CONFLUENCE
ENVIRONMENTAL COMPANY

To: Grizelda Sarria, Tetra Tech, Inc.
cc: Kevin Goss, David Scott, and Ben Nelson

From: Jessica Côté, PE
Date: August 2, 2019

Re: Mercer Island Interceptor and Enatai Interceptor Upgrade Project Wind-Wave Analysis (Rev 2)

Enclosures: N/A

Confluence Environmental Company (Confluence) conducted a desktop analysis to develop estimates of wind-wave conditions from southerly directions that could impact the proposed Mercer Island and Enatai Interceptor Upgrade Project (NME Project) design. Specially, this memorandum calculated the wind-waves at three sites: (1) Enatai Beach Park, Bellevue, WA; (2) the entrance to Mercer Slough, Bellevue, WA; (3) the shoreline at the Mercer Island Boat Launch, Mercer Island, WA. This analysis used wind analysis and wave predictions developed through previous numerical modeling, which was done for the City of Seattle to calculate the wind-wave energy affecting Lake Washington shorelines (CHE, 2015). Confluence also utilized wind speed statistics calculated for the numerical modeling to develop additional wind-wave hindcast calculations using empirical equations. This memorandum provides a summary of the calculations and resulting design wave conditions.

1.0 DESIGN WIND CONDITIONS

Wind data at the State Route (SR) 520 Bridge were collected by the Washington State Department of Transportation (WSDOT) between 1997 and 2013. These data were processed and analyzed to determine the general trends and extreme statistical parameters of wind conditions at the SR 520 bridge (CHE 2015). Figure 1a shows the directional distribution of wind speeds in 22.5-degree direction bands and where each ring represents the frequency of occurrence in 3% increments. Figure 1b shows the maximum wind speed for return periods of 2, 5, 10, 25, 50, and 100 year extremal events at 10-degree directional bands.

Based on the wind rose diagram (Figure 1a), winds blow out of the south and south-southeast (157.5 degrees to 202.5 degrees) approximately 25% of the time. In addition, winds with the largest wind speeds are also from the south-southeast (Figure 1a and 1b). The 100-year return period maximum wind speed was reported as 65 miles per hour (mph) from a direction of 170 degrees relative to true North (TN [Figure 1b]).

For in-water structural design projects, the 100-year return period wind speed is typically used as the design criteria. As a comparison the wind design criteria for the Washington SR 520 bridge, which is immediately north of the NME Project site has evolved over time from 77 mph in 1999 to the current standard of 89 mph (WSDOT 2017). The bridge design criteria include an additional factor of safety to reduce the risk of failure and potential for endangerment the public. For this project, we are providing wind-wave estimates to determine sediment transport potential and for temporary in-water structures.

The 100-year return period wind condition is the design criteria for in-water structures for this project since these structures are temporary and present a low risk of endangering the public if they fail. The slightly more conservative WSDOT 1999 design wind condition will be used as the design criteria for the shoreline designs since they are protecting a pipeline with a longer design life and located in public areas.

Both the 100-year return period wind and the WSDOT design wind speeds will be used to calculate wind-waves at the Enatai Beach Park site since this site is exposed along the direction of maximum wind speed. However, the Mercer Slough and Mercer Island Boat Launch sites are sheltered from the direction of maximum wind speed and therefore the WSDOT design wind speeds are not applicable to these sites. The 100-year wind speed along the direction of maximum fetch will be used to calculate the wind-waves at the Mercer Slough and Mercer Island Boat Launch sites for the NME Project site.

In addition, the 25-year return period wind was used to calculate wind-waves at all three of the NME Project sites to provide a more frequently occurring wind-wave condition to be used for sediment transport calculations and in shoreline protection design.

2.0 FETCH DIRECTIONS AND DISTANCES

One of the factors and inputs for calculating wave height and wave period of wind-generated waves is the fetch. The fetch is the uninterrupted distance of open water over which the wind blows without significant change in direction.

