

# Topographic Wind Speed-up and Directionality Factors for Use in the City and County of Honolulu Building Code

Gary Chock<sup>1\*</sup>, Jon Peterka<sup>2</sup>, Guangren Yu<sup>3</sup>

<sup>1</sup>President, Martin & Chock, Inc, Honolulu, HI, USA, gchock@martinchock.com

<sup>2</sup>Principal, Cermak Peterka Petersen, Inc., Fort Collins, CO, USA, jpeterka@cppwind.com

<sup>3</sup>Engineer, Martin & Chock, Inc, Honolulu, HI, USA

## INTRODUCTION

The project has undertaken new wind speed design mapping and technical provisions to enable the adoption of the International Building Code and ASCE-7 standard by the City and County of Honolulu, which is located within a hurricane hazard region. Consistent with the requirements of the International Building Code and intent of the ASCE-7 standard, customized wind design factors were developed from site-specific wind-tunnel test data for: 1) specification of topographic effects factor  $K_{zt}$ , 2) directionality weighting,  $K_d$ , in consideration of the probability of critical windspeed, and 3) mapping of Exposure Categories for determination of  $K_z$ , exposure coefficient. A risk-consistent level of protection for hurricane hazard can thus be achieved in structural design of new buildings in the City and County of Honolulu, Hawaii, USA.

**KEYWORDS:** Wind Speed, Topographic Speed-up, Directionality, Exposure, Hurricane, Building Code

## OBJECTIVES

The probabilistic treatment of directional winds and the topographic speed-up of amplitudes are important design considerations. Implementation of the modern International Building Code and ASCE wind standards in Hawaii requires an empirical evaluation of the  $K_{zt}$  topographic and  $K_d$  wind directionality terms that are an integral part of the ASCE-7 standard, so that they can be adapted for use in the complex terrain of the island of Oahu in the State of Hawaii.

The ASCE Standard 7 [1] specifies the following equation for velocity pressure:

$$q = 0.00256 K_z K_{zt} K_d V^2 I$$

where:

$K_z$  is the velocity pressure exposure coefficient that is defined according to system or component design cases and terrain category (B, urban, suburban or wooded or C, flat, unobstructed, open terrain without substantial development),

$K_{zt}$  is the topographic speed-up factor,

$K_d$  is the wind directionality factor which accounts for the fact that the probability that the maximum wind may not impact the structural component or system in its weakest orientation,

$V$  is the peak gust windspeed associated with a 500-year return period, divided by  $\sqrt{1.5}$ , and

$I$  is the Importance Factor of the building or structure, based on its occupancy type, which functions as an implicit adjustment factor to the return period.

The project is making several needed technical modifications so that wind-tunnel-based research results can be used by structural engineers in design applications through the ASCE 7 Analytical Method:

1. Derivation of the appropriate design wind speed utilizing a Monte Carlo simulation of the East-Central Pacific region.

---

\* Corresponding author. Tel.:+1-808-521-4513; fax:+1-808-531-4508

Mailing address: 1132 Bishop Street, Suite 1550, Honolulu, Hawaii, 96813, USA

2. Probabilistic wind speed hazard micro-zonation or contour mapping incorporating topographic effects appropriate for structural design specification of  $K_{zt}$ .
3. Incorporation of  $K_d$ , directionality weighting of the probability of critical wind orientation for sites with significant directional wind amplitude variation within a hurricane hazard region.
4. Exposure Category wind profile classification with adjustments to account for terrain roughness/land use or other topographic factors contributing to boundary layer turbulence, resulting in a map useful for the determination of  $K_z$ , exposure coefficient.

In this paper the particular methodologies used to determine Hawaii-specific values for  $V$  and the  $K_z$ ,  $K_{zt}$ , and  $K_d$  factors are discussed. Data products suitable for local amendments to the City and County of Honolulu wind design code are shown

## PEAK GUST DESIGN WINDSPEED $V$

The 3-second peak gust is the wind velocity parameter now used in American Society of Civil Engineers (ASCE-7), *Minimum Design Loads for Buildings and Other Structures* [1], which is the reference standard of the *International Building Code 2003* (IBC). The UBC fastest-mile windspeed is equivalent to a 96 mph 3-second gust. It was based on a conservative evaluation of Honolulu data from two weather stations by H.C.S. Thom in 1968 that did not include *any* consideration of hurricane data, and therefore this code did not provide an appropriate basis for direct conversion to an IBC 3-second gust.

Design windspeeds in Hawaii are governed by hurricanes, i.e., the governing extreme winds in Hawaii are produced by rare tropical cyclones that have no direct relationship with a parent population of regular wind climatology. The current IBC 3-second gust value, associated with a 500-year return period divided by  $\sqrt{1.53}$ , was partially based on an earlier study, *Design Windspeeds for Honolulu, Hawaii* [2], conducted by J. Peterka in 1993 immediately after Hurricane Iniki. Later in 2002, the Hawaii hazard curves for wind speeds and directional probabilities due to tropical cyclones were reanalyzed by a 1000-year computer simulation; a much improved methodology was used by Peterka and Banks in *Windspeed Mapping of Hawaii and Pacific Insular States by Monte Carlo Simulation* [3, 4], to establish design hurricane windspeeds for individual islands in Hawaii. The Peterka simulation of 1000 years, utilizing a more robust dataset of historical storms and simulating hundreds of thousands of storms in the east and central Pacific, indicates that Oahu hurricane hazard has been underestimated in past codes. The City of Honolulu is located on the island of Oahu. The hazard curve for tropical cyclone-produced winds on Oahu is shown in Figure 1:

