8. Wind Basics

Lesson Objectives:

1) Describe the basics of wind engineering concepts and identify its design importance.
2) Outline the basics of wind including: velocity quantity, velocity gradient, Newton's Law of Viscosity, and the developed normal stresses.
3) Describe the measurements of pressure magnitudes and categorize positive and negative pressures and their flow direction.
4) Define laminar and turbulent flows and categorize the key features and assumptions.
5) Analyze the kinematics of wind flow through using key terminology of pathlines, streaklines, and streamlines.
6) Qualitatively apply Bernoulli equation and interpret the relationship between pressure, force, and Reynold's number.
7) Classify and summarize the mechanisms within Bluff Body Aerodynamics.

Background Reading:

1) Read ____.

Wind Engineering:

1) Wind Engineering in a complete form requires known of various factors:
   a. The __________________________ of the natural wind.
   b. __________________________________ around structures and buildings. This is also known as the environmental factor.
   c. Loading of structures and buildings by the wind. This is also known as the loading aspect.
2) This assessment requires a complex interdisciplinary interaction between
   a. Meteorology
   b. Aerodynamics and fluid mechanics
   c. Structural analysis

d. Human psychology - due to the comfort of vibrations within structures

3) The above knowledge is applied through the use of engineering models which are mathematical representations of reality (structures and loads) to quantify numerical values.

Wind Basics:

1) Within the US, numerous wind hazards exist. Examples include (shown in Figure 1):
   a. ______________________________
   b. ______________________________
   c. ______________________________
   d. ______________________________

2) Wind storms are typically the largest source of insured losses in the United States. This is illustrated in the schematic in Figure 2.

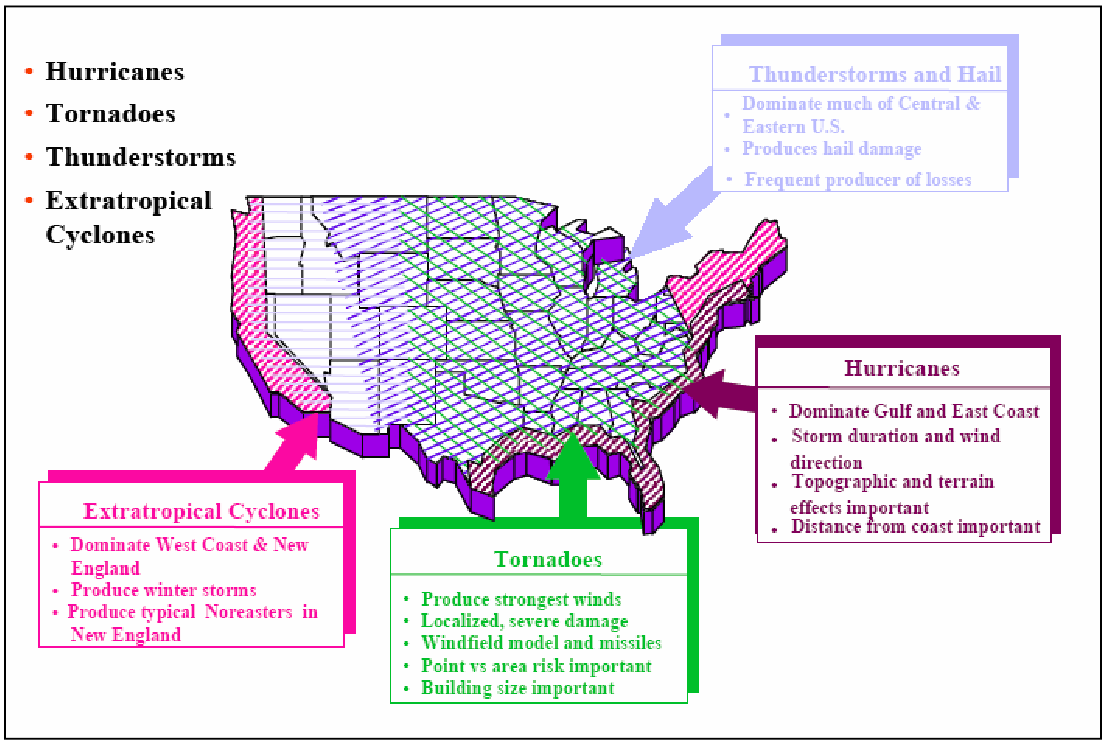


Figure 1. Examples of wind storms for the continental United States. Note from HAZUS Hurricane Model (FEMA, 2003).

