Paper 12

THE DRAG OF BLUFF BODIES IMMERSED IN A TURBULENT BOUNDARY LAYER

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Abstract

Pressure measurements taken at full scale on a tall, slab-like building (145 feet high), showed contours of overall pressure coefficient which were quite different from results found from wind tunnel studies on models. Even when the model was immersed in the turbulent boundary layer to the same relative depth and the approaching velocity profile was altered altered by roughness to the same relative value as the full scale, the differences persisted. These differences are attributed to the gusty nature of the real wind.

In an attempt to gain greater physical insight into the problem, tests have been conducted in a wind tunnel on a two-dimensional bluff plate immersed in a turbulent boundary layer. Correlation of the drag coefficient with boundary layer parameters has been found for quasi-equilibrium type layers. A logarithmic wall similarity law for the drag and a drag-defect law of behaviour have been shown to exist analogous to the well known law of the wall and velocity-defect law of zero pressure-gradient boundary layers.

Some preliminary experiments have been undertaken to find the effect of aspect-ratio on the drag coefficient of a three-dimensional bluff plate immersed in a turbulent boundary-layer. It appears that aspect-ratio changes in the range 1 to ∞ have only a small effect on the drag coefficient. The size of the bluff plate in relation to the boundary layer thickness is a more important variable in determining the drag coefficient.

Résumé

Les auteurs ont effectué des mesures des pressions du vent affectant un édifice élevé en forme de parallélépipède plat d'une hauteur de 145 pieds, et ont obtenu des courbes d'égal coefficient de pression qui étaient très différentes de celles obtenues au cours d'essais avec modèles en soufflerie. Les différences ont persisté même quand le modèle fut pongé à la même profondeur relative dans la couche turbulente de surface et que le profil des vitesses fut modifié par un changement de rugosité du modèle pour lui donner la même valeur relative qu'en grandeur nature. Les auteurs attribuent ces différences à l'existence de rafales de vent naturel.

Ils ont mené à bien des essais en soufflerie à l'aide d'une plaque massive à allongement infini plongée dans une couche de surface turbulente. Ils ont établi une corrélation entre le coefficient de traînée et les paramètres de la couche de surface pour les couches en quasi-équilibre. Ils montrent qu'il existe une loi de similarité logarithmique de la traînée des murs et une loi de comportement par défaut de traînée analogues aux lois bien connues concernant les murs et les gradients nuls de pression par défaut de vitesse dans les couches de surface.

Les auteurs ont entrepris quelques expériences préliminaires pour déterminer les effets du rapport envergure/profondeur sur le coefficient de traînée d'une plaque massive d'allongement fini plongée dans une couche de surface turbulente. Il semble que les variations du rapport envergure/profondeur compris entre 1 et ∞ n'ont qu'un faible effet sur le coefficient de traînée. Le paramètre le plus important est la relation entre la taille de la plaque massive et l'épaisseur de la couche de surface pour la détermination du coefficient de traînée.

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Notation

C_f'	-	local skin friction coefficient
U_τ	-	friction velocity
$\frac{\Delta u}{U_\tau}$	-	roughness function as defined by Clauser (1956)
δ	-	boundary layer thickness
h	-	building height and bluff plate height
k	-	length scale associated with size of roughness
U_1	-	local free stream velocity
ν	-	kinematic viscosity
D	-	drag force
ρ	-	density of air
y	-	distance measured normal to the ground
C_{D_1}	-	drag coefficient $= D / \frac{1}{2}\rho U_1^2 .$ Frontal area
κ	-	universal constant
A	-	" "
u	-	mean velocity at distance y from the ground
Π	-	profile parameter
C_{D_τ}	-	drag coefficient based on U_τ and $= \frac{D}{\frac{1}{2}\rho U_\tau^2 . \text{ Frontal Area}}$
w	-	universal function of y/δ
p_1	-	free stream static pressure of the reference profile
p_b	-	base pressure : the average pressure on the downstream face of the bluff plate or building
ϕ	-	deviation function of h/δ
A	-	frontal aspect ratio $= b/h$
b	-	frontal transverse dimension of building or bluff plate

Other symbols are defined in the text.

This paper is divided into three parts. Part 1 deals with full-scale measurements of wind pressure on a large 145 feet high slab-like building. Parts 2 and 3 deal with some basic wind tunnel studies which have been made following the full scale work.

Part 1 Full Scale Measurements

Introduction

Wind loads are frequently a critical factor in the design of exposed structures and the value adopted as the design load may have a significant effect on the safety and cost of the structural system. However, existing methods for assessing actual loads are largely unsubstantiated and are open to question.

One of the questionable aspects is the distribution of pressure on structures exposed to natural winds. A great deal of detailed information exists on pressure distributions obtained from wind tunnel studies on models. The form of pressure distributions to be used in design may therefore be thought to be well established. These results have, however, been obtained under steady conditions and actual distributions under natural wind conditions may vary significantly from these idealised results which neglect the real wind structure. It is the purpose of Part 1 of this paper to consider the effects of real winds on structures. Previous attempts to observe pressure distributions on actual buildings are discussed in the following section and a description is then given of an investigation carried out at the University of Melbourne.

Effect of Real Wind Structure on Wind Forces

Real winds are extremely turbulent near the ground and there are continual and random changes in speed and direction both horizontally and vertically. The design assumption is usually made that an equivalent static distribution of pressure can be obtained by superimposing an allowance due to gusts on the distribution obtained from model tests in a wind tunnel with steady flow conditions. Although such tests provide some guidance, steady state conditions cannot be expected to represent actual real wind conditions. For example, the vertical velocity component may alter the angle of incidence of flow on an inclined roof to such an extent that the negative pressure associated with horizontal flow is completely replaced by positive pressure. The detailed and closely tabulated recommendation for pressure distributions on roofs which are given in some codes therefore give an impression of accuracy which is more apparent than real.

Jensen (1958) has investigated the effect of natural wind on a relatively small scale building. He found good correlation with wind tunnel tests on the geosim when the velocity profiles, as represented by a log law, were similar. However the scale of the building was small compared with the scale associated with the transverse variations of wind velocity.

Few detailed observations of pressure distribution on large buildings are available. A study of such investigations as are reported does not encourage the belief that the usual recommended distributions are an accurate representation of the actual wind forces. The results of several investigations on buildings will serve to illustrate this point.

Empire State Building

Rathbun (1940) reports the results of five years of tests on this structure and comments that the observed currents about the building were

"far from simple". In some cases a 70 m.p.h. wind at the top of the building was accompanied by calm conditions with zero measured pressures below the 70th floor, and conditions were observed with negative pressures developed on what was apparently the windward side! One conclusion was that "a comparison of the pressures on the model and those of the building shows clearly that the natural wind movements are not at all like those in a wind tunnel".

Another conclusion was "that the data has not shown that 20 lb/ft^2 is an improper value for the assumed lateral load for similar buildings and environments". This is, perhaps, one way of saying that actually there was no real consistency between the wind tunnel results and measured pressures or forces on the building, but, that since the building did not fail, the design estimates must have been conservative.

In this investigation ten liquid manometers were placed at each of the floors, Nos. 36, 55 and 75, and recordings were made by photographing at regular intervals during storms. Wind speeds were measured by an anemometer on the tower on the top of the building but it was recognized that the presence of the building influences the velocities at this point. Values from other recording stations in the city were reported but continuous correlation with manometer readings was not obtained.

