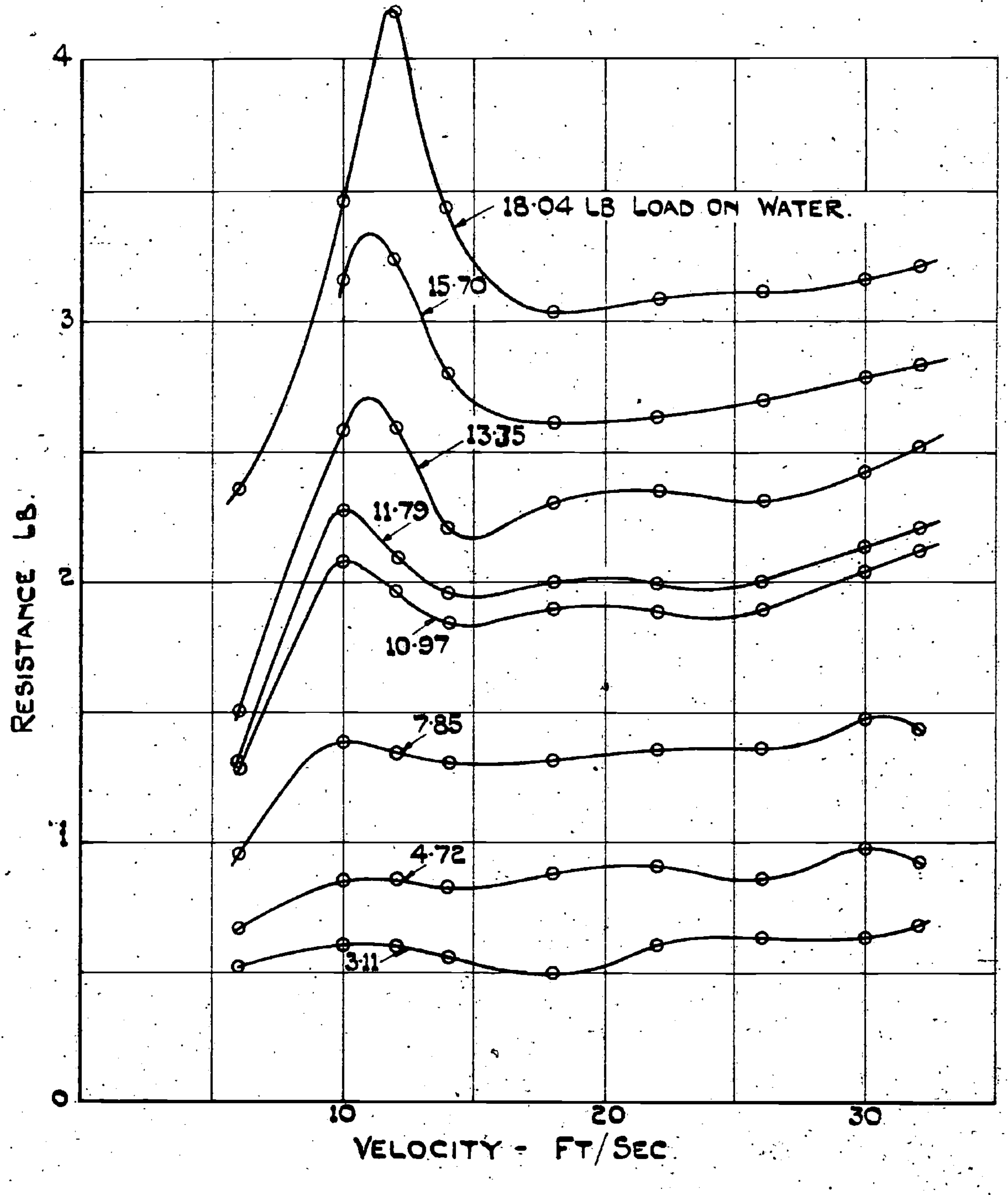
(5) Results (1) - (4) are the basis of a new method of analysing the forces on seaplane tank models. Measurements of resistance, moment and draught, usually given in more than 20 curves, can be expressed non-dimensionally in 6 curves. For a geometrically simple planing form the forces can be separated into components due to hydrostatic pressure, hydrodynamic pressure and skin friction. This gives precise information for the investigation of scale effect. In a case where the skin friction coefficient is not independent of Reynolds number the analysis will still be possible though more complicated.

The method is soundly based on both theory and experiment and does not depend on any empirical quantities.

REFERENCES

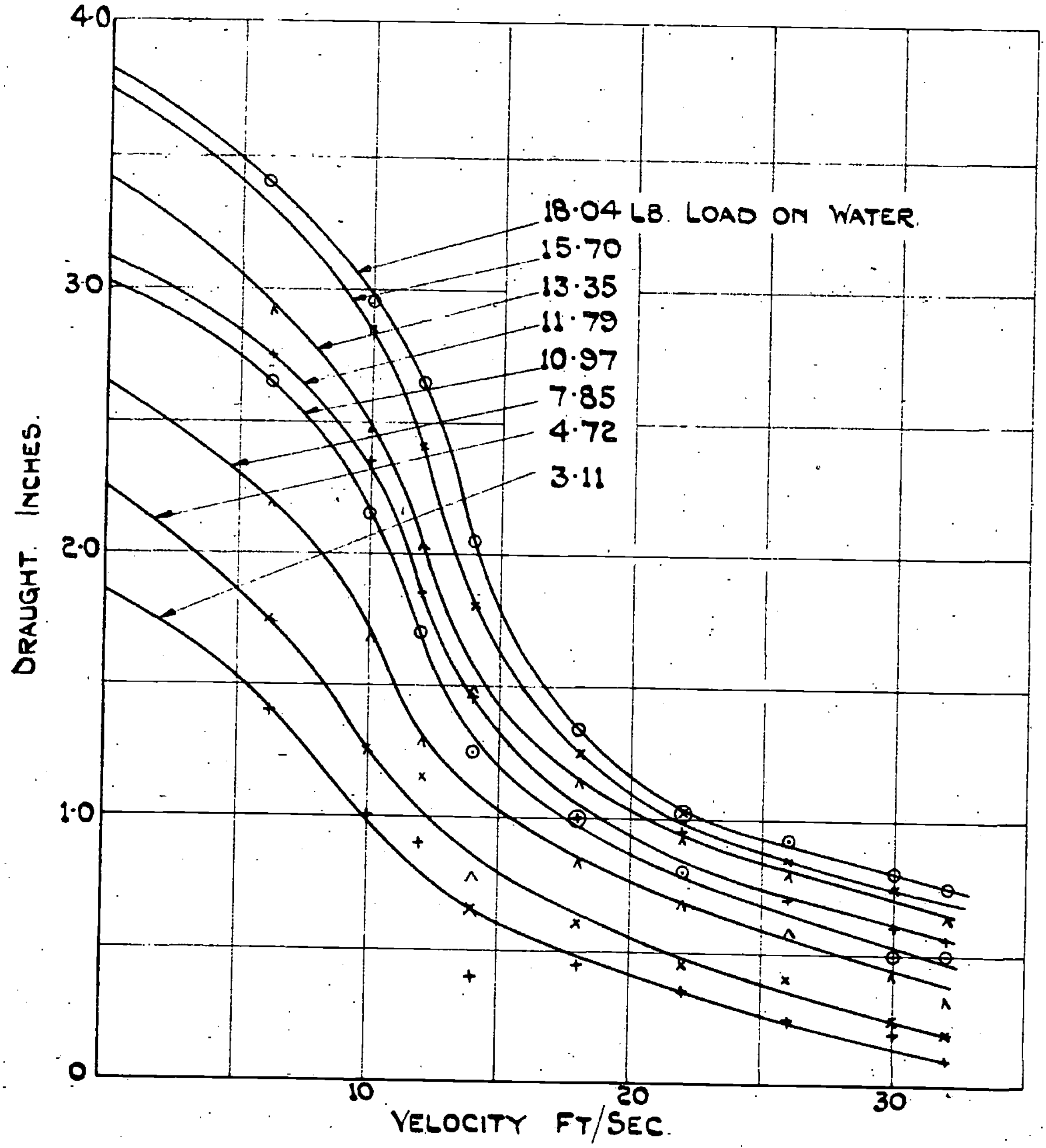
No.	Author	Title, etc.
1	Cushing and Garner.	Basic curves for water resistance. M.A.E.E. Report No. F/Res/87. August, 1935.
	Staff of M.A.E.E. and Tank staff of R.A.E.	Basic curves for water resistance. M.A.E.E. Report No. F/Res/94. March, 1936.
2	Gott.	Comparison of results of tests of the Singapore IIc model hull in five tanks. R.A.E. Report No. B.A.1339. (2715) September, 1936.
3	Dawson.	A complete tank test of the Sikorsky S.40 flying boat. N.A.C.A. Tech. Note No.512. December, 1934.
4	Kossoürov.	The gliding of keeled bottoms. (Transactions of the 1st All Union Conference on Hydrodynamics Moscow, 1933.) (A.R.C. Translation No.3040 or S.338).

FIG. 1.

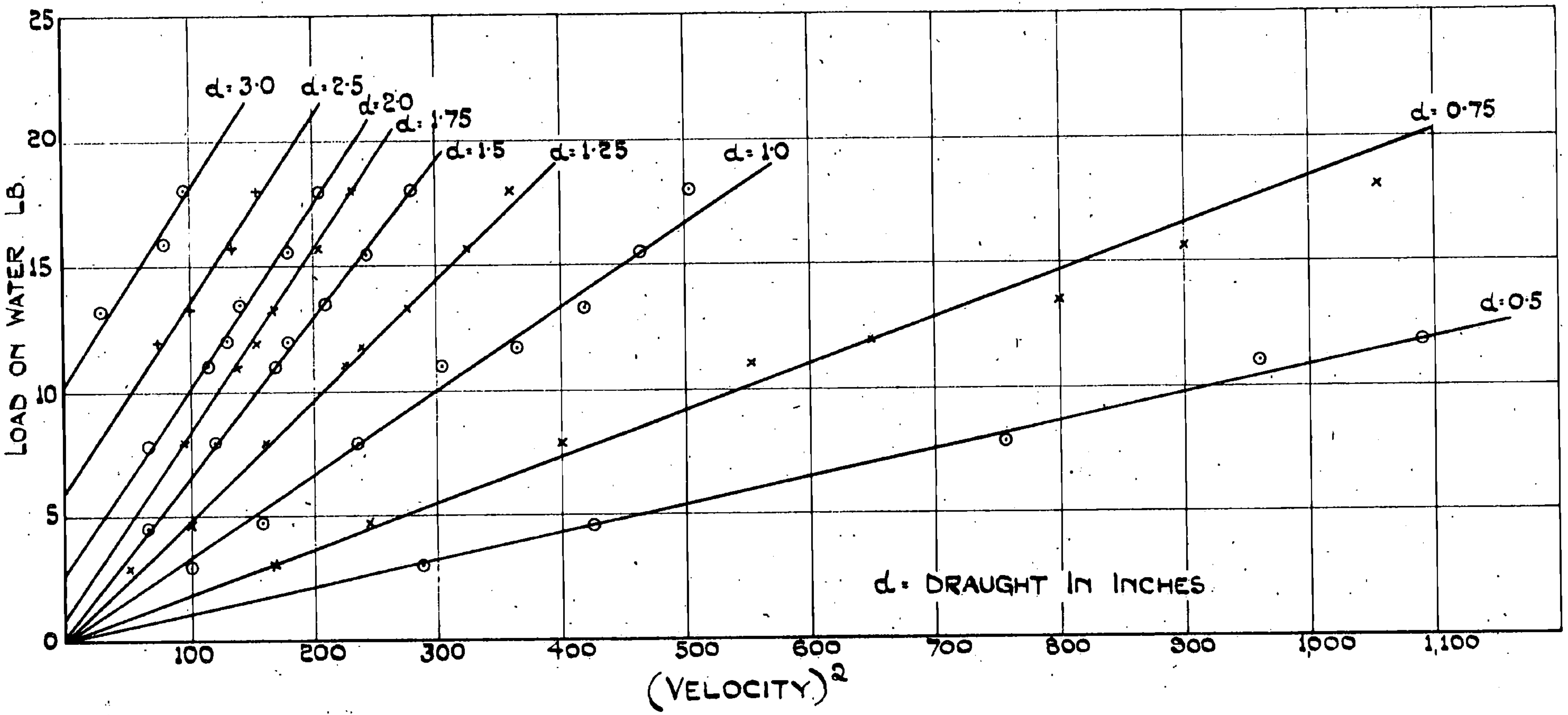


RESISTANCE OF SINGAPORE IIc MODEL AT 7°

FIG. 2.

