THE DEVELOPMENT OF A PROCEDURE FOR THE DESIGN OF ROOFTOPS AGAINST GRAVEL BLOW-OFF AND SCOUR IN HIGH WINDS

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This paper sets forth a method of designing a loose gravel aggregate roof surfacing to resist scour and blowoff at design wind speeds. Major design variables include stone size, parapet height, and location of concrete paved slabs, if required, to prevent wind-caused aggregate movement in critical areas of the roof.

This design procedure has two aspects:

(1) Determining the required design wind speed
(2) Determining the design parameters (e.g., gravel size, parapet height) required to prevent aggregate blowoff and scour at design wind speed.

The procedure for computing design wind speed focuses on three major determinents:

- Local wind climate
- Building Height
- Nature of terrain upwind from building site

Information for computing these variables comes from the published literature. Also considered are building proportions and building orientation with respect to wind direction. Design data for evaluating blowoff-scour-resistant design came from 1:10 models in a 30 x 30-ft. wind tunnel test section.

1. INTRODUCTION

Loose gravel placed on flat rooftops acts as a ballast, provides shielding from solar radiation, and also provides a wear surface. High winds can scour some areas of a rooftop clear of stones, leaving the membrane unprotected. Moreover, stones blown from rooftops may damage vehicles or nearby structures. This paper outlines a design method for averting these hazards.

The design method must consider a variety of factors:

- Wind Climate at the building site
- Roughness of the terrain upwind of the building
- Gravel size
- Parapet height
- Building height, shape and orientation

In the most vulnerable areas for gravel scour and blowoff concrete slabs instead of loose gravel may prove necessary.

Blowoff-preventive design requires a determination of two factors:

(a) Design wind speed, at a probability of occurence representing an acceptable degree of risk, and
(b) Wind speed required to cause scour or blow-off of gravel from a particular roof.

In the final roof design (b) should of course exceed (a).

This paper presents a procedure for determining the design wind speed and another for estimating the wind speeds required to cause scour or blow-off of rooftop gravel for various building configurations. The first procedure is based on information available in the literature while the second relies mainly on data from model tests condcuted at 1:10 scale in a 30 x 30-ft. wind tunnel. We discuss various factors affecting the gravel scour and blow-off phenomena, the wind tunnel tests, and outline the development and limitations of design procedures.

SYMBOLS

Symbol	Definition
a,b	paving block array dimensions (see Figure 9)
d	nominal gravel size as determined by sieve analysis (50% by weight is larger than this size and 50% by weight is smaller)
E	exposure factor; the ratio of mean wind speed at rooftop level at the building site to that at the standard reference height/terrain condition
EG	exposure-gust factor (EG = E x G)
Fp	parapet height/paving block array factor
G	gust factor; ratio of one-second gust speed to hourly mean wind speed
g	gravitational acceleration
H	parapet height (see Figure 9)
h	building height (see Figure 9)
k	average height of roughness elements (trees, other buildings, etc.) upwind of building site
ℓ	building length (see Figure 9)
V	wind speed
V_{c1}, V_{c2}, V_{c3}, V_{c4}	critical wind speeds; see Section 5
w	building width (see Figure 9)
z	height above ground level
α	wind angle (see Figure 9)

Subscripts

ref	denotes reference conditions
1, 2, 3	refers to critical speeds V_{c1}, V_{c2}, and V_{c3}

2. FACTORS AFFECTING GRAVEL SCOUR AND BLOW-OFF

When wind speed increases above a certain critical value, loose snow or desert sand particles are blown about. Wind-induced gravel motion is an essentially similar phenomenon. Figure 1 illustrates the moment balance for a particle or stone lying loose at the surface. The wind exerts an aerodynamic drag force D on the particle; as the wind speed increases this drag force also increases, and eventually the moment due to the drag exceeds that due to the particle weight. Then the particle begins to move and tends to be 'caught up' by the wind. The conditions at which such movement begins will be referred to as "critical conditions" and the corresponding wind speeds as "critical wind speeds", denoted by symbol V_c.

Critical wind speeds increase with particle size. This is so because the weight of the particles increases as d^3 while the frontal area on which the wind can act only increases as d^2 (d is the nominal partical size—see Figure 1 and symbols). In any given situation, the aerodynamic force exerted by the wind on the stones increases as V^2, where V is the wind speed. It follows that the ratio of aerodynamic forces to gravitational forces acting on the stones is proportional to $V^2d^2/d^3 = V^2/d$. At a critical value of this ratio, stone motion will begin and consequently the critical wind speed should be proportional to $\sqrt{d}$. Measuring wind speeds required to initiate motion of desert sand for a wind range of sand particle sizes, Bagnold (Ref. 1) confirmed that

$$V_c = \sqrt{d} \qquad (1)$$

for mean particle sizes of 0.2 mm or larger. Preliminary to the present work, critical speeds were measured in a wind tunnel for loose beds of much larger particles—3/8 in. natural gravel and 3/4 in. natural gravel and crushed stone. The results also agreed with equation (1); moreover the relevant constant of proportionality between V_c and $\sqrt{d}$ was found to have the same value for both the gravel and the much smaller sand particles (ref. 2, 3). It follows that the wind speed required to blow gravel off rooftops tends to be proportional to $\sqrt{d}$, provided that the distance and height that the stones must travel are relatively small, as is often the case.