State House Studies

Building Research Station in the United Kingdom is currently engaged in measuring wind pressure on buildings and an investigation has been made on State House, a 15 storey building in London (Newberry, 1963). A limited number of pressure measuring units have been used and only a few tentative conclusions have so far been published. Diaphragm gauges with electronic high frequency recorders enable fluctuations during gusts to be studied in detail, and very rapid changes have been noted; peak values being reached from zero in less than a second on many occasions, while reversals from positive to negative pressure have also been noted in similar time intervals. The progression of individual gusts across the face of the building has been observed, but cases have occurred where sudden pressure rises have simultaneously developed over a complete face. It was observed that the patterns of pressure distributions have a general similarity, but some differences from, the pattern obtained in wind tunnel experiments.

The rate of increase of pressure in many instances has been found to be much greater than that expected from the knowledge of increase in speed in a gust. It is suggested that these changes are due to changes in wind direction rather than speed. These changes can occur very rapidly and, by altering the angle of incidence, markedly change the pressure.

High negative pressures over the leeward side were only obtained when gusts lasting several seconds permitted full development of the wake, but momentary high localised negative pressures were obtained with the wind at a variable glancing angle.

This project has been a pilot study with the intention of more extensive recordings on other suitable buildings in the future. Up to 12 simultaneous recordings have been taken, and these have been compared with the gust speeds recorded at the nearby meteorological station at Kingsway. However, continuous correlation with the incident wind structure was not possible since no means was provided for measuring the spatial distribution of velocities.

None of these investigations has provided a generally applicable solution to the problem of the effect of real wind structure on pressure distributions on large buildings. The number of points at which pressures have been measured has in general been too small to obtain a sufficiently well defined overall picture of the distribution, and methods of recording have not always been appropriate to distinguish the effects under consideration. However, the major deficiency in all studies has been the almost complete lack of knowledge of the incident wind structure, and hence the inability to obtain a meaningful correlation.

It would appear that the problems of wind loads on large structures need to be redefined and the appropriate means for obtaining the required solution selected accordingly.

Thus, to determine overall effects which influence the structure as a whole, keeping in mind the low frequency response of the building, relatively slow acting pressure measuring instruments would be satisfactory and there must be a large number of measuring points distributed over all faces.

For localised effects on cladding elements and their fasteners, the rapid variations in positive and negative pressures indicates the need for high rate of response instruments. However, fewer of these instruments are required since simultaneous recording over the whole structure is not then required and different areas can be studies at different times for a sufficient period to obtain representative records. If sufficient of these instruments were available however, it would be possible to obtain a detailed and continuous record of overall drag variations with time.

For both of these types of investigation a detailed knowledge of the incident wind structure is needed if the results are to have significance for application in other circumstances. Wind structure is the only satisfactory classification by which results can be compared. It will therefore be essential to obtain measurements for a variety of sites, which generate a range of different wind structures before adequate data is available to enable design pressures to be derived on a rational basis.

Measurements of Wind Pressures on a Multi-Storey Building

Description of Building

The building involved in the test was the "Barry Building" (see plate 1) which is situated on the campus of the University of Melbourne. This twelve storey building is 200 feet long x 42 feet wide x 145 feet high, having a lift tower attaining a height of 200 feet at the east end. The longer length of the building runs east and west as shown in figure 1. A series of tennis courts and a general recreation area occupy the land north of the building allowing 600 feet to the nearest sizeable construction in this direction. Some trees to the north vary in height from 25 feet to 40 feet. On the south side there is a space of 150 feet between the building and another three-storey block (the Commerce building). The Zoology block lies 25 feet to the west but is only 40 feet high. Three lecture theatres protrude from the south face of the building to a height of 20 feet, while one of height 40 feet is situated at the west end of the north face. A 30 feet high building lies 75 feet to the east.

There is little interruption to the flow of wind from the north, the trees and buildings lying in this direction acting only as relatively small roughness elements on the approaching turbulent boundary layer.

Hence the test was planned for a north wind which is one of the more consistently strong winds and provides the most significant flow situation.

An almost symmetrical grid was formed on the north and south faces of the building by 65 pressure points (see figure 2). On each of the floors 4, 6, 8, 10 and 12, seven points were situated on the north face and five in the south. It had been shown in model tests that the pressure did not vary as much on the leeward face as on the windward; a reduced number of points on the south wall was therefore accepted. It was found too difficult to pressure tap the lift tower, the side walls and the roof because of lack of access. Because of the expected irregularities in flow at the second floor from the trees and lecture theatre, readings were not taken on the north side at this level but only on the south side.

Each pressure point consisted of a sheet of pressed hardboard fitted firmly into the lower portion of the window frame. A copper tube was attached to the centre of the sheet forming a flush hole on the outside. A plastic tube of ½" internal diameter connected the pressure point to a multi-tube inclined manometer. There was one manometer situated on each floor where measurements were taken.

Initial tests were made on the plastic tubing to find the lag in pressure measurement due to differences in length. This was found to be negligible for lengths from 4 to 100 feet as detected by the manometer.

The tests on the Empire State Building suffered from not knowing the true wind velocity. Other full scale tests have used meagre methods for measuring the wind. This seemed to be an important feature of the test and therefore a tower (see plate 2), 108 feet high, was erected in an open space 500 feet directly north of the building. Twelve total-pressure tubes were arranged at regular intervals up the tower. These pitot tubes could be swivelled together into the wind direction which was indicated by a wind vane at the top of the tower. The pitot tubes were connected by plastic tubes to a multi-tube inclined manometer.

As a check on the wind velocity measured by the pitot tubes, four 3-cup rotating anemometers were attached to the tower at the 105 feet, 65 feet, 49 feet, 15 feet levels. The electrical signals generated by these anemometers were automatically recorded.

It was found during the course of testing that there were no long periods when the wind remained steady. The gusts were observed at the tower and those of longer duration and with the steadiest velocity were selected for evaluation. After a suitable delay to allow the gust to envelop the building, observers recorded the pressures registered on the building manometers. Three measurements of the pressure at each point were recorded during a test and a mean taken as the actual reading for the purposes of data reduction.

Results of Experiments

Fifteen test runs were performed on the full scale building. Because of the unknown variation of static pressure with height, it was not possible to plot contours of pressure coefficient on the faces of the building which could be directly compared with those obtained from model tests. To overcome this difficulty, the pressure differences across the building, that is between corresponding points on the north and south faces, were reduced to coefficient form. The dynamic pressure used for this calculation was that obtained at

the top of the wind measuring tower, this corresponding to a height of about two thirds that of the building. The building drag coefficient was found by integrating the pressure difference coefficients over the building and dividing by the frontal area. Profiles of overall pressure difference coefficient are shown in figure 3 for four runs. The fifteen tests produced a range of drag coefficients from 0.82 to 1.55. These are shown in the form of a histogram in figure 4.

A plot of five wind profiles measured in front of the building is shown in figure 5, these being for different tests. Anemometer readings are also shown for comparison with the pitot-tube readings. The profile for 1.25 p.m. corresponds to the pressure distribution of figure 3 having a drag coefficient of 1.36. This profile is the only one which showed any resemblance to those of turbulent boundary layers produced in the laboratory. It was analysed on this basis (e.g. see Perry & Joubert 1963, Hama 1954, Clauser 1954) and was found to have a value of skin friction coefficient $C_f{}'$ of .009 and a roughness function $\frac{\Delta u}{U_\tau}$ of 19.6. The 99% thickness δ was 67 ft. The authors, however, wish to emphasize that it is questionable to assume that this "short term mean profile" can be compared with the mean profiles associated with the "stationary random turbulence" obtainable in a wind tunnel.