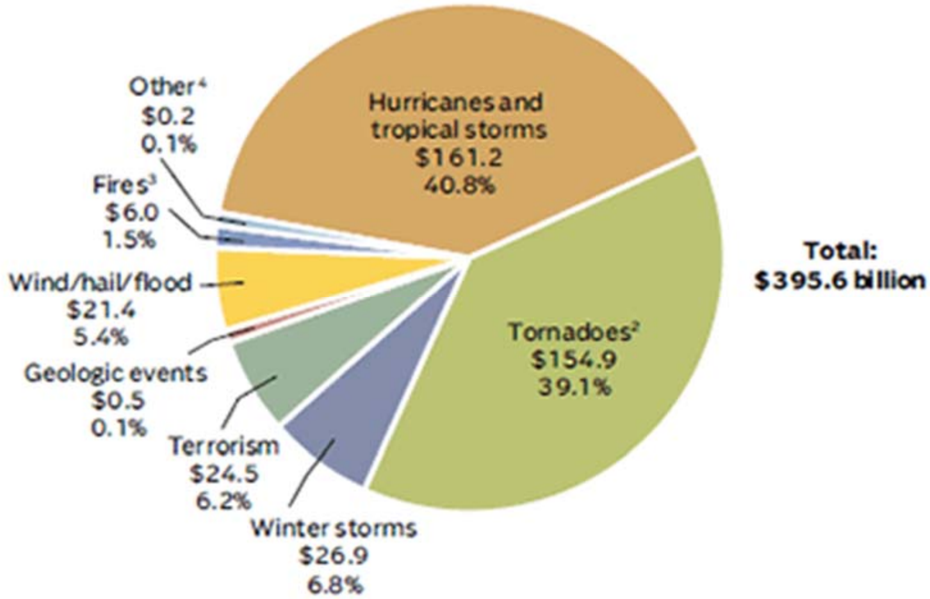


Figure 2. Inflation-Adjusted U.S. Insured Catastrophe Losses by Cause of Loss, 1995-2014 (in 2014 $USD Billions)[1].

3) Therefore it is of the utmost importance to design structures to withstand wind loads.
    a. All possible storms?
    b. Code specifies different return intervals, just like for seismic loads.
4) Before examining, let's discuss on how wind loads act on structures at various terrains.

Wind Loads on Structures:

1) Wind loading of structures is due to the air flow.
2) Within air (in a gaseous state) this behaves similarly to a liquid or a fluid when uncompressed.
    a. Note this is the primarily state.
    b. ________________________________ of air are negligible when the velocity is less than approximately one-third of Mach (speed of sound).

[1] Insurance Information Institute (2016), Archived Graphs. http://www.iii.org/graph-archive/96104.

c. This is about 230 mph.

d. Correlate to tornadic winds? EF-5 is defined as greater than __________________.

3) One definition of a fluid is a substance that deforms continuously under the application of a shear (or tangential) stress, no matter how small the shear stress may be.

a. Fluids flow as long as the shear stress is applied (and deforms continuously).

b. Sketch:

Velocity Quantity:

1) The velocity quantity of wind is commonly written as vector quantity **V**.

2) The common notation for velocity in three spatial directions in Cartesian Coordinates:

a. u = component in the x-direction (typically the major direction of flow – horizontal)

b. v = component in the y-direction (typically transverse to the flow or "sideways")

c. w = component in the z-direction (typically vertical)

3) In an __________________________ – no ______________________ exists and is not encountered realistically. In this case the viscosity of the air is much less than the viscosity of water, but is still an important parameter is defining the behavior of fluids at the boundary layer. This would led to "no slip" conditions at the boundaries.

Velocity Gradient:

1) Since viscosity ___________________ in practice (due to friction), the amount of horizontal displacement varies with distance (y and/or z) from the boundary layer. This gives rise to a velocity gradient.
    a. du/dy = change in velocity with lateral distance away from the boundary
    b. du/dz = change in velocity with height about the boundary
    c. This can be written as:

$$\frac{du}{dy} = \frac{d}{dy}\left(\frac{dx}{dt}\right)$$

2) A velocity profile shows how the velocity changes with distance away from any type of boundary.
3) The slope of the velocity profile (in either direction) is called the velocity gradient.
4) Velocity gradients are ____________________________ near the boundary (more than in u per distance y) as well as the largest shear stresses are present here.
5) Velocity profile sketch:

Newton's Law of Viscosity and Normal Stresses:

1) Within Newton's Law of Viscosity, the shear stress is proportional to the viscosity (μ) and velocity gradient.
2) This can be written as:
3) Where: τ is the applied ______________________ and μ is the dynamic ________________.
4) Recall that a Newtonian Fluid is ________________________________ and follows the Law of Viscosity that is the shear stress is directly proportional to the rate of deformation.
5) Herein, the developed normal stresses are commonly termed as pressures.
6) Pressure is the same in all directions, ____________________, thus this is a scalar quantity.
7) Note that air cannot develop in tension.
8) Air is under compression due to atmospheric pressure.
9) Sketch:

Measurements of Pressure Magnitudes:

1) In air, the values of pressures are always defined as positive. This is relative to the absolute zero of pressure or a vacuum.
2) ________________________ is the absolute zero of pressure and no fluid pressure can be less than this value. At this point, the pressure on the fluid has just overcome atmospheric pressure and would be in tension if it went any lower.