Fetch directions and distances to the three sites were calculated along the direction of the maximum wind speed and the direction of maximum fetch. and. The average water depth across the fetch was determined based on the National Oceanic and Atmospheric Administration (NOAA) Nautical Chart 18447 of Lake Washington. Table 1 summarizes fetch direction, distance and average water depth over fetch for the three sites evaluated.

At Enatai Beach Park fetch were calculated along two directions; condition 1 (190 degrees TN) is the direction of the longest fetch distance and condition 2 (170 degrees TN) is the direction from which the largest wind speeds occur. The calculations for the Enatai Beach Park site are applicable to both the shoreline and swim beach as the fetch did not vary significantly to warrant separate calculations.

The entrance to Mercer Slough is sheltered from the directions of largest wind speeds (170 to 210 degrees TN) and therefore the largest fetch distance in a southerly direction (220 degrees TN) was measured to use in the design wind-wave calculations for this site.

The shoreline at the Mercer Island Boat Launch is sheltered from southerly winds by land and the I-90 floating bridge. The largest winds speeds at the Mercer Island Boat Launch blow out of the north-northwest and north (340 degrees to 0 degrees TN). The largest fetch at this site in the direction of the largest wind speeds is along an azimuth of 336 degrees TN.

Table 1: Fetch Conditions at Enatai Beach Park

Location	Direction (degrees TN)	Distance (miles)	Avg. Water Depth (ft)
Enatai (condition 1)	190	5.5	55
Enatai (Condition 2)	170	1.5	40
Mercer Slough Entrance	220	1.5	50
Mercer Island Boat Launch Shoreline	336	2.2	80

3.0 WAVE CONDITIONS

Fetch-limited wind-wave hindcast equations from the U.S. Army Corps of Engineers (USACE) Coastal Engineering Manual (USACE, 2002, CERC, 1992) were used to estimate the significant wave height and peak wave period for each of the fetch conditions and sites outlined in Table 1. Table 2 provides a summary of these calculations.

The wind-wave model predictions for the City of Seattle showed a 100-year wind event from 170 deg North would generate a wind-wave of approximately 3.5 feet height with a wave period of approximately 3.0 seconds at the Enatai Beach site. The wave hindcast estimate for this same condition (condition 2b [Table 1]) agrees relatively well with this prediction. Wind-wave hindcast results are typically slightly more conservative (i.e., the wave heights are over predicted) than numerical model predictions.

As surface waves propagate into shallower water, the wave height changes once the wave interacts with the bottom (e.g., wave shoaling). According to linear wave theory, wave shoaling starts to occur at a water depth that is equal to approximately one-half the deep-water wave length (Dean and Dalrymple 1991). The deep-water wave length is dependent on the wave period and the depth at which waves shoal decreases with decreasing wave period.

The wind-wave estimate for Condition 1a represents the largest wave and longest wave period of 4.6 seconds. The deep-water wave height of 8 ft is valid for water depths of 16.5 ft or greater. The smallest wave predictions with a wave period of 2.6 seconds and the wind-wave height of 2.4 feet is valid in water depths of 5.0 feet or greater.

Table 2: Estimated Wave Conditions

Site & Condition	Wind Condition	Wind Speed (mph)	Fetch Distance (miles)	Hsig[1] (ft)	Tp[2] (s)
Enatai 1a	WSDOT 1999 Design Standard	77	5.5 (190deg)	8	4.6
Enatai 1b	100 year	60	5.5 (190deg)	6	4.2
Enatai 1c	25 year	55	5.5 (190deg)	5.4	4.0
Enatai 2a	WSDOT 1999 Design Standard	77	1.4 (170 deg)	4.2	3.0
Enatai 2b	100 year	65	1.4 (170 deg)	3.5	2.8
Enatai 2c	25 year	60	1.4 (170 deg)	2.8	2.6
Mercer Slough Entrance	100 year	60	1.5 (220 deg)	3.2	2.8
Mercer Slough Entrance	25 year	55	1.5 (220 deg)	3.0	2.7
Mercer Island Boat Launch Shoreline	100 year	48	2.2 (336 deg)	3.0	2.9
Mercer Island Boat Launch Shoreline	25 year	40	2.2 (336 deg)	2.4	2.7

[1] Significant wave height
[2] Peak wave period

4.0 DESIGN WAVES AND WATER LEVELS

Waves at the NME sites will be limited by depth-induced breaking. As water depth decreases, waves shoal and break, dissipate energy, and result in smaller wave heights at the shoreline. Individual maximum wave heights will typically be limited to 0.78 times the local water depth. The depth of wave breaking has been calculated for each of the sites and conditions shown in Table 4.