Thes results for the full scale building have been compared with three series of tests on the geosim;

(i) Tests with a boundary layer of negligible thickness. (Stevens, Joubert & Robertson 1961). The pressure distributions have been redrawn to give the overall pressure coefficients shown in figure 6.

(ii) In this series, test conditions were similar to (i), but ribbing was placed on the face of the model to reproduce the major surface features of the windward face of the full scale building. There was no significant change in the results from those shown in figure 6.

(iii) Tests were carried out with a 4½" high model immersed in a turbulent boundary layer on a rough wall. For complete similarity between a model and full scale with a stationary turbulent boundary layer, the following parameters must be held constant : $\frac{h}{\delta}$, $\frac{k}{\delta}$ and $\frac{hU_1}{\nu}$. (See Notation). Furthermore, the roughness geometry in the model should be identical with that of the full scale. The latter condition is very inconvenient and the condition for $\frac{hU_1}{\nu}$ to be the same is virtually impossible to achieve. Fortunately, the same mean velocity profile can be produced by a variety of roughness geometries and there is some evidence for believing that the significant components of the turbulence structure through most of the boundary layer thickness are independent of the detailed roughness geometry and scale provided U_τ and δ are specified (Hinze, 1959). This also follows from an extension of Townsend's Reynolds number similarity hypothesis (Townsend 1956). If this is true, a convenient form of roughness can be used (rectangular rods in the case of this test) and its scale can be adjusted to give the appropriate value of U_τ and δ for a given free stream velocity.

If the flow is completely rough, the mean velocity profiles and turbulence structure approaching the building and its model will be independent of viscosity. The assumption is that the boundary layer characteristics associated with the outer part of the layer and the size of this layer relative to the building will determine the modes and positions of separation phenomena. Therefore fluid viscosity and surface roughness will not have an explicit influence on this and can be excluded from the problem. Therefore, as in the usual model testing philosophy, the Reynolds number condition can be relaxed. Then the drag force, D, on the building should depend only on h, δ, U_τ and U_1 and so $\frac{D}{\frac{1}{2}\rho U_1^2 h^2} = f(C_f', \frac{h}{\delta})$.

For similarity then, only C_f' and $\frac{h}{\delta}$ need to be the same for model and full scale. For the tests reported here C_f' was .009 for the full scale against .011 for the model. $\frac{h}{\delta}$ was approximately 2.1 for both full scale and model. The discrepancies in C_f' would amount to only about 10% difference in the distributions of mean velocity and turbulence intensities for a given $^y/_\delta$. For completeness the 'non-similarity" parameters should be specified. The Reynolds number of the full-scale tests (based on the building height h) was 2.7×10^8 ; for series I and II model tests 8.3×10^5 and for series III, approximately 2.2×10^5. The roughness function $\frac{\Delta u}{U_\tau}$ for full scale was 19.6 and 16 for the model. The roughness geometry has been described by Perry & Joubert (1963); the ratio of roughness element height to building height for the model was $\frac{1}{36}$.

The pressure distribution for this series III model test is shown in figure 7.

A comparison of the values of drag coefficient and the ratio of the centre of pressure height to building height is given in Table I for the full scale building, the series (i) and (iii) model tests and values obtained from the Australian code. The value given for the full scale building is the mean of the fifteen tests and has a standard deviation of 0.21.

	Full scale building	Model Series I	Model Series III	Australian Code
Drag coefficient	1.08 (mean value)	1.10	1.02	1.20
Ratio of centre pressure height to building height	0.53	0.50	0.53	0.50

Table I Comparison of full scale and model data for drag coefficient and position of centre of pressure.

Discussion

One of the most important features of the full scale tests was the unsteady nature of the wind. A gust giving a reasonably steady velocity profile such as shown in figure 5 might last for thirty seconds. The wind might then drop to a lower velocity for some minutes before another gust would envelop the building. The authors have examined records of wind speed collected by Deacon and have found similar plateaus of reasonably steady wind velocity. Only those gusts which were considered to be sufficiently steady and of sufficient duration to allow full wake development and adjustment of the base pressure were chosen for analysis.

The forms of the contours of pressure coefficients on the building are different for different tests (see figure 3). They were also different

from the contours found on the models. Many of the full scale tests showed the pressure coefficient increasing with height and usually with the maximum values off the centre line of the building, whereas, the models always had the region of maximum pressure located some distance below the roof line. Reproducing the full detailed site roughness and immersing the model in the turbulent boundary layer certainly raised the centre of pressure above that for the model tested in a uniform stream, but did not reproduce the full scale contours. It is likely that the lateral distribution of wind velocity would have a considerable effect on these variations of the full scale contours. Thus, measuring only the vertical distribution of wind velocity did not provide sufficient information to correlate the wind structure with the pressure contours. Future tests should use more than one velocity-measuring tower.

Although the average values of total drag coefficient for the building are in reasonable agreement with those found from the model tests, the standard deviation is quite high and indicates that significantly larger drag coefficients may have occurred under the real wind conditions. A re-definition of the drag coefficient, taking into account variations in the lateral velocity distribution, might possibly reduce the deviation. Further, the pitot tube readings of wind velocity did not agree completely with the readings of the rotating cup abemometers. For example on the profile recorded at 1.25 p.m. the anemometer at the 97 foot height was reading 21.2 m.p.h. compared with the pitot reading of 19.7 m.p.h. The pitot tube reading was considered more reliable and was used in calculating the pressure coefficients. However, in view of these discrepancies, it would be difficult to guarantee the accuracy of these coefficients more closely than is indicated by this difference.

Another effect which could have contributed to errors in readings is the local effect of the window sills on pressure readings. In regions of high local velocity which occur near the edges of the building on the windward face, local regions of separation may be formed by these minor projections. These would, however, generally cause a lowering of the local pressure. The opposite effect was in fact observed.

Conclusions

Full scale pressure measurements on a tall slab-like building showed contours of overall pressure coefficient which were quite different from results found from wind tunnel studies on models.

Further results need to be collected on similar buildings, preferably with as complete a picture as possible of the nature of the gusts which envelop the building. Both lateral and vertical distributions of velocity should be measured.

Part 2 Drag of a Two-Dimensional Bluff Plate Immersed in a Turbulent Boundary Layer

Introduction

It became obvious from the large scale study that if any physical understanding of the processes involved was to be obtained, then the problem needed to be subdivided into a number of simpler problems such as:

A. The effect of a turbulent boundary layer on the drag of a bluff body.

B. The transient effects of gusts on the pressure experienced by a bluff body.

C. The difference between real winds and boundary layers formed in wind tunnels.

Parts 2 and 3 of this paper describe some work on the first of these simpler problems.

This investigation was concerned with the relationship between the pressures experienced by a two-dimensional, bluff fence (the "bluff-plate") and the characteristics of the smooth-wall, turbulent boundary-layer in which it is immersed. The experimental situation is illustrated in figure 8. A full report of the study is to be published elsewhere (Good & Joubert 1967); only the major results which are of relevance to wind effects on buildings are reported here.