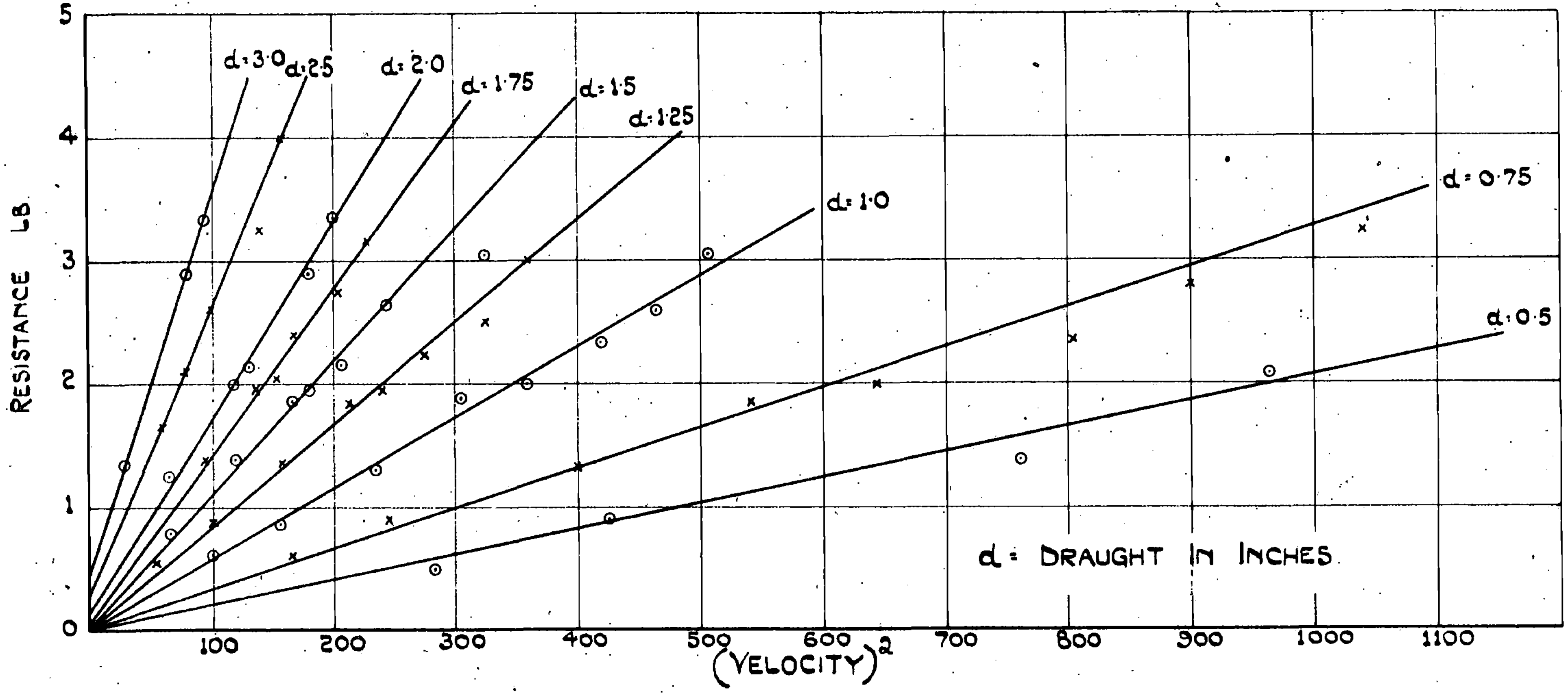


DRAUGHT OF SINGAPORE IIC MODEL AT 7°



ANALYSIS OF LOAD ON WATER. SINGAPORE IIC MODEL AT 7°

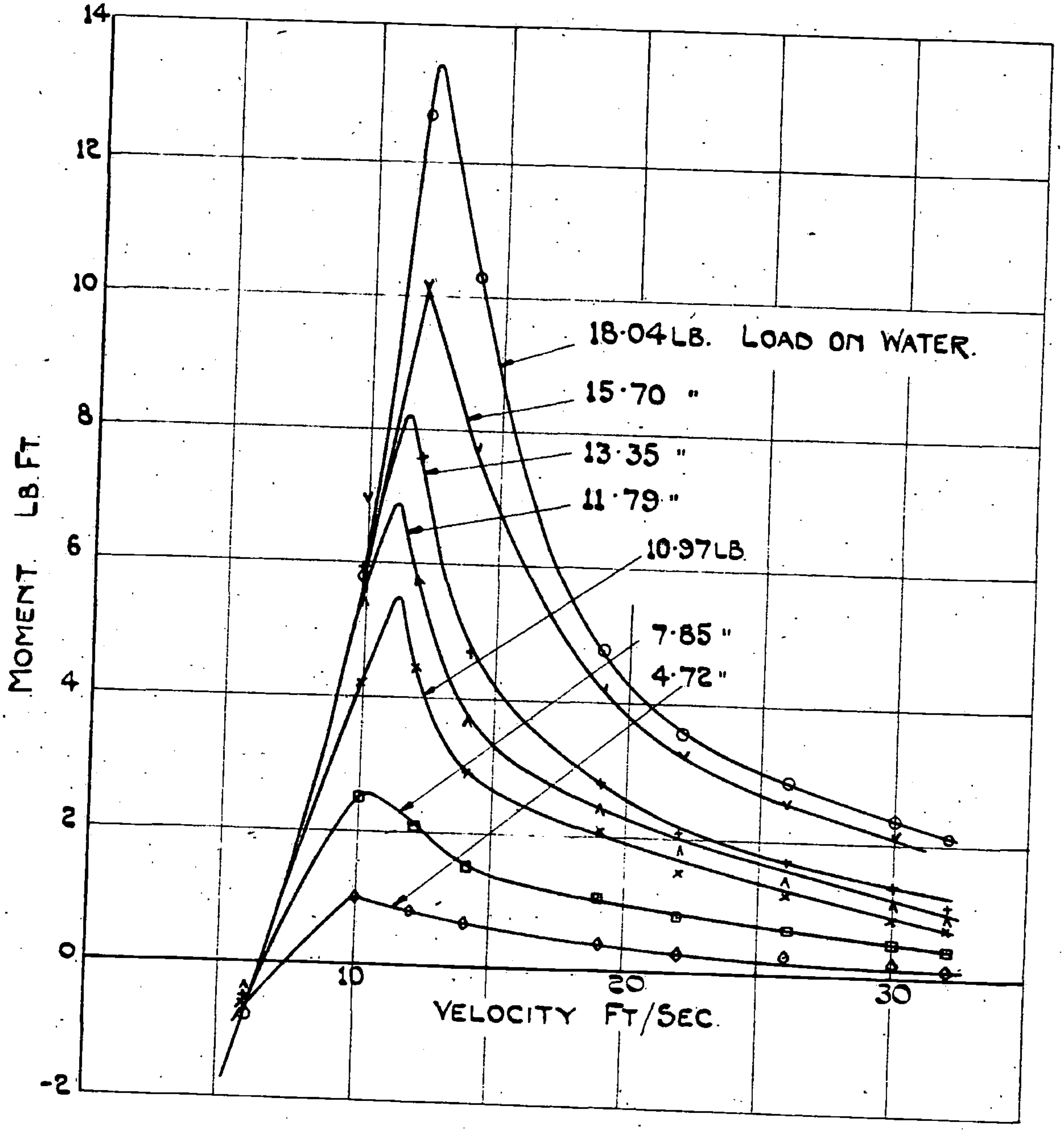
FIG. 3.



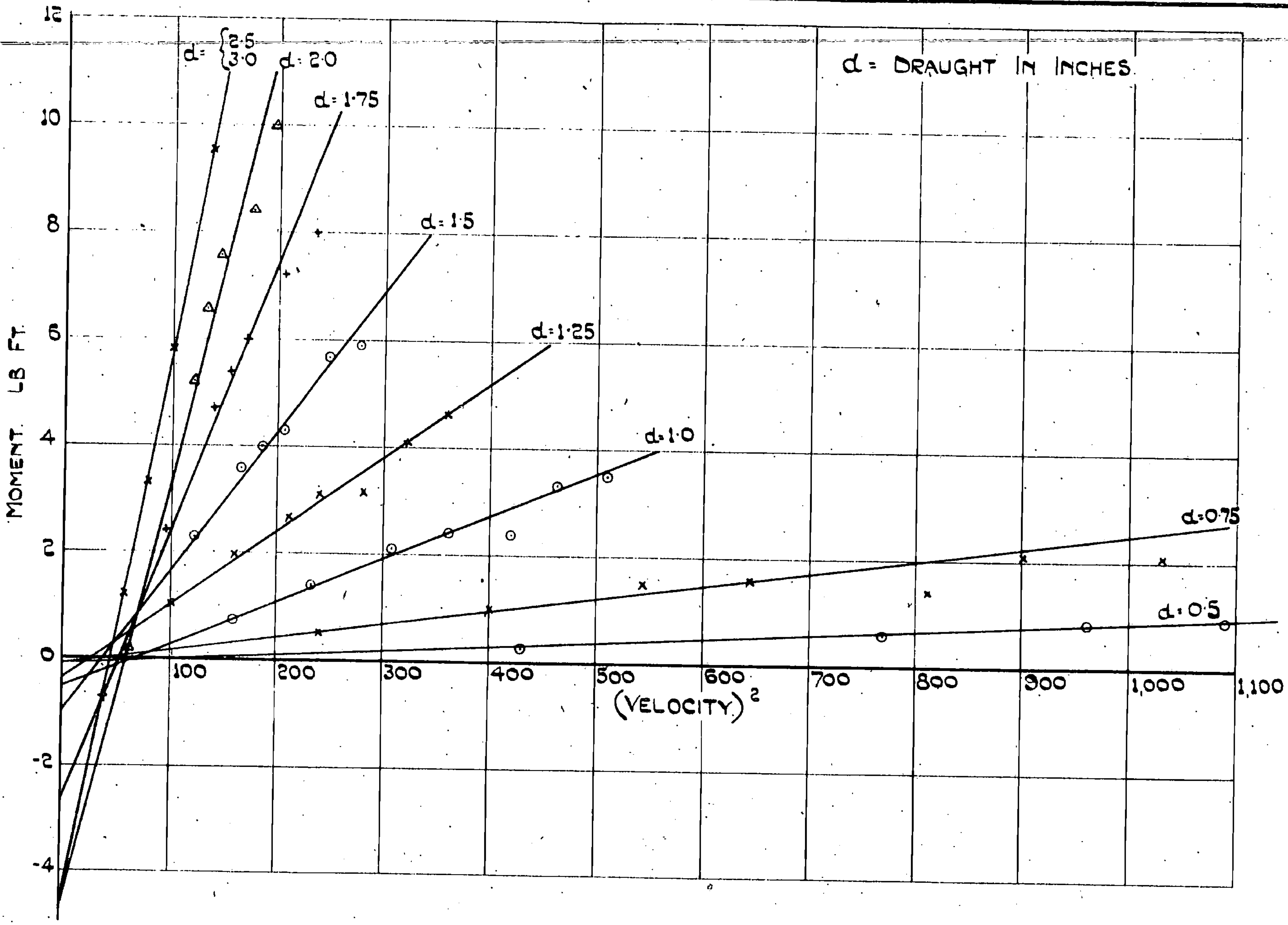
ANALYSIS OF RESISTANCE. SINGAPORE IIC MODEL AT 7°

FIG. 4.