3) Within wind engineering and meteorology, the pressure is measured relative to some reference pressure. This is termed ________________ pressure.
   a. Note pressure gauges will have a reference side – often this is atmospheric pressure, one example is a manometer.
4) Typically the atmospheric pressure is used as reference, particularly within field measurements.
   a. Note there may be a difference in the wind tunnel to allow for static pressures in the wind tunnel itself. This is commonly the case.
5) As for sign conventions:
   a. __________________ pressure (+) is the pressure greater than the reference value.
   b. __________________ pressure (-) is the pressure lower than the reference value. Note this is ________________________.
6) Remember air will always flow from a _________________ pressure to a _____________ pressure (similar to that of heat). This means that the it flow:
   a. From a positive pressure to a ____________________ pressure
   b. From a negative pressure to a _______________________ pressure. This is observed as the ________________ on a roof edge.
   c. From a positive pressure to a _______________________ pressure. This is observed _______________________ on a windward face.
7) However recall that pressure itself is isotropic, therefore it does not have a directional component.
8) However, engineers commonly think of the direction of the pressure in terms of the force that acts as a result of the distributed pressure acting on a surface. Recall that the force is the product of the pressure and area and is a vector quantity with directional components.
   a. Positive pressure acts ________________ the surface
   b. Negative pressure acts _______________ from the surface
   c. Pressure is often perceived to act orthogonally to the surface since we are interested in the resulting forces.
   d. In the sketch below, the directions of the internal and external pressures follow this sign convention. Acting in opposite directions, positive pressures tend to cancel out (smaller net pressure and force), while positive and negative pressures combine to

produce a larger net force. This is important in design for the possible internal pressures that may develop inside of a building (known as pressurization).

e. Sketch:

9) Examples of positive and negative pressure failures are illustrated in Figure 3.

(a) Positive pressure (b) Negative pressure or suction

Figure 3. Example wind pressure induced failures following the June 16-18, 2014 Tornado Outbreak at Pilger, Nebraska: (a) Wisner-Pilger Middle School and (b) Pilger Storage.

Wind Flow Types:

1) There are two types of common air flow, namely: laminar and turbulent.
2) ______________________ flow describes fluid that flows smoothly in laminae or layers.
    a. In this case, the particle moves in smooth and regular paths.
    b. There is no appreciable _____________.
    c. Energy dissipation is less than that of turbulent flow.
    d. For this flow, ___________________ dominates and the Reynold's number is low.
    e. Examples include the flow of honey, molasses, and water from an almost-closed tap.
3) _____________________ flow describes fluid that flows in an irregular and erratic pattern.
    a. Note this is not a constant with time.
    b. Vigorous ____________________ of particles occurs.
    c. Energy dissipation is larger than that of laminar flow.
    d. For this flow, the ______________ is negligible and the Reynold's number is large.
    e. Examples include boiling water and the tap is fully pen with a rough surface jet.
4) For wind flows around buildings, the Reynold's Number is very large and thus the flow can be described a ___________________________. An example is shown in Figure 4.

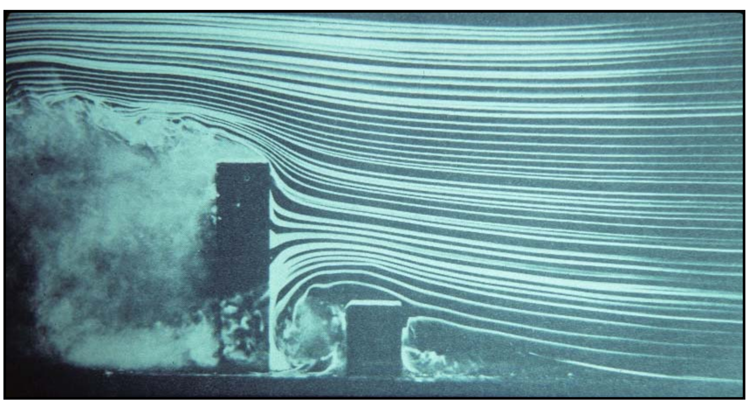


Figure 4. Example __________________________ wind flow around two building structures[2].

[2] Figure by Ingelman-Sundberg (Eidgenosssich Technishe Hochschule, Zurich), from Thomann, H., Wind effects on buildings and structures, Am. Sci, 63, 278-287 (1975).

Kinematics of Wind Flow:

1) The velocity field of wind can be described within each of the two types of flow as:
   a. ______________________ flow – velocity varies in both space and time. This is the most general case and describes turbulent flow in the building wake areas.