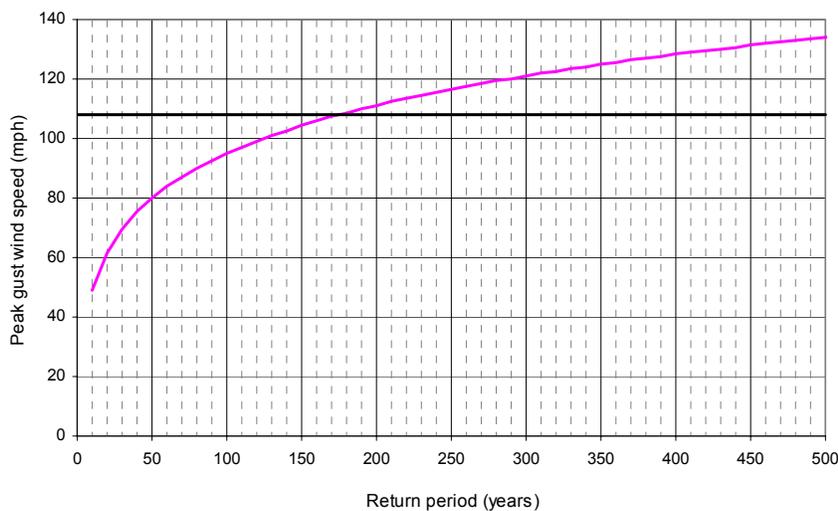


Figure 1 Tropical Cyclone Wind Hazard Curve for Honolulu, Hawaii

In 2001, a similar simulation was conducted under sponsorship of the State Department of Commerce and Consumer Affairs, *Hazard Mitigation Study for the Hawaii Hurricane Relief Fund* [5]. The two Monte-Carlo simulations found that the basic wind speed was underestimated in the UBC by approximately 5 to 10 mph, and verified that a 105 mph 3-second peak gust for Oahu is more appropriate for design in accordance with the ASCE-7 intent for a 500-year event reduced by  $\sqrt{F=1.5}$ . A 105 mph gust has a return period of approximately 150 years on Oahu. The ASCE-7 Commentary (Table C6-3) indicates that the return period of the mapped basic wind speeds of the continental U.S. range from 50 to 90 years. The 50-year *non-hurricane* gust wind speed for Oahu is approximately 70 mph, and so the implied hurricane importance factor ( $V_{500} / [\sqrt{1.5}] / V_{50}$ ) in this region would be 2.25, much higher than the 1.25 obtained in the continental U.S. Conversely, main wind-resisting structural elements of an Oahu structure designed to a 50-year non-hurricane wind speed would have an ultimate load capacity for a hurricane wind event of less than 100-year return period unless governed by higher seismic design loading. Conventional deemed-to-comply prescriptive wood framed residences would also fall into this category of structures reaching ultimate capacity at a relatively low return period event. In this context, the ASCE-7 provisions stipulating the 500-yr wind divided by  $\sqrt{1.5}$  appears prudent and conservative.

Another conclusion of the Peterka study was that the directional probabilities of windspeed (i.e., *without topographic effects*) for Oahu island were found to be approximately uniform (within about 5%) with direction, due to the general randomness of the distribution of expected storm tracks in the Hawaii region.

### TOPOGRAPHIC SPEED-UP FACTOR $K_{zt}$ METHODOLOGY

A 2002 NASA-sponsored project [6] produced new methodologies pertaining to modeling of island topographic effects. To determine speedup factors for Oahu and Kauai, terrain models of portions of the island terrain were constructed and tested in the wind tunnel. Data of the 358 sites of Oahu and Kauai for 16 directions of wind comprised 5728 records. Velocity measurements were made with a hot-film anemometer. A multi-parametric model was formulated to fit the measured data (see Figure 2), and that model was used to estimate the wind speedup in all other areas of the island of Oahu.

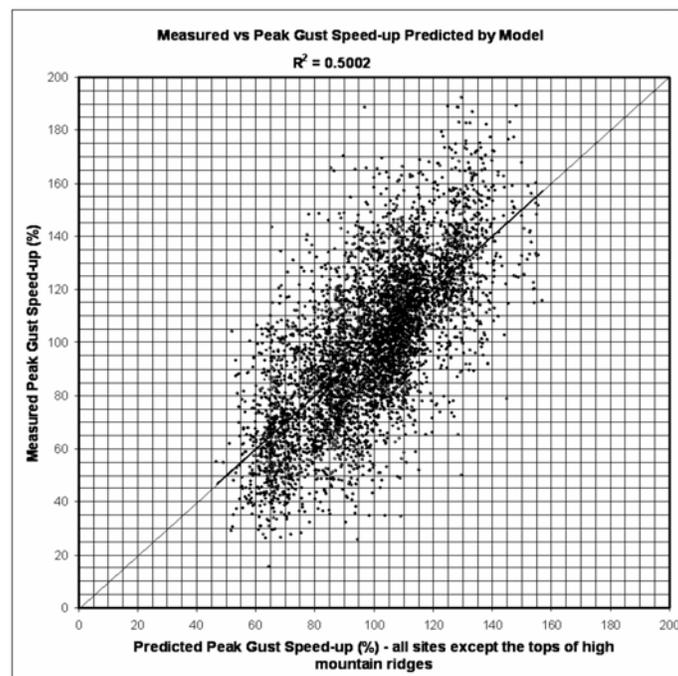


Figure 2 Multi-Parametric Wind Predictive Model Results

The topographic speed-up methodology does not include Fujita microbursts and mini-swirls. It does not include additional “katabatic” effects of an unstable atmospheric stratification; the katabatic contribution to downslope wind originates in a cooling, through vertical motion, of air at the top of the mountain. (The model includes downslope wind accelerations due to topographic induced convergence.)

It was found that the ASCE-7 provisions do not sufficiently account for the significant effect of topographic wind speed variations caused by the complex topography in Hawaii. The ASCE-7 topographic factor,  $K_{zt}$  in its default specification will not give accurate results nor can it be applied with consistency by practicing structural engineers for the complex topography of Hawaii.