FIG. 5.



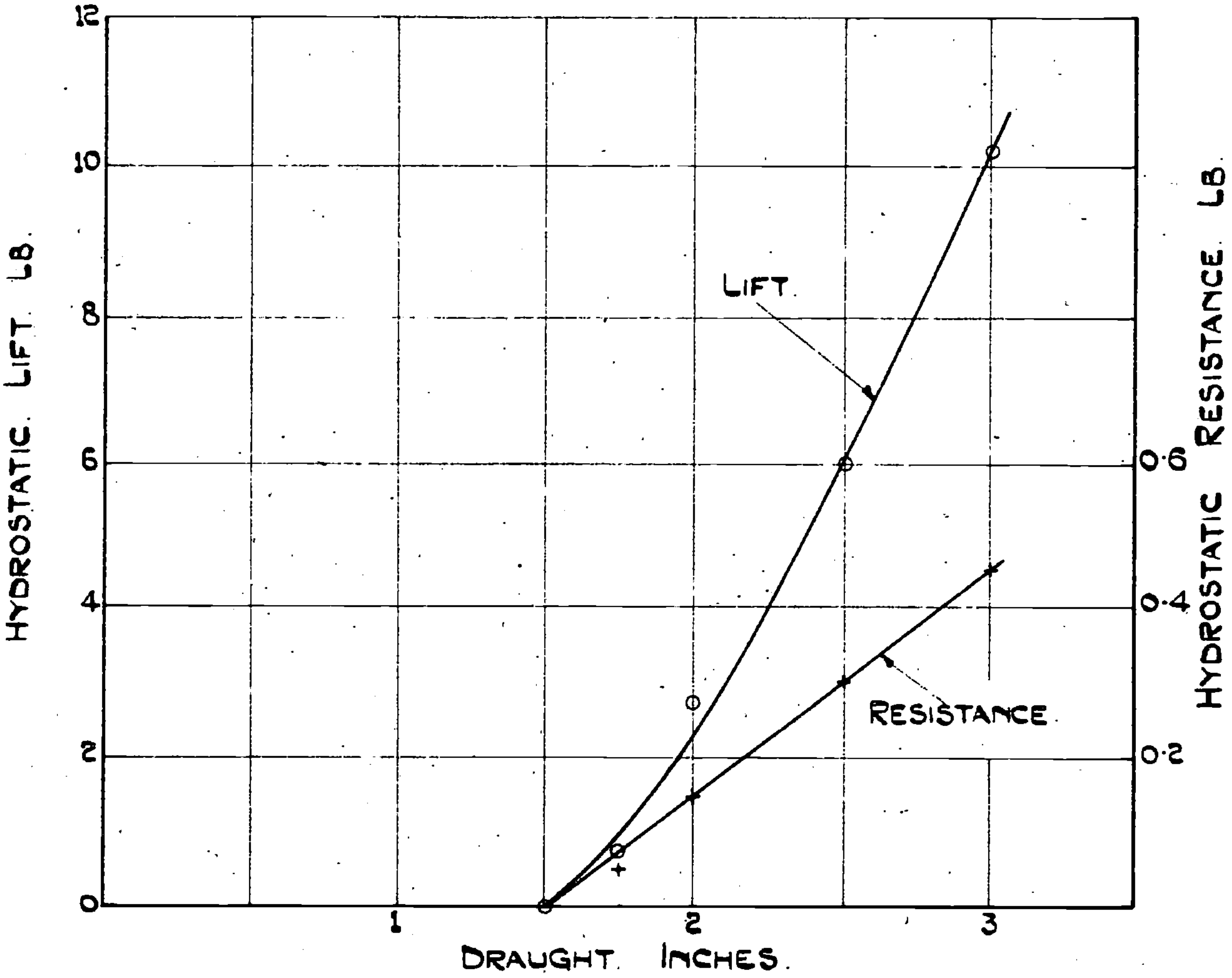
MOMENTS ON SINGAPORE IIC MODEL AT 7°



ANALYSIS OF MOMENTS ON SINGAPORE IIC MODEL AT 7°

FIG. 6.

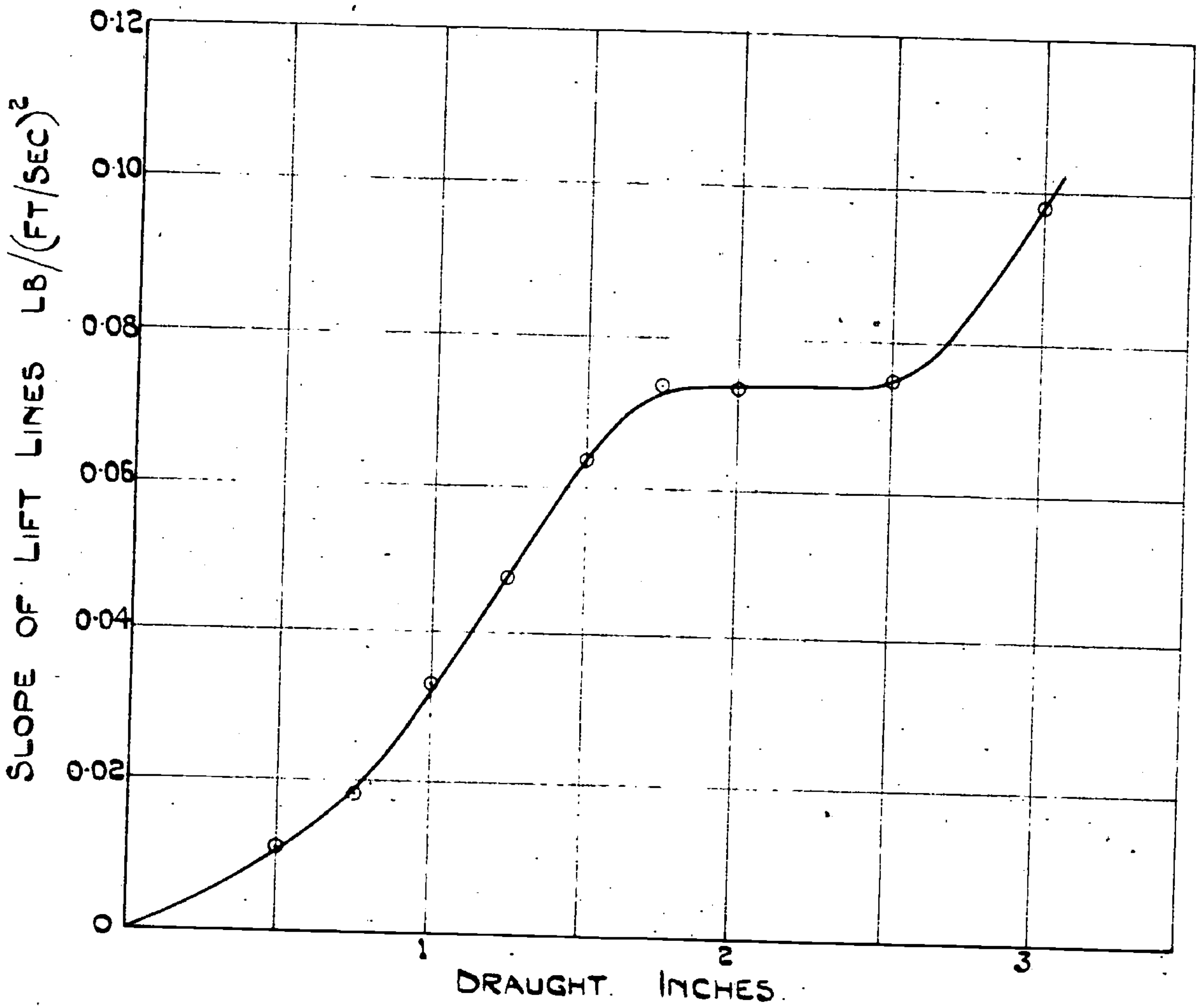
FIG 7.



HYDROSTATIC LIFT AND RESISTANCE

SINGAPORE IIc MODEL AT 7°.

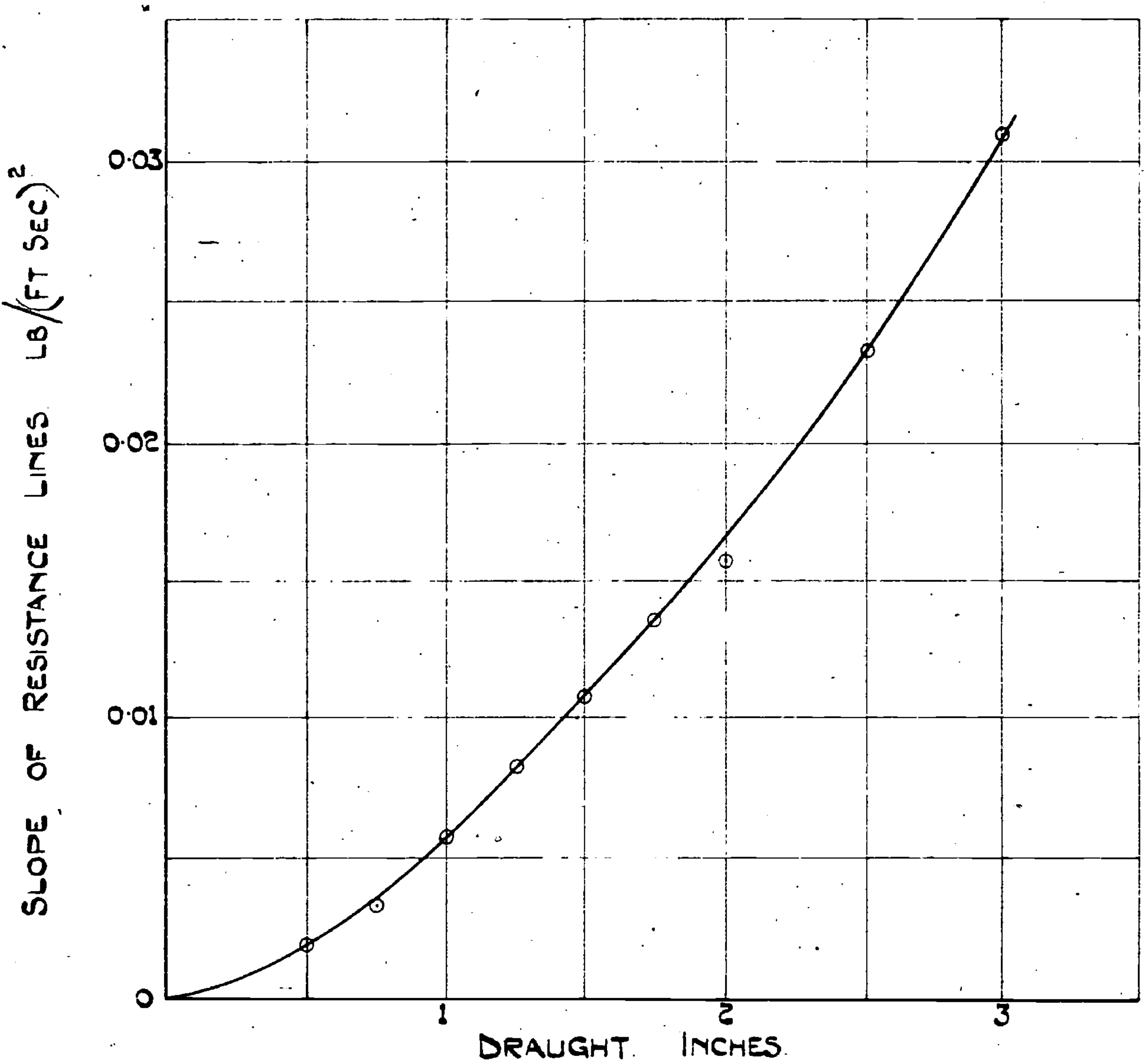
FIG. 8.



