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Paper No. 5367

"Wind-Pressure on Buildings including Effects of Adjacent Buildings."*

By Alfred Bailey, M.Sc., Assoc. M. Inst. C.E., and Noel David George Vincent, B.Sc.

(Ordered by the Council to be published with written discussion.)†

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Introduction.

In the design of many buildings and structures the maximum loads which are likely to be imposed by winds are of considerable importance, but up to the present the factors used in this connexion have been based on very incomplete data.

On account of the complicated nature of the conditions met with in practice the determination of the actual forces in any particular case would present a problem of extreme difficulty, and to obtain, from full-scale experiments, sufficient data to formulate rules which might be applicable to the general case, would be a formidable task.

The use of models in a wind-tunnel, the technique of which has been developed during the past 35 years, has thrown much light on the nature of the problem presented, and, by providing control over the many factors involved, enables a more detailed study to be made of the conditions which are likely to prevail.

A considerable quantity of data has been accumulated by several experimenters working on these lines, with model buildings under fully-exposed conditions[1], but the results are not always comparable, since

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† Correspondence on this Paper can be received until the 15th January, 1944, and will be published in a subsequent number of the Institution Journal. Contributions should be limited to 600 words.—Sec. Inst. C.E.

[1] The references are to the bibliography, on p. 275, *post*.

they may be affected by the relative size of tunnel and model and by the position of the model in the tunnel in relation to the wind-gradient; no systematic investigation appears to have been made into the modifications caused in the pressures on a building when other buildings are in close proximity, but one such series of experiments has been made in connexion with a model of the Empire State Building, New York City[2].

In an endeavour to determine any general relations which may exist between wind-speed and the distribution of wind-pressure over buildings of various forms, both under fully exposed conditions and when in close proximity to other buildings, tests have been carried out on a number of model buildings in a wind-tunnel, and a description of these tests, together with a discussion of the results obtained, is given in this Paper.

Description of the Models.

The tests were carried out on seven model buildings, the forms of which are shown in *Figs. 1* and *2*. For convenience of reference the different models are referred to by letters A to G and are briefly described in the following table :—

Model.	Height to eaves: inches.	Overall height: inches.	Length: inches.	Width: inches.	Type of roof.
A	1·20	1·68	5·0	2·12	Sloped at 23½ degrees
B	1·20	2·31	5·0	2·12	Sloped at 45 „
C	2·50	3·61	5·0	2·12	Sloped at 45 „
D	1·20	1·84	5·0	2·12	Sloped at 30 „
E	1·20	1·23	5·0	2·12	Flat
F	2·50	2·53	5·0	2·12	Flat
G	—	5·20	8·0	2·0	Stepped

Models A, B, C, and D are representative of simple form buildings with roofs of different slope, whilst the flat and stepped-roofed models are more representative of modern designs.

Pressure-holes, about 0·01 inch diameter, were drilled in the central cross section of the surface of the models at the points indicated in the sketches, and each hole was connected to one limb of a multi-tube manometer by rubber tubing, attached on the inside of the model. In model G, holes were also drilled at a cross-section 2 inches away from the end of the model, which is at one-quarter of the length, and measurements were also made at this section under fully exposed conditions. It was found that the results were approximately the same as at the mid-section, and it is therefore concluded that the conditions are practically uniform over an appreciable distance on either side of the central section; other model tests have shown that there is some falling off of pressure near the edges,

but the assumption of uniform conditions would only involve a small overestimate of the total load. Only one pressure-point was taken on the leeward wall, since previous experiments had shown that the pressure on this wall is practically uniform.

Relative Size of Model and Wind-Tunnel.

The tests were carried out in a 3-foot square, National Physical Laboratory type, wind-tunnel, the model being mounted on the wall of the tunnel so that the tunnel surface formed a ground plane; it will be seen that the largest model (model G) has a height of 5·2 inches, which is about 15 per cent. of the width of the tunnel. There appears to be little experimental evidence on the effect of model-tunnel ratio, but from general experience it is considered that this is about the maximum ratio which should be used.

The Wind-Gradient.

The reason for mounting the model on the wall of the wind-tunnel was to obtain the effect of a wind-gradient. In the early days of model testing the models were usually mounted at the centre of the tunnel with no ground plane, but more recently it has been appreciated that, in practice, the wind-velocity varies with the distance from the ground, and to obtain a similar effect in the tests the models have been mounted either on a thin flat sheet, parallel with the direction of air-flow, or on the tunnel wall. The effect of this surface, or ground plane, is to produce a wind-gradient, and the magnitude of this will depend on the length and roughness of the surface on the upstream side of the model. In an interesting Paper [3] by Nøkkentved attention has been drawn to the effect of wind-gradient on model tests, and it is shown that the form of the wind-gradient curve in the tunnel should correspond to the natural wind-gradient to be expected, on the same scale as that of the model.

The natural wind-gradient is, of course, a very variable quantity, but from a large number of observations the Meteorological Office have adopted an average relationship for the variation of wind-velocity with height, near the ground, over open grass land, and this is set out on M.O. Form 3093.

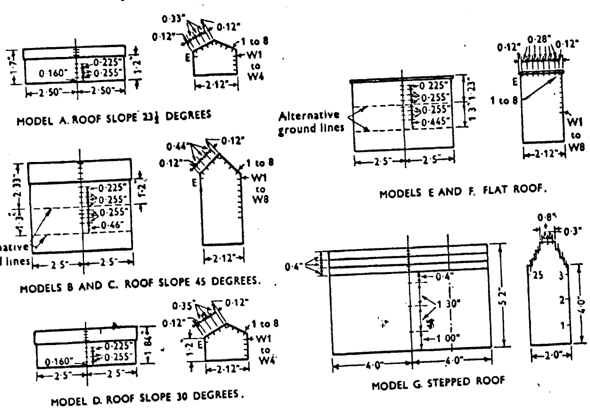
The formula adopted is :—

$$V_H/V_{10}=K\{1{\cdot}00+2{\cdot}81 \log (H+4{\cdot}75)\}$$

where H denotes height above ground, in metres, V_H wind-velocity at height H, and V_{10} wind-velocity at a height of 10 metres.

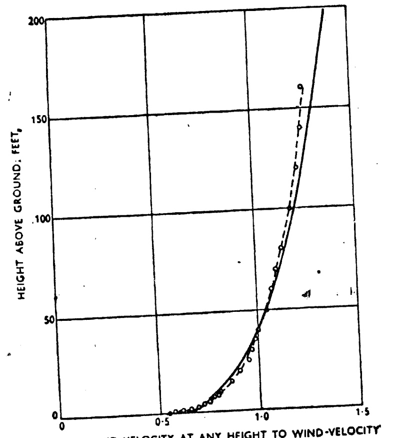
A graph of this function is shown in *Fig. 3*, together with a graph showing the measured wind-gradient at the working section of the wind-tunnel used in the present experiments, both curves being plotted to corresponding scales, assuming the model tests to be on a scale of 1/240. It

Figs. 1. *Figs. 2.*



MODELS USED IN TEST, SHOWING POSITIONS OF PRESSURE HOLES.

Fig. 3.



RATIO OF WIND-VELOCITY AT ANY HEIGHT TO WIND-VELOCITY AT 40 FEET ABOVE GROUND.

The solid line is calculated from the relationship $\frac{V_H}{V_{10}}=K[1{\cdot}00+2{\cdot}81\log(H+4{\cdot}75)]$

The dotted line is obtained from wind tunnel observations.

will be seen that the tunnel gradient approximates reasonably to the natural gradient.

Description of the Tests.

In order to establish correspondence of conditions in the various tests the results have been referred to the air-velocity at a distance of 2 inches from the wall in the unobstructed tunnel, which is equivalent to a height of 40 feet, assuming a scale ratio of 1/240.

When the model was in position the air-velocity was measured by means of a pitot tube, placed at such a position that the velocity was unaffected by the presence of the model, this pitot tube having been previously correlated to a similar tube placed at the reference point with the model removed.

Tests were made at wind speeds of approximately 35 feet and 45 feet per second, measured at the reference point.

As previously stated, each pressure-hole on the model was connected to one limb of a multitube manometer and the opposite limb was connected to a static pressure-hole in the wall of the tunnel; the reading of the manometer, therefore, gave the difference between the pressure at the particular point on the surface of the model and the static pressure in the tunnel.

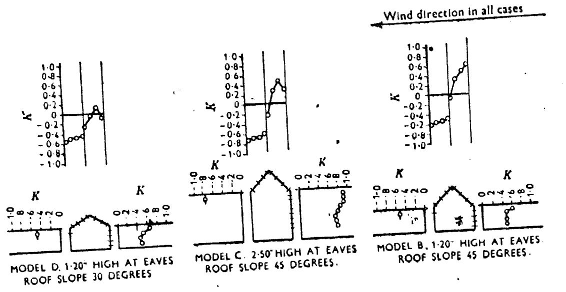
The results of the tests are given in the form of graphs showing the coefficient k in the formula: $p-P_0=k\times\frac{\rho v^2}{2g}$, where p denotes normal pressure at the point on the surface of the model; P_0 denotes static pressure in the air-stream; ρ, density of air at reference point; v air-velocity; and g the gravitational constant.