      $\boldsymbol{V} = f(x, y, z, t)$

   b. ______________________ flow – velocity varies in space, but not time. This describes the laminar flow approaching the building.

      $\boldsymbol{V} = f(x, y, z)$

2) Geometric Representations of the Velocity Field (refer to Figure 4):
   a. ______________________________: A line traced by one individual particle in the fluid. This provides a time history of the particle position. Due to flow continuity, the pathline cannot end – each fluid particle must go somewhere.
   b. ______________________________: A line connecting all fluid particles that have passed through a certain point. (Release die at specific point, either continually or at time intervals. Resulting lines are streaklines.) For steady flow, this will look similar to pathline, as all particles will follow an identical path (approach before the structures). This is not the case for unsteady flow (wake flow after the wind passes the structures)
   c. ______________________________: An imaginary line drawn in the flow field. Here the velocity (vector) is tangent to the streamline. By this definition, there can be no flow across a streamline. The streamline can "end" (touch at surface at right angle) at a stagnation point.
      i. For ________________ flow, the streamline will look like a streakline and pathline.
      ii. In _________________ flow, it is necessary to consider averaged streaklines to obtain average streamline patterns.
      iii. Where streamlines get closer together, this is a point of increased velocity and decreased pressure (Bernoulli). Streamline gives ____________________ of velocity, but not magnitude.

3) Analogous to flow in a pipe and within steady flow, a streamline paths are can be derived analytically using the Navier-Stokes and Bernoulli Equations.

Bernoulli Equation:

1) Bernoulli equation relates pressure, velocity, and height (expressed as gravity) along a streamline.
2) Sketch:

3) This equation can be written as (from the integration of Euler's Equation of Momentum):

4) This equation has a few limitations, this includes:
   a. Only applicable for ___________________ flows (does not vary with time)
   b. ________________________ flows (density is constant)
   c. ____________________ flow (no effects of viscosity)
   d. Application for flow along the same ___________________________. Constant only along a single streamline. Oftentimes the value of the constant is not critical, only the relative values of pressure and velocity along each streamline.

5) This can be written in terms of pressure to express a balance of pressure, velocity and the gravitational potential:

6) Often times it is of interest to compute changes in p, V, z along a steamline.
7) For the above sketched streamline, it is known that:

8) For wind (air flows), typically the gravitational or elevation term is neglected. Note this is not the case for water (which has the density of about 800 times that of air). This can simplify as:

9) Recall the limitations for this equation, note that for most applications within wind engineering unsteady or turbulent flow exists. Viscous effects may or may not be important. These equation will therefore not provide exact answers, but a very good approximation and it is the basis for computing pressures from velocities.
10) Note the velocity term in the expression for pressure. The velocity term is squared and leads to a critical fundamental premise for wind engineering.
    a. A two-fold increase in wind speed results in a four-fold increase in pressure.

Wind Coefficients:

1) A pressure coefficient can be defined as:

2) A force coefficient can be defined as::

   a. The resulting force on an object can be resolved into two components:

      i. ________________ (F_L): force __________________ to the flow direction.

      ii. ________________ (F_D): force __________________ to the flow direction.

3) Reynold's Number (denoted as Re):
    a. A ratio of ________________ and _________________ forces.
    b. Large Re indicates that inertial forces _______________________.
    c. Most important non-dimensional parameter for describing the flow around objects.
    d. Flow around bodies is generally the same for same Re.
    e. This can alter the velocity, density, and/or the viscosity (different fluid) to main Re similarity

4) The ____________________ determines the flow path around an object in terms of both the ________________ and the _____________________ points.
    a. The drag coefficient is dependent on the size of the wake.
    b. With low Re the viscous forces dominant, and therefore the flow "sticks" to the body (Figure 5).
    c. With larger Re, flow changes from laminar to turbulent at the separation point(s) (Figure 6).
    d. For still larger Re, inertial forces begin to dominate the viscous forces – the flow no longer wants to stick to the body, but rather is "thrown" far from the body upon separation (Figure 7).
    e. This is analogous to you driving a car around a corner – at higher speeds, you are less able to turn a tight corner because of inertial effects.
    f. Note that above Re > 5×10^4, the wake begins to narrow, and the drag is reduced.