The current ASCE 7-02 provisions would theoretically require the assessment of up to 16 different wind loadings, each with a directionally specific  $K_{t\theta}$  value. This would be considered impractical for design purposes. Based on the wind-tunnel model and predictive speed-up computations, the single map shown in Figure 3 below is a representation of the raw data of maximum speed-up from any direction, or the envelope values of  $\sqrt{K_{zt}max}$ , for the case where  $z = 10$  meters.

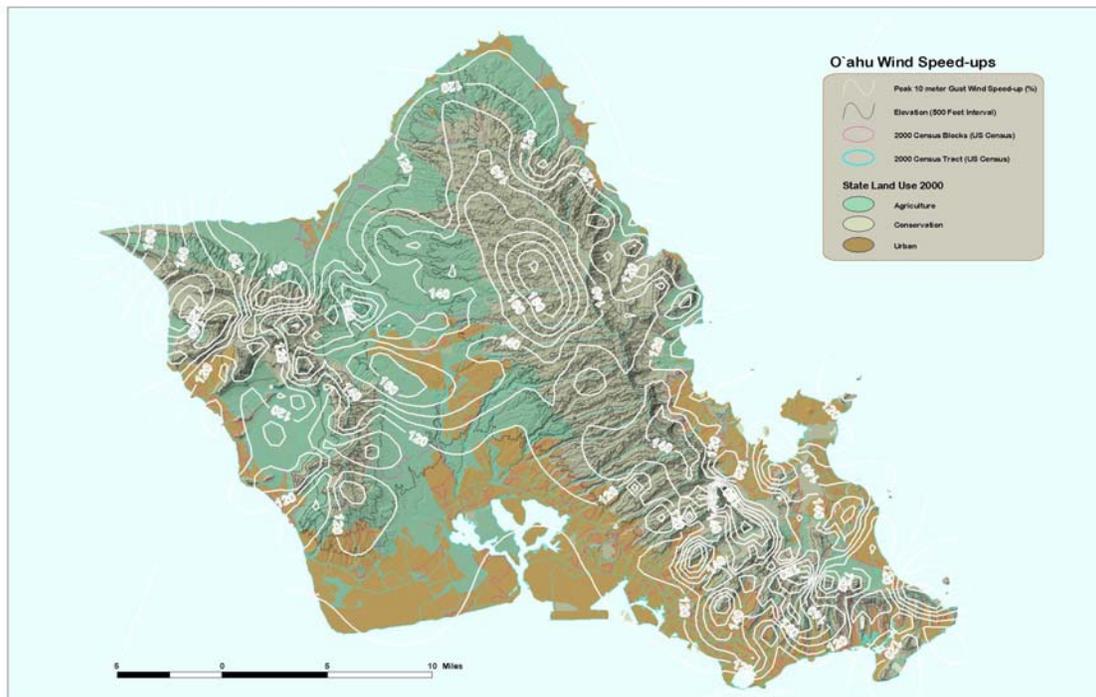


Figure 3 Peak Gust Maximum Speedup from Raw Data (in percentage)

## TOPOGRAPHIC EFFECTS ON LOCAL WIND DIRECTION

Subsequently, additional wind-tunnel testing and statistical modeling/analysis of sample sites in various landforms was performed to establish the landform diversion of incipient wind flow. The additional testing was desirable to determine to what extent the wind flow azimuth may not be uniformly distributed at a local site due to orographic channeling. Directional windfield wind tunnel tests were conducted using more refined surfaces of the original 2002 physical models of South Oahu and North Oahu at a scale of 1:6000. These tests provided confirming data for validation of the final wind directionality factors,  $K_d$ , wind vertical profiles and the effect of topography on  $K_z$  exposure coefficient profiles. Tests included 16 wind directions to provide measurement of the wind directional vectoring and profile measurements at 24 of the original Oahu test points using refined surface treatments of the original physical models. An Aeroprobe 5-hole probe allowed simultaneous measurement of fluctuating pressures at all 5 ports at the equivalent of 18m above the local terrain. At each instant, the vector magnitude and direction of flow can be calculated if the vector is within 70 degrees of the probe axis. Data were taken at 4 elevations above the surface, 60, 120, 195, and 315 ft (18, 36, 59, and 96 m). In addition, another

measurement point was obtained at most locations at 4600 ft (1400 m) to check that the velocity probe was aligned as intended. In general, the original data taken with the hot-film anemometer appears to be conservative for the locations studied, in that it typically overestimates the wind speed measurements of the new refined terrain model due in part to an improved local surface roughness on the model. In general, when the local direction of flow is greatly different from the global approach flow, the gust speeds are not very high, indicating that terrain channeling was not particularly effective in creating speed-up for highly diverted flow.

ASCE values of  $K_1$  and  $K_2$  will not be included in the procedure since all topographic effects defined by a 10-meter digital elevation model have been incorporated in the map of  $K_{zt}$ . The  $K_3$  adjustment was found to lack applicability in this island's topography. The test data wind vertical profiles were found to be dominated by 3-dimensional non-equilibrium flows and macroscale turbulence, in that the wind profiles do not have sufficient fetch of uniform terrain to achieve equilibrium as successive topographic features are encountered in the flow. A revised map rendering  $K_{zt}$  at 10 meters is given below in Figure 4, including the data from the 24 retested sites in urban or agriculturally-zoned areas. Multiquadric Radial Basis Functional interpolation was used to produce the gridded surfaces contoured in the figures. All contouring was done in an isotropic method, i.e., no specified favored axis weighting factors were used.