The aerodynamic force exerted by the wind on the stones is quite simply related to the air speed right at the level of the gravel. Unfortunately, however, air speed varies greatly with position in the flow field. At the gravel, it generally differs greatly from the nominal ambient wind speed as reported by meteorological stations. There is no simple relationship, because the air speed at gravel level depends not only on nominal wind speed, but also on the airflow pattern. This, in turn, depends on a host of factors - e.g., the terrain upwind of the building, building orientation with respect to wind direction, geometry (e.g. height, shape, parapet height, geometry of rooftop paving block arrays, rooftop protusions, etc), and the effects of nearby buildings. All these factors must therefore be considered in the design procedures. Their effects are discussed in the following paragraphs.

Since wind speed increases with increasing height above the surface of the earth, building height is an important factor. Furthermore, the rate at which the wind speed increases with height depends on terrain roughness. For the same wind conditions at high altitude (above about 1500 ft.) wind speed near the earth's surface is lower over rough terrain than over smooth terrain. Figure 2 illustrates this behavior. Natural wind is also gusty. The degree of gustiness depends on height above ground level and on terrain roughness.

The orientation of the building with respect to the wind direction can have a profound effect on the airflow pattern over the rooftop and thus on the aerodynamic force acting on the stones for a given wind speed. If, for example, the wind is approximately normal to the upstream face of the building ($\alpha = 90°$), the airflow separates at the upstream edge of the rooftop and the gravel is in a 'sheltered' region. If, on the other hand the wind blows in a diagonal direction ($\alpha = 45°$) strong vortices form along the upstream edges of the rooftop as sketched in Figure 3. These vortices effectively amplify wind speed, subjecting the stones under the vortices to relatively large aerodynamic forces. The danger of gravel blow-off thus tends to be greatest for wind angles of about 45°.

Flow pattern over the building, and in particular over the rooftop, will naturally be influenced by shape. This paper deals explicity only with the simplest of building shapes: rectangular parallelepipeds. Yet even with these shapes the height: length: width ($h:\ell:w$) proportions are of some importance; one would expect the flow over the rooftops of low-rise buildings ($h \ll \ell w$) to be somewhat different from that over medium-rise ($h \simeq \ell, w$) and high-rise ($h \gg \ell, w$) buildings.

As might be expected, parapet height is of major significance. Parapets effectively shield the stones from the wind. For a given wind speed, increasing parapet height reduces the aerodynamic force on the stones. When the wind angle a is roughly 45°, parapets cause the cores of the vortices mentioned earlier to form at greater heights above the gravel, thus reducing the effects of these vortices.

When the wind angle α is roughly 45°, arrays of slabs or paving blocks placed near the upstream corner of the rooftop cause an increase in the nominal wind speed at which stones begin to move. The paving blocks do not significantly modify the airflow pattern. Rather, they simply replace the roofing gravel in the regions where the aerodynamic forces on stones would otherwise be most intense (i.e. under the vortices). The size, shape, and location of the regions where the aerodynamic forces are potentially most intense depends on the airflow pattern over the rooftop and hence on building geometry. The effects of building shape, parapet height and paving block array geometry are therefore interdependent; they can't be dissociated into independent factors.

The analysis design procedure outlined in this paper includes steps to deal with each of the above factors. Due to lack of detailed information, many of the factors can only be dealt with in approximate fashion.

3. DETERMINING DESIGN WIND SPEED

In many cases local building codes specify maximum wind speed that the building and its elements must be designed to withstand. In these cases, the design wind speed is determined simply by consulting the local building code. In other cases, the designer himself will have to determine a design wind speed on some rational basis. This section presents a method of doing this when blow-off of rooftop gravel is of concern. The method is based on the best information currently available regarding the nature of the wind, and the results are considered, if anything, a little conservative. Nevertheless the structure of the wind near the earth's surface is complex, highly variable and only imperfectly understood. Moreover, winds are the result of 'weather', an imperfectly understood phenomenon, so that the wind climate of a particular region can only be predicted by extrapolation of previous records. 'Freak' occurences of unexpectedly high winds may occur.

Information regarding wind climate is based on data collected by meteorological stations. These stations usually report only mean wind speeds, that is, time-averaged speeds for an averaging period ranging from about five minutes (common in the U.S.) to one hour (in Canada and Britain). In the U.S. the data are sometimes presented in terms of the speed of the "fastest mile of wind", with averaging time inversely proportional to wind speed (e.g. a 'fastest mile' speed of 60 mph implies an averaging time of one minute). The probability that, in a given year, the wind speed will exceed a given value is expressed in terms of the 'return period' or 'period of recurrence'. For example, if the return period of 70-mph winds is 30 years, the probability that the wind speed will exceed 70 mph in any one year is 1/30 or 0.033. The designer must decide what return period represents an acceptable level of risk in any particular case. (For local values of the maximum probable wind speeds for various return periods, see ref. 4, 5 and 6.) The data in such publications normally provide mean wind speed (usually either hourly mean, or five-minute mean, or fastest-mile speed) at a standard height/terrain condition, namely 30 ft. or 10-meter height over level open terrain. Thus the designer can determine suitable maximum probable mean wind speeds for the standard height/terrain condition for any locality directly from these published data. A sample map giving such wind-speed data is shown in Figure 4. The designer must then apply suitable adjustment factors to these speeds to obtain the maximum probable gust speed at rooftop level appropriate to the nature of the terrain upwind of the building site.

Observation shows that up to the so-called gradient height, the wind speed varies in a power law fashion as illustrated in Figure 2. Both the gradient height and the power law exponent depending on the roughness of the terrain over which the wind is blowing. The National Building Code of Canada (ref. 7) classifies terrain roughness into three categories:

Exposure A (open or standard exposure)—open level terrain with only scattered buildings, trees or other obstructions, open water or shoreline thereof.