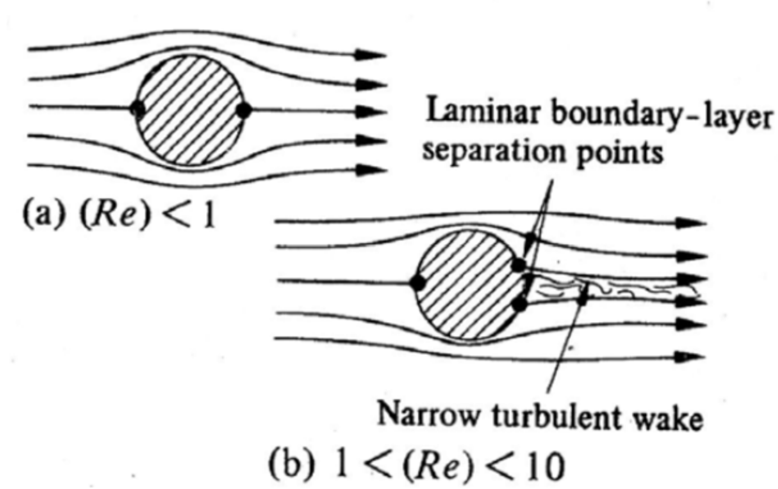


Figure 5. Flow around bodies – lower Re numbers[3].

[3] Figure obtained from: Houghton, E. L., & Carruthers, N. B. (1976). *Wind forces on buildings and structures: an introduction*. John Wiley & Sons.

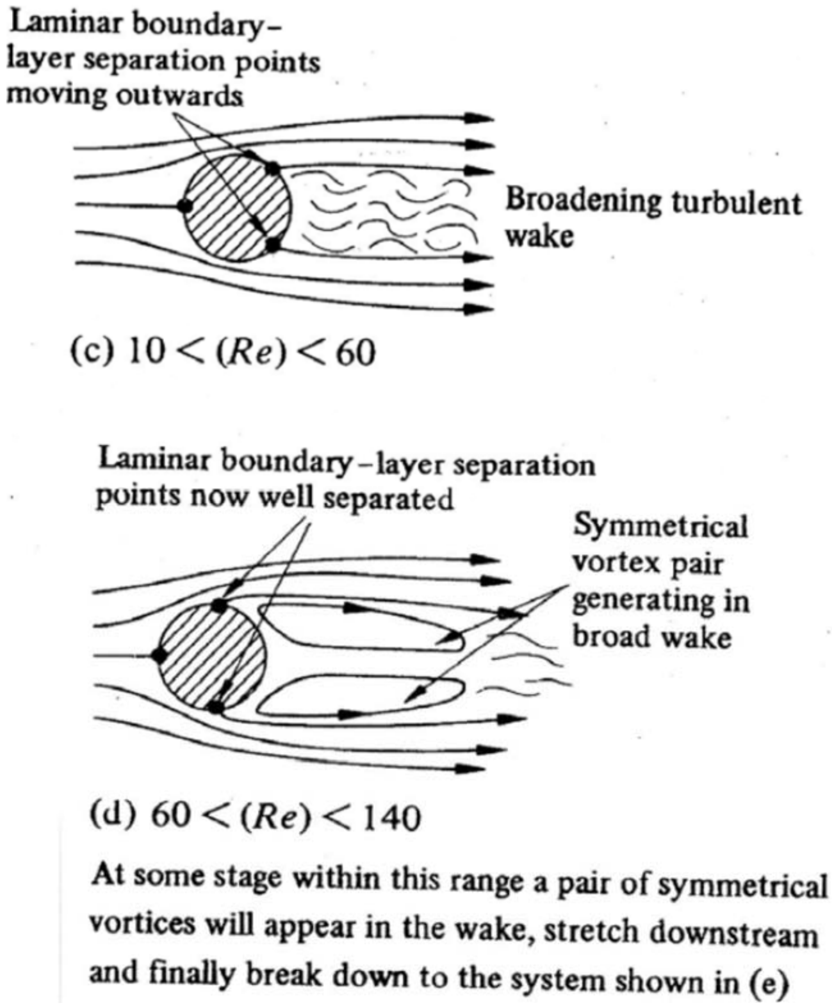


Figure 6. Flow around bodies – moderate Re numbers[4].

[4] Figure obtained from: Houghton, E. L., & Carruthers, N. B. (1976). *Wind forces on buildings and structures: an introduction*. John Wiley & Sons.