SLOPE OF LIFT LINES.

SINGAPORE IIC MODEL AT 7°

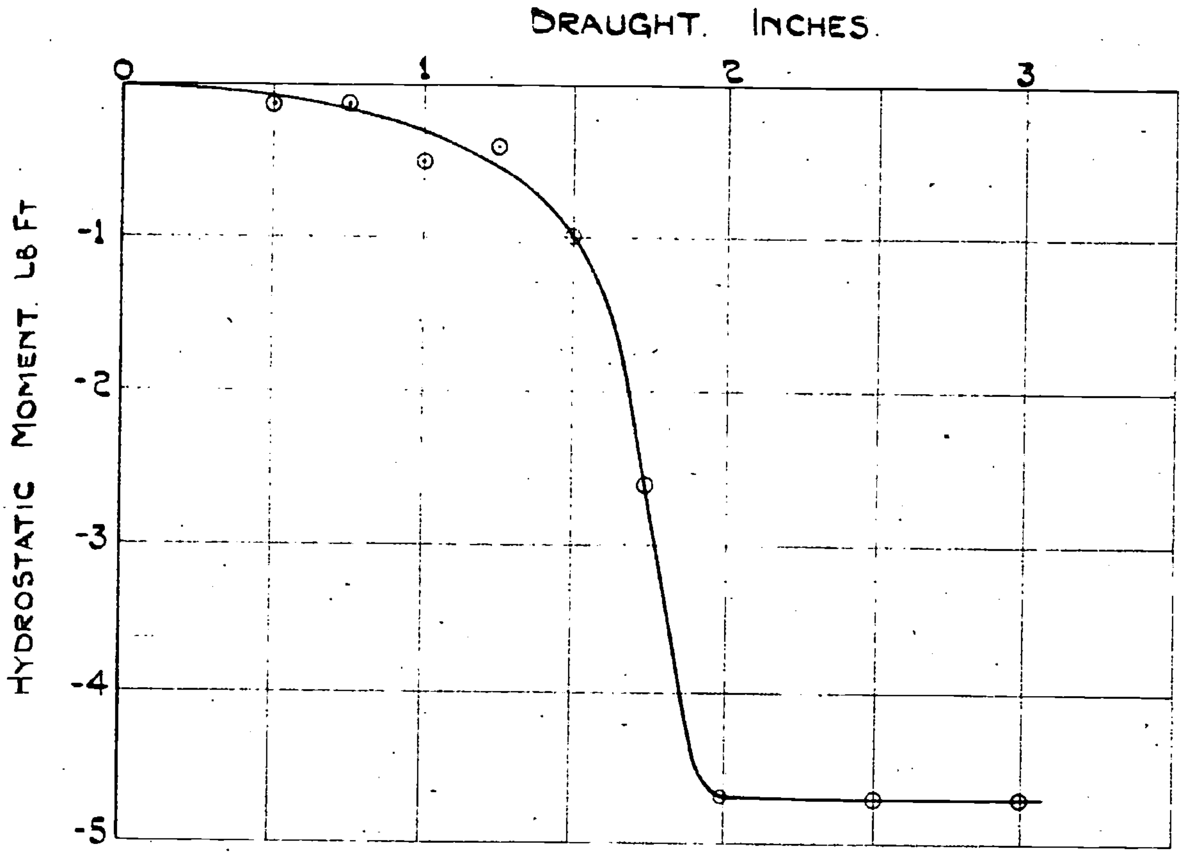
FIG. 9



SLOPE OF RESISTANCE LINES

SINGAPORE IIC MODEL AT 7°

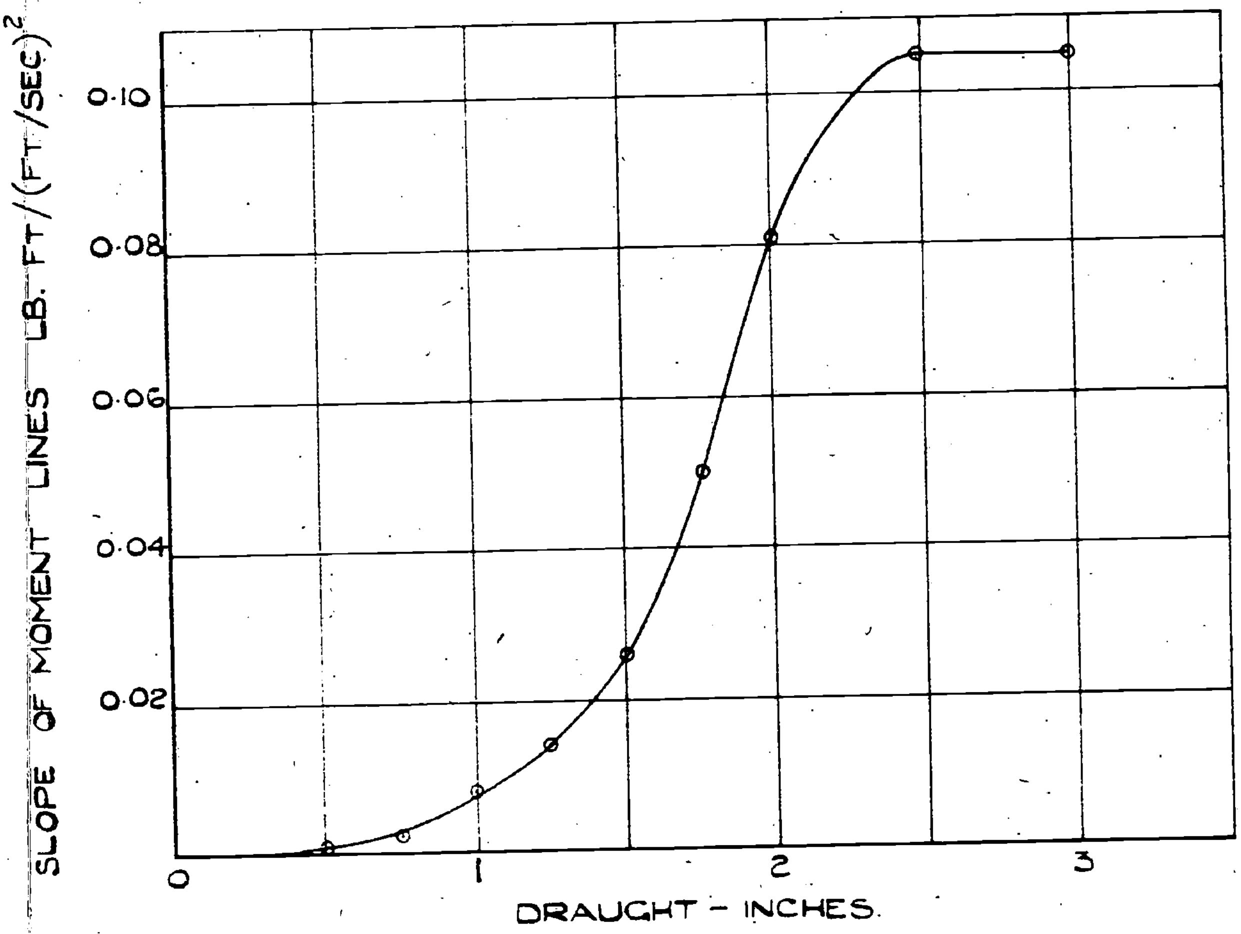
FIG. 10.



HYDROSTATIC MOMENT.

SINGAPORE IIC AT 7°

FIG. 11



SLOPE OF MOMENT LINES

SINGAPORE IIC AT 7°

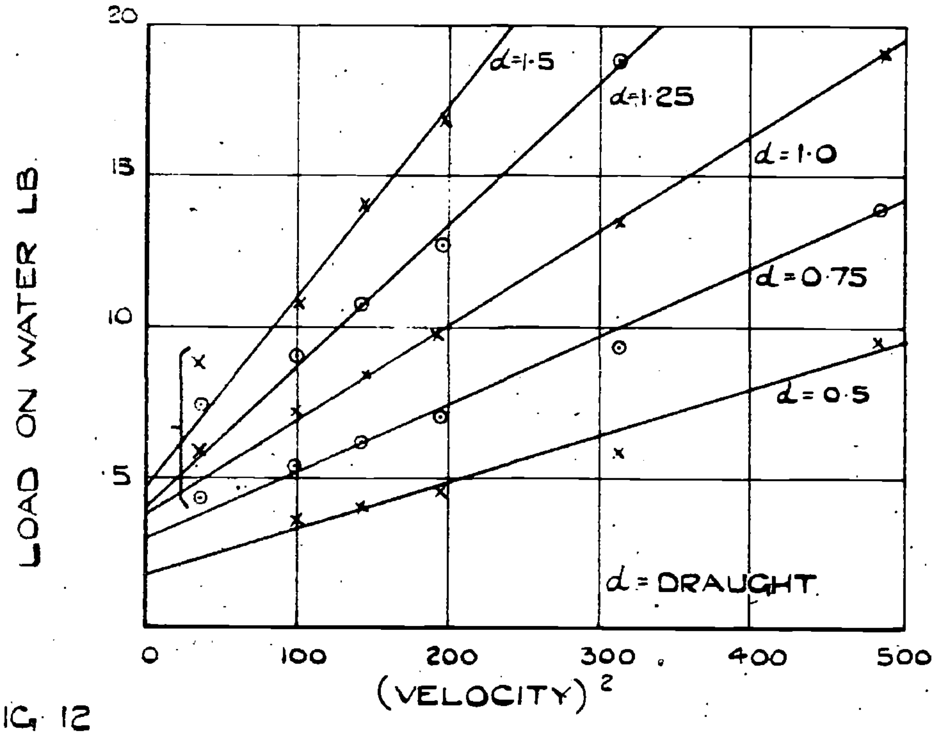


FIG. 12

ANALYSIS OF LOAD ON WATER.

SINGAPORE II c MODEL AT 13°

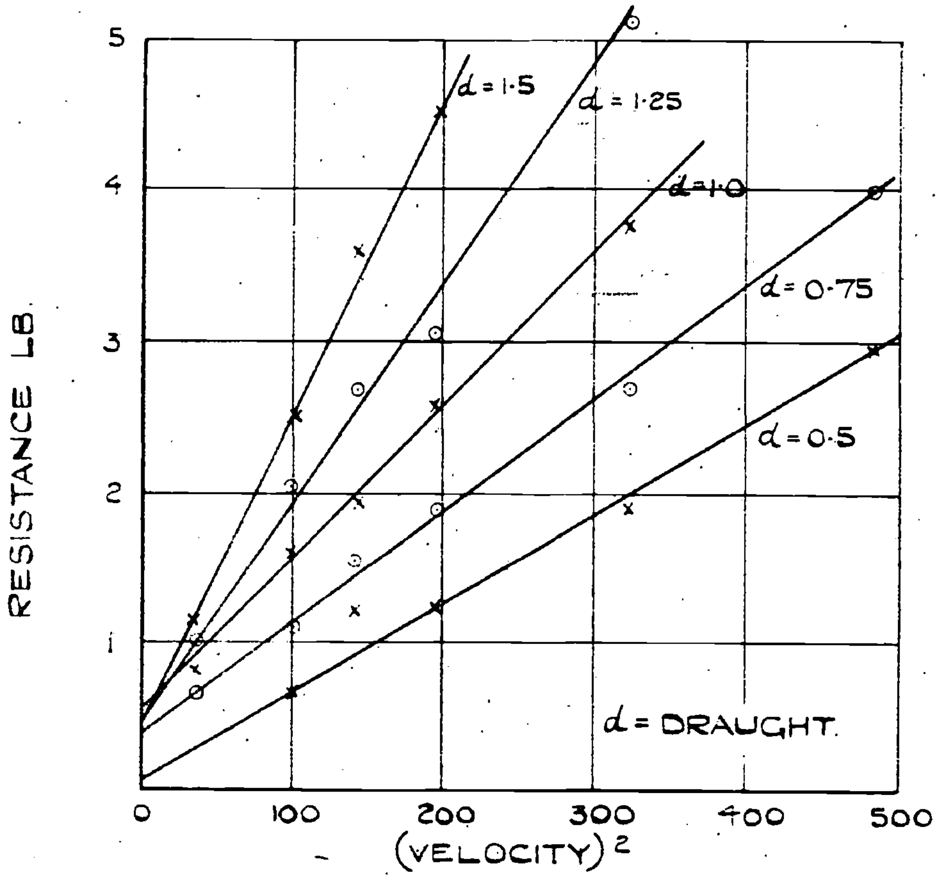


FIG. 13

ANALYSIS OF RESISTANCE

SINGAPORE IIc MODEL AT 13°

FIG: 14.