Exposure B—suburban or urban areas, wooded terrain, or centres of large towns.

Exposure C—centres of large cities with heavy concentrations of tall buildings. At least 50 percent of the buildings exceed four stories.

Values of gradient height and power-law exponent adopted by the Code for these three exposures or terrain types appear in Figure 2. Relatively close to the rough surface, for example, near and below the rooftops of arrays of buildings, the wind speed no longer varies in a power law fashion. The average height, k, of the roughness elements is estimated to be about 3 ft. for Exposure A, 20 to 30 ft. for Exposure B and 50 to 100 ft. for Exposure C. Data in References 8, 9 and 10 suggest that within reasonably homogenous roughness the mean wind speed remains approximately constant from ground level to about mid-height of the roughness elements; above this level speed rises rapidly. (At the top of the roughness mean wind speed is approximately twice that near ground level.) With the variation of mean wind speed established as outlined above, you can determine an 'exposure factor', E, defined as the ratio of the mean wind speed for any terrain/height combination. Meteorological stations are usually situated in open level terrain (Exposure A), recording wind speeds at a standard anemometer height of about 30 ft. (10 meters). This standard height/terrain combination thus serves as a convenient reference case.

The exposure factor is plotted in Figure 5 as a function of height above the ground for exposure or terrain types A, B and C. Wind speeds within arrays of tall buildings can sometimes be exceptionally high due to channelling of the wind; Figure 5 does not apply in such conditions.

You can calculate maximum mean wind speed for any given return period at rooftop level at any building site by multiplying the corresponding wind speed at the reference height/terrain condition by the exposure factor appropriate to the level of the rooftop and to the type of terrain upwind of the building. In judging whether Exposure A, B or C is appropriate, remember that the corresponding terrain type should persist for a distance of at least one mile in the upwind direction. If in doubt, be conservative: choose a more open exposure, e.g. A rather than B, or B rather than C. The exposure factor should be varied according to the terrain if the roughness differs from one direction to another. If the building is situated on a fairly abrupt and isolated hill, measure the height used in determining the exposure factor from the general level of the surrounding terrain rather than from building site ground level (ref. 11). Use extra caution on peaks and in valleys in mountainous regions where unusual wind conditions may occur. For mountainous topography try to get wind-speed data for the immediate locality (e.g. for the particular valley or peak in question).

The designer must also make an adjustment to account for wind gusts. Gust factor, G, is defined herein as the ratio of the maximum probable one-second gust speed to the hourly mean wind speed. Shellard (ref. 11) quotes results given by Durst, for the standard reference height/terrain condition, of the ratio of maximum probable wind speed in gusts of various averaging time periods to the hourly mean wind speed. Durst's results are plotted in Figure 6. Similar results are given in Reference 12. We assume that gusts having a period as short as one second can blow gravel off rooftops. Figure 6 shows that at the reference height/terrain condition the maximum speed of such gusts is about 60% greater than the hourly mean wind speed, giving a gust factor G of about 1.6. This value is expected to vary with height and terrain type. This variation of G was estimated, with guidance from References 8, 13 and 14, by making a few reasonable assumptions (see ref. 15 for details). The product of E and G gives a combined exposure-gust factor EG. The exposure-gust factors adopted in this presentation are plotted in Figure 7. The speed of one-second gusts at rooftop level is obtained simply by multiplying the hourly mean wind speed at the standard reference terrain/height condition by the appropriate value of EG. Figure 7 is not valid where 'channelling' of the wind occurs or within roughness which is not reasonably homogeneous.

To use Figure 7 for relatively low buildings with Exposure B or C, the designer must estimate the average height k of the roughness elements just upwind of the building site. As mentioned earlier, k should have a value in the range 20 to 30 ft. for Exposure B and 50 to 100 ft. for Exposure C. If in doubt assume the lowest reasonable value of K.

In summary, the design wind speed, if not specified by a local building code, is determined as follows:

(1) From meteorological data obtain the maximum probable wind speed at the reference height/terrain condition having the desired return period.

(2) If necessary, convert this speed to an equivalent hourly mean speed, using the information of Figure 6.

(3) Multiply by the exposure-gust factor EG given by Figure 7 for the appropriate rooftop elevation and terrain type upwind of the building.

The result is the design wind speed.

This procedure assumes that only the gust speed at rooftop level is significant. Our experimental program indicated that this assumption is satisfactory.

4. DESCRIPTION OF THE MODEL TESTS

Once the design wind speed is determined, the designer must establish what wind speed the tentative rooftop design (i.e. gravel size, parapet height and paving block array geometry) can withstand. For this information, we turned to wind-tunnel model testing, a well established design technique that plays a vital role in design of aircraft; long span bridges; tall slender buildings; and other major structures. As discussed earlier, the critical wind speeds required to cause scour or blow-off of rooftop gravel depend on many factors, several of which are interdependent. Complete documentation of the combined effects of these factors would therefore require testing of a large number of combinations of building shape, parapet height, and paving block arrays. This was of course impracticable. Only flat-roofed rectangular buildings were tested and the tests were confined mainly to low-rise shapes, plus a few high-rise configurations. Most of the tests were done with the walls of the building at 45° to the wind direction, the most critical orientation.