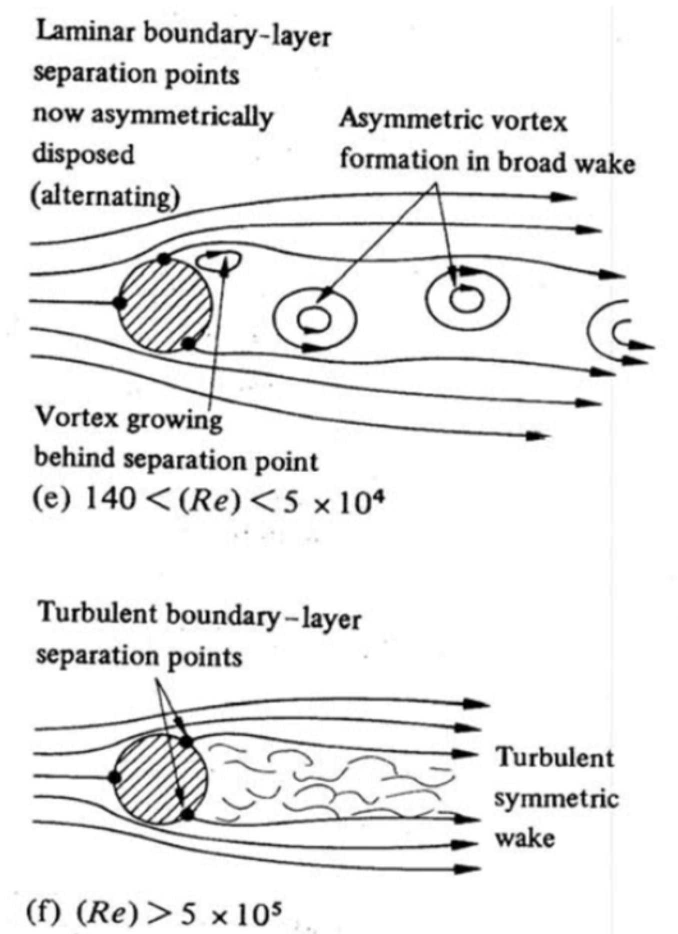


Figure 7. Flow around bodies – large Re numbers[5].

[5] Figure obtained from: Houghton, E. L., & Carruthers, N. B. (1976). *Wind forces on buildings and structures: an introduction*. John Wiley & Sons.

Bluff Body Aerodynamics:

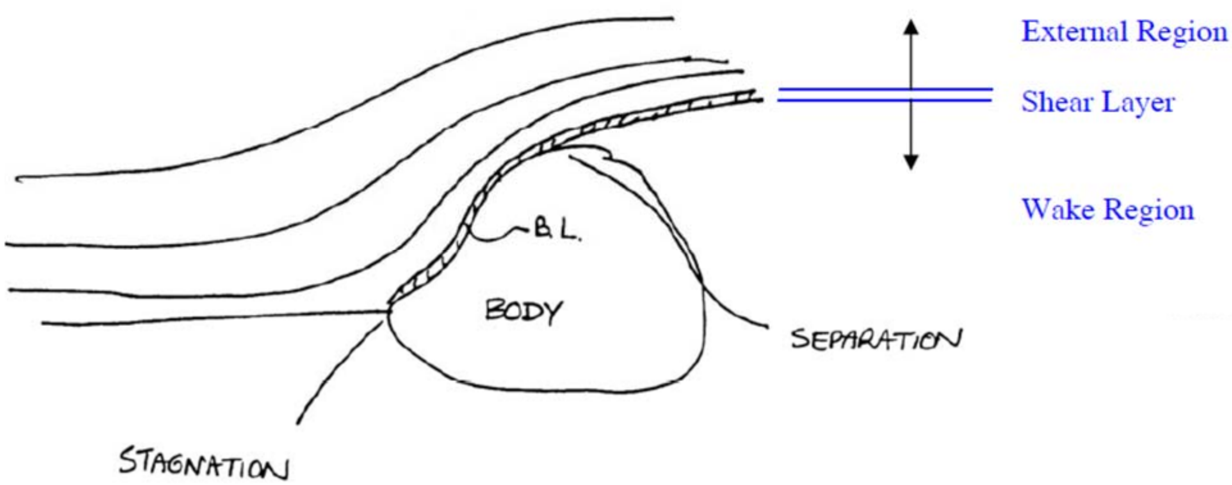
1) The fluid flow around a structure can be classified as either streamlined or a bluff body.
    a. Note both types of stagnation points and may or may not have separation.
2) _________________ body – separation well towards rear and characteristic of a small wake.
    a. Dominate force is lift – normal to the direction of flow.

3) _____________________ body – separation well force and characteristics of a large wake.
    a. Dominate force is drag – parallel to the direction of flow.

4) First type of a bluff body – the separation points are ________________ defined, for example of corners. Negotiating a sharp corner would require an infinite acceleration.

5) Second type of a bluff body – the separation points are ____________ defined, for example curve surfaces. The separation is velocity dependent (function of the Reynold's Number).

6) Summary of Bluff Bodies:



7) List of common definitions:

a. ____________________________ – point where the flow is brought to a standstill. The kinetic energy is converted to pressure energy.

b. ________________________ Layer – viscosity induces velocity gradients adjacent to the surface with zero velocity at the surface.

c. ____________________ – surface boundary layer unable to remain attached.

d. ____________________ – highly disturbed by eddying, recirculating flow leading to energy dissipation through turbulence.

e. External Region – largely undisturbed region that is nearly frictionless.

f. _________________ Layer – essentially a boundary layer that has left the body. Represents a region of transition with a very large velocity gradient. Recall Newton's Law of Viscosity – steep slope due to du/dy is associated with large shear stresses.