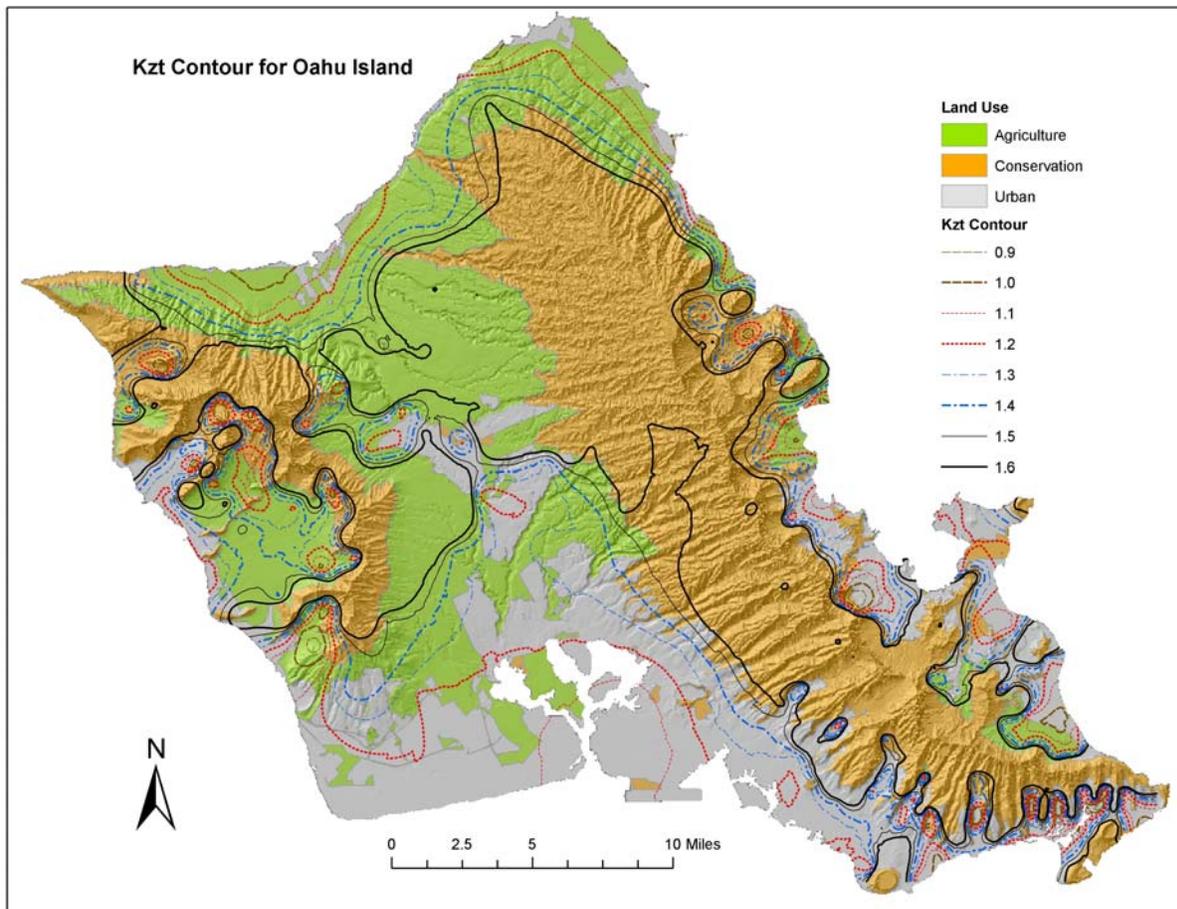


Figure 4 Topographic Factor  $K_{zt}$  at 10 meters

Fig

Use of a single map for design representing the maximum  $K_{zt}$  value of topographic speed-up squared from any direction would be the simplest to apply, although overly conservative. ASCE provides a basis for making an adjustment of wind load by means of the directionality factor  $K_d$ , which can mitigate this over-conservatism by taking into account the probability that the predominant extreme wind speed-up may not coincide with the least favorable orientation of a structural component or system.

## WIND DIRECTIONALITY FACTOR $K_d$ METHODOLOGY

Wind directional dependencies may arise from several effects:

1. The possibility of statistical directionality of extreme winds, such that the winds corresponding to the design return period may have lower values for some directions. However, the directional probabilities of the basic windspeed for Oahu were found to be approximately uniform within about 5%, so that no regional directionality dependence of wind need be taken in Hawaii for effect 1.
2. The possibility that the extreme wind for an event may not coincide with the least favorable orientation of a structural component or system, i.e., that even if given that an extreme wind event has occurred, the probability is less than 1 that the wind direction will impact the structure or a structural component in its critical (weakest) direction. This takes in account that the wind load on any structural system or component varies with wind direction.
3. The possibility that the surrounding upwind terrain surface roughness category conditions are directionally varied. ASCE 7 allows for directional wind load calculations only for the main wind resisting system, based on the highest wind loads resulting from the exposure categories in two 45° upwind sectors to either side of the selected approaching wind direction. Effect 3 can then be incorporated in the determination of the  $K_z$  velocity pressure exposure coefficient for that direction of analysis.
4. The possibility that topography creates significant speed-up and sheltering effects at a local site and thus creates a directional dependency of wind speeds for a given mean return period. The effect of topographic speed-up directional dependence is not currently considered in the ASCE value of  $K_d$ . Topographic speed-up has been shown [6] to be extremely varied in Hawaii.

ASCE provides a basis for making an adjustment of wind load by means of the directionality factor  $K_d$  [7, 8, 9]. That factor is currently based on flat terrain conditions without orographic channeling and topographic amplification of extreme winds. The procedure developed in this study for the Honolulu Building Code utilizes a customized derivation of the values of  $K_d$  wind directionality factor, which accounts for effect 2, the probability that the maximum wind may not impact the structural component or system in its weakest orientation, and effect 4, that the wind speeds at a site corresponding to a mean return period have directional dependence. Effect 4 can have a greater significance than effect 2 in Hawaii.

Detailed calculations have been performed so that the designer will not have to derive the net contribution of these effects. The basic calculations consisted of determining the likelihood of occurrence of the wind speed exceeding the aerodynamic boundary of structural capacity defined by the directionally contoured response function for the structure. This is done for a wind environment at a non-topographically affected flat open terrain control site assuming a typical ASCE 7  $K_d$  value of 0.85, and then for every site-specific directional wind rose of wind speed. The values of  $K_d$  that result in an equal probability of exceedence are determined so that an equal risk exists at all sites on the island, and at the same time risk-equivalent to the intent of ASCE-7 as used elsewhere on flat land sites in the continental United States. To do this, a procedure to determine the probability of wind speed exceeding (or outcrossing) the structural capacity of a component or system is utilized.