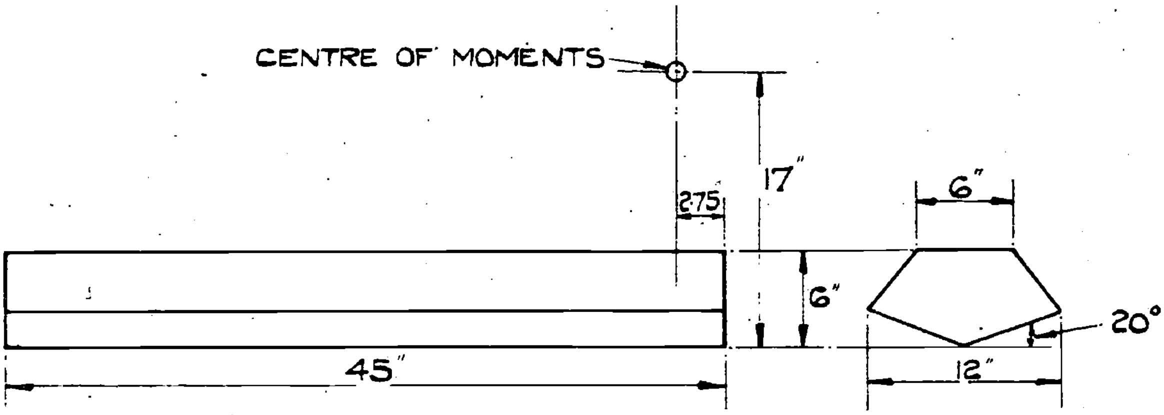


FIG. 14. A

DIMENSIONS OF 20° WEDGE.

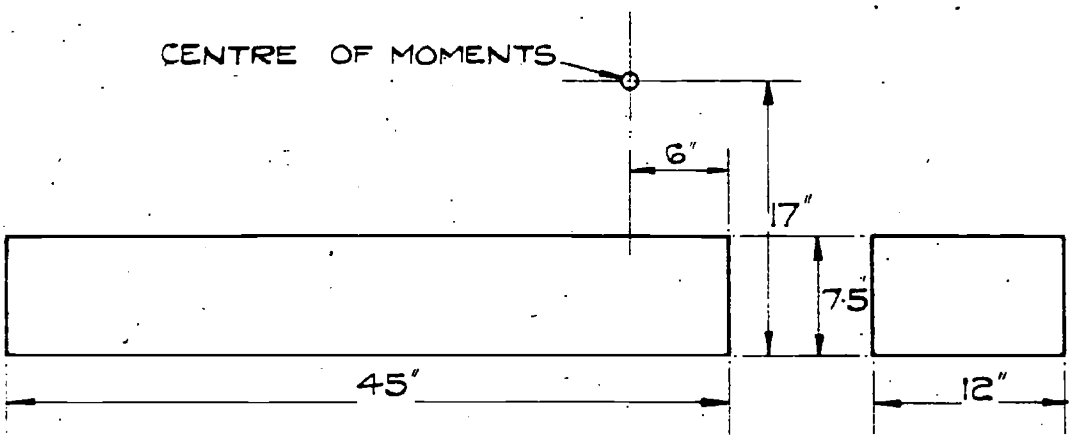
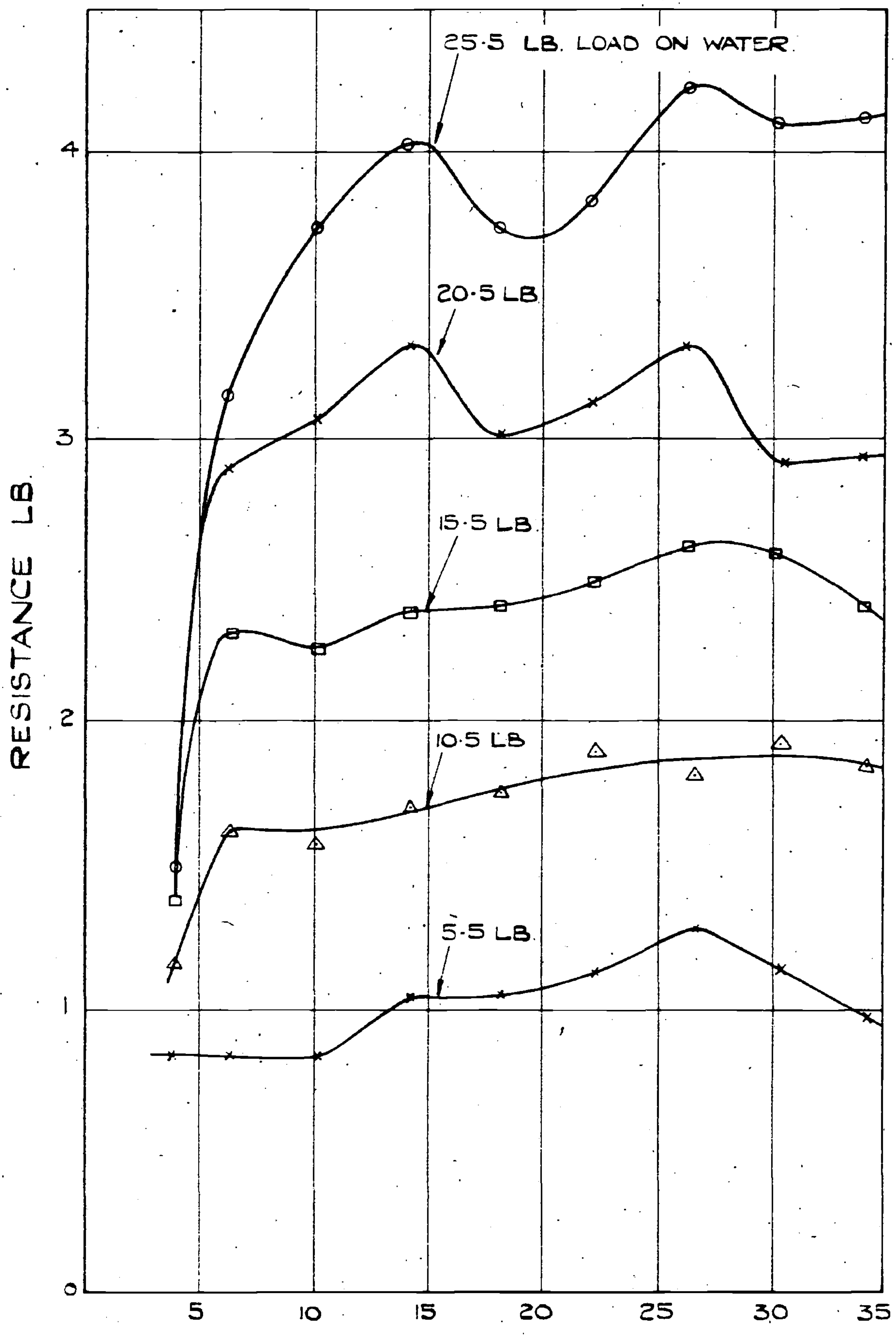


FIG 14. B.

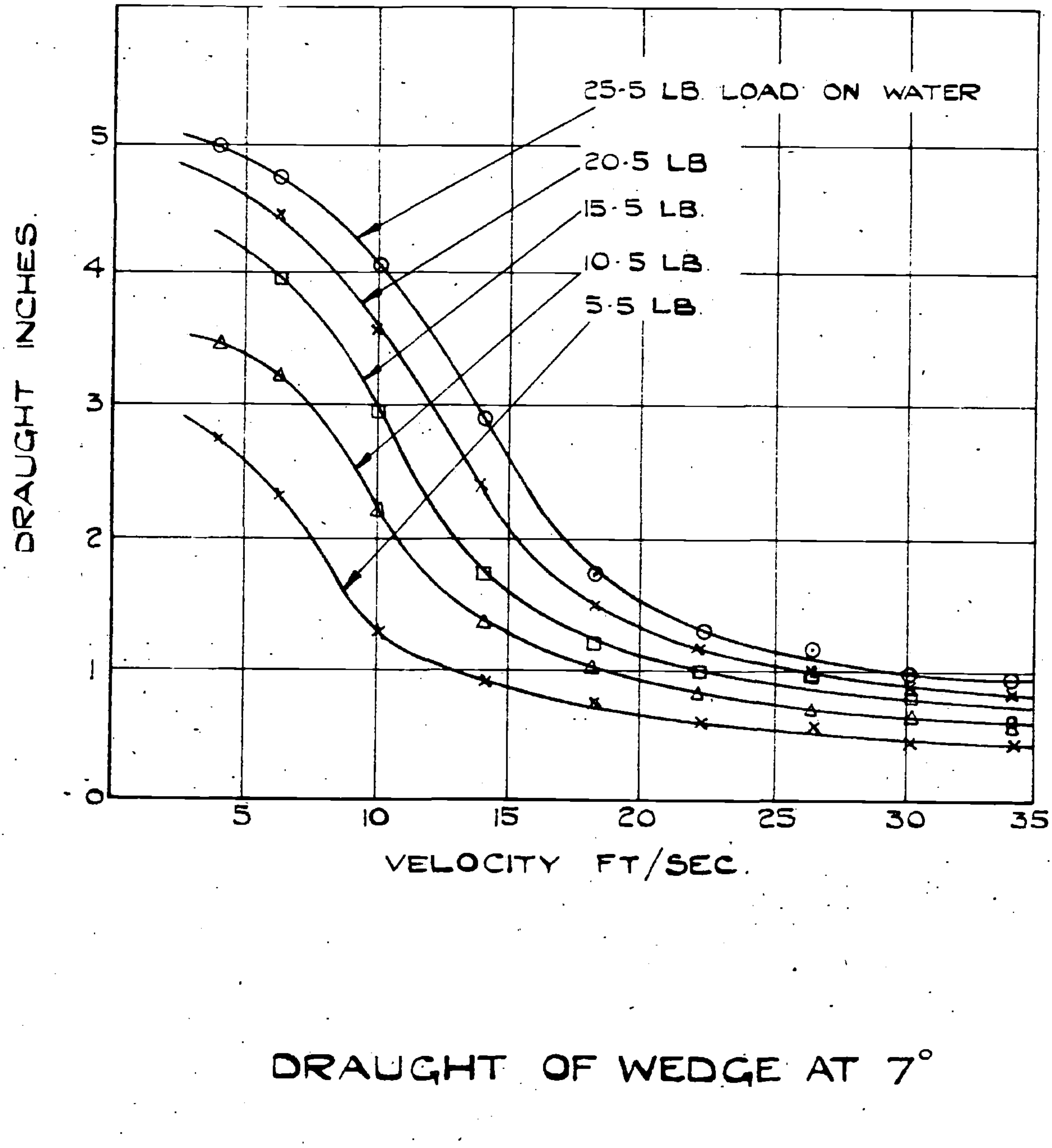
DIMENSIONS OF FLAT PLANING SURFACE.