4.1 Containment Design Conditions

The breaking wave depth should be used in planning of the installation of the containment devices. The water depth at which the waves break will be a location of the largest wave heights and the maximum force on in-water structures and devices. It is important to note that the wave breaking depths reported in table 4 are for a specific wave conditions, but the range of wave conditions and therefore range of breaking depths should be expected to occur at each site. For example, wave breaking at the Enatai Beach Park will occur in water depths of approximately 3.5 ft to 10 ft depending on the storm event. The range of wind-waves heights and breaking wave depths provided in Table 4 can be used as a look up table to estimate the wave conditions at a site based on the water depth in which the containment device is located and the projected or reported wind speed during construction activities. Wave run-up and set-up are not likely to be applicable to containment design.

4.2 Shoreline Design Conditions

The effect of wind-waves on the shorelines will be observed through wave set-up and wave run-up on the beach slope. Wave set-up and run-up represent the vertical component of wind-waves on the beach slope above the still water level.

Combined wave set-up and wave run-up was calculated according to the theories presented by Komar (1998) for reflective beaches based on deep-water wave height, water depth of wave breaking, and beach slope. The combined wave set-up and wave run-up was calculated for all of the wave conditions which were presented in Table 2.

Wave run-up is dependent on beach slope. Beach slopes at the project sites ranged between 1:8 (vertical: horizontal) and 1:9 based on the existing bathymetry. However, the wave set-up and run-up did not vary significantly for these two slopes, so an average slope of 1:8.5 was used for the wave run-up calculations.

The wave set-up and run-up calculations are added to the still water elevations to approximate total water levels at the project sites which can be used for the basis of design. Water levels in Lake Washington are managed at a level between the Low Water Datum (LWLWD) of 16.77 ft NAVD88 and Ordinary High Water (OHW) Datum of 18.60 ft NAVD88 by the US Army Corps of Engineers. The LWLWD is maintained through most of the winter months, and then water levels are increased by 2 feet starting in February or March and maintained at OHW through July to accommodate fish passage and higher water usage during these months. From August through November, water levels decrease gradually to LWLWD. These water levels are shown in Table 3.

Table 3: Water Level Datums

Condition	King County Metro (ft)	NAVD88 (ft)
Ordinary High Water	115.03	18.60
Lake Washington Low Water	113.20	16.77
NAVD88	96.43	0

The total water levels based for each site and conditions are provided in Table 4. OHW is used as the still water level in the total water level calculations for the NME project. While some wind-wave events will occur during months when Lake Washington is maintained at LWLWD, using OHW provides a more conservative estimate for the total water level as the highest elevation in which wind-waves will reach during any season.

Table 4: Design Wave Conditions and Water Levels

Site & Condition	Wind Condition	Hsig[1] (ft)	Breaking Wave depth (ft)	Run-up and Set-up (ft)	Total Water Level (ft NAVD88)	Total Water Level (ft Metro)
Enatai 1a	WSDOT Design Standard	8	10.3	2.9	21.5	117.9
Enatai 1b	100 year	6	7.7	2.2	20.8	117.2
Enatai 1c	25 year	5.4	6.4	1.8	20.4	116.9
Enatai 2a	WSDOT Design Standard	4.2	5.4	1.4	20.0	116.5
Enatai 2b	100 year	3.5	4.5	1.2	19.8	116.2
Enatai 2c	25 year	2.8	3.6	1.0	19.6	116.0
Mercer Slough Entrance	100 year	3.2	4.1	1.1	19.7	116.2
Mercer Slough Entrance	25 year	3.0	3.8	1.0	19.6	116.1
Mercer Island Boat Launch Shoreline	100 year	3.0	3.8	1.1	19.7	116.1
Mercer Island Boat Launch Shoreline	25 year	2.4	3.1	0.9	19.5	115.9

Since the largest range of conditions were evaluated at the Enatai site, the total water levels also show the largest range. The depth of wave breaking varies between 3.5 feet and 10 feet based on the wind condition. In addition, the total water levels at the shoreline vary by up to 3 feet based on the wind condition.