With air at a temperature of 15° Centigrade, a barometric pressure of 760 millimetres, and an air-speed of 80 miles per hour, the value of $\frac{\rho v^2}{2g}$ is 16·4 lb. per square foot; multiplying this by the observed coefficient gives the pressure-difference at the point, in pounds per square foot.

Results of Tests.

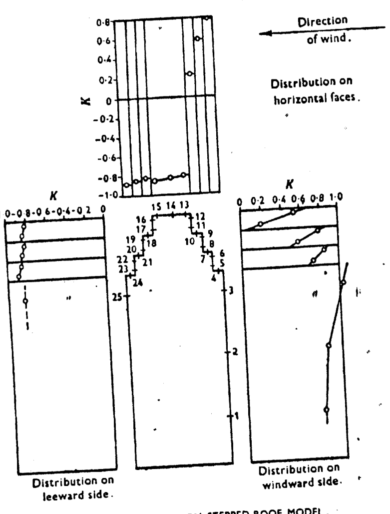
Fully Exposed Conditions.—Tests were first carried out with each of the models fully exposed to the wind, and the results of these tests are shown in *Figs. 4* to *6* in the form of graphs, the value of the coefficient k being plotted opposite to the point to which it refers on the cross-section of the model. The coefficient has been taken as positive when the corresponding pressure-difference acts towards the inside of the building, and vice versa. The general features to be noted are that k has a positive value on all windward walls and a negative value on all leeward walls and leeward roofs; the values of k on the windward side of the roof are very dependent on the slope of the roof and the height of the building, and may be either positive or negative. In the case of the stepped-roofed model there is a positive pressure on the vertical portions of the windward

Figs. 4.



PRESSURE DISTRIBUTION ON MODEL BUILDINGS.

Fig. 5.



PRESSURE DISTRIBUTION ON STEPPED-ROOF MODEL.

roof, and this is slightly reduced at each rise, no doubt due to the eddy set up at each set-back; the pressure on the horizontal portion of each set-back is practically the same as that at the lower point on the vertical portion.

The effect of height on the coefficient is clearly seen by comparing the tests on models B and C; with the higher building the average value of the coefficient for the windward wall is about +0·8, whilst with the lower building it is about +0·5, and on the leeward wall the values are of about the same magnitude, but negative. On the leeward roof the average values are about —0·7 and —0·6 respectively, but on the windward roof the pressures are rather less on the higher building than on the lower, especially at the point immediately above the eaves.

A similar comparison can be made in the case of the two flat-roofed models, E and F. In this case the pressures on the windward wall are about the same as in the other pair, and on the leeward walls the coefficients are respectively —0·5 for the high building and —0·3 for the low building. On the roof there is a larger negative pressure on the low building as compared with the sloping roof.

Shielded Conditions.—To determine the effects of adjacent buildings the measurements made on the fully exposed buildings were repeated with other similar models placed in various relative positions. The results of these tests are shown in *Figs. 7* to *44*, where the graphs represent the variation in the value of k for any one point as the shielding model is moved into different positions, the width, B, of the shielding model being taken as the unit of distance. When the shielding model is moved to an infinite distance away, the conditions are, of course, those of the fully exposed building, and this value has been indicated in the graphs by an arrow at the extreme right, the curves being shown by a broken line over the range in which observations were not made.

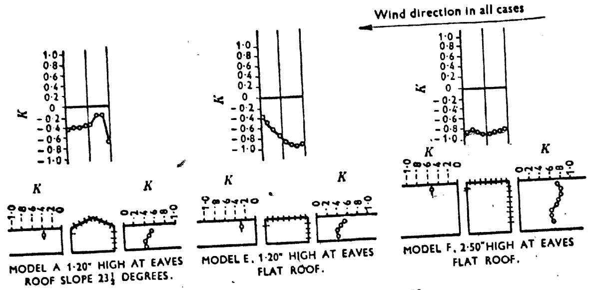
The arrangements tested, with a brief description of the general effects, were as follows :—

1. Model A, roof slope 23½ degrees, height to eaves 1·2 inch, *with model of same form and size on windward side* (*Figs. 7* and *8*).

The effects on the windward wall and leeward slope are shown in *Fig. 8*, and it will be seen that, as the shielding building approaches from infinity, the pressure on the windward wall is gradually reduced and becomes zero when the distance between them is a little less than twice the width of the building; as the distance apart is further reduced this pressure becomes negative. On the leeward slope the negative pressures are generally reduced a little until the buildings get nearly into contact, and they ultimately revert to approximately the fully exposed values; thus it appears that the negative pressures on the second leeward slope of a two-bay building of this type differ little from those on a single-bay building.

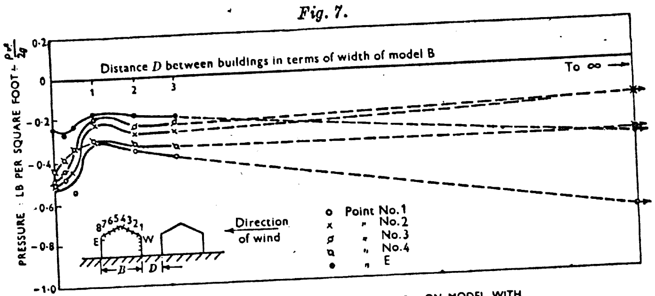
The effects on the leeward wall and the windward slope are shown in

Figs. 6.



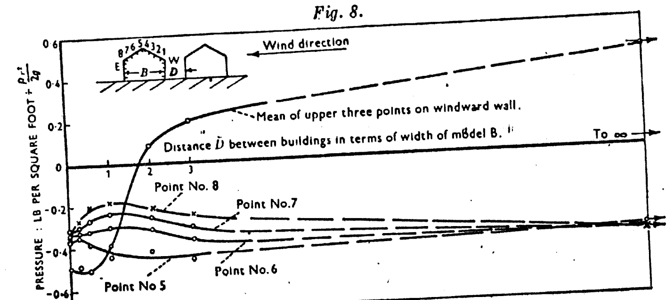
PRESSURE DISTRIBUTION ON MODEL BUILDINGS.

Fig. 7.



VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH ROOF SLOPE 23½ DEGREES. EAVES 1·20" ABOVE GROUND.

Fig. 8.



VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH ROOF SLOPE 23½ DEGREES. EAVES 1·20" ABOVE GROUND.

Fig. 7; the greatest effect is at point No. 2, where the negative coefficient is changed from —0·2 to —0·5, and a somewhat similar change takes place at point No. 3. At point No. 1, immediately over the eaves, and on the leeward wall, the negative pressures are reduced numerically as the buildings come nearer together, until the distance between them is one width, and they then increase as the buildings come into contact, finishing with rather lower numerical values than for the single bay.

2. Model A, with two-bay model, *each bay having the same form and dimensions as model* A *on the windward side* (*Figs. 9* and *10*).

As before, the positive pressure on the windward wall is reduced and becomes negative at about the same point as with a single shielding building, but the maximum negative pressure attained on contact (that is, in the second valley of a three-bay building) is smaller in magnitude. The suctions on the windward slope are reduced and become practically zero when the distance between the buildings is one width. When the buildings are in contact, that is, corresponding to the last section of a three-span roof, the suction on the windward slope is approximately uniform and equal to about half that on the corresponding two-span roof. The variations on the leeward slope were similar to those with the single shielding model, except that there was an increase in suction at point No. 5 in the present case, and the suction is not uniform when the buildings are in contact.

3. Model A, with two single buildings on the windward side, *each having the same form and size as model* A (*Figs. 11* and *12*).

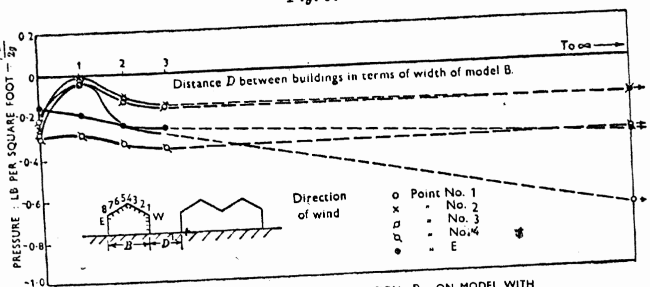
The variations in the pressures and suctions are somewhat similar to those obtained with the double-roofed buildings, the change over from positive to negative pressure on the windward wall taking place when the buildings are one width apart instead of nearly two as previously.

In this series of tests measurements were also made on the central building, but the results were found to be almost identical with those given on *Figs. 7* and *8*, indicating that the presence of a building of equal dimensions on the leeward side has little effect.