The necessary data were obtained by placing scale model buildings with scale model gravel on the rooftop, in a wind tunnel having a 30 ft. sq. by 75 ft. long test section. Figure 8a shows the test set-up. The wind speed was gradually increased until gravel scouring began and further increased until stones were blown off the rooftops. A typical scour pattern, shown in Figure 8b, is similar to what had been observed on full scale buildings. All model dimensions, including gravel size, were one-tenth those of the full-scale or prototype buildings. The motion of the air and stones in the model tests must be dynamically similar to that in the prototype situation if the model tests are to be meaningful. Similarity theory shows that this is achieved if certain non-dimensional ratios have the same numerical value for both the model and the prototype cases. For the present tests the pertinent non-dimensional ratio is the so-called Froude number, $(V\sqrt{Lg})$. V is a reference velocity (e.g. the wind speed at some standard height above ground level), L is the reference length (e.g. the height of the building), and g is the gravitational acceleration. The ratio of gravel density to air density must also be the same in the model and prototype cases; this is easily achieved by using real stone for the model gravel. Since gravitational acceleration is fixed, equality of the model and prototype Froude numbers implies that the model and prototype wind speeds are related as follows:

$$V_P = \sqrt{\frac{L_P}{L_M}}\ V_M = \sqrt{10}\,V_M \qquad (2)$$

For example, a wind speed of 50 mph in the wind tunnel model tests corresponds to a full-scale wind speed of $50\sqrt{10}$ = 158 mph.

Strictly speaking, the wind approaching the model buildings should have the same velocity variation with height (see Figure 2) and the same gustiness as the natural wind. This was impossible to achieve in the present tests because it would have required a wind layer about 1000/10 = 100 ft. thick. However, since the gravel scour and blow-off phenomenon should be sensitive mainly to wind conditions at rooftop level, an approximate simulation of the natural wind was considered satisfactory for the present tests. Spires at the upstream end of the test section, followed by cube roughness elements (see Figure 8), were used to introduce suitable gustiness and velocity variation with height into the wind approaching the model buildings.

Tested models corresponded to full-scale buildings with the following dimensions:

(a) Low-rise shapes: 75 ft. x 75 ft. x 15 ft. high;
75 ft. x 225 ft. x 15 ft. high.
(b) high-rise shapes with l = w: 30 ft. x 30 ft. x 75 ft. high.
(c) high-rise shapes with l=2w: 30 ft. x 60 ft. x 75 ft. high.

As will be seen in the next section, the test results for each shape category can be generalized to apply to a much wider range of dimensions than those actually tested. Each building model was tested with several different parapet heights and paving block array dimensions. Most of the tests were conducted using a full-scale-equivalent gravel size, d, of either 0.9 or 1.5 inches; since as discussed earlier, the critical wind speeds are proportional to $\sqrt{d}$, the results can be adjusted to apply to virtually an gravel size. (Detail of the model tests are available in References 16 and 17).

5. TEST RESULTS—GUST SPEEDS REQUIRED TO ROOFTOP LEVEL TO CAUSE SCOUR OR BLOW-OFF GRAVEL

The test results are presented in terms of four different critical wind speeds:

- V_{c1} the gust speed at rooftop level at which the wind moves one or more stones several inches.
- V_{c2} the gust speed at rooftop level above which scouring of stones would continue more or less indefinitely if the wind speed were maintained.
- V_{c3} the gust speed at rooftop level above which an appreciable number of stones (six or more) leave the roof over the upstream parapet (AB in Figure 9).
- V_{c4} the gust speed at rooftop level above which an appreciable number of stones leave the roof by going over the downstream parapet (BC in figure 9). V_{c4} is generally equal to or greater than V_{c3}.

These critical wind speeds will, of course, depend on the rooftop design and on the wind direction, and the aim of this design procedure is to enable the designer to predict their values. The nomenclature used in the presentation of the results is illustrated in Figure 9.

Only 'worst-case' wind angles α (see Figure 9) of about 45° will be considered, when $\alpha = 45°$; the flow pattern near the upwind corner of a building does not depend on its absolute length, width or other dimensions, but only on whether it is a low, medium or high-rise building. In effect, the flow near the upwind corner of one building is a 'scale model' of that for another building of different size but of the same shape category. The events associated with V_{c1}, V_{c2} and V_{c3} occur near the upwind corner and therefore also depend only on the shape category of the building. This fact gives the test results a considerable degree of generality.

We have accordingly chosen certain cases as references or benchmarks. Critical gust speeds for other cases can be determined by multiplying the corresponding critical speed for the reference case by appropriate factors to account for differing gravel size, paprapet height and paving block array geometry. This approach permits presentation of the available results in concise form. It also allows full advantage to be taken of their generality. For example, the measurements taken on the specific low-rise building model used in the tests are applicable to any low-rise builling, and the results are presented in such a way that it is a straight-forward matter to use them for any low-rise building. One expects the flow over the rooftops of low-rise buildings to be somewhat different from that over high-rise buildings. Consequently a separate reference case and set of results are required for low-rise building shapes and for each :w ratio for high-rise shapes. Medium-rise shapes would also require separate reference cases and sets of results, but none of these were tested. The results for low-rise buildings are included in this paper as a sample; the complete results are available in Reference 15.

The aforementioned generality does not, unfortunately, apply to the results for V_{c4} because the events associated with this critical speed are not confined to the upwind-corner region of the rooftop. The results for V_{c4} therefore apply only to the specific building configurations that were tested; they are available in Reference 15.