Boundary Layer Development and Velocity Gradients:

1) Based on the terrain, the air flow and its corresponding velocity gradient is a function of the ground ______________________.
2) This is accounted for in ASCE 7-10 as the Surface Roughness Categories (Figure 8).

26.7.2 Surface Roughness Categories

A ground Surface Roughness within each 45° sector shall be determined for a distance upwind of the site as defined in Section 26.7.3 from the categories defined in the following text, for the purpose of assigning an exposure category as defined in Section 26.7.3.

Surface Roughness B: Urban and suburban areas, wooded areas, or other terrain with numerous closely spaced obstructions having the size of single-family dwellings or larger.

Surface Roughness C: Open terrain with scattered obstructions having heights generally less than 30 ft (9.1 m). This category includes flat open country and grasslands.

Surface Roughness D: Flat, unobstructed areas and water surfaces. This category includes smooth mud flats, salt flats, and unbroken ice.

Figure 8. Surface roughness categories and their resultant velocity profiles.

3) For various surface roughness values, the velocity distributions will be modified. In the next section of notes, this will be accounted for in basic wind design by ASCE 7 and IBC codes.

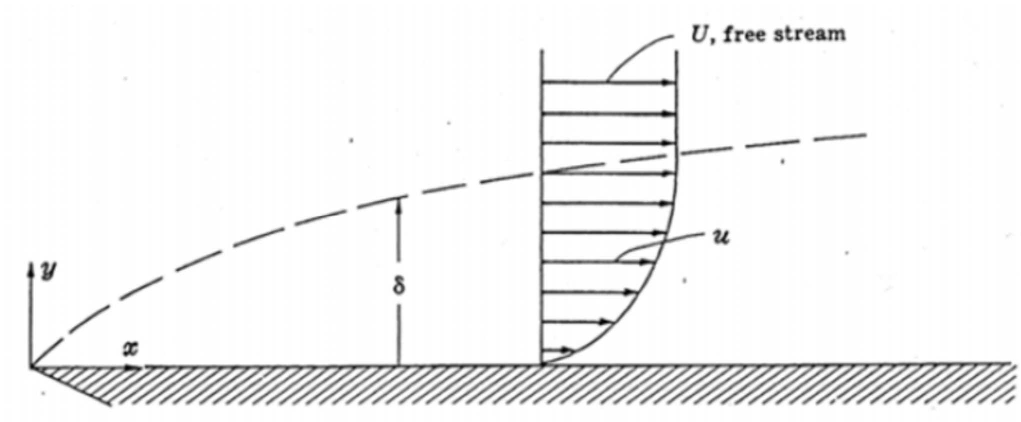


Figure 9. Basic velocity gradient.

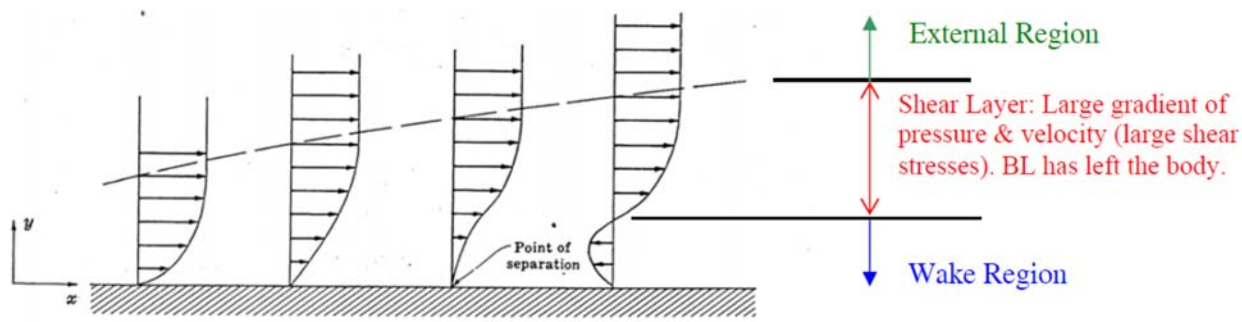


Figure 10. Various velocity gradient by "exposure type"