A response function is the aerodynamic response boundary that defines the wind speed required for a given azimuth to produce a limiting structural capacity in a system or component. Although the code provides maximum pressure coefficients for simplicity, the actual values vary with wind direction. Following a quasi-static assumption, the fluctuating pressure on a structure is assumed to follow variations in the upstream wind velocity time series, such that peak pressures can be approximately derived by multiplying the mean pressure coefficients with a peak gust factor. Therefore, the shape of the peak pressure coefficient as a function of angle of attack,  $C_p(\theta)$ , will be very similar to the shape of the mean pressure coefficient. In general, the response function shape  $V_R$  is related to the directional pressure coefficient,  $C_p(\theta)$ , or force coefficient,  $C_f(\theta)$  as:

$$V_R(\theta) = f(\sqrt{C(\theta)})^{-1}$$

Definition of representative response functions in terms of velocity allows an analysis of the probability of a windspeed outcrossing the limiting structural capacity of the structure, as illustrated diagrammatically in Figure 5 below:

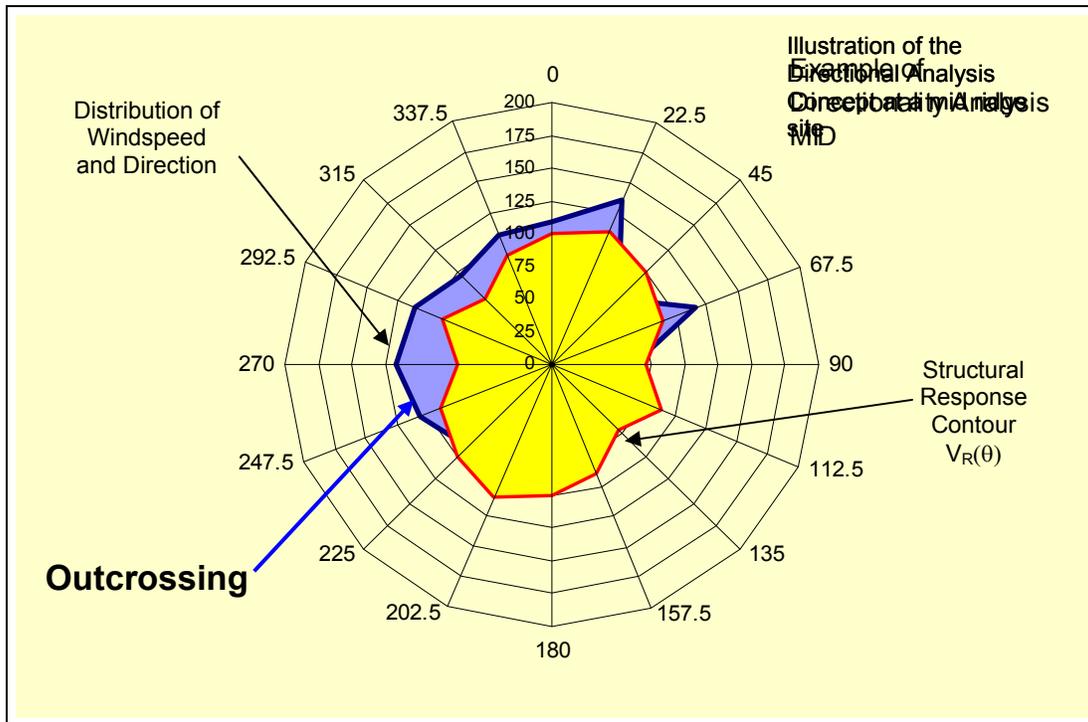


Figure 5 Structural Response Function and Wind Speed Variation By Wind Direction

Several characteristic structural response shape functions for cladding and components as well as main wind resisting systems have been developed for analysis of the wind directionality factor. These response functions were derived from wind-tunnel and full-scale test data and structural analysis to represent roof components, wall components, and uncoupled and fully coupled main wind force resisting systems [10, 11]. In this context, an uncoupled system is one in which the lateral load resisting system oriented in one principal direction does not share common elements with the system oriented in the orthogonal direction. A fully coupled system is one in which the critical elements governing the design of the two-way system participate in resisting load from all angles of attack. For main wind-resisting systems, wind-tunnel and full-scale testing of buildings have measured the directional dependence of forces and overturning moments.

Texas Tech University has a full-scale building on a turntable that allows pressure coefficient data to be determined at a number of pressure tap locations as a function of wind angle of attack (See Figure 6). Full-scale data has been used at a number of tap locations to derive response functions representative of structural roof and wall components. Uncoupled response shapes from Dalglish [10] are shown in Figures 7. Fully coupled response shapes derived for prototypical tube and box-like configurations are shown in Figure 8.