Consideration of the flow processes involved showed that, in general, the overall history of the boundary layer was likely to affect pressures experienced by the bluff-plate. It would be convenient, however, if these pressures could be correlated with mean-flow parameters of a single boundary-layer profile which is representative of the shear flow disturbed by the bluff-plate. The reference profile chosen for this purpose was that which would exist at the bluff-plate station if the bluff-plate was absent. In an attempt to ensure that the history of the shear flow would be uniquely represented by the reference profile, the following limitations were placed on the scope of the study:

(a) The distance from the leading edge of the smooth wall to the bluff-plate station was made large in comparison with the length of the region of upstream influence of the bluff-plate.

(b) Only quasi-equilibrium shear flows of the type described by Coles (1956) were considered. That is, the reference profile could be represented by

$$\frac{u}{U_\tau} = \frac{1}{\kappa} \ln \; (yU_\tau / \nu) \; + \; A \; + \; \frac{\Pi}{\kappa} \; w \left[y/\delta \right], \qquad (1)$$

where u is the velocity at distance y from the wall, U_τ is the friction velocity, δ is the boundary-layer thickness, κ and A are universal constants, and w is a universal function of y/δ (square brackets are used to denote a functional dependence). Π , a profile parameter, depends on the upstream distributions of pressure gradient and wall shear stress. The value of Π is constant for zero pressure-gradient boundary layers.

To relate the form drag D (say) of a bluff-plate of height h to the characteristics of the reference profile, the following correlation scheme appeared likely to be the most fruitful:-

$$C_{D_\tau} = D/\tfrac{1}{2}\rho U_\tau^{\;2} h = f[hU_\tau/\nu \; , \; h/\delta \; , \Pi \;] . \qquad (2)$$

Thus, for zero pressure-gradient flows (Π = constant), all the results would be accounted for by

$$C_{D_\tau} = f[hU_\tau/\nu \; , \; h/\delta] \; , \qquad (3)$$

while, for small h/δ, a wall similarity law

$$C_{D_\tau} = f[hU_\tau/\nu] \qquad (4)$$

might be expected. It was hoped that the variable Π would account for the pressure-gradient history of the flow. It should be noted here that this correlation scheme appeared to be successful in representing the upstream history of the boundary layer. In flows with streamwise pressure-gradients, however, it was found that pressure gradients in the free stream downstream of the bluff-plate could also affect the drag.

Experiments

The boundary layers were formed on a smooth wall, 22 ft. long by 4 ft. wide, placed vertically between the floor and ceiling of the working section of the large wind tunnel at the University of Melbourne. The height of a 4 ft. long, pressure-tapped bluff-plate was varied between 1/8 in. and 4 in. in three zero pressure-gradient boundary-layers and in a number of adverse pressure-gradient profiles.

Results and Discussion

A. Zero Pressure-Gradient Experiments

From measurements of the surface pressure distribution on the smooth wall upstream of the bluff-plate, it was found that the relative extent of upstream influence of the bluff-plate on the boundary layer varied markedly with h/δ. For a boundary-layer Reynolds number of $\delta U_1/\nu = 1.3 \times 10^5$, this relative distance x_1/h increased from 10 to 112 as h/δ decreased from 1.75 to 0.054. The variation was well expressed by

$$x_1/h = 15(h/\delta)^{-0.7} \qquad (5)$$

Apparently the disturbance to the boundary layer is relatively more severe if the bulk of the shear flow which is actually disturbed by the bluff-plate (i.e. that part of the reference profile between $y = 0$ and $y = h$, say) is initially more retarded.

Pressures on the front face of the bluff-plates were found to follow a wall-similarity law of the form

$$(p - p_1)/\tfrac{1}{2}\rho U_\tau^{\,2} = g_1\left[y/h\right]\log(hU_\tau/\nu) + g_2\left[y/h\right]. \qquad (6)$$

Here p is the pressure at a height y on the front face of the bluff-plate, p_1 is the free-stream static pressure of the reference profile and g_1 and g_2 are functions of y/h only. The variation of g_1 and g_2 is shown in figure 9. For the lower 80% of the front face of the bluff-plate, this wall-law held over the whole range of h/δ tested (viz 0.05 to 1.75). Pressures on the top 20% of the front face were influenced by the value of the base pressure, which itself followed a logarithmic wall-law, but only for $h/\delta < \tfrac{1}{2}$. These results are demonstrated in figure 10, where the drag coefficient, $C_{D_\tau} = D/\tfrac{1}{2}\rho U_\tau^{\,2}h$, the base-pressure coefficient, $C_{b_\tau} = (p_b - p_1)/(\tfrac{1}{2}\rho U_\tau^{\,2})$ and the average pressure coefficient on the front face, $C_{u_\tau} = C_{D_\tau} + C_{b_\tau}$, are plotted

against hU_τ/ν. The equations for the wall-similarity laws for these quantities are

$$C_{D_\tau} = 277\log_{10}(hU_\tau/\nu) - 268 \qquad (7)$$

$$-C_{b_\tau} = 152\log_{10}(hU_\tau/\nu) - 147 \qquad (8)$$

$$C_{u_\tau} = 125\log_{10}(hU_\tau/\nu) - 121 \qquad (9)$$

The deviations from wall similarity for the drag coefficient, due to effects of the outer-flow variables on the base pressure, were found to depend on h/δ only. This is demonstrated, in figure 11, by the existence of a "drag-defect law",

$$C_{D_\tau}(h) - C_{D_\tau}(\delta) = f\left[h/\delta\right], \qquad (10)$$

analogous to the well-known "velocity-defect law" for the reference profiles, viz.

$$\frac{u(y) - u(\delta)}{U_\tau} = \frac{u(y) - U_1}{U_\tau} = f\left[y/\delta\right]. \qquad (11)$$

Thus the complete equation for the form drag can be written

$$C_{D_\tau} = 277\log_{10}(hU_\tau/\nu) - 268 + \phi\left[h/\delta\right] \qquad (12)$$

Tentative values for the deviation function ϕ are given in table II. Note that with the information given here the distribution of pressure on a bluff-plate may be predicted from a knowledge of δ and U_τ for the reference profile.

h/δ	$\phi[^h/\delta]$
0 - 0.4	0
0.5	6
0.6	14
0.7	24
0.8	37
0.9	51
1.0	67
1.1	86
1.2	106
1.3	128
1.4	153
1.5	179
1.6	207
1.7	236
1.8	268

TABLE II Tentative values for the proposed universal drag-deviation function for zero pressure-gradient flows.

The above results indicate that, although pressures on the bluff-plate are viscosity-dependent, changes in pressure with changes in plate height are independent of the fluid viscosity. The wall-similarity relationships obtained over such a surprising range of h/δ suggest that the boundary-layer separation induced upstream of the bluff-plate is sufficiently rapid to be of the type postulated by Stratford (1959) and Townsend (1960, 1962). The effects of the boundary-layer history are manifested only in the long separation bubble downstream of the bluff-plate.

A selection of pressure distributions measured on bluff-plates of heights varying between 3/8 in. and 4 in. is shown in figure 12. It can be seen that the shape of the normalised distributions are similar but vary slightly with the value of hU_τ/ν, especially in the region exposed to the front separation bubble.