For low-rise buildings the reference conditions and critical speeds are as follows:

—gravel size d_{ref} = 3/4 in.	—$V_{c1_{ref}}$ = 62 mph
—parapet height ratio $(H/h)_{ref} = 0.1$	—$V_{c2_{ref}}$ = 79 mph
—paving block array: none	—$V_{c3_{ref}}$ = 86 mph

Since critical speeds are proportional to $\sqrt{d}$, results need only be multiplied by $\sqrt{d/d_{ref}}$ to account for gravel sizes, d, which differ from the reference size d_{ref}.

As discussed earlier, the interdependent effects of building shape, parapet height, and paving block array geometry cannot be dissociated. A graph giving a combined parapet height/paving block array factor F_p has been prepared, on the basis of the test results, for each of the three building shape categories listed earlier. Figure 10 shows the graphs for low-rise buildings. The factor F_p represents, by definition, the ratio

$$F_p = \left[\frac{V_c \quad d = d_{ref}}{V_{c\,ref}}\right] \tag{3}$$

It can be argued (ref. 15) that F_p should have the same value for critical speeds V_{c1} and V_{c2} (fig. 10a); it will tend to have somewhat different values for V_{c3} (fig. 10b). For gravel size d_{ref} the critical gust speed for a particular building configuration is obtained by multiplying the corresponding reference critical speed by the appropriate value of F_p.

Note that all lengths appear in non-dimensional form as H/h, a/h etc. in Figure 10. This is because the building height, h, is the appropriate length scale to use in non-dimensionalizing the results for low-rise buildings: only the height, h, matters to the flow near the upwind corner of the rooftop; it establishes the size or length scale of this flow. Being non-dimensionalized in this way, the data of Figure 10 apply to the low-rise building shape $(h \ll \ell, w)$ regardless of its actual height, length or width. The data for high-rise building shapes $(h \gg \ell, w)$ are similarly non-dimensionalized; in their case, building width, w, is the appropriate scaling length.

No rigid criterion is known for distinguishing between low-rise, medium-rise and high-rise building shapes. We suggest the following:

Low-rise: $2.5\,(h + 3H) \lessapprox (\ell \text{ and } w)$ (4)

High-rise: (if $\ell/w = 1$, $h \gtrapprox 2w$ or more generally,

$$h \gtrapprox (w + \ell) \tag{5}$$

6. EXAMPLE

To illustrate the procedures outlined in this paper, they will be carried out for a hypothetical example.

The example building is 20 ft. high x 100 ft. wide x 150 ft. long, located in suburban Washington, D.C. Design the rooftop to resist gravel blowoff for winds of 50-year return period.

—h = 20 ft.; w = 100 ft.; ℓ = 150 ft.

—50-year return period.

—From Figure 4, the fastest-mile wind speed for a 50 year return period is 85 mph at Washington, D.C.

—For a fastest-mile speed of 85 mph, averaging time is (1/85) hour = 42 seconds; therefore using Figure 6 the corresponding hourly mean wind speed is 85/1.28 = 66 mph.

—Exposure B is judged appropriate.

—20 ft. is the estimated value of the roughness height k.

—From Figure 7, the exposure-gust factor EG is 1.2.

—Thus design wind speed is 1.2 x 66 = 79 mph.

—Select tentative gravel size of 3/4 in., parapet height near zero (gravel-stop edge), and no paving blocks.

—Since $h \ll \ell$, w Figure 10 is appropriate; using it with $H/h = 0$ and $a = b = 0$, we find $F_{pl,2}$ = 0.75 and F_{p3} = 0.7

—Reference critical speeds (listed in Section 5) are $V_{c1_{ref}}$ = 62 mph; $V_{c2_{ref}}$ = 79 mph; $V_{c3_{ref}}$ = 86 mph. The tentatively selected gravel size is the same as the reference size.

—Then V_{c1} = 0.75 x 62 = 47 mph

V_{c2} = 0.75 x 79 = 59 mph

V_{c3} = 0.7 x 86 = 69 mph

—Since these values for V_{c2} and V_{c3} are less than the design wind speed of 79 mph, alter the tentative design to raise the values. This can be done in several ways: use of larger gravel size and/or higher parapets, and/or paving block arrays.

—For example, increase the parapet height to 2 ft. while maintaining gravel size at 3/4 in. and paving block array size at zero.

- Then H/h = 2/20 = 0.1 and Figure 10 gives $F_{pl,2}$ = 1.0; F_{p3} = 1.0

—Then V_{c1} = 1.0 x 62 = 62 mph

V_{c2} = 1.0 x 79 = 79 mph

V_{c3} = 1.0 x 86 = 86 mph

—Thus the revised design is satisfactory.

As an alternative satisfactory revision, install 6-ft. square paving block arrays in the corners of the rooftop while maintaining gravel size at 3/4 in. and parapet height near zero.