4. Model A, with two similar models placed on the windward side, in contact with Model A and having a gap, which was *adjustable, between their adjacent ends* (*Figs. 13* and *14*).

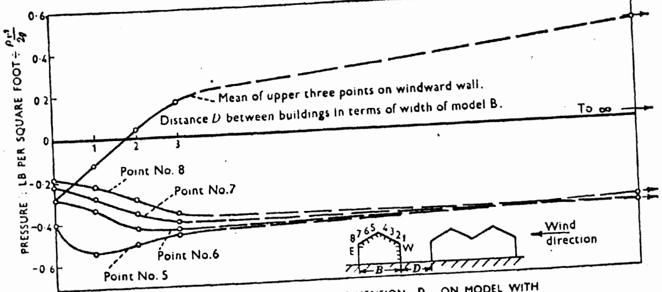
The pressure on the central section of the windward wall is maintained nearly constant until the gap is about three times the width of the building, after which it begins to fall and would presumably be zero when the shielding buildings are in contact. The effect of this arrangement on the leeward slope is negligible, but on the windward slope there is a substantial increase in the suction at points just over the eaves, the coefficient at point No. 1 increasing from —0·66 to 1·04. It is worthy of note that the maximum value of the suction at this point was attained when the distance apart of the shielding buildings was approximately equal to the length of the test-model; it is possible, therefore, that the length of the test-model affected the results, probably by allowing leakage through the gaps when the distance D was greater than the length, but the results give a general indication of what would be the result of such an arrangement.

Fig. 9.



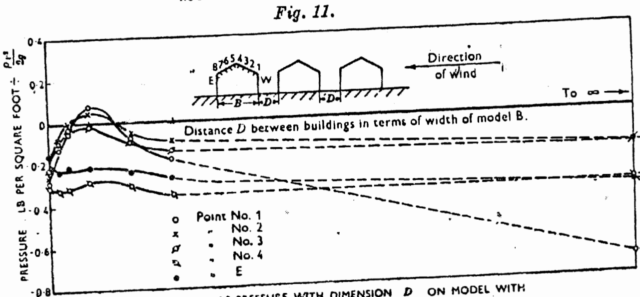
VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH ROOF SLOPE 23½ DEGREES, EAVES 1·20" ABOVE GROUND.

Fig. 10.



VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH ROOF SLOPE 23½ DEGREES, EAVES 1·20" ABOVE GROUND.

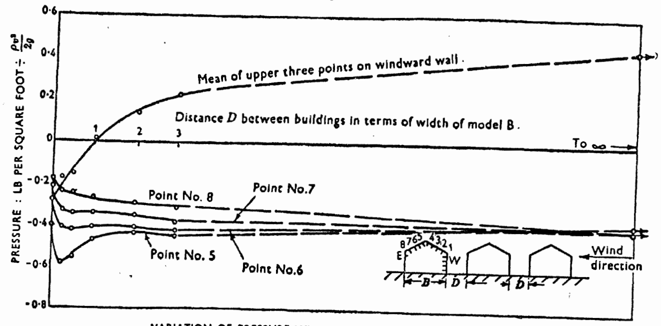
Fig. 11.



VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH ROOF SLOPE 23½ DEGREES, EAVES 1·20" ABOVE GROUND.

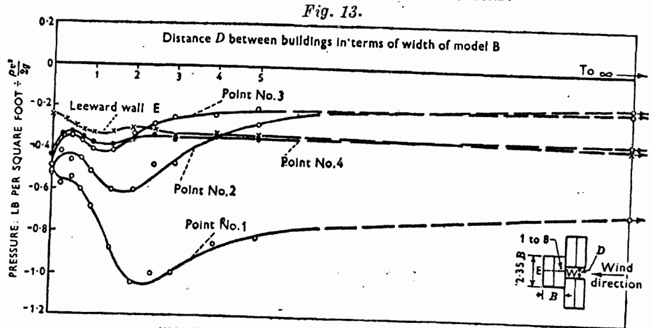
5. Model B, roof slope 45 degrees, height to eaves 1·2 inch, *with model* A *on the windward side* (*Figs. 15* and *16*).

Fig. 12.



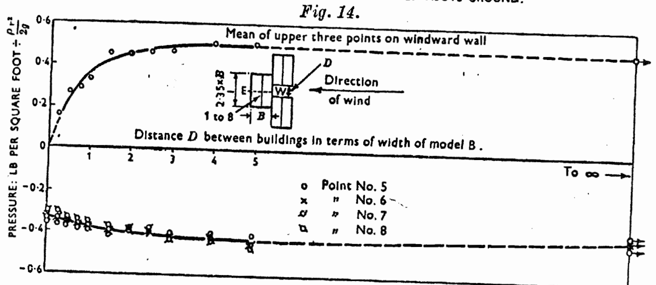
VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH ROOF SLOPE 23½ DEGREES, EAVES 1·20" ABOVE GROUND.

Fig. 13.



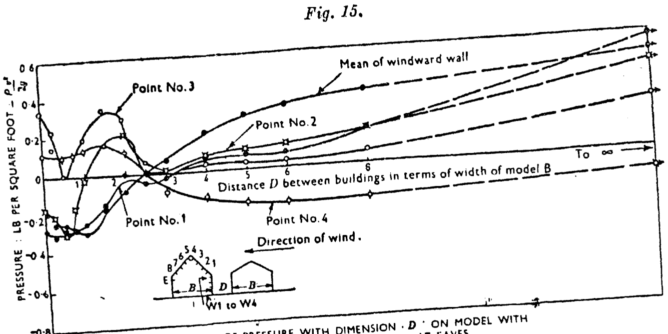
VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH ROOF SLOPE 23½ DEGREES. EAVES 1·20" ABOVE GROUND.

Fig. 14.



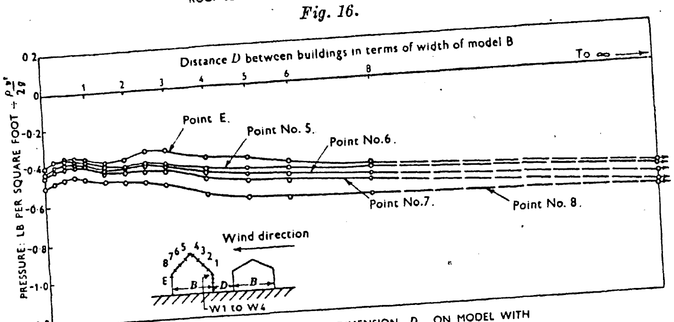
VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH ROOF SLOPE 23½ DEGREES, EAVES 1·20" ABOVE GROUND.

Fig. 15.



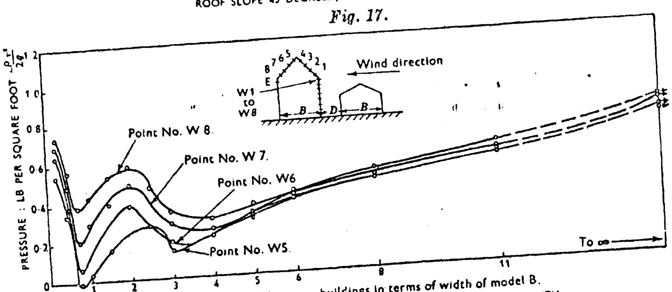
VARIATION OF PRESSURE WITH DIMENSION · D · ON MODEL WITH ROOF SLOPE 45 DEGREES, 1·20" HIGH AT EAVES.

Fig. 16.



VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH ROOF SLOPE 45 DEGREES, 1·20" HIGH AT EAVES.

Fig. 17.



Distance D between buildings in terms of width of model B.
VARIATION OF PRESSURE WITH DIMENSION D · ON MODEL WITH ROOF SLOPE 45 DEGREES. 2·50"HIGH AT EAVES.

The pressure on the windward wall varies in much the same way as in case 1, and the maximum negative pressure is reached with about the same relative positions, but the magnitude is less.

In this case all but the highest point on the windward slope show positive pressures when fully exposed, and these pressures are reduced to zero when the shielding model is at a distance of about three widths. This position is evidently critical, as further movement towards the building causes the pressure to rise at first and then to fall again.

On the leeward slope and wall pressures are all negative and approximately of uniform value and the shielding model has the effect of slightly reducing these values.

6. Model C, roof slope 45 degrees, height to eaves 2·5 inches, *with model A on the windward side* (*Figs. 17* to *20*).

The effect of the shielding model is much more pronounced in this case than in those previously tested, and is noticeable at a greater distance; the positive pressures on the windward wall do not become negative, but there is a critical point when the distance apart is about three widths. The most important point with this arrangement is the increase in the positive pressure on the windward slope when the buildings are about two widths apart. The negative pressures on the leeward side are not much affected.

7. Model D, roof slope 30 degrees, height to eaves 1·2 inch, *with Model* A *on windward side* (*Figs. 21, 22,* and *23*).

The effects of shielding on the 30-degree roof model are similar to those on the 23½-degree roof model under the same conditions.