The wave heights for the 25-year and 100-year storm events at the Mercer Slough entrance and Mercer Island Boat Launch are similar and therefore, the wave run-up and set-up only vary slightly (+/- 0.1 ft). Therefore, the slightly more conservative 100-year storm event conditions should be used for all project design elements.

5.0 SEDIMENT COMPOSITION AND TRANSPORT

Wind-waves are the primary mechanism of sediment transport along the shorelines of Lake Washington. Wind-waves which hit the shoreline at an oblique angle as will occur at Enatai Park and Mercer Island Boat Launch can transport material alongshore (parallel to the shoreline) and generally in the direction in which the wind is blowing. The goal of this project is to protect the shoreline and pipeline from erosion and therefore to limit the potential for sediment transport under wind-waves.

5.1 Existing Sediment Composition

The sediment grain size distribution along the existing shoreline at the project area at Enatai Beach park is mixed sand and gravel with a maximum grain size of approximately 2 inches up to LWLWD. The sediments above LWLWD which interface with the existing lawn are also mixed sand and gravel but have a larger maximum grain size of approximately 3 to 4 inches. There is some evidence of erosion of the upland lawn and fill at the shoreline of Enatai Beach Park which is an indication of shoreline change caused by wind-waves and the potential for sediment transport of placed material at this site.

The existing shoreline at the Mercer Island Boat Launch is fronted by a concrete bulkhead which intersects with lawn on the upland side and mixed sand and gravel below LWLWD. The sediment grain size distribution below LWLWD at the shoreline has a maximum grain size of approximately 2 inches. There is also evidence of erosion along the shoreline at Mercer Island Boat Launch as well as erosion of the upland slope from runoff.

The shoreline restoration design for both the Enatai Beach Park and Mercer Island Boat Launch are intended to improve habitat conditions. One of the required design elements is the placement of spawning gravel from the shoreline out to a water depth of at least 6 feet. Spawning gravel is typically composed of sediment ranging in grain size from fine sand to 2-inch gravel and has a median grain size of approximately 0.5 inches.

5.2 Bed Shear Stress

Sediment transported under wind-waves on mixed sand and gravel beaches occurs primarily as bed load transport moving low in the water column across the bed and beach. This is in contrast to sand beaches which are primarily affected by suspended load transport where sediment gets stirred up into the water column and transported. The friction of the wave orbital velocities on the beach slope generate shear stress and mobilize sediments which can then be transported alongshore.

Bed shear stress under wind-waves have been calculated based on a combination of methods from Soulsby (2006) and Soulsby and Campbell (2005). These formulas were applied for the range of wind-waves, the range of water levels, and several median sediment grain sizes to represent wind-waves which can act on the shorelines at Enatai and Mercer Island. The bed shear stress estimated for the wind-wave conditions were then compared to critical bed shear stress based on Julien 1995 (USFS 2008) and to determine the maximum sediment grain size which would be mobilized by each condition. Below is a summary of the results of the analysis of bed shear stress under wind-waves:

- At Enatai Beach Park, the wave generated by the WSDOT design wind and the 100-year wind would produce bed shear stress of approximately 35 to 40 Newtons per meter squared (N/m2) or 0.7 to 0.8 lbs. per foot squared (lb/ft2). Bed shear stress of this magnitude are sufficient to mobilize sediment up to 2-inch median grain size.
- Wave generated by the 100-year return period wind at Mercer Island Boat Launch will produce bed shear stress on the order of 25 N/m2 (0.5 lb/ft2) and can mobilize sediment up to 1.25 inches in diameter.