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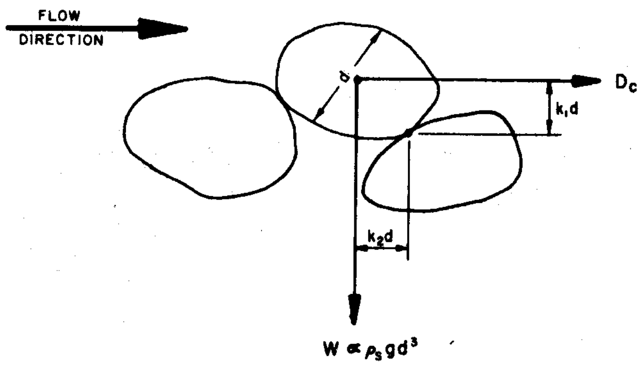


NOTE: k_1 AND k_2 ARE CONSTANTS OF PROPORTIONALITY WHICH DEPEND ON STONE SHAPE

FIGURE 1 - MOMENT BALANCE ON STONE AT CRITICAL CONDITION

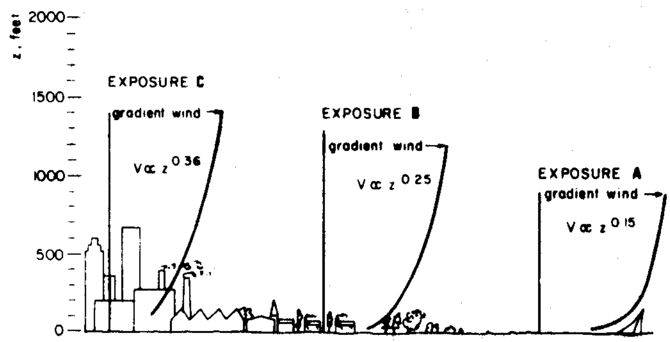


FIGURE 2 - PROFILES OF MEAN WIND SPEED OVER LEVEL TERRAINS OF DIFFERING ROUGHNESS (adapted from Ref. 18)

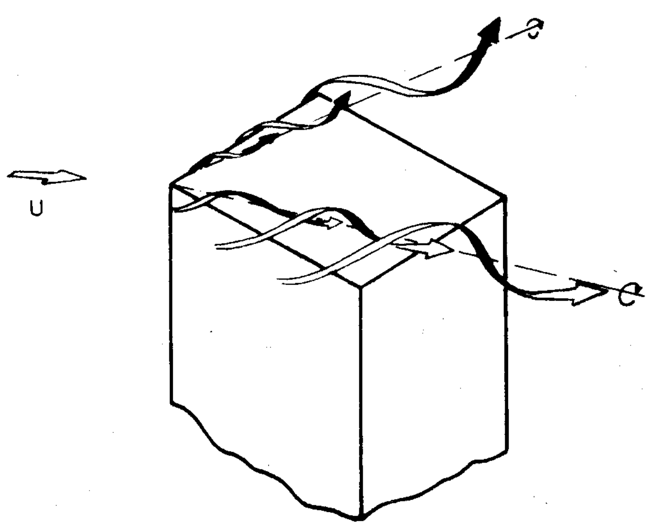


FIGURE 3 - FLOW STRUCTURE FOR WIND AT 45° TO WALLS OF BUILDING

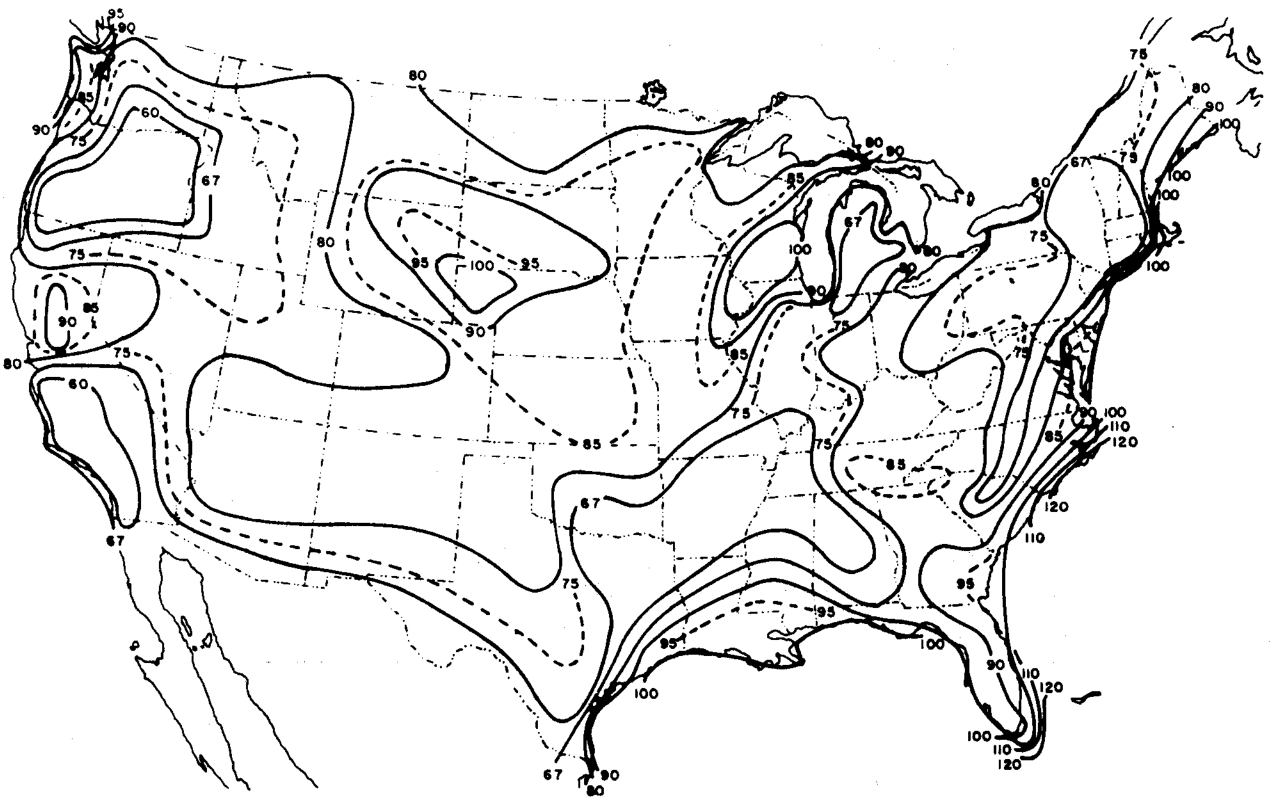


FIGURE 4 - FASTEST MILE WIND SPEEDS (mph) IN THE UNITED STATES FOR 50 YEARS RETURN PERIOD (from Ref. 5)