8. Model E, flat roof, height to eaves 1·2 inch, *with Model* A *on windward side* (*Figs. 24, 25,* and *26*).

The pressures on the windward wall in this case vary much the same as in case 7. The effect of shielding on the flat roof is to cause substantial reduction in the negative pressure as the buildings are brought nearer together. The effects on the leeward wall are negligible.

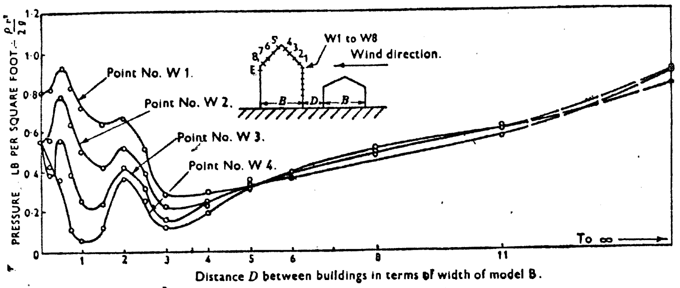
9. Model F, flat roof, height to eaves 2·5 inches, *with Model* A *on windward side* (*Figs. 27* to *30*).

The effects on the windward wall are very similar to those described in case 6. The variations of pressure on the roof are somewhat similar to those on the lower flat-roofed building until the distance apart becomes small; when the distance apart is about one width the negative pressures on the windward side of the roof are substantially greater than in the fully exposed condition.

10. Model G, stepped-roof model, with a model of the same *form and dimensions on the windward side* (*Figs. 31* to *36*).

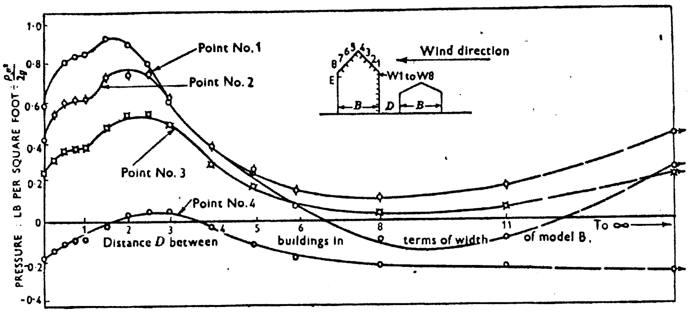
As the shielding model is moved towards the model under test both positive and negative pressures are gradually reduced in numerical value until the distance between the models is from six to eight times the width of the building. Beyond this position a negative pressure exists over the

Fig. 18.



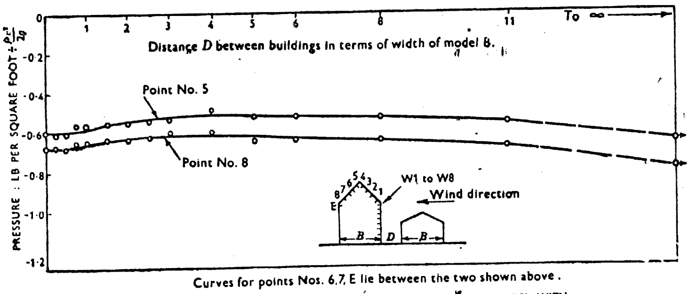
VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH ROOF SLOPE 45 DEGREES. 2·50" HIGH AT EAVES.

Fig. 19.



VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH ROOF SLOPE 45 DEGREES. 2·50" HIGH AT EAVES.

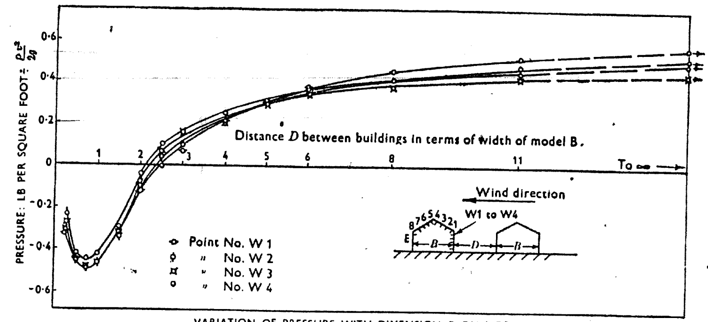
Fig. 20



Curves for points Nos. 6, 7, E lie between the two shown above.

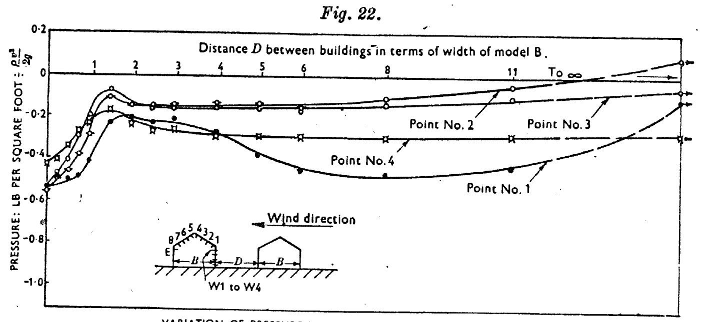
VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH ROOF SLOPE 45 DEGREES, 2·50" HIGH AT EAVES.

Fig. 21.



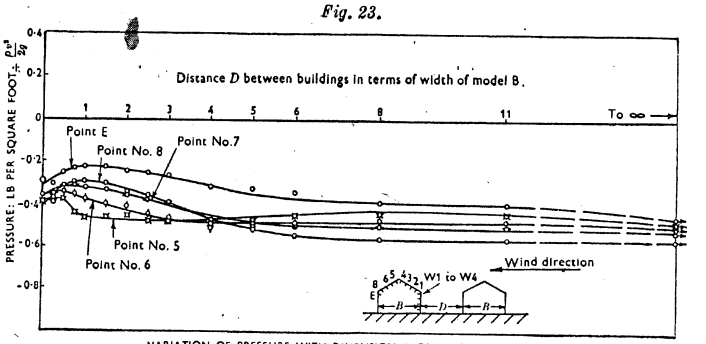
VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH ROOF SLOPE 30 DEGREES, 1·20" HIGH AT EAVES.

Fig. 22.



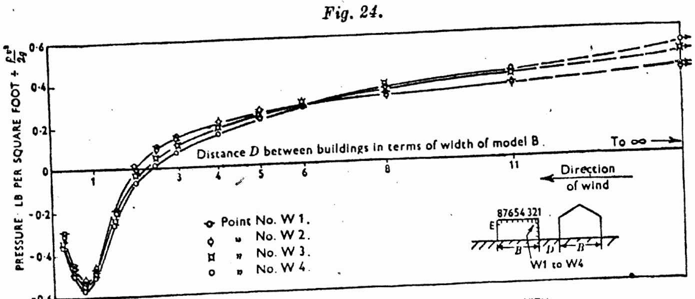
VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH ROOF SLOPE 30 DEGREES, 1·20" HIGH AT EAVES.

Fig. 23.



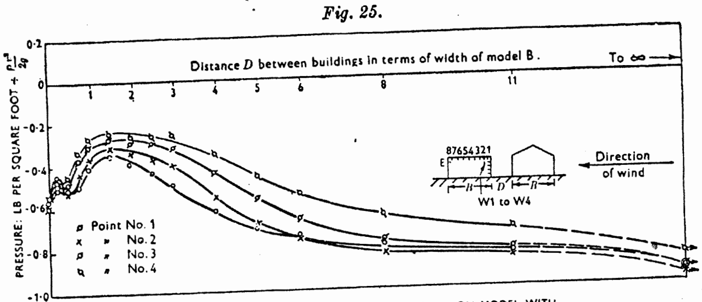
VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH ROOF SLOPE 30 DEGREES, 1·20" HIGH AT EAVES.

Fig. 24.



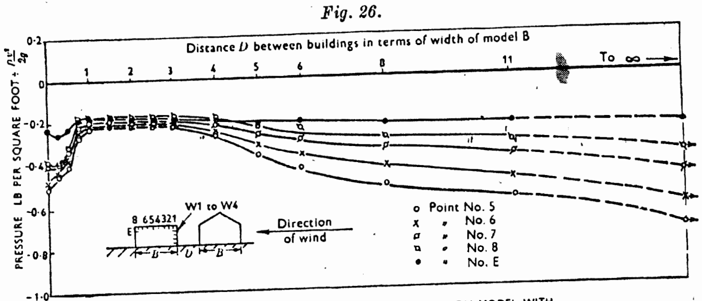
VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH FLAT ROOF, EAVES 1·20" ABOVE GROUND.

Fig. 25.