B. Adverse pressure-gradient experiments

The experiments with adverse pressure-gradient profiles were designed to test the adequacy of the correlation scheme of equation (2). It was found that, in addition to the variables listed in that equation, the flow in the rear separation bubble (and, hence, the base pressure) was sensitive to pressure gradients in the free stream downstream of the bluff-plate. However, the results indicated that the upstream history of the boundary layer was adequately accounted for by equation (2), although more extensive tests are required to verify this conclusion. The significant result obtained from these experiments was that pressures on the front face of the bluff-plates were independent of pressure gradients. That is, they followed the wall-law found from the zero pressure-gradient data.

Implications for wind-load research

The work described was concerned with two-dimensional, smooth-wall boundary layers. From the wind loading point of view it would be interesting to find out if similar wall-similarity relationships could be found for three-dimensional bluff bodies and for rough-wall boundary layers. The results of some preliminary work on the effects of aspect ratio are presented in Part 3.

Part 3 Drag of Three Dimensional Bluff Plates Immersed in a Turbulent Boundary Layer

Introduction

The effect of aspect ratio on the drag of bluff plates placed in uniform, unbounded streams is shown in figure 13 (Hoerner 1958). The curve is, of course, symmetrical about $A = 1$, and is almost independent of Reynolds number. The drag coefficient, $C_{D_1} = D/\frac{1}{2}\rho U_1^2\, bh$, is fairly insensitive to the frontal aspect ratio, $A = b/h$, in the range $\frac{1}{4} < A < 4$ (Here D is the drag on the plate, U_1 is the velocity of the uniform stream, b is the breadth of the plate and h is its height). Quite different effects can be expected when one edge of the plate is attached to a wall, and the incident stream is no longer uniform. For one thing the effect of low aspect ratio will be quite different from high aspect ratio; i.e. the curve will not be symmetrical about $A = 1$. Also it is apparent that the ratio of plate height to boundary layer thickness, h/δ, will have an important effect on the drag coefficient for a given aspect ratio.

For small values of h/δ the following form of correlation scheme is likely to be the most useful (for the zero pressure-gradient flows considered in this paper):

$$C_{D_\tau} = D/\tfrac{1}{2}\rho U_\tau^2\, bh = f\left[\frac{hU_\tau}{\nu}, \frac{h}{\delta}, A\right] \qquad (13)$$

Then, for very small h/δ, a wall-similarity law should be obtained. That is, equation (3.1) reduces to

$$C_{D_\tau} = f\left[hU_\tau/\nu\right] \quad (h/\delta \ll 1) \qquad (14)$$

The usefulness of the Preston Tube and the 'sublayer fence' as skin-friction measuring devices depends on the existence of just such a correlation. For large h/δ the alternative correlation scheme,

$$C_{D_1} = f\left[h/\delta, U_\tau/U_1, A\right] \qquad (15)$$

may be useful. For very large h/δ this would reduce to

$$C_{D_1} = f\left[A\right] \quad (h/\delta \gg 1) \qquad (16)$$

This latter situation corresponds to the conventional wind-tunnel simulation of a two-dimensional body; end plates are used to make h/δ, and the effects of Reynolds number, small.

The experiments reported here were of an exploratory nature only, and the measurements turned out to be not as accurate as we might have wished. However, important trends in the data seem quite clear and may be compared with data obtained for a two-dimensional bluff-plate (part 2).

Experiment

Pressure-tapped bluff plates were inserted through a smooth wall mounted in the 13½ in. by 10½ in. closed-working-section of a small wind tunnel at the University of Melbourne. The bluff plates, whose heights varied between $\frac{1}{8}$ in and ½ in, were tapped on both sides in such a way as to allow the drag to be calculated by a simple summation of pressure differences. As the thickness t of all the plates was $\frac{1}{8}$ in, and the top surface was only slightly bevelled (to give a knife edge to the front face), the results for the smallest plate heights may also reflect the effect of the side aspect ratio t/h (See Joubert, Stevens & Perry 1962). The experiments, which were performed with approximately zero pressure-gradient boundary layers, covered the following range of variables:

$$0.15 \leq h/\delta \leq 1.25$$

$$0.25 \leq A \leq 8$$

$$1.95 \times 10^3 \leq \frac{U_1 h}{\nu} \leq 2.21 \times 10^4$$

Results and Discussion

A selection of the results is plotted, according to the correlation scheme of equation (13), in figure 14. The wall-similarity law obtained for $A = \infty$ is also shown. The accuracy of the present measurements is not sufficient to confirm the existence of extensive regions of wall similarity. However, it can be seen that aspect ratio has a small, but consistent effect on the drag coefficient. The results for $A = 1$ appear very little different from those for $A = \infty$.

The present results for $A = 1$ are compared with the measurements of Tillmann and Engelhardt (Tillmann 1951) in figure 15. The latter measurements were made with a drag balance and represent the form drag of the bluff plate minus the change in skin-friction drag of the smooth wall. For small h/δ, therefore, the drag balance measurements should be slightly lower than the present measurements of form drag only. Considering this, and the differences in local Reynolds number ($U_1 h/\nu$), the agreement between the two sets of data is satisfactory.

To allow comparison with the curve for uniform, unbounded flows, the variation of the drag coefficient C_{D_1} with A is shown in figure 13. For clarity, only a summary of the results is shown. The heavy lines indicate the range of the actual measurements. The lighter lines show conjectured variation outside this range. Note that, in general, the results depend on Reynolds number and so the curves in figure 13 are meant to give an order-of-magnitude impression only. The conjectured curve for $h/\delta \rightarrow \infty$ has been drawn on the assumptions that -

(a) The case $A \to 0$ corresponds to Fage & Johansen's (1927) measurement on a two-dimensional bluff plate in free flow.

(b) The case $A = 1$ corresponds to the asymptotic value of C_{D_1} found by Tillmann (1951) for large h/δ. (Figure 15).

(c) The case $A \to \infty$ corresponds approximately to the free-flow measurement of Arie & Rouse (1956) on a two-dimensional bluff plate with a downstream splitter.

Conclusions

It appears that, for bluff plates immersed in turbulent boundary layers, aspect ratios in the range 1 to ∞ have only a small effect on the drag coefficient. The size of the bluff plate in relation to the boundary layer thickness is a more important variable in determining the drag coefficient.