FIG. 15



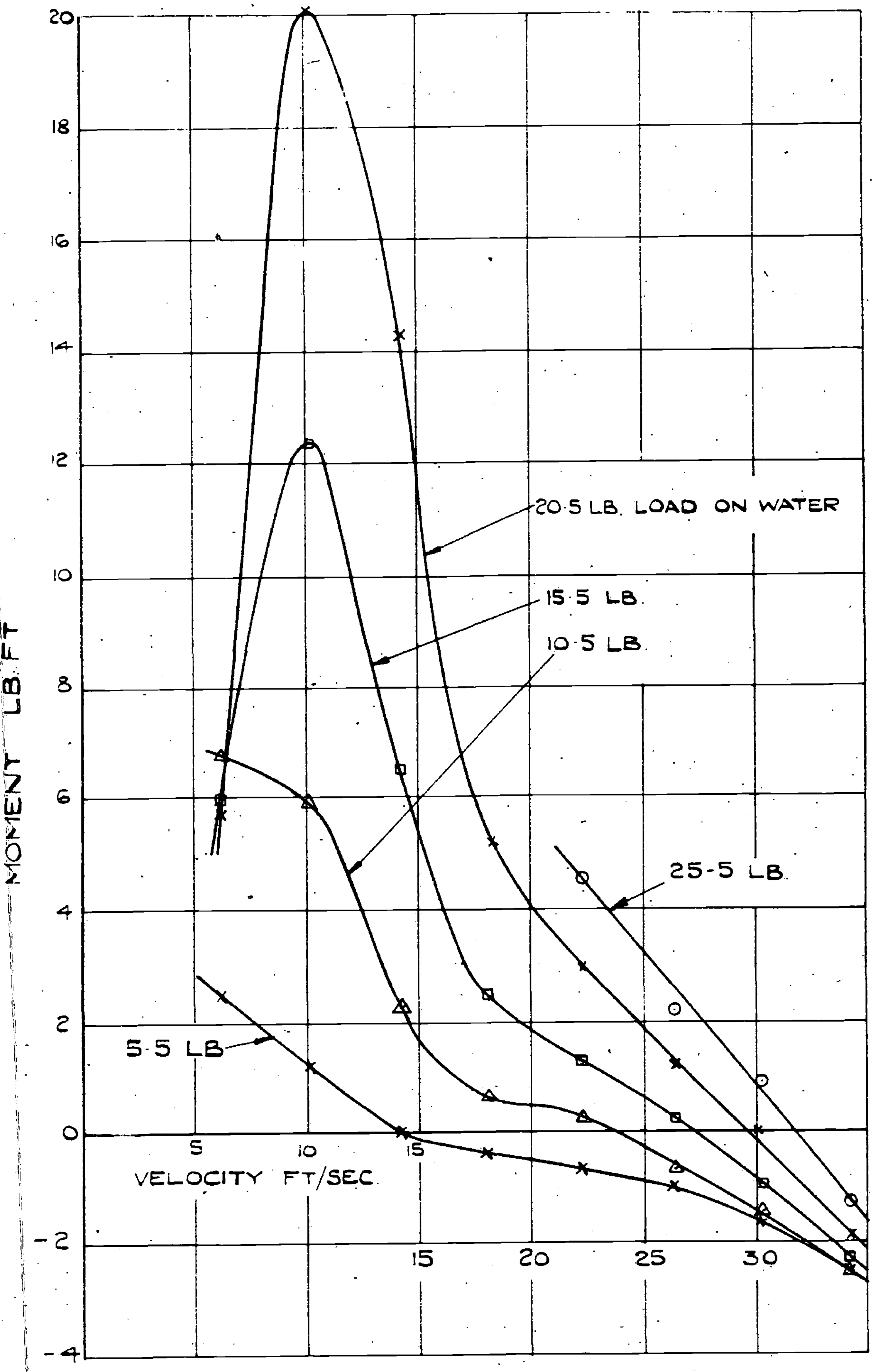
RESISTANCE OF WEDGE AT 7°

FIG 16

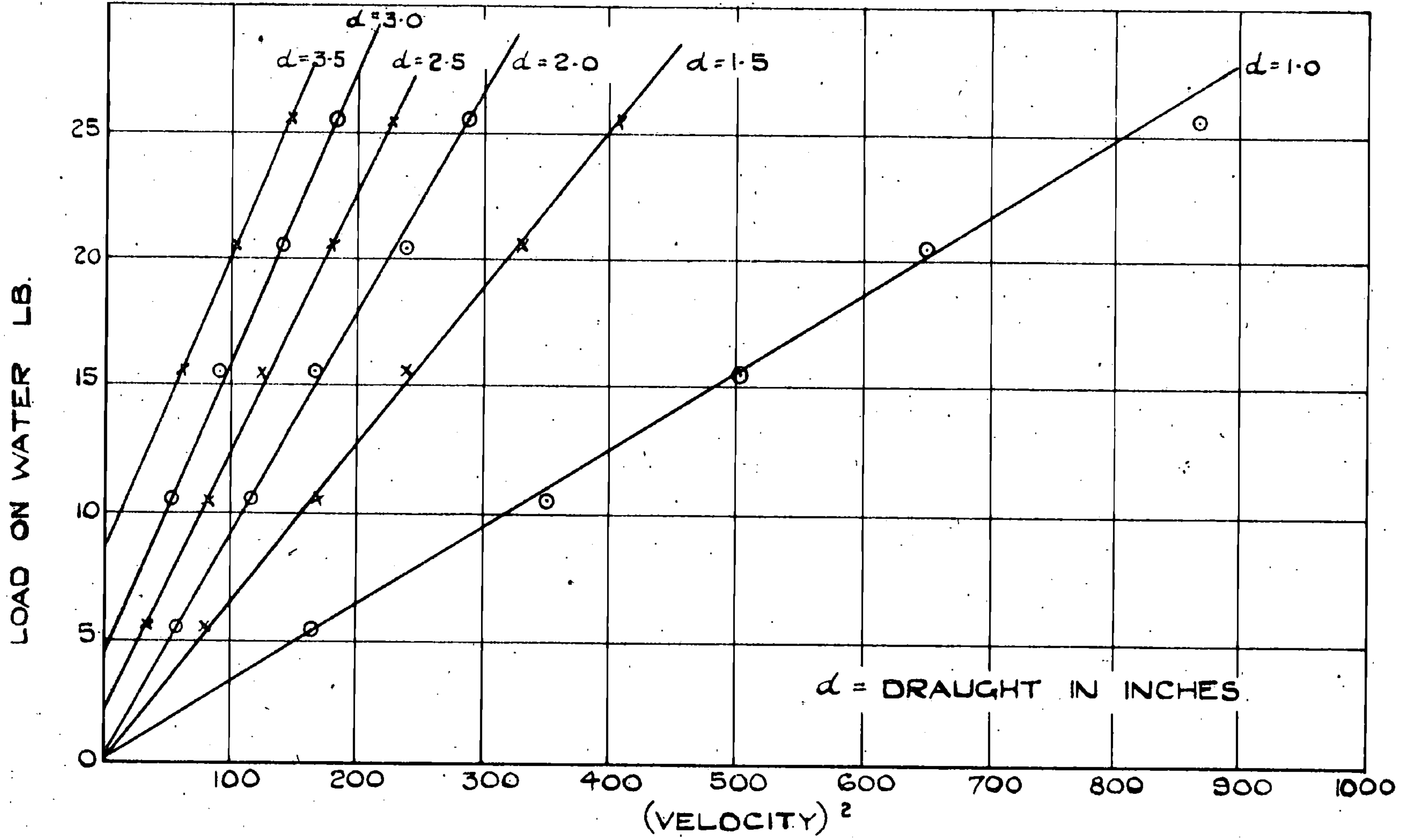


DRAUGHT OF WEDGE AT 7°

FIG 17

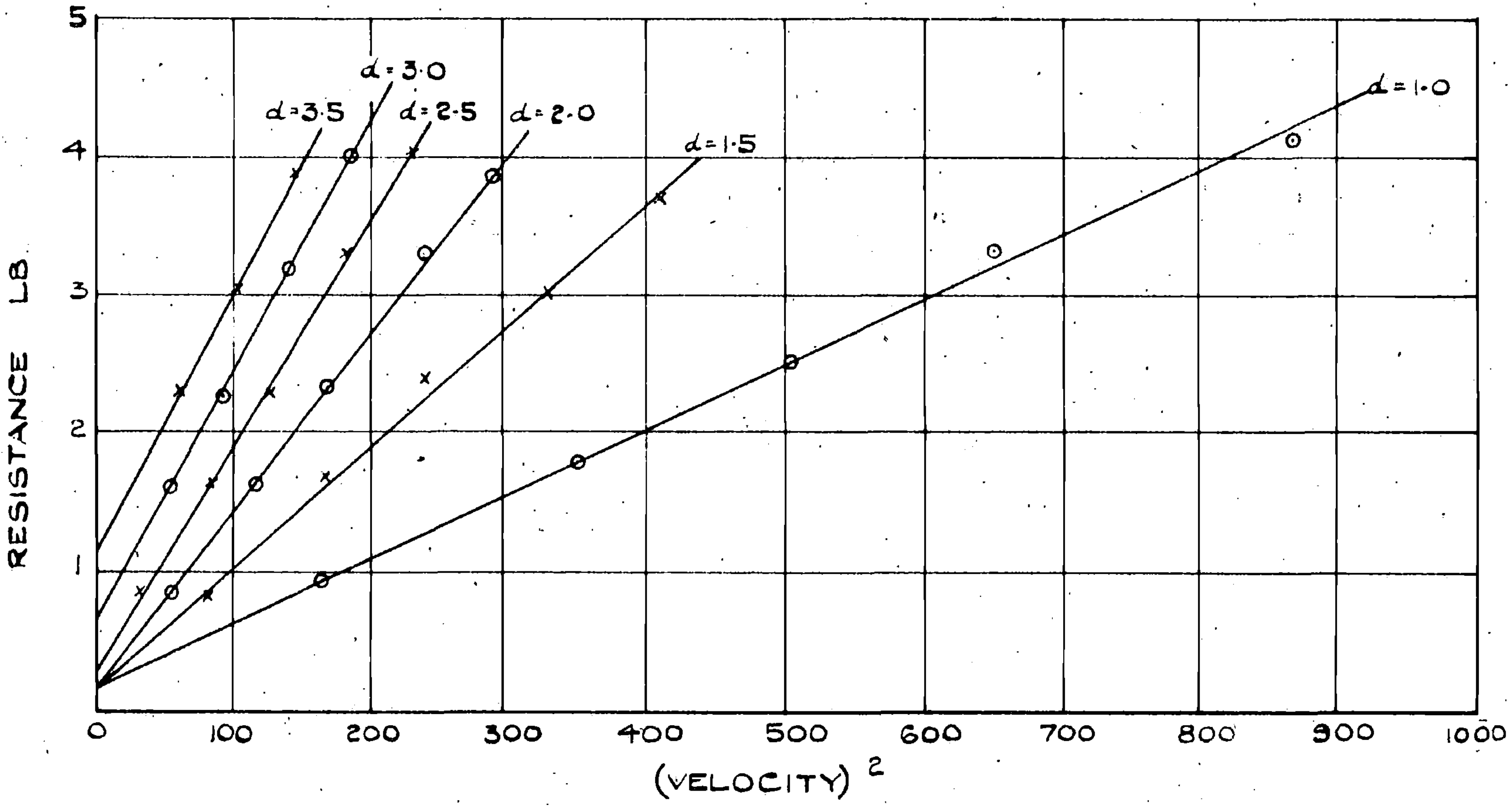


MOMENT ON WEDGE AT 7°



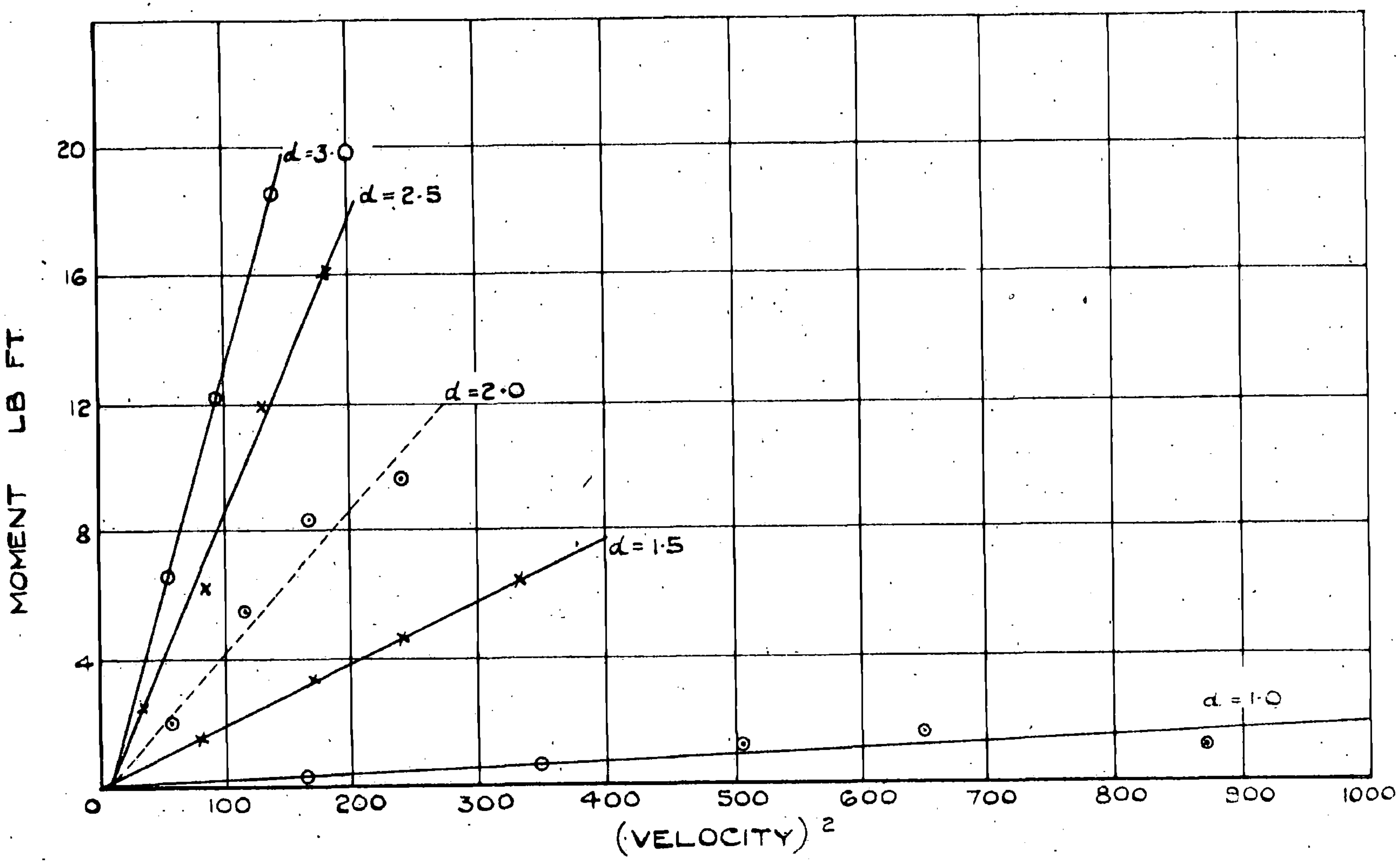
ANALYSIS OF LOAD ON WATER FOR WEDGE AT 7°

FIG. 18.