Bed shear stress has been calculated and compared to critical shear stress for a median grain particular grain size. Based on the observations of sediment grain size distribution at the project sites, these shear stress estimates appear to be conservative, meaning higher bed shear stress is being estimated that might be occurring at the sites on a regular basis. The research on sediment mobility of mixed sand and gravel beaches under wind-waves is very limited because coarser grained beaches are not as common as sand beaches. However, research on bedload transport in rivers can be applied in a general sense to bedload transport on beaches particularly related to critical shear stress which is simply a hydrodynamic force acting on the particles to initiate motion.

Several studies have shown that beaches with a poorly sorted sediment distribution rather than a uniform sediment distribution tend to have higher critical shear stress for sediment grain sizes of 2 inches and smaller (USFS 2008). More recent studies on bedload transport in rivers has shown the critical shear stress can be 20% to 50% higher in channels where the ratio between the D50 (median grain size) and D85 (85% passing grain size) is between 2 and 4 (Ferguson 2012).

Most mixed sand and gravel beaches have a ration of D50 to D85 of 3 to 4 and therefore are expected to have a higher critical shear stress than the critical shear stress for only the D50.

5.3 Beach Restoration Grain Size Specifications

Based on this information and additional design criteria discussed in the following sections, three sediment grain size distributions have been specified for the beach restoration sites. These sediment grain size distributions are described generally in the bullet points below and are provided in detail in Tables 1 through 3.

- Gradation 1 (Type J on design plans) is a 2-inch minus spawning mix which is placed waterward of the LWLWD where the slopes are generally shallow (1:15). This grain size distribution will be placed in a 24-inch thick layer. It is predicted this material can be mobilized under the largest WSDOT and 100-year wind-wave events and transported short distances alongshore.

- Gradation 2 is the beach nourishment to be placed between the LWLWD and OHW which is expected to receive wind-wave run-up particularly during winter months.
    - Enatai Beach Park (Type K on design plans) is a 6-inch minus mix placed in a 24-inch thick layer between LWLWD and OHW. This gradation has a wider grain size distribution with coarse gravels and cobbles to remain stable under the larger wind-waves which are expected at this site.
    - Mercer Island Boat Launch (Type L on design plans) is a 4-inch minus mix placed in a 24-inch thick layer between LWLWD and OHW. This gradation has a median grain size (D50) of 2-inches, and is supplemented with 4-inch gravel to remain stable on the steeper slope and under wind-waves.
- Gradation 3 is the beach nourishment to be placed between the OHW and the 100-year or WSDOT design water level including wind-wave run-up and set-up. This grain size distribution is the same for Enatai Beach Park and Mercer Island Boat Launch (Table 4). It has a median grain size distribution of 1-inch with a fraction of coarser sediment to resist wind-waves which might occur during higher water levels and be stable on the upper slope. This gradation also has additional fine material to assist with planting. This sediment gradation will be achieved by placing 12-inches of Type K material (Table 2) at Enatai Beach Park and Type L (Table 3) material at Mercer Island Boat Launch and then 12-inches of Type J (Table 1) material.

Table 1. Gradation 1 for shoreline restoration designs (Type J).

Sieve Designation U.S. Standard Square Mesh	Percentage by Weight Passing
2 Inch	85
1 Inch	65
¼ Inch	50
No. 10	40
No. 40	25
No. 100	10

Table 2. Gradation 2 for Enatai Beach Park (Type K)

Sieve Designation U.S. Standard Square Mesh	Percentage by Weight Passing
4 Inch	85
2 Inch	50
1 Inch	15
1/2 Inch	10
No. 4	5

Table 3. Gradation 2 for Mercer Island Boat Launch (Type L)

Sieve Designation U.S. Standard Square Mesh	Percentage by Weight Passing
6 Inch	90
3 Inch	70
1 Inch	50
½ Inch	30
No. 4	20
No. 8	10
No. 16	5

Table 4. Gradation 3 for both shoreline restoration designs

Sieve Designation U.S. Standard Square Mesh	Percentage by Weight Passing
4 Inch	95
2 Inch	85
1 Inch	50
1/2 Inch	35
No. 4	25
No. 8	15
No. 16	10