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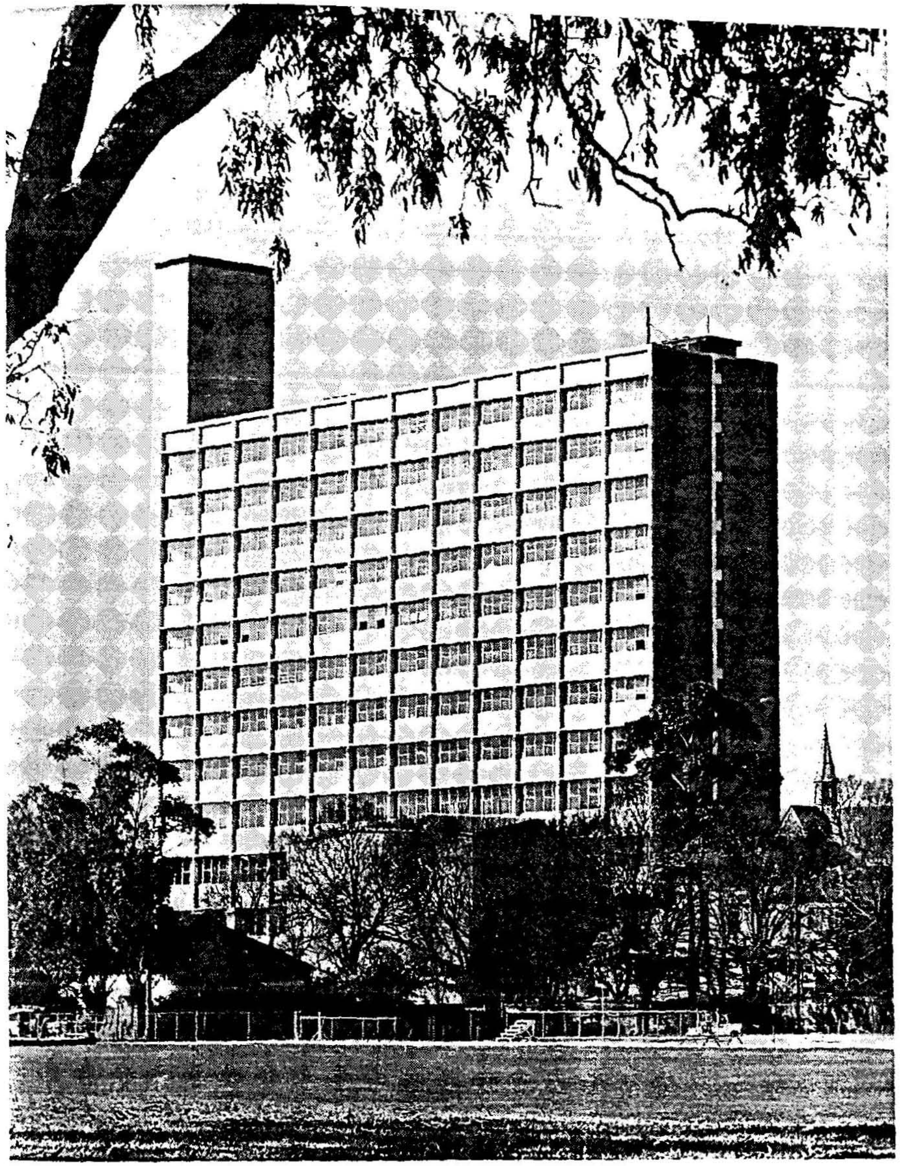