ANALYSIS OF RESISTANCE FOR WEDGE AT 7°

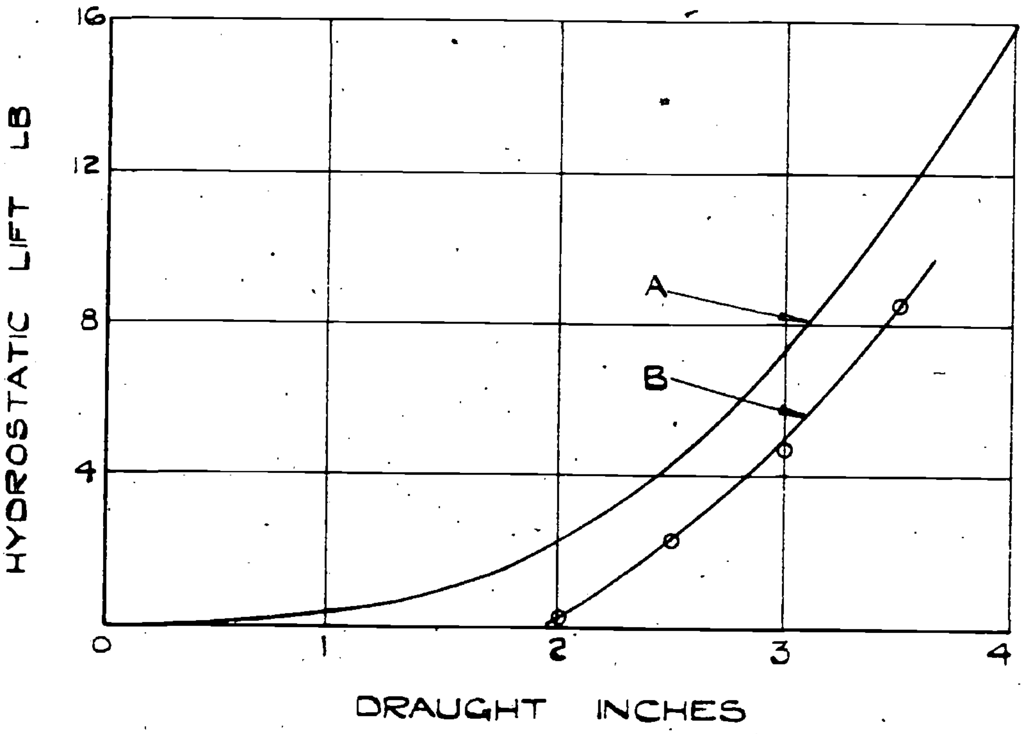
FIG: 19



ANALYSIS OF MOMENTS ON WEDGE AT 7°

FIG: 20

FIG: 21



HYDROSTATIC LIFT ON WEDGE.

FIG. 22 & 23

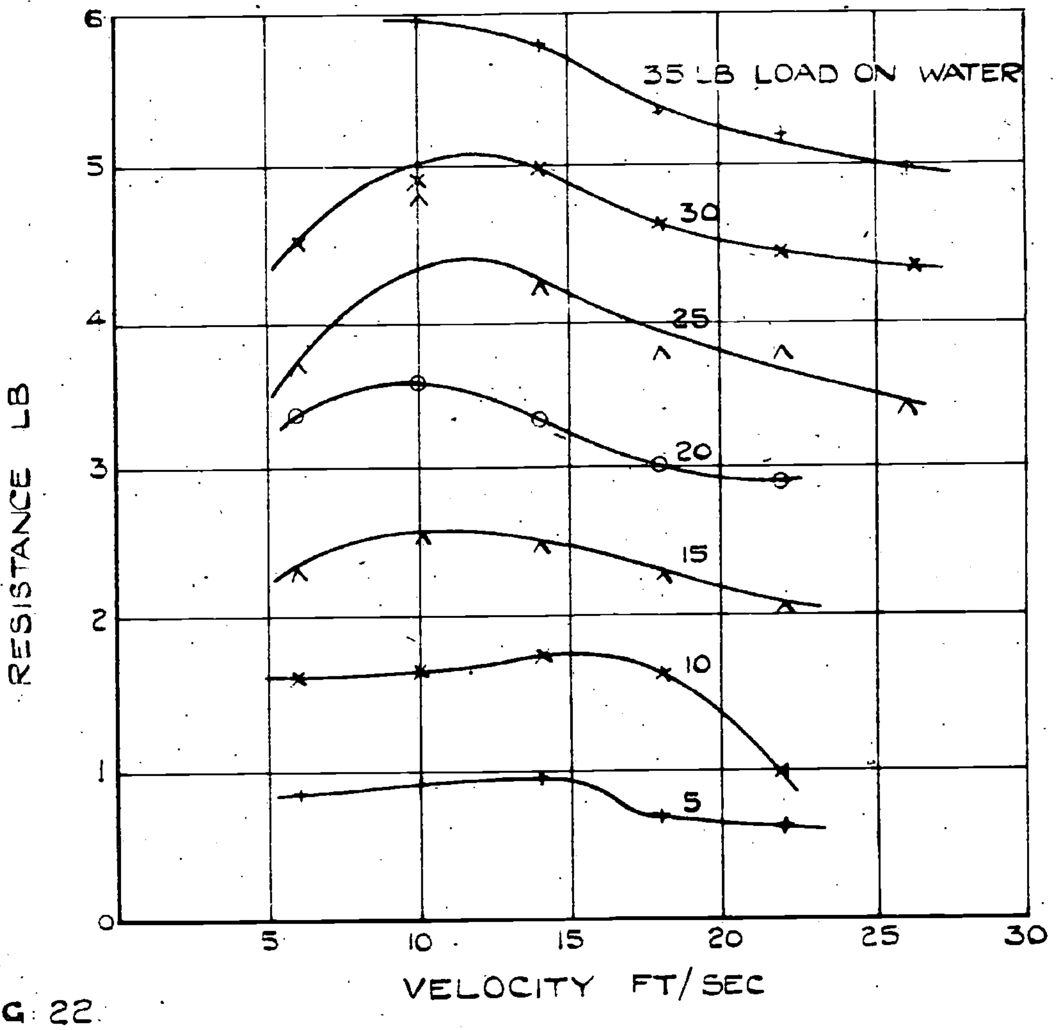


FIG. 22.

RESISTANCE OF FLAT PLANING SURFACE AT 7°

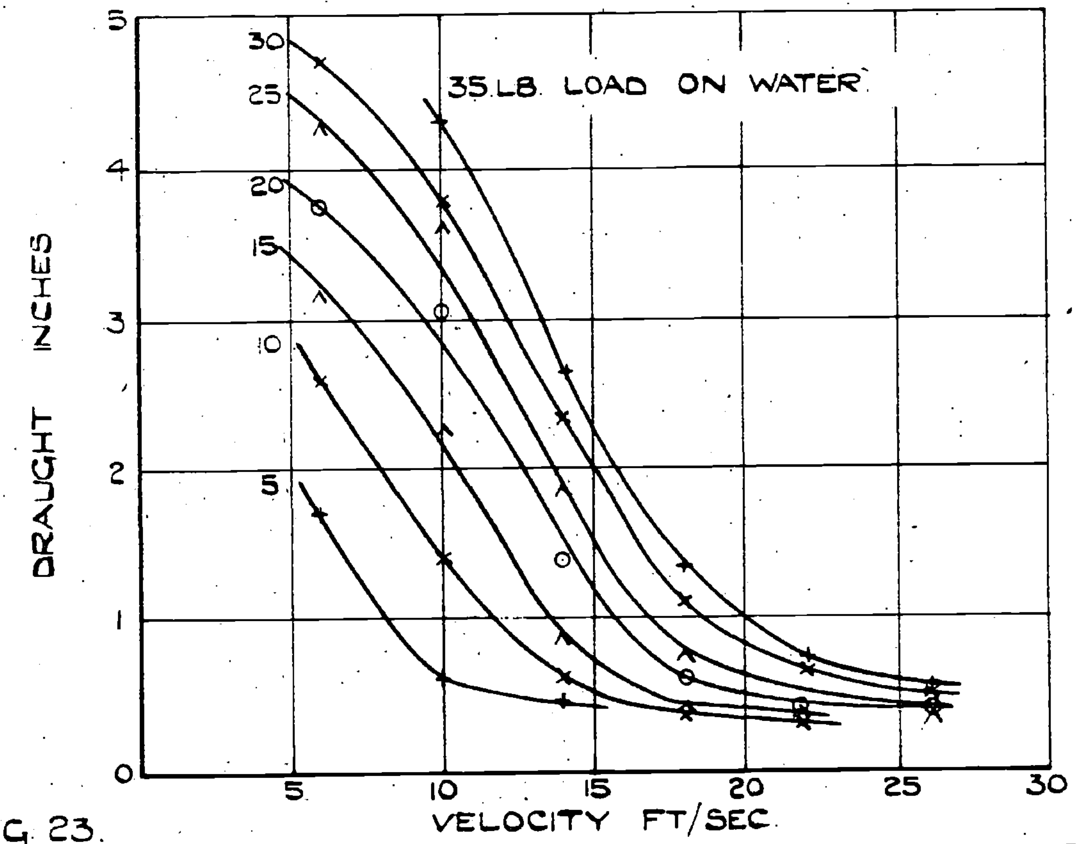


FIG. 23.