MODE 04 TRANSDUCER LOCATIONS

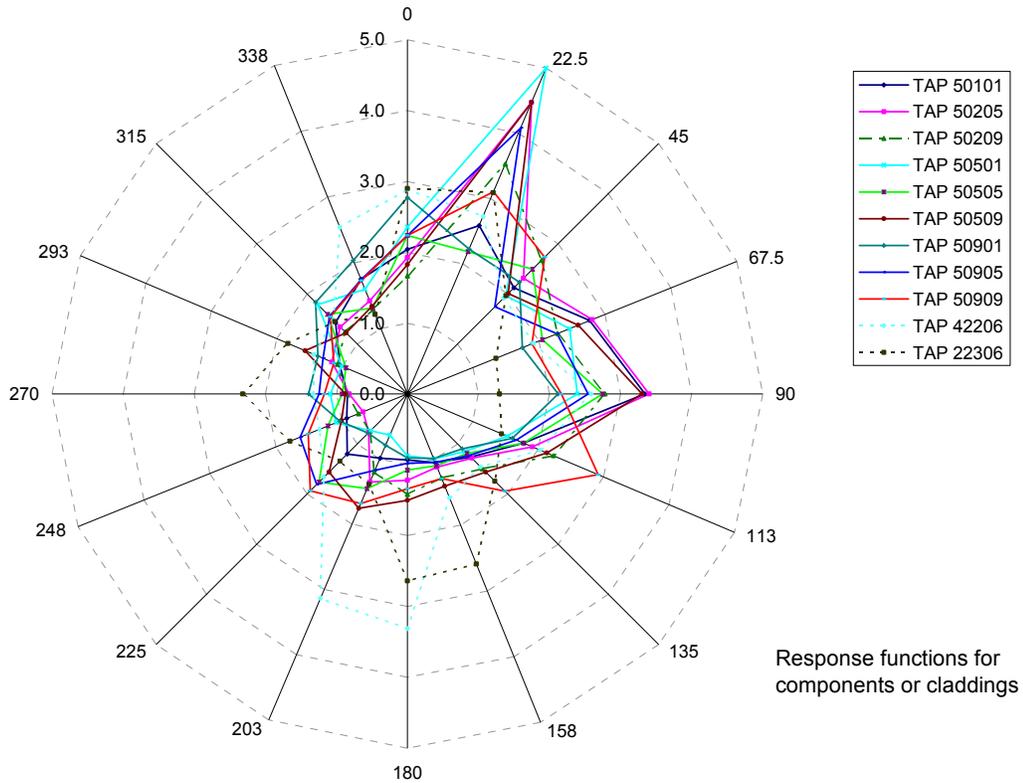
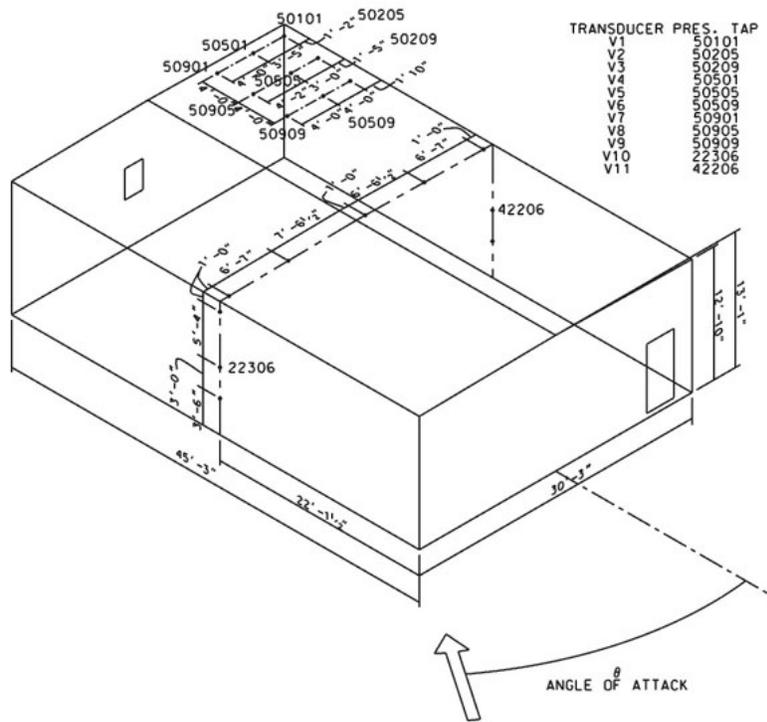


Figure 6 Azimuthal Plot of the Response Function Shapes Derived from the TTU  $C_p$  data

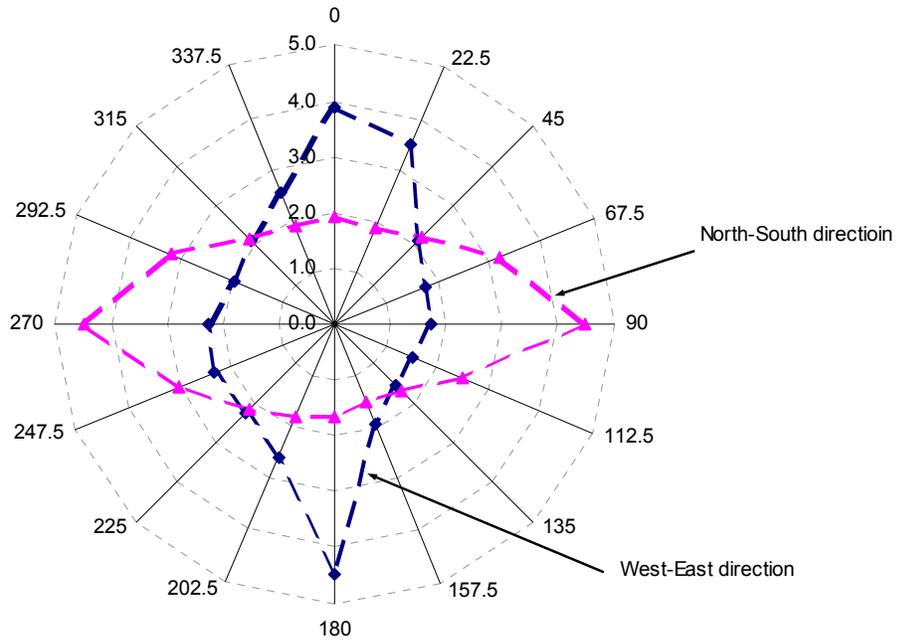


Figure 7 Response Function shapes of Uncoupled Lateral Load Resisting Systems Based on Wind-Tunnel and Full-Scale Tests (after Dalglish, 1975)