6.0 SHORELINE DESIGN CRITERIA

The shoreline design at each site has three primary goals:

- Protect toe of slope at shoreline from wave energy so as built slope angles are maintained
- Protect newly installed sewer lines and pipes from wave energy by maintaining depth of burial of pipe
- Replace shoreline hard armoring with soft shore design elements including large wood and sediment grain composition that will provide habitat
- Augment shorelines with native vegetation and wood that provide shoreline complexity

The generalized design criteria for the shoreline enhancements are as follows:

- The new beach slope should be stable for the given hydrodynamic conditions and as close to the slope that would naturally occur at the site.
- The new soft shore protection design should be able to dissipate wave energy from a 100-year storm event combined with ordinary high water, for a total water level of approximately 116 feet Metro at the Mercer Island Boat Launch Shoreline and 118 feet Metro at the Enatai Beach Shoreline
- The design should be able to withstand annual inundation to a total water level of 116 ft Metro, which represents OHW + 25-year wind-wave

6.1 Enatai Beach Park Shoreline

The major design elements of the shoreline at Enatai Beach Park Shoreline include:

- Installation of spawning gravel beach nourishment from 105 ft Metro to LWLWD
- Beach nourishment installed from LWLWD to 118 ft Metro in the gradations specified in section 5.3 at a slope of approximately 1:10
- Large wood installed shore parallel or slightly oblique to shore and anchored at an the LWLD elevation and the OHW elevation.
- Smaller cedar logs installed at OHW (below large anchored logs) as would naturally occur along the shoreline.
- Installation of overhanging vegetation that is slope stabilizing and will provide shade and leaf litter. If vegetation is not tolerant of regular inundation it must be installed above 117 ft Metro.

6.2 Mercer Island Boat Launch Shoreline

The major design elements of the shoreline at Mercer Island Boat Launch should include:

- Installation of spawning gravel beach nourishment from 105 ft Metro to LWLWD
- Beach nourishment installed from LWLWD to 118 ft Metro in the gradations specified in section 5.3 at a slope of approximately 1:8
- Large wood installed shore parallel or slightly oblique to shore and anchored at an LWLD elevation and the OHW elevation. No additional cedar wood is recommended at this site as there is not sufficient space to accommodate due to the steeper slopes.
- Installation of overhanging vegetation that is slope stabilizing will provide shade and leaf litter. If vegetation is not tolerant of regular inundation it must be installed above 116.5 ft Metro.

6.3 Anchored Large Wood

The placement and stability of large wood is integral to the shoreline design. Large wood is being buried and anchored at the LWLWD to stabilize the nourishment placed between LWLWD and OHW and to protect the shorelines from erosion from wind-waves. Wood at LWLWD will be subjected to buoyancy forces when the lake levels are raised to OHW and therefore require a robust anchoring system.

Large wood being buried and anchored at the OHW will provide stabilization of the nourishment above the OHW which also provides stability for vegetation being planted above the OHW. While the large wood at the OHW is not expected to be buoyant, all shorelines are susceptible to erosion and a robust anchoring system provides an extra measure of safety against movement of the large wood and destabilization of the shoreline.

There are not formal design guidelines for anchoring large wood on shorelines as soft shoreline design is still a relatively new practice. The only design manual on using large wood in hydrodynamic conditions is the National Large Wood Manual (USBR and ERDC 2016) for fluvial systems. This manual provides an excellent overview of techniques used to anchor wood and the following recommendations:

- Passive anchors where the shape, weight, and ballast of the large wood is adequate to resist movement are not recommended if there is infrastructure or structures which will get frequently overtopped by water.
- Mechanical anchors (helicoil or manta ray) all require material covering the earth anchors to remain static.

- Guidelines generally discourage use of earth anchors because if there is a failure in slopes or erosion occurs the anchors will pull out.