PLATE 1

THE BARRY BUILDING AT THE UNIVERSITY OF MELBOURNE SHOWING THE NORTH FACE

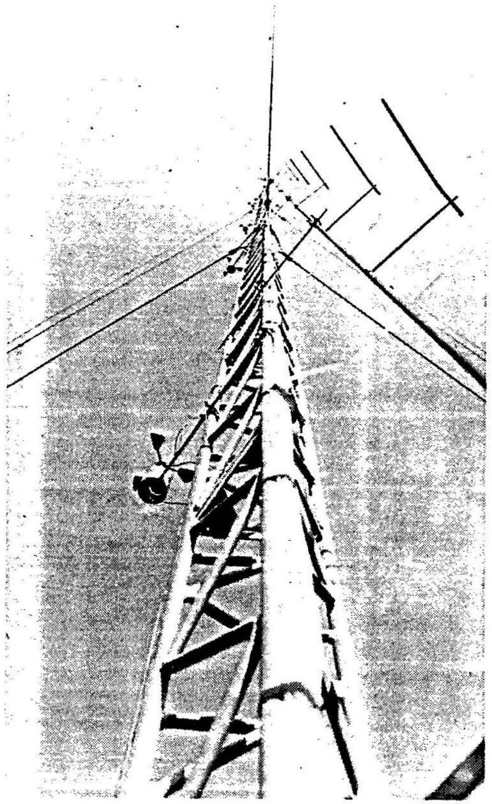

PLATE 2

THE 108 FT HIGH TOWER FOR MEASURING THE WIND PROFILE, SHOWING THE PITOT TUBES AND CUP ANEMOMETER

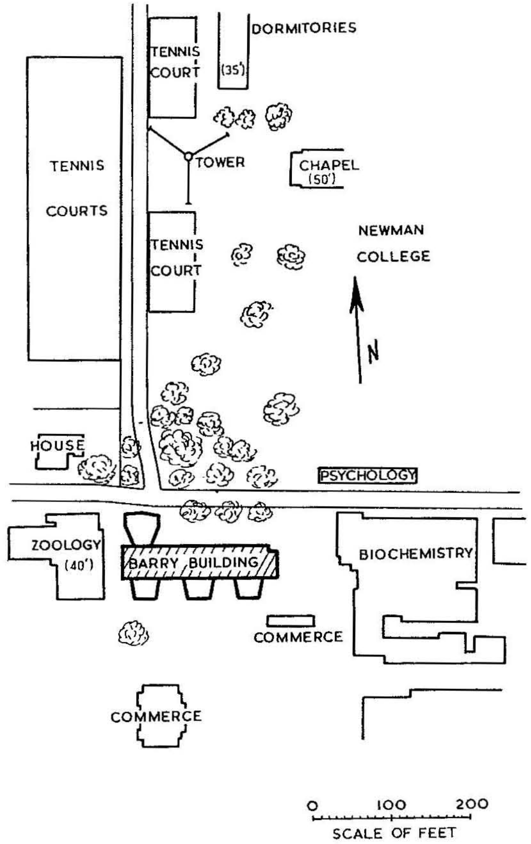

FIGURE 1 LAYOUT OF THE AREA

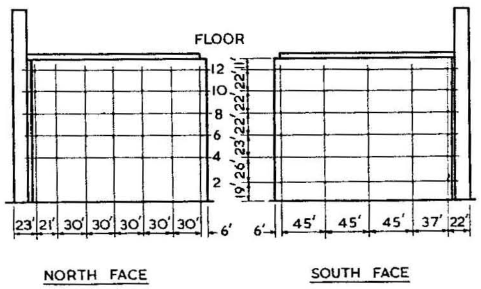

FIGURE 2 LAYOUT OF THE PRESSURE MEASURING POINTS

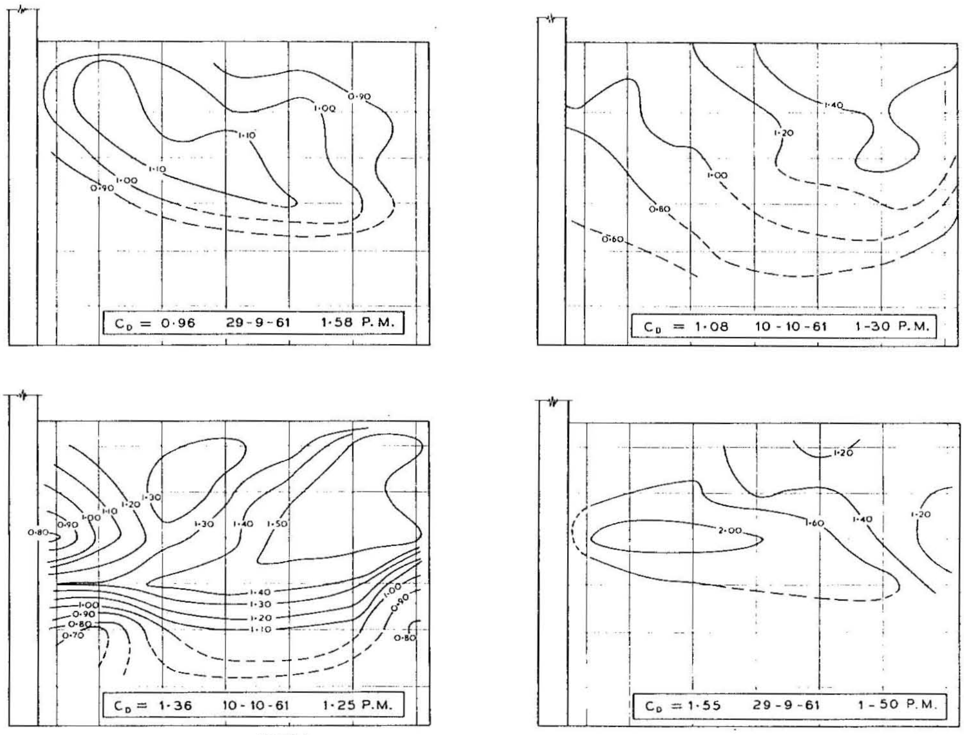

FIGURE 3
CONTOURS OF OVERALL PRESSURE DIFFERENCE COEFFICIENT FOR THE FULL-SCALE BUILDING

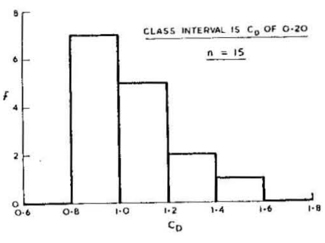

FIGURE 4 HISTOGRAM OF DRAG COEFFICIENTS

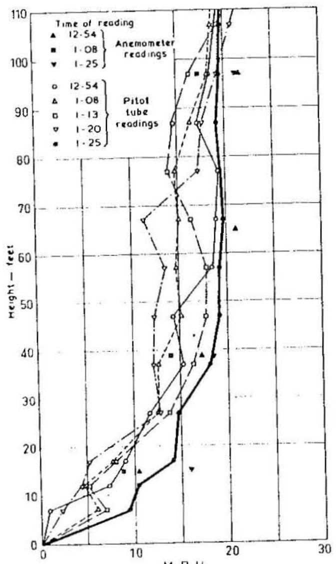

FIGURE 5
SAMPLE WIND PROFILES ACTING ON THE BUILDING

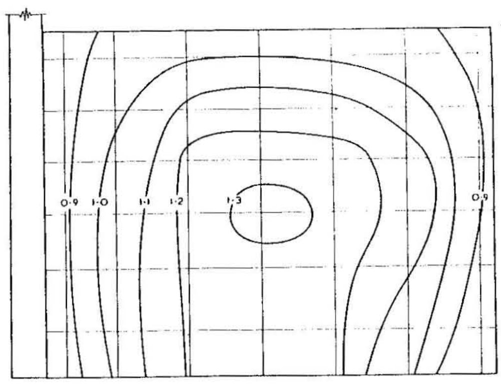

FIGURE 6 CONTOURS OF OVERALL COEFFICIENT FOR MODEL SERIES (i)

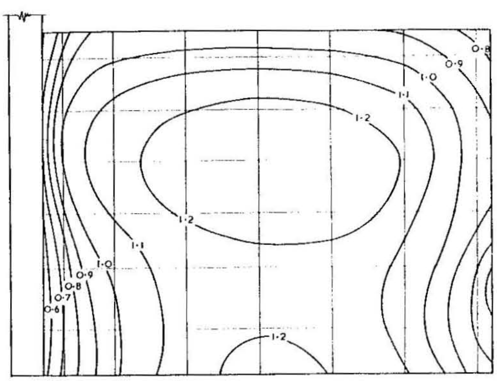

FIGURE 7
CONTOURS OF OVERALL PRESSURE COEFFICIENT FOR MODEL SERIES (iii)

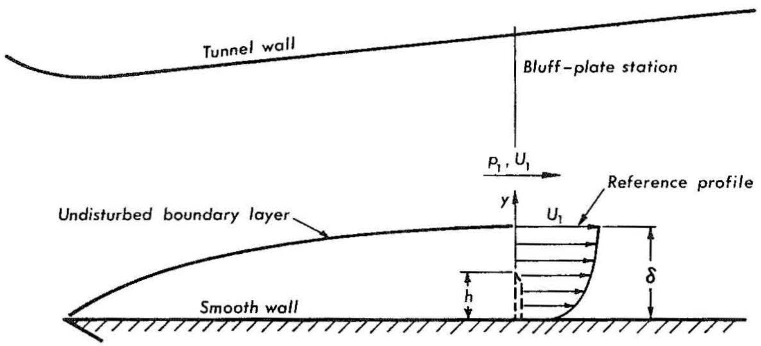

FIGURE 8 EXPERIMENTAL SITUATION

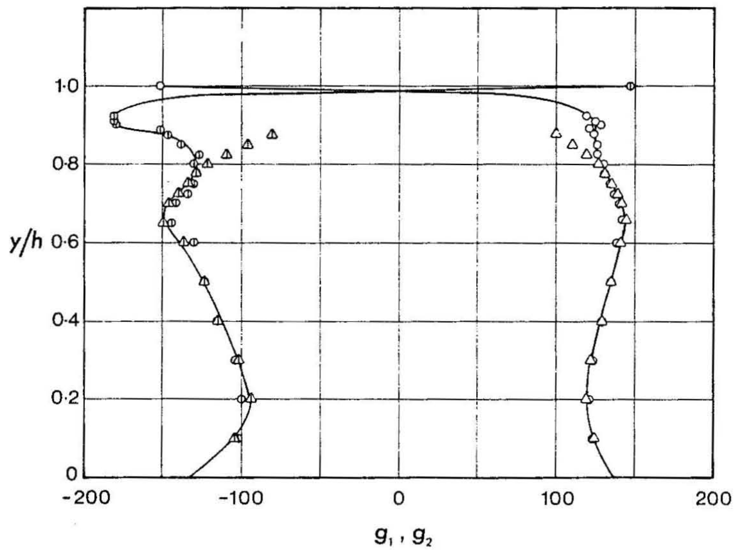

FIGURE 9

DISTRIBUTION OF FUNCTIONS DEFINING SHAPE OF PRESSURE DISTRIBUTION ON BLUFF-PLATE. VALUES OBTAINED BY FITTING SEMI-LOG LINES TO DATA OVER WHOLE RANGE OF h/δ`
△, g_1 [y/h] ; △, g_2 [y/h] . VALUES OBTAINED FOR h/δ < 0.5 ONLY: O, g_1 [y/h] ; Φ, g_2 [y/h]