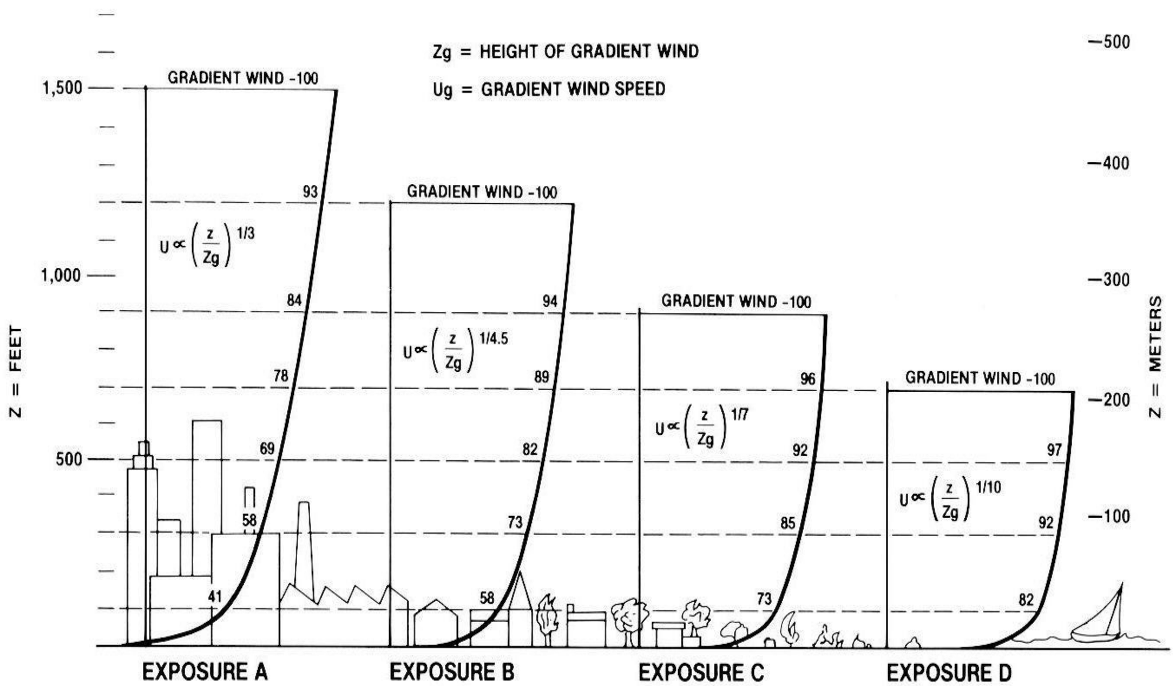


Figure 11. Velocity gradients shown against various terrains, according to ASCE 7-10.

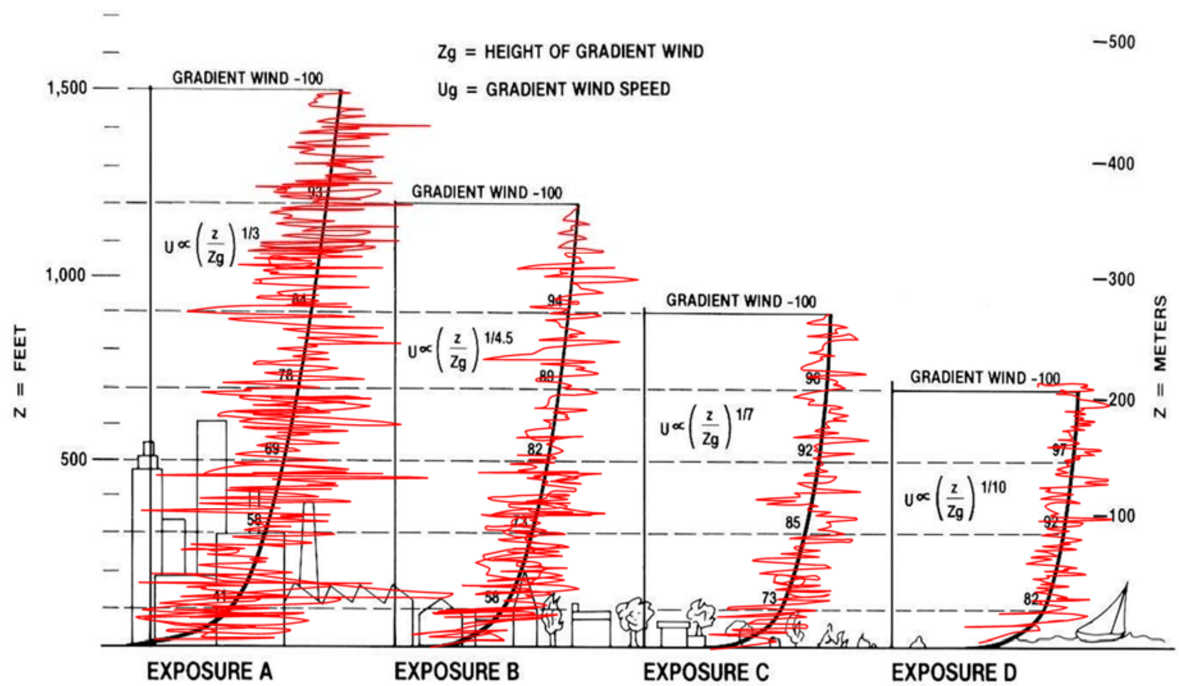


Figure 12. Velocity gradients shown against various terrains, according to ASCE 7-10 with identified variations in the wind profile. Note the distributions are a best-fit representation.