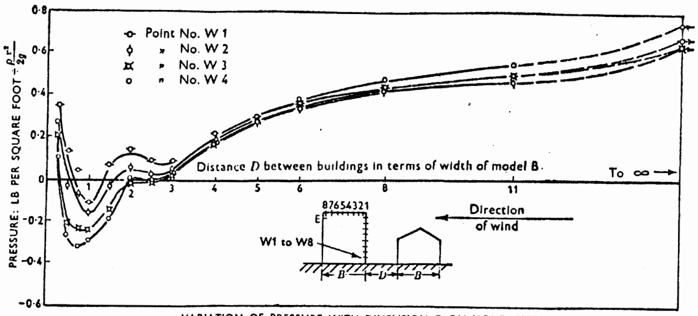
VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH FLAT ROOF, EAVES 1·20" ABOVE GROUND.

Fig. 26.



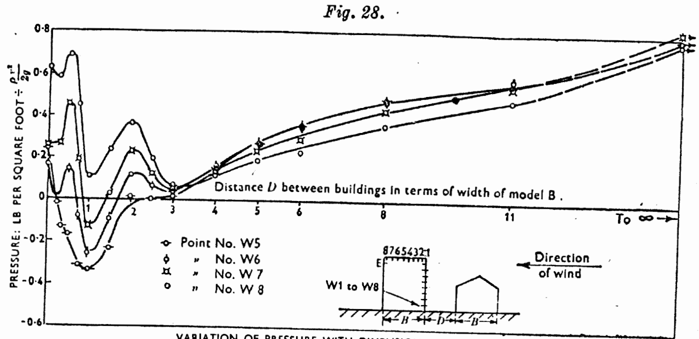
VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH FLAT ROOF, EAVES 1·20" ABOVE GROUND.

Fig. 27.



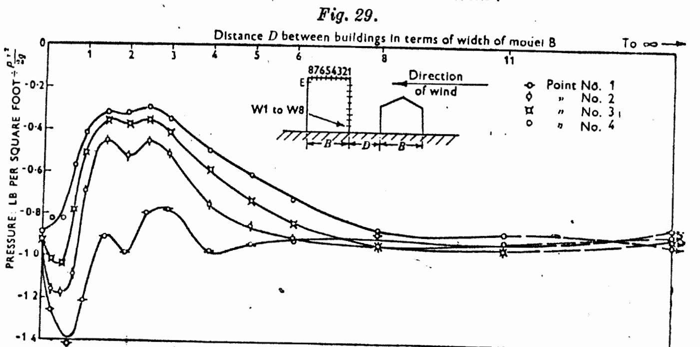
VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH FLAT ROOF, EAVES 2·5" ABOVE GROUND.

Fig. 28.



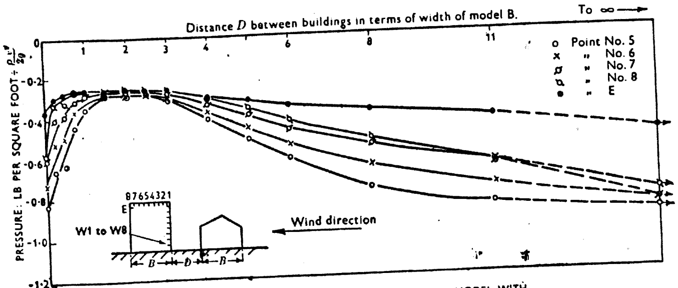
VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH FLAT ROOF, EAVES 2·50" ABOVE GROUND.

Fig. 29.



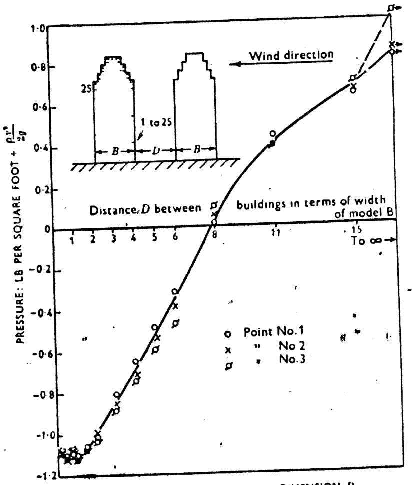
VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH FLAT ROOF, EAVES 2·50" ABOVE GROUND.

Fig. 30.



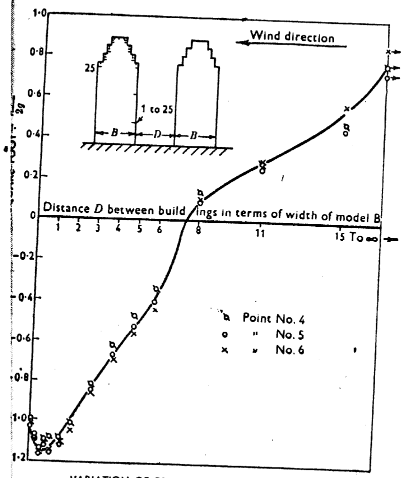
VARIATION OF PRESSURE WITH DIMENSION *D* ON MODEL WITH
WITH FLAT ROOF. EAVES 2·50" ABOVE GROUND.

Fig. 31.



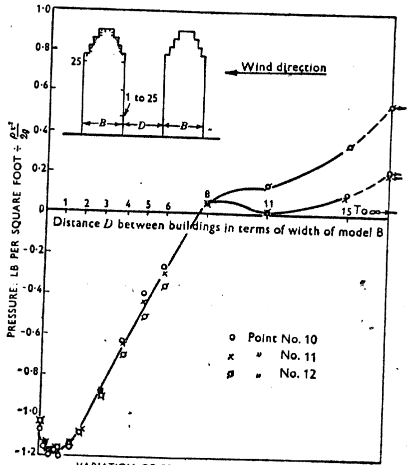
VARIATION OF PRESSURE WITH DIMENSION *D*
ON STEPPED-ROOF MODEL.

Fig. 32.



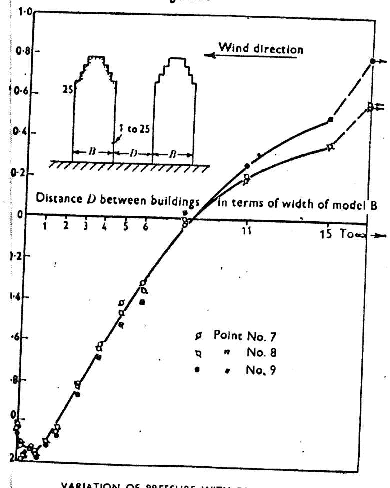
VARIATION OF PRESSURE WITH DIMENSION *D*
ON STEPPED-ROOF MODEL.

Fig. 34.



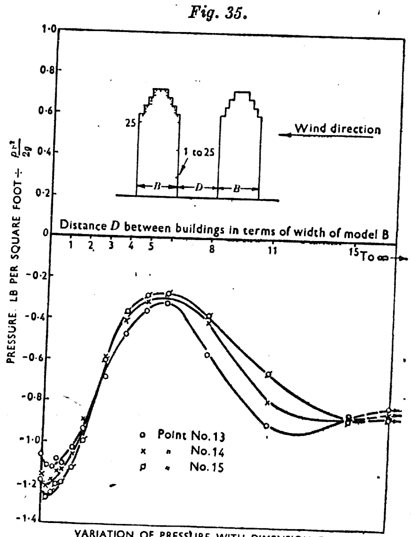
VARIATION OF PRESSURE WITH DIMENSION *D*
ON STEPPED-ROOF MODEL.

Fig. 33.



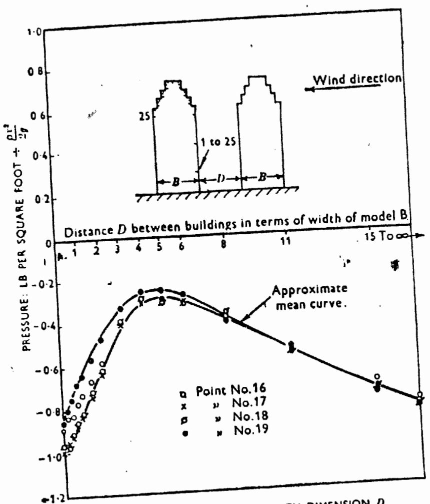
VARIATION OF PRESSURE WITH DIMENSION *D*
ON STEPPED-ROOF MODEL.

Fig. 35.



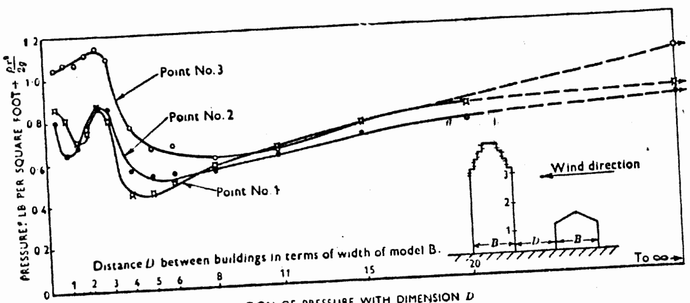
VARIATION OF PRESSURE WITH DIMENSION *D*
ON STEPPED-ROOF MODEL.

Fig. 36.