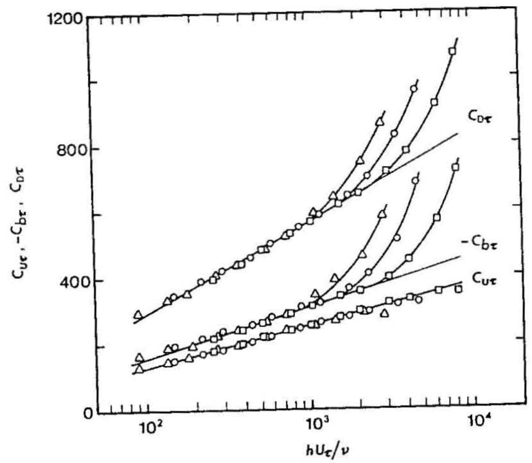

FIGURE 10

WALL SIMILARITY RELATIONSHIPS FOR FORM DRAG, BASE PRESSURE, AND AVERAGE PRESSURE ON UPSTREAM FACE OF BLUFF-PLATE

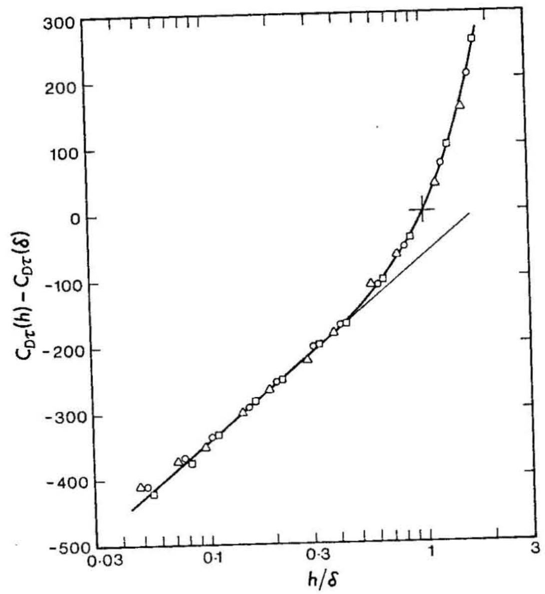

FIGURE 11

"DRAG-DEFECT" LAW. □, U_τ/U_1 = 0.0348; O, 0.0360; △, 0.0375

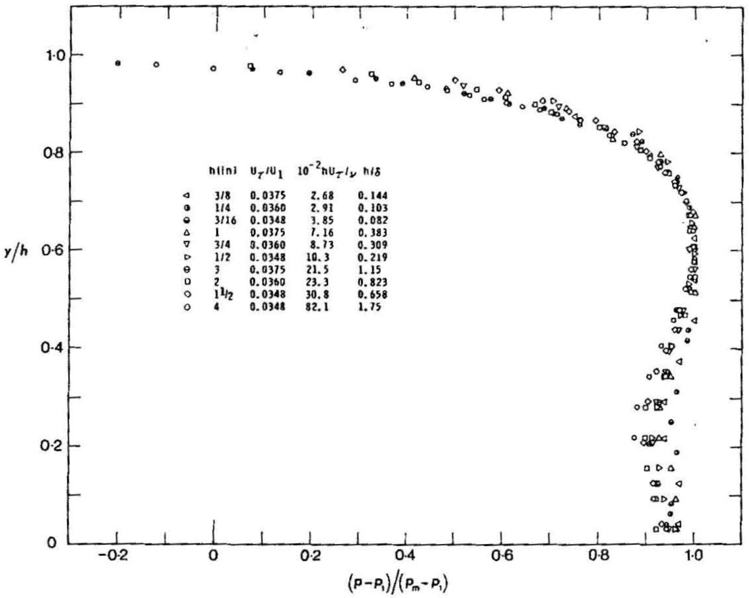

FIGURE 12

A SELECTION OF PRESSURE DISTRIBUTIONS ON UPSTREAM FACE OF BLUFF-PLATE NORMALISED BY MAXIMUM PRESSURE

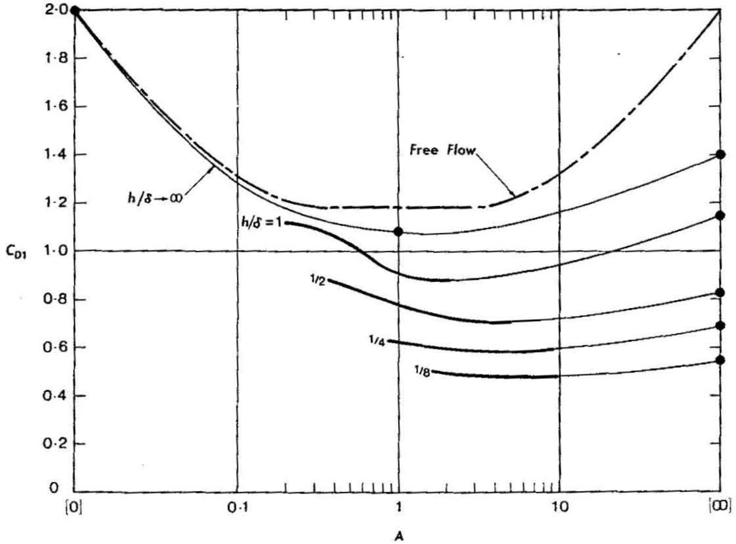

FIGURE 13

CONJECTURED MAP OF RELATIONSHIP $C_{D_1} = f\ [h/\delta, A]$ FOR HIGH AND APPROXIMATELY CONSTANT REYNOLDS NUMBERS. BASED ON PRESENT RESULTS AND DATA QUOTED BY HOERNER (1958), TILLMANN (1951) AND ARIE & HOUSE (1956).

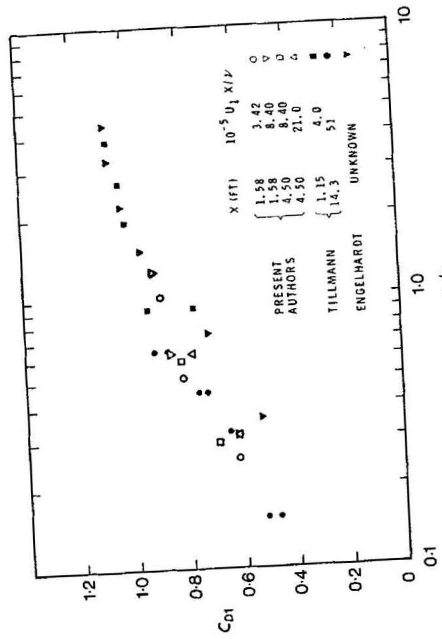

FIGURE 15

COMPARISON OF PRESENT RESULTS FOR A = 1 WITH THOSE OF TILLMAN AND ENGELHARDT

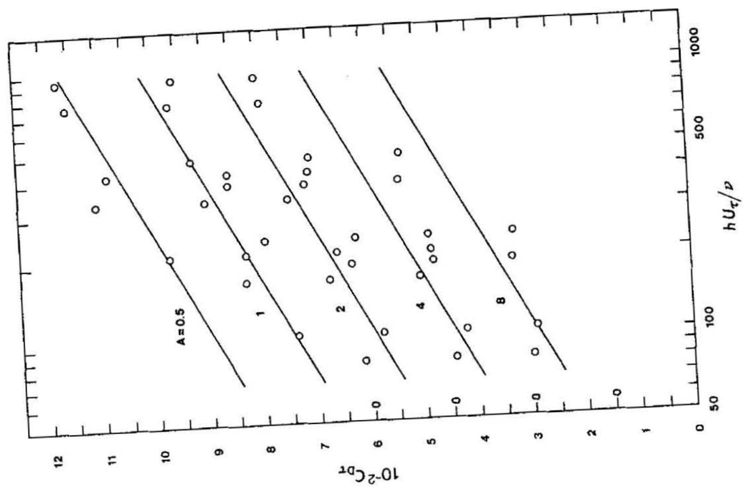

FIGURE 14

COMPARISON OF DRAG COEFFICIENTS FOR VARIOUS ASPECT RATIOS WITH THE WALL-SIMILARITY LAW FOR INFINITE ASPECT RATIO (—)
NOTE: CURVES DISPLACED VERTICALLY FOR CLARITY.