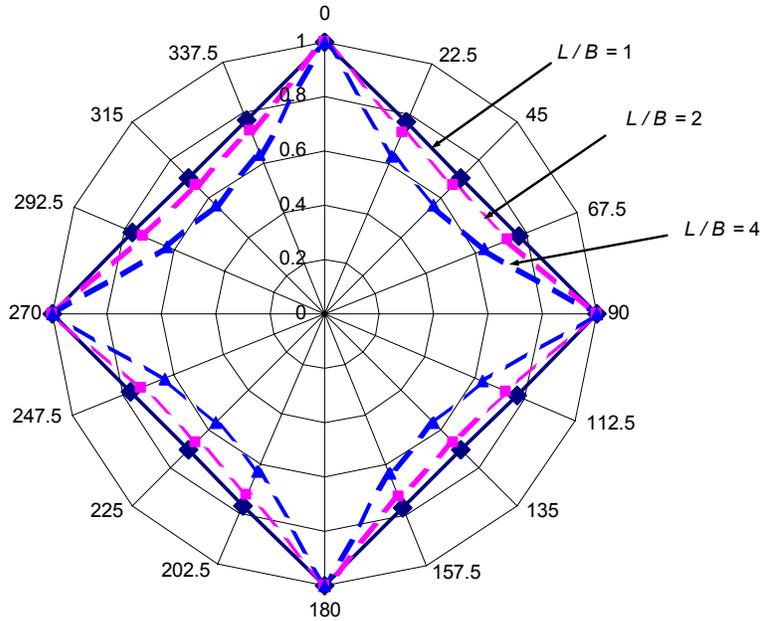


Figure 8 Response Function shapes for Fully Coupled Lateral Load Resisting Systems of Various Aspect Ratios

To accomplish the calculation of  $K_d$  involving determining the probability of wind speed exceeding the structural capacity of a component or system, the wind hazard curve must be expressed as a function of mean return period or probability of exceedence. A previously conducted Monte Carlo simulation by Peterka and Banks [3, 4] provides the data for this expression. Based on Peterka and Banks (2002), the hurricane wind speed for Honolulu with a certain return period can be approximately predicted using the following equation for the wind hazard curve:

$$V_T = 3.5272[\ln(12T)]^{1.6814}$$

in which  $T$  (in years) is return period and  $V_T$  is hurricane wind speed with the return period of  $T$ . Based on this research, a nominal wind speed of 108 mph for Honolulu was obtained, which has consistent risk with ASCE 7. The annual exceedence probability ( $P_{exceedence}$ ) for a given wind speed is the inverse of return period ( $T$ ) for the wind speed. Accordingly, the exceedence probability for given gust wind speed ( $V_T$ ) can be derived from the equation above:

$$P_{exceedence} = 12e^{-\left(\frac{V_T}{3.5272}\right)^{0.59474}}$$

The procedure for determining site-specific values of  $K_d$  is outlined in the following steps, accompanied by illustrative diagrams:

**$K_d$  Calculation Step 1: Determine the hurricane wind outcrossing exceedence probability of the selected response function for a flat land site (using the ASCE standard value of 0.85).**

The selected response function is scaled so that its most critical point of minimum capacity just touches the prototypical flat land wind rose, representing a design point without consideration of the standard  $K_d$  (i.e., a  $K_d$  of 1.0). Then the response function is scaled by a factor of 0.922 (the square root of 0.85). The net out-crossing probability ( $P_{target}$ ) for the response function is calculated. This step is illustrated in Figure 9.

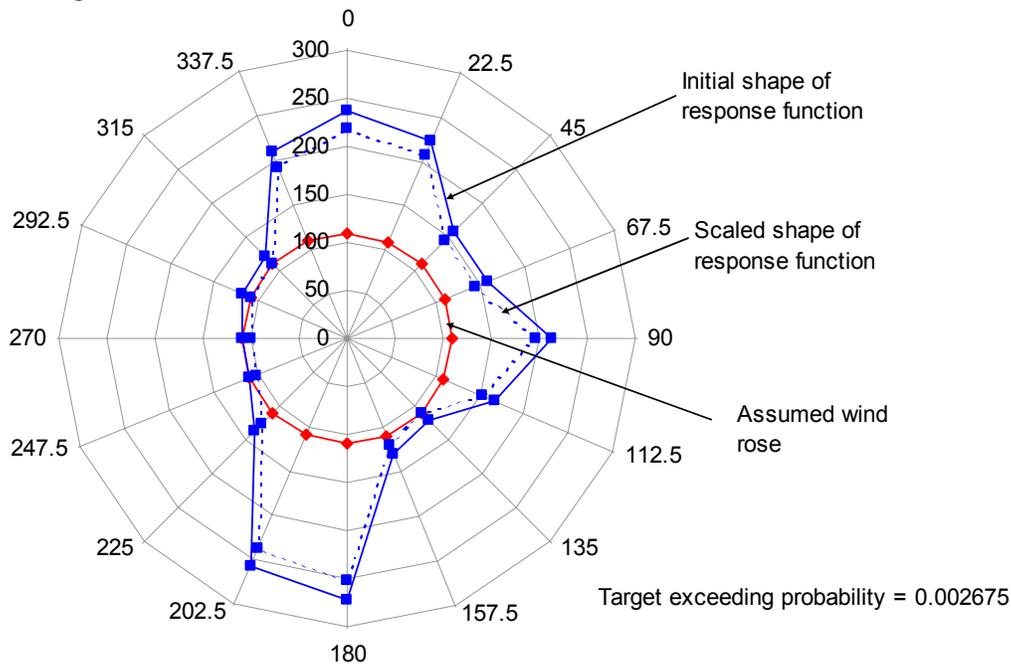


Figure 9 Response Function Scaling

**$K_d$  Calculation Step 2: Determine the value of  $K_d$  necessary for the selected response function to have a wind hazard exceedance probability equal to the control site.**

After  $P_{target}$  is determined,  $K_d$  can then be derived for the non-uniform directional wind rose at a topographically influenced specific site by the procedures as follows:

