Wind

Air and water are fluids; one is gas and the other liquid. For engineers they are indeed similar because they impose load on fixed structures when they move. However, from an engineering perspective their movements are different. A building subject to wind sees a stream of air particles pass by; an offshore platform subject to sea waves is repeatedly and cyclically hit by the same water particles. Figure 1 illustrates the concepts. The air velocity in wind typically increases with height above ground or sea surface, while the wave motion diminishes exponentially with depth from the sea surface. In the Vancouver area the building code specifies wind pressures around 0.35kN/m^2 for 10-year return period, and **0.45kN/m^2 for 50-year return period**.

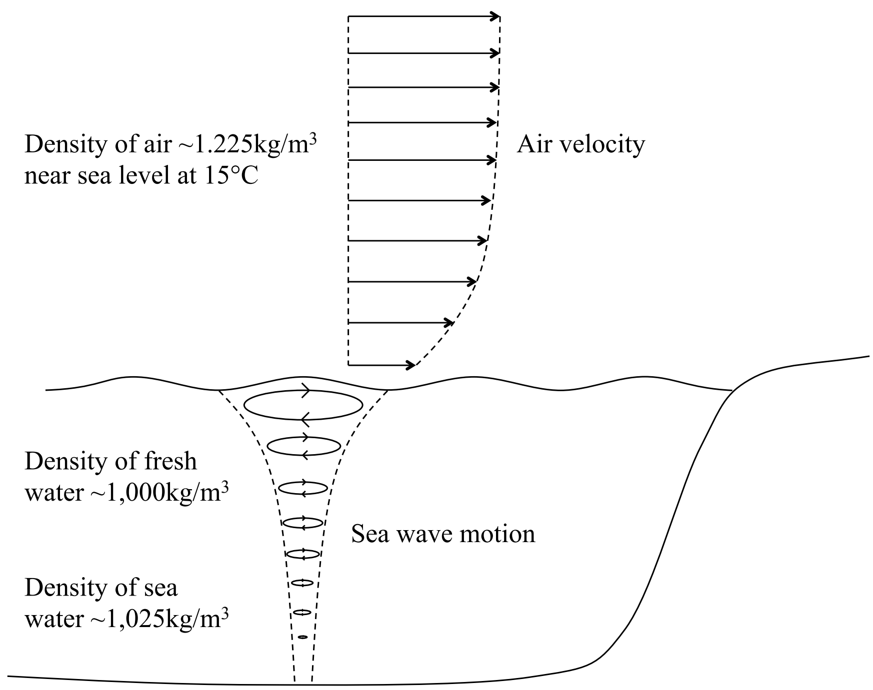

Figure 1: Motion of air and sea waves.

Wind Velocity

The wind velocity determines the pressure that the wind exerts on a structure. Although the wind velocity increases on average with distance from the ground, the velocity field is locally random, both in space and time. The severity of wind can be quantified in different ways, including:

- Peak gust velocity
- Sustained wind velocity over a few seconds
- Spatial dimension of the entire weather system

A relatively strong windstorm may have sustained winds around **100km/h**=27.8m/s, with gusts around **150km/h**=41.7m/s. A relatively strong hurricane/typhoon may have sustained winds around **200km/h**=55.5m/s.

Beaufort Scale for Windstorms

For windstorms that are usually below hurricane strength the Beaufort wind force scale has twelve categories. Similar to the Modified Mercalli scale for earthquakes, the Beaufort scale relates the severity of the windstorm to observed damage. Category 1 on the Beaufort scale indicates “flat sea” and “smoke raises vertically.” Category 12 indicates “huge waves” at sea and “very widespread damage to vegetation” on land. Category 12 is associated with wind velocities above **118km/h**=32.8m/s. Category B wind implies a velocity roughly equal to

$$v = 0.836 \cdot \sqrt{B^3} \tag{1}$$

in m/s at 10 meters above ground level. The Beaufort scale has been extended with Categories 13 through 17 to apply to tropical cyclones.

Saffir-Simpson Scale for Hurricanes

For tropical cyclones forming in the Atlantic or Northern Pacific oceans, i.e., hurricanes, the Saffir-Simpson hurricane wind scale has five categories. Each category is associated with a range of sustained wind velocities, namely average velocity during 10 minutes measured at 10 meters above the ground:

- Category 1: Sustained winds at 118-153km/h = 32.8-42.5m/s
- Category 2: Sustained winds at 154-177km/h = 42.8-49.2m/s
- Category 3: Sustained winds at 178-208km/h = 49.4-57.8m/s
- Category 4: Sustained winds at 209-251km/h = 58.1-69.7m/s
- Category 5: Sustained winds above 252km/h = 70m/s

Below those categories there is a tropical storm, with sustained winds at 63-117km/h=17.5-32.5m/s, and tropical depression, with sustained winds up to 62km/h=17.2m/s.