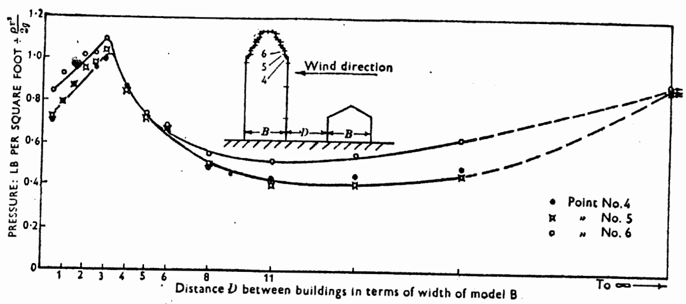
VARIATION OF PRESSURE WITH DIMENSION D ON STEPPED-ROOF MODEL.

Fig. 37.



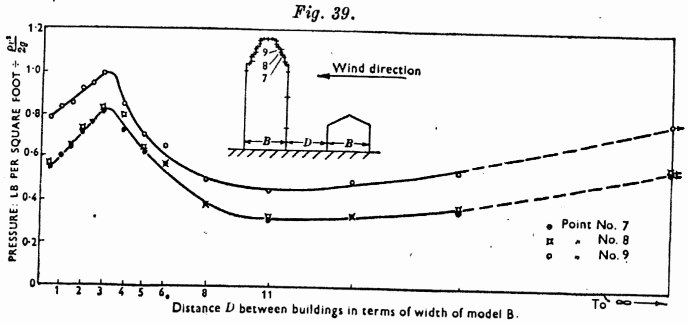
VARIATION OF PRESSURE WITH DIMENSION D ON STEPPED-ROOF MODEL.

Fig. 38.



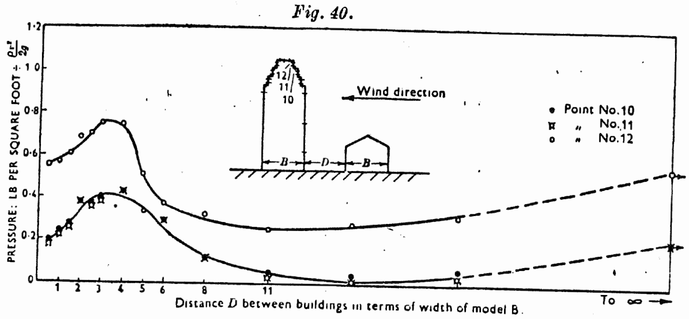
VARIATION OF PRESSURE WITH DIMENSION D ON STEPPED-ROOF MODEL.

Fig. 39.



VARIATION OF PRESSURE WITH DIMENSION D ON STEPPED-ROOF MODEL.

Fig. 40.



VARIATION OF PRESSURE WITH DIMENSION D ON STEPPED-ROOF MODEL.

whole of the building and this negative pressure gradually increases and becomes approximately uniform as the buildings come nearer together.

11. *Model* G, *with Model* A *on the windward side* (*Figs. 37* to *41*).

As with the tests described under case 6, the shielding model becomes effective at a considerable distance; all the pressures on the windward side of the roof are gradually reduced until the distance apart is about eleven widths, when they begin to increase again and reach a maximum, which is generally greater than that of the fully exposed model, when the distance apart is three widths. On the top of the roof and on the leeward side, the effect of the shielding model is negligible.

12. *Model* E, *with Model* G *on leeward side* (*Figs. 42* to *44*).

These tests show the effect of a tall building on the leeward side of a low one, and it will be seen that the effect is to cause a positive pressure over the whole surface of the low building when it is fairly close to the tall one. This would probably have the effect of relieving the structure of load as compared with the fully exposed conditions.

Discussion of the Results.

The object of investigating wind pressures is to determine coefficients which can be used to estimate the wind loading on actual structures. The use of models as described above has provided a convenient method of determining these coefficients, since experiments on full-scale buildings under natural conditions involve extreme difficulties, on account of the irregularities of the natural wind conditions, even over short periods, and also the fact that winds of suitable intensity are infrequent.

The problem arises, however, as to whether the results of model tests carried out in a wind-tunnel can be directly applied to the full-scale building in a natural wind. It is well known, from aerodynamical experiments, that the pressure-distribution on forms such as cylinders and aerofoils depends to a large extent on the value of the Reynolds number and the roughness of the surface. This is ascribed to the change in the positions at which the stream breaks away from the surface; and since, in sharp-edged obstacles, this position is generally fixed, it has been considered that there would be no scale effect in such cases, but there appears to be little experimental evidence on this point.

Experiments on wind-pressures on a full-scale building under natural conditions and on its counterpart in a wind-tunnel, carried out by one of the Authors[4], indicate that, whilst the general form of pressure-distribution is similar, there is a greater reduction of pressure on the leeward side of the full-scale building than would be estimated from the model tests; similar evidence on this point was obtained by Stanton[5]. These appear to be the only experiments in which such comparisons have been made, and before any general relationship could be deduced it would be necessary to make comparisons of other types and sizes of buildings.

Until the relationship has been more definitely established, the model tests give an approximate basis for preliminary calculations.

In the case of buildings of light construction, in which the pressure factor is of first importance (such as hangars, large industrial buildings, etc.), a test of a model of the actual building, and if necessary with its adjacent buildings, is an economical method of determining suitable wind coefficients.

In the general case the wind factor is of less importance and it is probably sufficient to take the average coefficients obtained from model experiments on typical buildings such as are described above.

Two aspects of wind-pressure effects have to be considered in the design of the building :—

1. Its effect on the strength of the structure as a whole.
2. The local effects on roof coverings, windows, panels, etc.

For the design of the main structure the requirement is to know the total horizontal force at any section above the ground, and, being independent of the internal pressure, this can be obtained direct from the results of the experiments by summing the horizontal components of the measured forces. This summation has been carried out, assuming a scale 1/240 and a wind-velocity of 80 miles per hour at a height of 40 feet from the ground; the results for models C and G are shown in *Figs. 45* and *46*.

Fig. 45 refers to model C, and it will be seen that the results of the experiments under the assumed conditions give a shear diagram which approximates closely to a straight line; the same result would be obtained by assuming a uniform horizontal pressure of 23 lb. per square foot acting over the whole projected area.

Fig. 46 refers to model G, and in this case a similar result is obtained, corresponding to a uniform pressure of 27½ lb. per square foot.

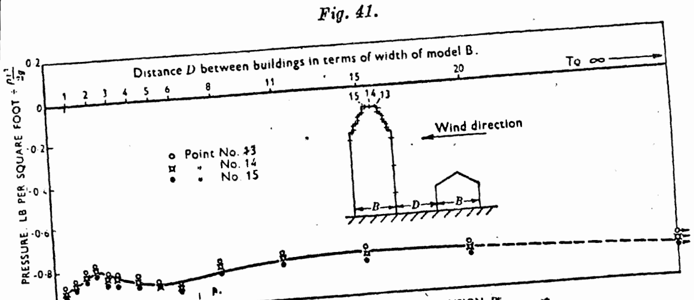
The results are deduced from measurements at the central section of the model, but the assumption that these conditions prevail over the whole length of the building would only result in a small overestimate of the total wind load, as explained on page 245, *ante*.

The analysis of the results on the remainder of the models showed that in all cases the effect is practically equivalent to a uniform pressure over the whole projected height, and the corresponding values are as follows :—

Model.	lb. per sq. foot.
A	10
B	15½
D	14
E	12
F	20

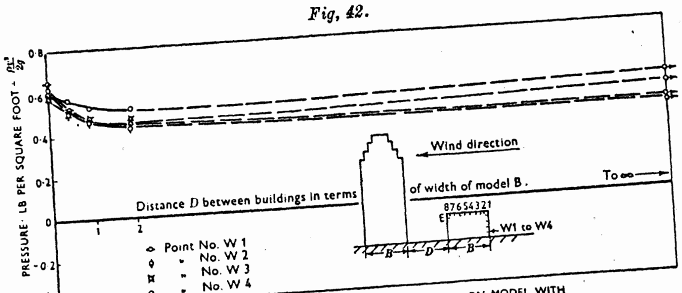
The different values obtained in the experiments have been plotted against the corresponding overall height of the building, and the result is shown in *Fig. 47*: from this, it appears that the wind loading to be taken for the design of the main structure is not very dependent on the

Fig. 41.



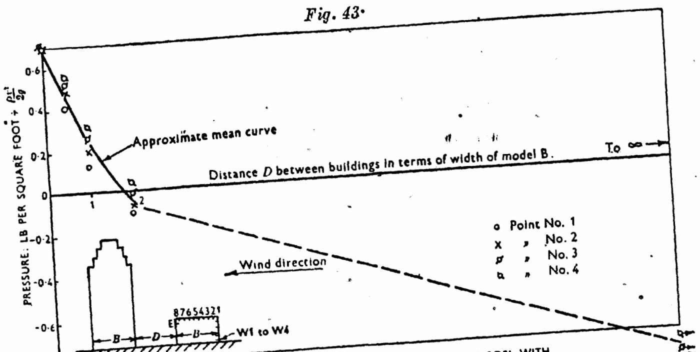
VARIATION OF PRESSURE WITH DIMENSION D ON STEPPED-ROOF MODEL

Fig. 42.



VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH FLAT ROOF, EAVES 1·20" ABOVE GROUND.

Fig. 43.



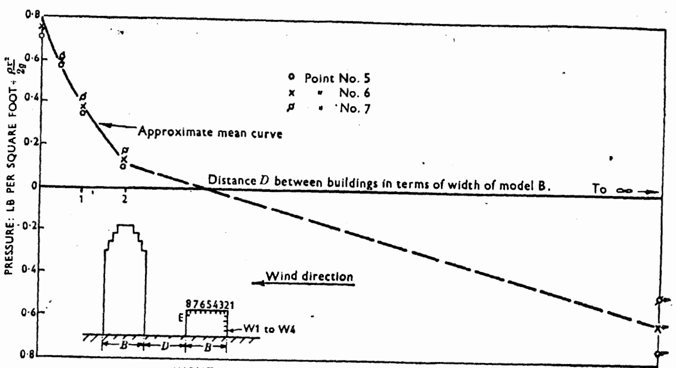
VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH FLAT ROOF, EAVES 1·20" ABOVE GROUND.

shape of the roof and that a uniform horizontal pressure can be assumed, the intensity of the pressure to be taken depending on the overall height of the building.

If this result is general, the wind-pressure to be used in the case of a fully exposed building can be determined from the mean curve through these plotted points, necessary corrections being made for the maximum velocity to be anticipated at the site and also for any " scale " effect.

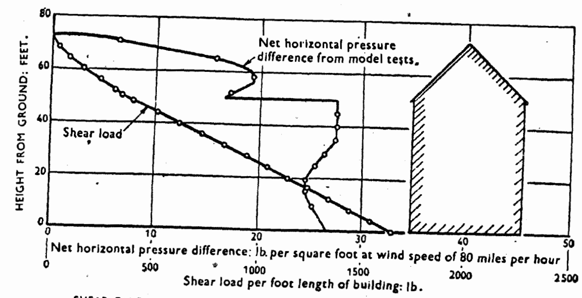
From this curve the following would appear to be reasonable values to be taken for the design of the main structure of a building which is fully exposed.

Fig 44.



VARIATION OF PRESSURE WITH DIMENSION D ON MODEL WITH FLAT ROOF, EAVES 1·20" ABOVE GROUND.

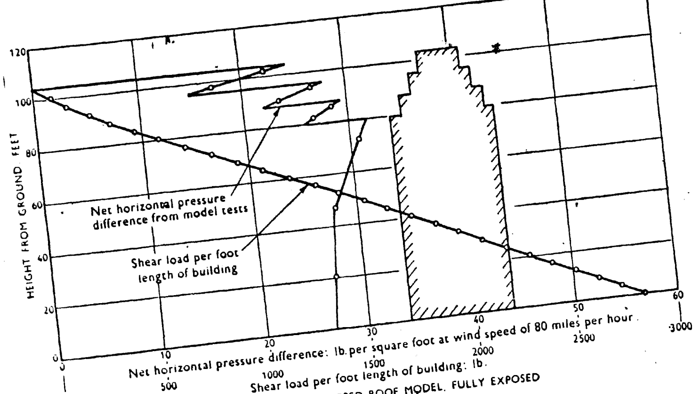
Fig. 45.



SHEAR DIAGRAM. 45 DEGREES ROOF. HEIGHT TO EAVES 2·5". FULLY EXPOSED.

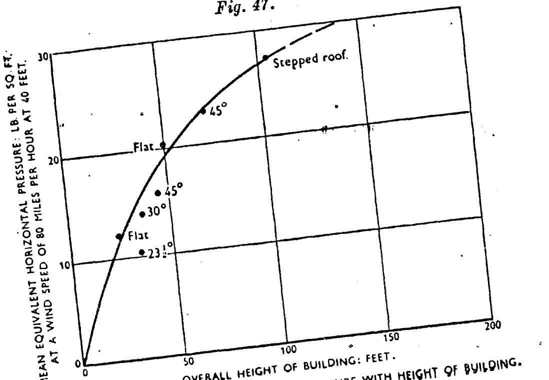
Overall height of building: feet.	Wind-pressure coefficient, k.	Equivalent wind-pressure assuming a wind-velocity of 80 m.p.h. at an effective height of 40 feet.
Up to 25	0·79	13
25–50	1·16	19
50–75	1·46	24
75–100	1·65	27
100–150	1·83	30
Over 150	1·95	32

Fig. 46.



SHEAR DIAGRAM FOR STEPPED-ROOF MODEL. FULLY EXPOSED

Fig. 47.



VARIATION OF EQUIVALENT HORIZONTAL PRESSURE WITH HEIGHT OF BUILDING.

Probable wind-velocities at different sites.—The values of wind loading quoted above have been worked out for an assumed maximum wind-velocity of 80 miles per hour, and as is well known, the actual intensity of pressure will vary in proportion to the square of the wind-velocity; thus before the probable maximum wind loading can be determined the value of the probable maximum velocity must be obtained.

Information on the measurement of wind-velocities, covering a considerable period at a large number of stations in the British Isles, was given by Lieut.-Col. E. Gold, D.S.O., M.A., F.R.S., in his Presidential Address to the Royal Meteorological Society in 1936. A table is given showing the highest gust-velocity recorded by a Dines anemograph, at each of the places, since the installation of the instrument, which in some cases covers about 30 years.

The velocity recorded depends on the height of the anemometer head above the ground, on account of wind gradient, and also on the nature of the surroundings; values are given in the table for the "effective" height of the head, an allowance having been made for the exposure. Thus the effective height of the instrument at South Kensington, London, is given as 30 feet, although the head is 110 feet from the ground and 35 feet above the general roof-level. The maximum gust-velocity recorded at each station and the effective height have been abstracted and are given in Table I, together with the corresponding velocity reduced to a standard effective height of 40 feet by means of the formula for wind gradient given on p. 245, *ante*.

Such a Table extended over a sufficiently long period would enable a reasonable estimate to be made of the maximum velocity to be expected at each station. Some of the records cover only 1 or 2 years, and the maximum period is 30 years; this fact must be taken into account in considering the values given. Over a considerable area of Southern England it would appear reasonable to assume a maximum gust-velocity of 80 miles per hour at an effective height of 40 feet, but near the coast and in the north and west much higher velocities are to be expected.

Scale Effect.—As regards the scale effect, the full-scale experiments, to which reference has already been made, indicated that the reduction of pressure on the leeward side of the building was of the order of 50 per cent. greater than would be estimated from the model tests. In general the model tests show that the reduction of pressure on the leeward side has a numerical value of from 50 to 100 per cent. of the increase of pressure on the windward side, so that the correction of the total shearing force would on this account require an increase of about 15 to 25 per cent. It is considered, however, that there is not sufficient knowledge to warrant this correction being accepted, and that in any case the difference is probably within the limits of accuracy with which all the conditions are known.

Effects of Adjacent Buildings.—To determine the effects of an adjacent building on the windward side a similar analysis has been made of the

TABLE I.
MAXIMUM GUST-VELOCITIES.

Station.	Number of years over which measurements made.	Speed of highest gust recorded: m.p.h.	Effective height: feet.	Velocity at effective height of 40 feet: m.p.h.
Lerwick (Shetlands)	13	94	39	94
Kirkwall (Orkneys)	6	89	35	91
Butt of Lewis (Lewis)	6	92	35	94
Aberdeen	28	82	32	86
Balmakewan (Aberdeen)	20	83	20	95
Bell Rock (Forfar)	6	100	126	80
Edinburgh	21	85	23	94
Tiree (Argyll)	9	108	42	106
Paisley (Renfrew)	22	104	31	108
Abbotsinch (Renfrew)	2	84	33	87
Eskdalemuir (Dumfries)	25	90	35	92
South Shields (Durham)	25	87	44	85
Catterick (Yorks)	3	77	33	79
Spurn Head (Yorks)	14	84	34	86
Cranwell (Lincs)	12	80	33	83
Gorleston (Norfolk)	25	77	34	80
Felixstowe (Suffolk)	12	70	40	70
Cardington (near Bedford)	4	81	135	63
Shoeburyness (Essex)	24	83	89	71
Birmingham	12	78	73	69
South Kensington (London)	6	70	30	74
Kew (London)	30	72	50	69
Croydon	13	81	70	72
Dover	11	85	60	77
Lympne (Kent)	12	79	48	76
Calshot (Hants)	14	81	42	80
Boscombe Down (Wilts)	3	70	33	68
Larkhill (Salisbury Plain)	6	75	36	77
Fleetwood (Lancs)	10	84	31	88
Manchester	2	74	80	64
Southport	29	96	33	99
Liverpool	7	91	39	91
Holyhead	30	86	38	87
Sealand (Cheshire)	7	75	42	74
Plymouth	26	96	65	87
Pendennis Castle (Cornwall)	23	103	42	101
Lizard (Cornwall)	1	92	60	85
St. Ann's Head (Pembroke)	1	100	—	—
Scilly Isles	28	111	57	104
Dunfanaghy (Donegal)	7	94	30	99
Aldergrove (near Belfast)	8	84	20	97
Quilty (Co. Clare)	25	>112	32	>116
Valentia (Cahirciveen)	19	96	33	99
Cork	2	69	40	69