Based on the large wood manual, the use of passive or mechanical anchors are not recommended for this project because (1) the sediment in a coastal environment are always somewhat dynamic (not static) and (2) if the sediment erodes, the earth anchors will pull out and risk failure of the shoreline design and exposure of the pipelines. Use of concrete blocks buried beneath the substrate to provide mass with a chain connected to the large wood have been used in many restoration applications on the shorelines of Puget Sound. The Marine Shoreline Design Guidelines (MSDG) a publication prepared for WDFW and Ecology recommend large wood be anchored and buried to assure they are not moveable in the future (Johannessen et al 2014). The MSDG further states that buried large concrete blocks placed well below the finished grade are a reliable approach to anchoring wood and the disturbance caused by the process to bury the blocks is extremely short in duration on beach environments (Johannessen et al 2014).

7.0 REFERENCES

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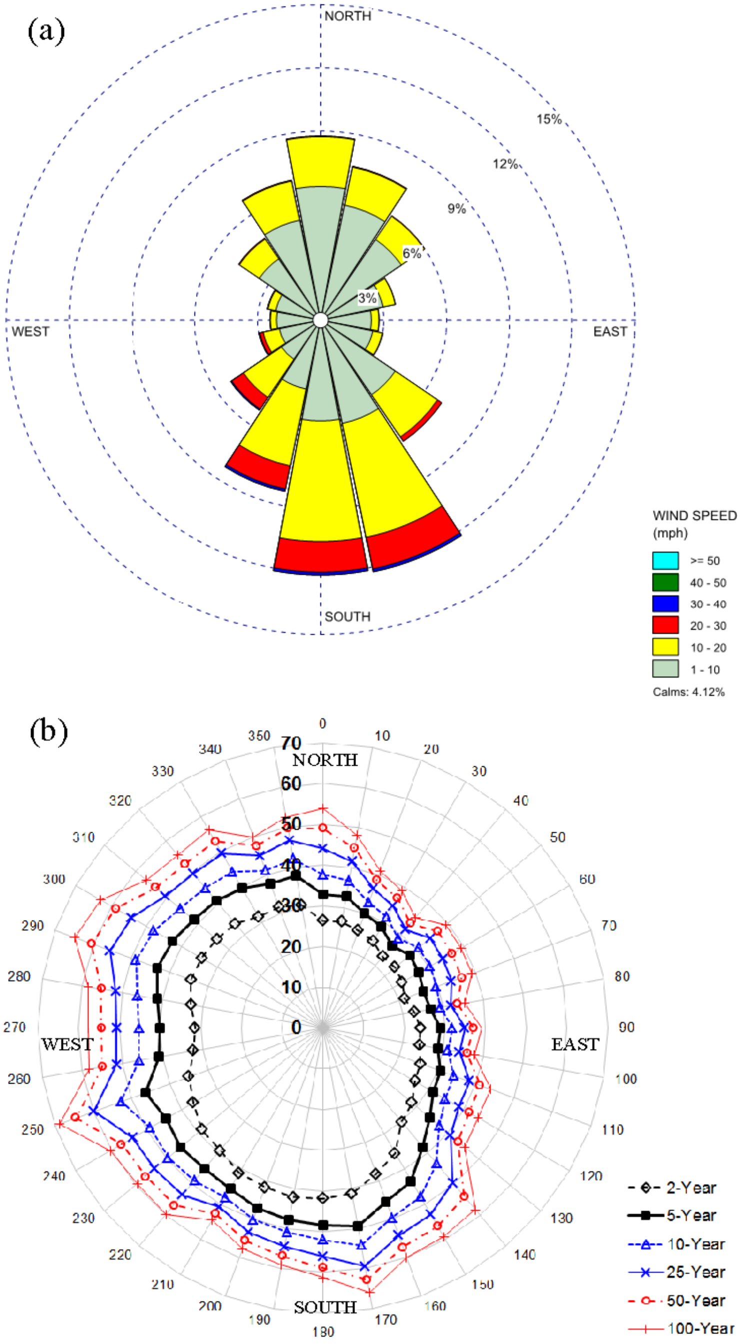

Figure 1. The directional distribution of wind speeds in 22.5-degree direction bands and the maximum wind speed for return periods of 2, 5, 10, 25, 50, and 100 year extremal events at 10-degree directional bands (adopted from CHE 2015).