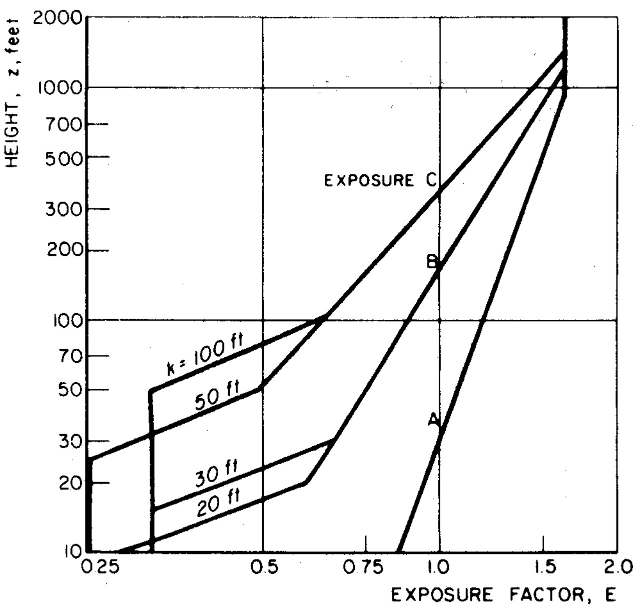


FIGURE 5 - EXPOSURE FACTOR VS. HEIGHT ABOVE GROUND LEVEL

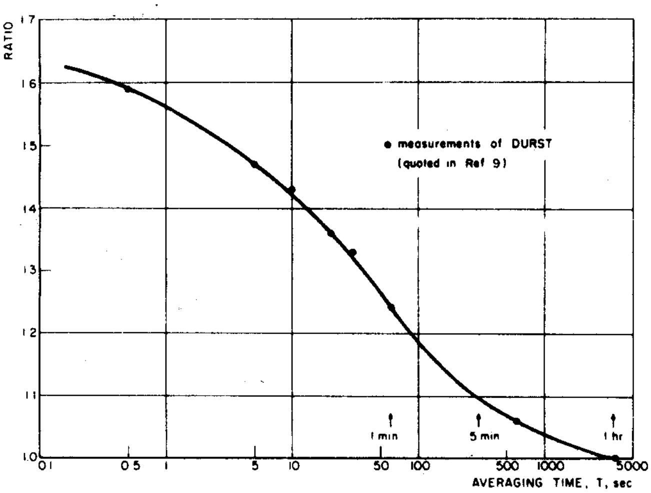


FIGURE 6 - RATIO OF PROBABLE MAXIMUM WIND SPEED AVERAGED OVER TIME T TO THAT AVERAGED OVER ONE HOUR
(z = 30 ft., Exposure A)