series of tests Nos. 10 and 11; a shear force diagram has been drawn for the conditions at several different positions of the shielding model, and it is found that, as before, a uniform intensity of pressure taken over the whole height of the building sufficiently represents the results at each position. The variation of the value of the equivalent uniform pressure,

with distance apart of the two high buildings, is shown by the graph in *Fig. 48*; it was found that a low building on the windward side of a high building (series 11) has little effect on the wind loading of the latter, the maximum reduction, as compared with the fully exposed conditions, being 20 per cent. when the distance apart is about eleven times the width of the building. When the shielding building also is high (series 10) there is a considerable effect, the wind loading falling steadily to zero when the distance apart is six times the width, and becoming negative at less distances. The negative shearing forces are not large compared with those to be considered in the fully exposed condition, the maximum reached being about 30 per cent., and since a building must be designed to resist the wind from any direction, the determination of these negative loads has no practical value.

The general conclusion to be drawn from these tests is that when a building is shielded by another of the same order of height on the windward side, a reduction in the wind-pressure factor is permissible, the amount depending on the distance apart; if the shielding building is relatively low only a small reduction, if any, is permissible.

These tests have been carried out with only one or two models to the windward of the test-model, but the shielding effects do not appear to be much affected by the number of models (see series 3 and 4), and it appears reasonable to suppose that the results would be applicable to a normal built-up area.

It is clear that for general design purposes it would not be practicable to treat each case separately and allow for the shielding effects of existing surrounding buildings, partly because this would be an unnecessarily complicated procedure but mainly because the conditions might be varied after the building was erected. On the other hand, the results of the tests show that in a built-up area, even with buildings quite large distances apart, there is a substantial shielding effect and it is unnecessary therefore to allow for the fully exposed loading. For instance, from *Fig. 48* it will be seen that the equivalent wind-pressure is reduced to one-half of the fully-exposed value when two buildings of the kind tested are as far apart as eleven times the width of the building, which corresponds to more than 400 feet in the full scale.

A practical method of making this allowance would be to take reduced values for the lower portions of a building up to some specified height, say 100 feet, above which the fully-exposed values would be taken. On this basis reasonable values would be, say, 10 lb. per square foot for the first 30 feet above ground-level, 15 lb. per square foot between 30 feet and 60 feet, 20 lb. per square foot between 60 and 100 feet, and 30 lb. per square foot on everything above 100 feet; 30 lb. per square foot should also be taken for all roof erections such as tanks, skysigns, etc., above the general level of adjacent roofs.

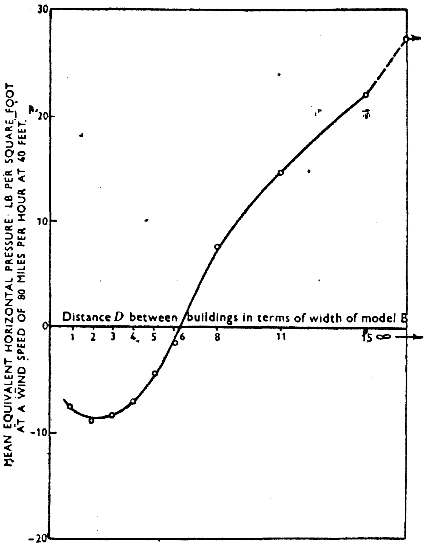
Local Effects.—So far it has not been necessary to consider the pressure inside the building, since this has no effect on the loading of the structure as a whole.

The local effects, however, such as the loading of a roof truss and wall panels, are caused by the difference between the external pressure at any point and the internal pressure.

Incidentally, it follows that the internal partitions must be capable of resisting a certain amount of this wind load.

In a steady wind the internal pressure is governed by the position of

Fig. 48.



VARIATION OF MEAN EQUIVALENT HORIZONTAL PRESSURE ON STEPPED-ROOF MODEL WHEN SHIELDED BY A SIMILAR MODEL.

the openings relative to the form of the building and the direction of the wind; thus, if the windward side of the building has a small opening, say a door or window, and the leeward side is completely closed, the internal pressure will rise to the value of the pressure on the outside at the opening; similarly, if the windward side is completely closed and the leeward side has a small opening the internal pressure will fall to that at the opening. In practice neither of these conditions is likely to be met completely; both windward and leeward faces of the building will have some means of leakage under a pressure-difference and the actual loading on a particular wall or panel will be, to some extent, dependent on the degree of freedom with which the air can flow through the building; on the other hand, in

the case of a wind-gust, the rise of pressure is very rapid and, since it only requires an increase of about 1 per cent. in the air-content of a given space to increase the pressure by about 22 lb. per square foot, an opening which is small relative to the volume of the space is sufficient to admit such a quantity of additional air in the short period in which the gust persists.

It is considered, therefore, that the maximum conditions should be assumed to apply in all buildings when the internal pressure-variation is likely to follow the wind-gust closely.

In the normal large office block, which is cellular in construction, the internal partitions will resist the flow of air so that, during the short period in which a high-speed gust persists, the outer walls are not likely to receive the full effects on the inner surface and some reduction in the internal loading would be warranted.

Roof Truss.—In the simplest case of the design of a roof truss, in which the loading can be taken as the average pressure on each slope of the roof, the extreme values of wind-pressure coefficient to be used have been determined from the present experiments on the low buildings, and the results have been plotted against the inclination of the roof in *Figs. 49* (the points for a "90-degree roof slope" have been obtained from the upper points of the windward and leeward faces of model F); from the fact that a smooth curve can be drawn through the plotted points, it is probable that the values for other slopes, at the same height, can be taken from this curve. The coefficient gives the equivalent loading normal to the roof-slope.

The following values have been taken from the graph:—

Height to Eaves=24 feet.

Angle of slope of roof to horizontal.	Average intensity of pressure-difference normal to slope (lb. per square foot), wind-velocity 80 m.p.h.			
	With maximum negative internal pressure.		With maximum positive internal pressure.	
	Windward slope.	Leeward slope.	Windward slope.	Leeward slope.
Degrees				
0	+1	+7	−24	−18
20	+5	+3	−16	−18
40	+10	+2	−10	−18
60	+17	+3	−6	−19

Note:—A positive pressure-difference acts in an inward direction, and vice versa.

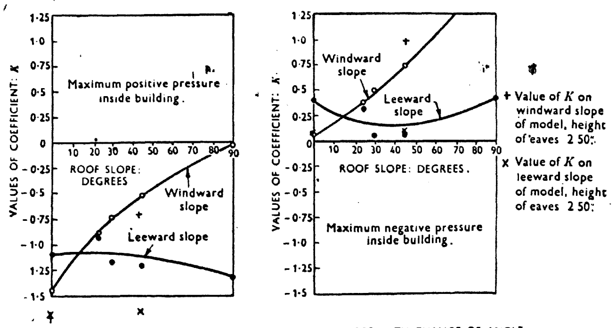
The corresponding values for the higher buildings tested have been calculated and although there are not sufficient data to obtain a similar series of curves, the results have been plotted in *Figs. 49*, and show that the value of k is numerically higher for the higher building.

For a more complicated case, where the span is large and the loads are taken at several points along the slope, it would be necessary to treat each case separately and determine from the experiments the approximate load-distribution, making the necessary allowance for internal pressure.

Roof Coverings, etc.—The damage caused by gales is most frequently of a local nature, such as the stripping of roof coverings and the collapse of walls, windows, etc. The conditions which apply to roof trusses are also applicable here, the loading being the difference in pressure on the two sides of the surface under consideration.

Experience shows that such damage is usually due to the negative, or outwardly acting, forces, especially in the case of light roof coverings, and

Figs. 49.



VARIATION OF MEAN NORMAL COEFFICIENT ON ROOF SLOPE WITH CHANGE OF ANGLE

therefore, when possible, these should be securely fixed and not depend only on their weight. In the case of tiles, where fastening is difficult, boarding the roof immediately beneath the tiles is an effective method of relieving them of wind loads, particularly if they are not close-fitting.

Acknowledgement.

This work, which forms part of the programme of the Building Research Board of the Department of Scientific and Industrial Research, was carried out in the Engineering Department of the National Physical Laboratory, and this Paper is published by permission of the Director of Building Research and the Director of the Laboratory.

The Paper is accompanied by forty-nine sheets of drawings, from which the Figures have been prepared.

References.

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