Tornadoes

A severe tornado many have wind velocities up to 500km/h=140m/s. A typical tornado has wind velocities at less than 200km/h=55m/s. The variation in air pressure with the radius, $\partial p/\partial r$, is called the “pressure gradient.” This derivative enter the following formula for the tangential wind velocity:

$$v^2 = \frac{r}{\rho} \cdot \frac{\partial p}{\partial r} \tag{2}$$

That is, for a pressure drop of 100millibars=10,000Pa and using the density of dry air at 0°C and standard atmospheric pressure 1.2929 kg/m^3 the velocity is:

$$v = \sqrt{\frac{500m}{1.2929\frac{kg}{m^3}} \cdot \frac{10{,}000\frac{N}{m^2}}{500m}} = 87.9\frac{m}{s} = 316.6\frac{km}{h} \tag{3}$$

Similar to the Beaufort scale the Enhanced Fujita scale ranks tornadoes according to observed damage in six categories, from 0 to 5. Only 1% of tornadoes are in category EF-5, which is most damaging:

- EF 0: Winds at 105-137km/h
- EF 1: Winds at 138-178km/h
- EF 2: Winds at 179-218km/h
- EF 3: Winds at 219-266km/h
- EF 4: Winds at 267-322km/h
- EF 5: Winds greater than 322km/h

Wind Pressure

Because air has non-zero mass density, air in motion causes pressure on surfaces that stand in its way. For undisturbed wind the theoretical pressure is

$$p = \frac{1}{2} \cdot \rho \cdot v^2 \tag{4}$$

where ρ=air density and v=air velocity. A density value is shown in Figure 1. The density decreases slightly with altitude due to atmospheric pressure and varies slightly with temperature and humidity. The density of dry air at 0°C and standard atmospheric pressure is 1.2929 kg/m^3. Using that value the pressure associated with a 98.1km/h=27.25m/s wind velocity is

$$p = \frac{1}{2} \cdot \left(1.2929 \frac{\text{kg}}{\text{m}^3}\right) \cdot \left(27.25 \frac{\text{m}}{\text{s}}\right)^2 = 480 \frac{\text{N}}{\text{m}^2} = 0.48\text{kPa} \tag{5}$$

Notice that a doubling in the wind velocity quadruples the wind pressure:

$$p = \frac{1}{2} \cdot \left(1.2929 \frac{\text{kg}}{\text{m}^3}\right) \cdot \left(54.5 \frac{\text{m}}{\text{s}}\right)^2 = 1{,}920 \frac{\text{N}}{\text{m}^2} = 1.92\text{kPa} \tag{6}$$

In practical situations the shape of the structure that is subjected to wind pressure creates local effects that alters the wind pressure. In that case Eq. (4) takes the form

$$p = \frac{1}{2} \cdot \rho \cdot c \cdot v^2 \tag{7}$$

where c is a constant coefficient called shape factor or drag coefficient.

Occurrence Rates

The frequency of windstorms of a given severity depend on several parameters (Della-Marta et al. 2009). The return period ranges from less than a month to hundreds of years. Windstorms are associated with low-pressure systems; high-pressure systems are associated with calm and sunny weather. The formation of such systems is caused by uneven absorption of solar radiation on different surfaces on Earth. The standard barometric pressure at sea level is 1,013.2 millibars with a plus/minus 50 millibars range of variation. For instance, an intense winter-storm in Northern Europe in January 1990 had a minimum pressure of 947millibars. A list of European windstorms is posted here: https://en.wikipedia.org/wiki/List_of_European_windstorms.

Tornadoes represent another cause of extremely strong winds. There are about 1,500 tornadoes every year in the central United States; many of them occur in April and May. Tornadoes appear in thunderstorms, but not all thunderstorms produce tornadoes. It is the thunderstorms that start experiencing a rotational motion of the air, due to incoming airflows, that are dangerous. The location in the thunderstorm that starts to rotate is called a super-cell. The forming of a super-cell is a warning signal that a tornado may be imminent. A number of factors contribute to the forming of super-cells and ultimately tornadoes. Some of the factors are warm humid air close to the ground, a cold front that causes the air to rise, and instabilities and interfering wind flows in the atmosphere.

References

Della-Marta, P. M., Mathis, H., Frei, C., Liniger, M. A., Kleinn, J., and Appenzeller, C. (2009). "The return period of wind storms over Europe." *International Journal of Climatology*, 20, 437–459.