DRAUGHT OF FLAT PLANING SURFACE AT 7°

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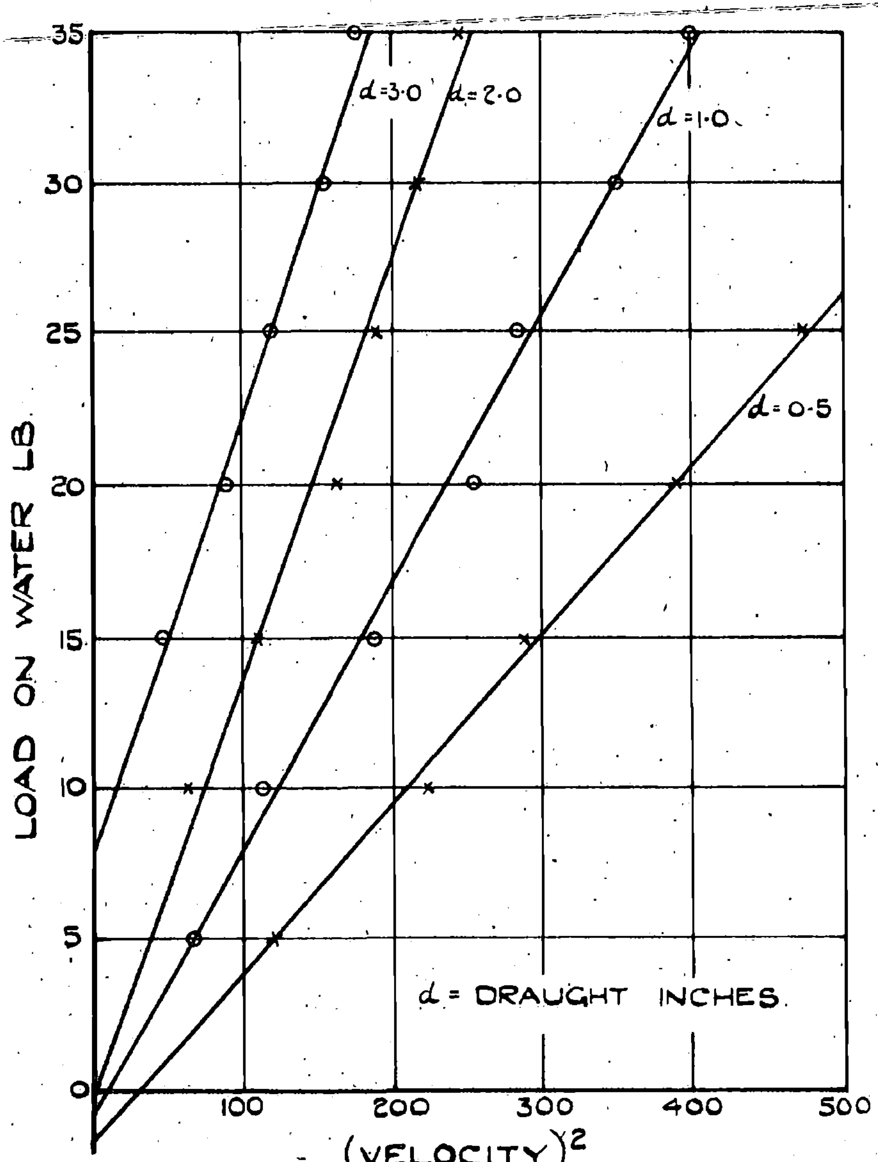


FIG. 24.
ANALYSIS OF LOAD ON WATER FOR FLAT PLANING SURFACE AT 7°

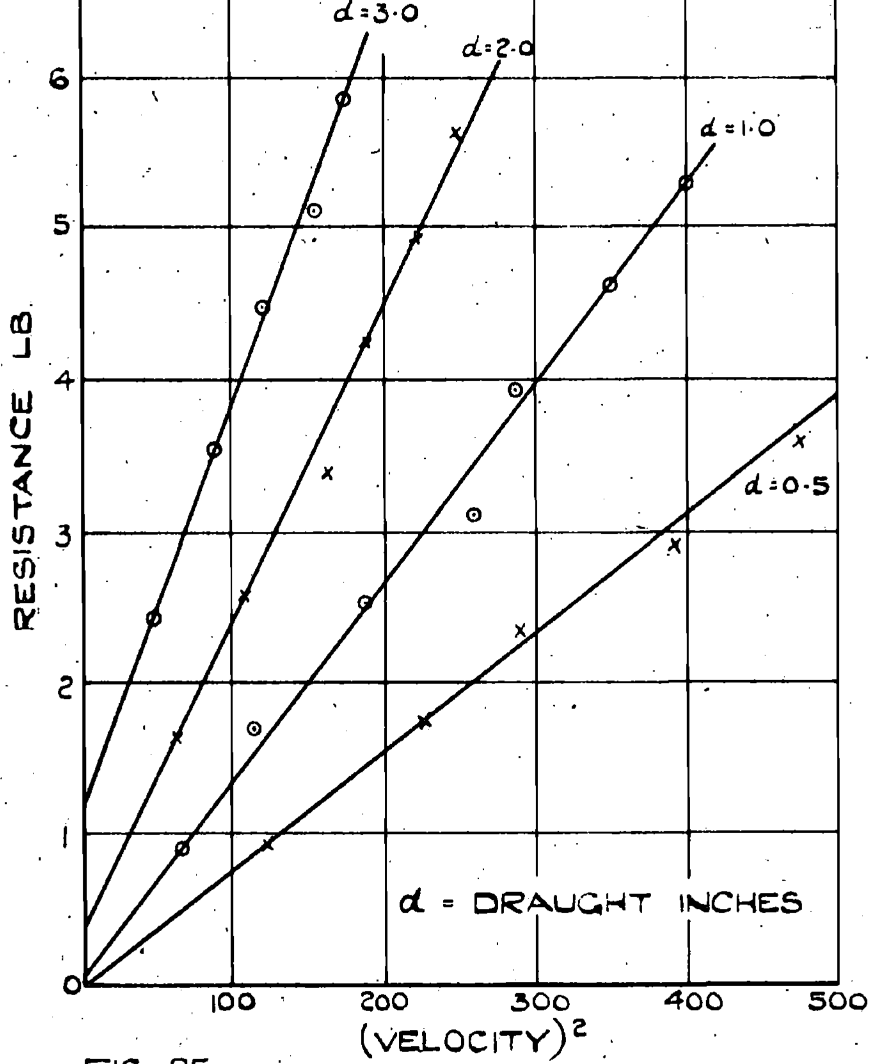
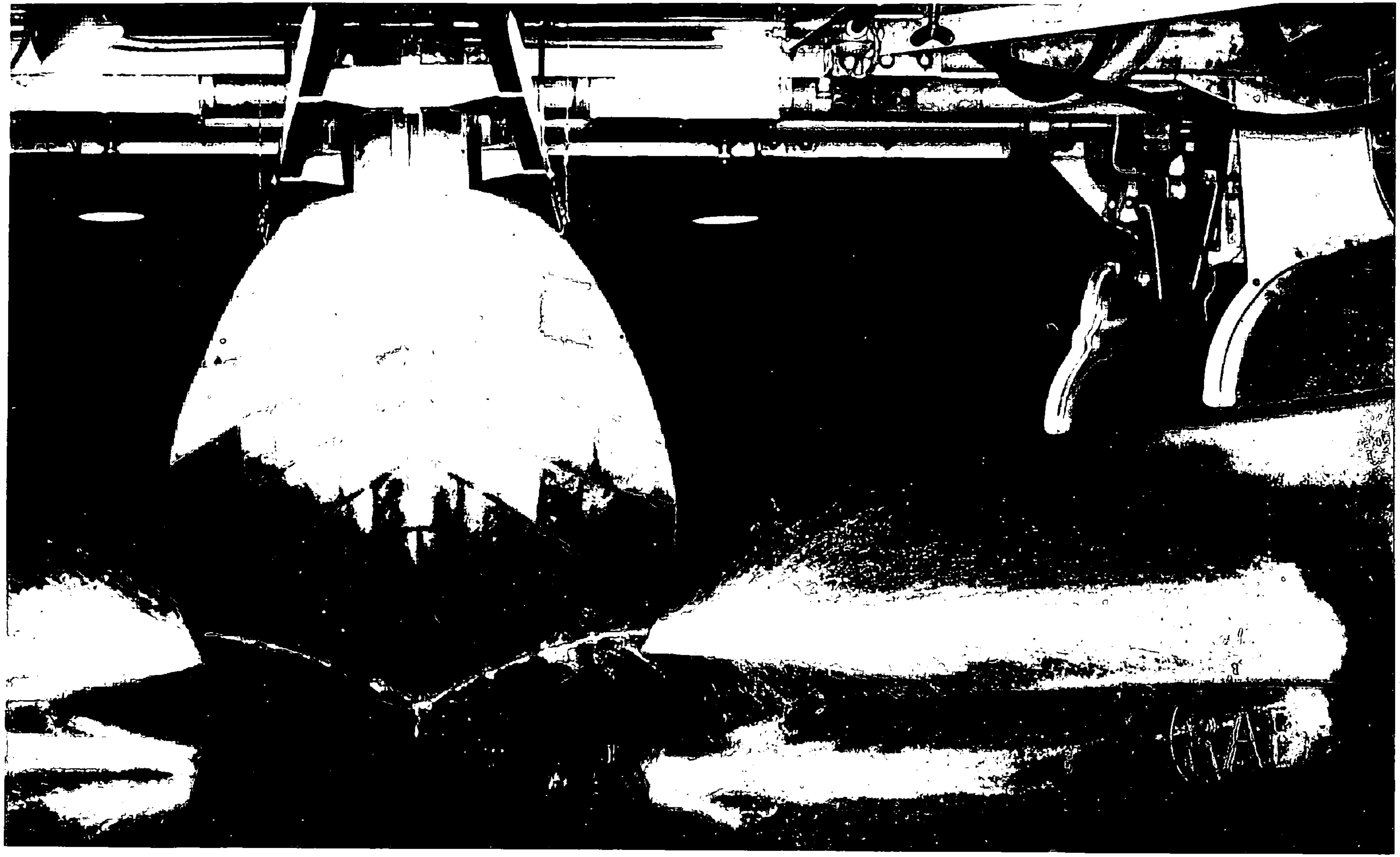


FIG. 25
ANALYSIS OF RESISTANCE FOR FLAT PLANING SURFACE AT 7°

FIG. 24 & 25


RAE