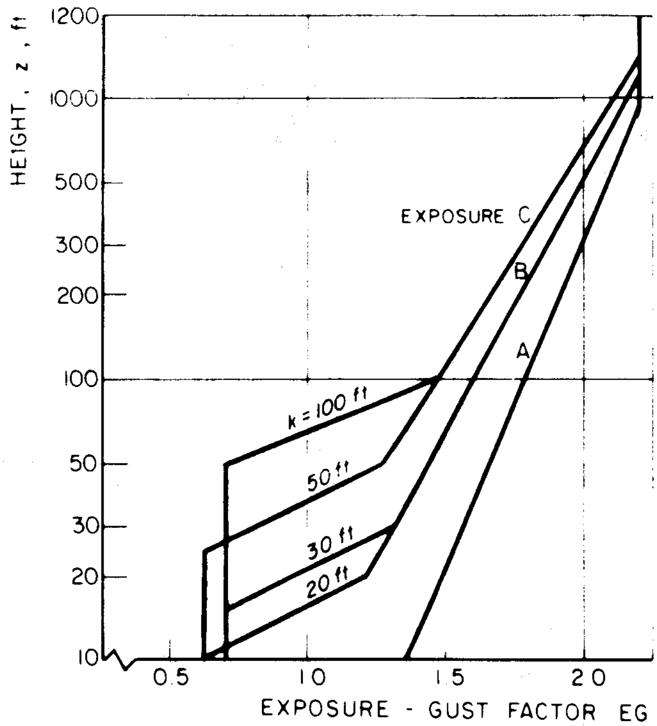


FIGURE 7 - EXPOSURE-GUST FACTOR VS. HEIGHT ABOVE GROUND LEVEL

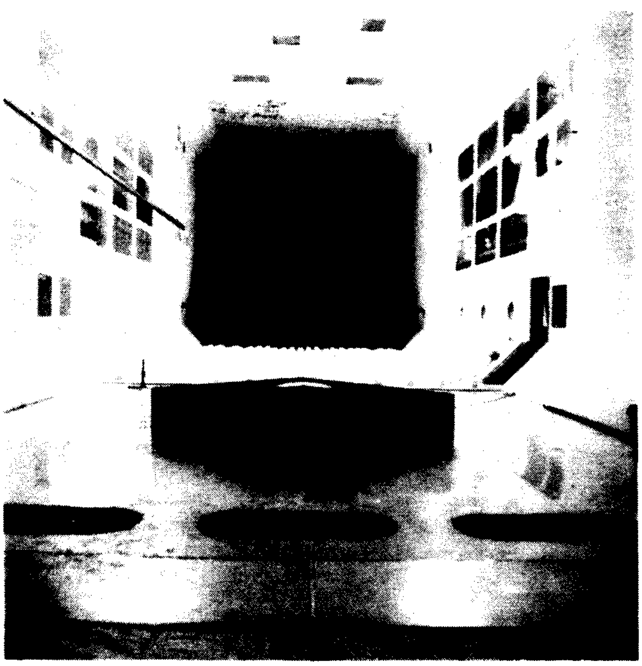


FIGURE 8a - TEST SET-UP

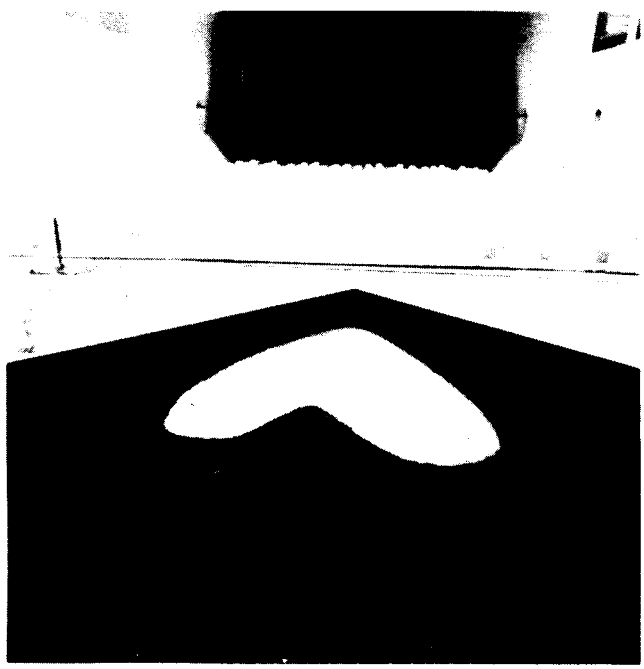


FIGURE 8b - TYPICAL SCOUR PATTERN

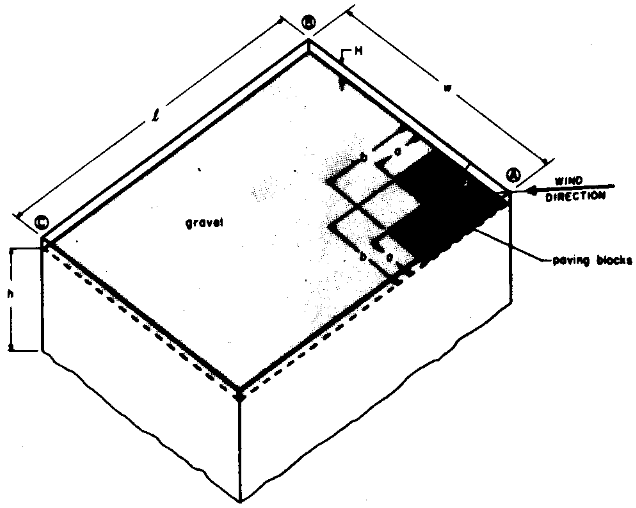
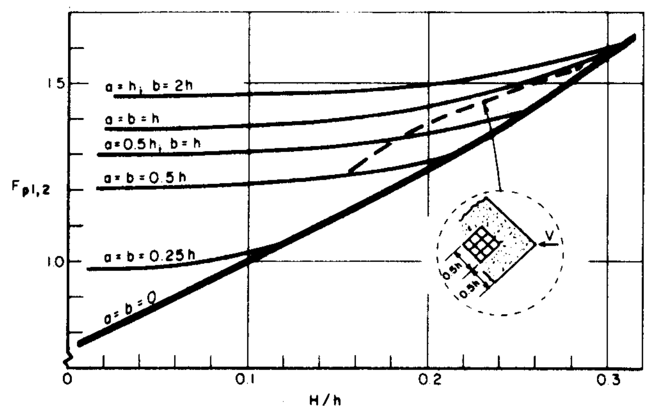
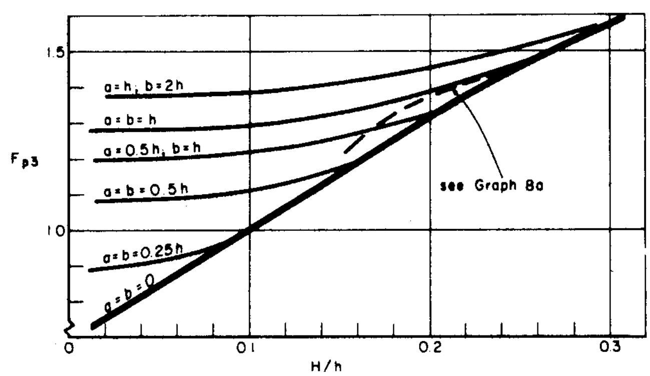


FIGURE 9-SKETCH OF BUILDING AND ROOFTOP
TO DEFINE NOMENCLATURE



(a) for V_{c1} and V_{c2} only



(b) for V_{c3} only

FIGURE 10- PARAPET HEIGHT/PAVING BLOCK
ARRAY FACTOR FOR LOW-RISE
BUILDINGS