1. At a starting orientation, scale the selected response curve so that it just touches wind-rose at the point with the smallest ratio of response to wind speed (demand) (See initial shape of response function in Figure 10).
2. Scale down the response curve by a trial factor of  $k_{di}$ , a function of the square root of  $K_d$  ( $i = 1$ , see scaled shape of response function in Figure 10);

3. Calculate the net out-crossing probability  $P_i = \sum_{j=1}^{16} P_{ij}$  ( $i = 1$ );

4. Check if  $P_i$  (i.e.,  $\sum_{j=1}^{16} P_{ij}$ ,  $i = 1$ ) =  $P_{target}$ . If yes, then directionality factor for this structural orientation would be  $k_{d1}^2$ . Otherwise, select another  $k_{d1}$  and repeat steps (3) and (4) until convergence to a equivalent exceedance probability of the flat land site, i.e.,

$$P_i \text{ (i.e., } \sum_{j=1}^{16} P_{ij}, i = 1) = P_{target};$$

5. Rotate the response function clockwise by one azimuth interval ( $22.5^\circ$ ). Repeat (1) ~ (4) and obtain  $k_{d2}$  for the structure orientation (i.e.,  $i = 2$ );

6. Repeat (5) until the response function for all orientations are addressed (i.e.,  $i = 3, \dots, 16$ ).

7. To account for random or unknown structural orientation, compute  $K_d = \frac{1}{16} \sum_{i=1}^{16} k_{di}^2$ .

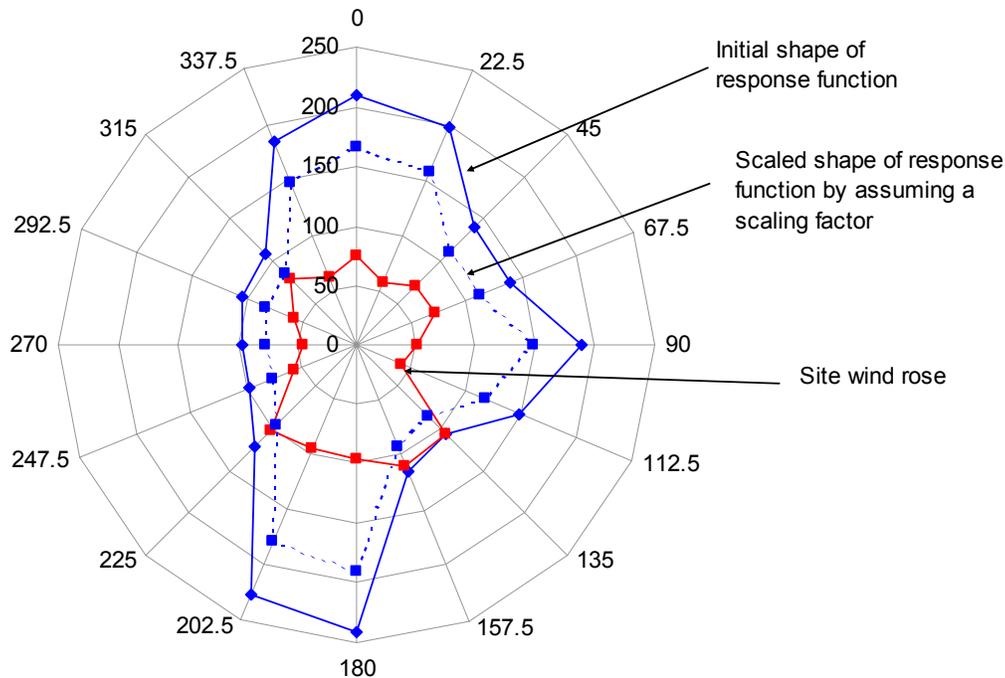


Figure 10 Calculating  $k_{di}$  for One of 16 Structural Orientations

## CONSERVATISM OF THE 0.85 STANDARD VALUE OF $K_d$ IN THIS REGION

In the first step of the procedure, the net outcrossing exceedance probability is calculated for the standard ASCE value of  $K_d = 0.85$  using a design windspeed corresponding to the ASCE value derived value of 108 mph, ( $V_{500} / \sqrt{1.53}$ ), which has a mean return period of about 170 years. These values are shown in Table 1 for a flat land Exposure C site. They indicate that the 0.85 value produces a large amount of conservatism, and that a lower value would appear justified in this wind environment. The minimum return period of exceedence is 200 years, which is greater than the 150 years expected to result from the 500 year wind divided by  $\sqrt{1.5}$ .

*Table 1 Exceedence Probabilities and Mean Return Periods When  $K_d = 0.85$  is Used at Sites Without Topographic Speed-Up (Uniform Wind Environment) With a Design Wind Speed of 108 mph*

P <sub>exceed</sub> for $K_d = 0.85$ @ Control Site On Flat Land													
TTU Roof Tap ID's									Wall Tap ID's		Lateral System		
# 50101	# 50205	# 50209	# 50501	# 50505	# 50509	# 50901	# 50905	# 50909	# 42206	# 22306	Uncoupled		Coupled
											E-W	N-S	
0.00203	0.00113	0.00154	0.00105	0.00196	0.00113	0.00173	0.00180	0.00194	0.00267	0.00258	0.00234	0.00209	0.00501
Mean Return Period (years)													
493	885	649	952	510	885	578	556	515	375	388	427	478	200
K <sub>d</sub> for P <sub>exceed</sub> = 0.00588 @ Control Site On Flat Land													
0.536	0.405	0.466	0.394	0.528	0.414	0.494	0.511	0.528	0.607	0.600	0.577	0.549	0.805

The procedure outlined above was modified to be capable of accepting arbitrary local wind directions in order to also analyze the data generated by the Aeroprobe tests, and to utilize 0.85 to establish the target exceedence probability at the control site. The directionality factors were calculated for all 229 sites over all azimuths, averaged by response function type and landform position. Based on these analyses, a conservative set of values in Table 2 follows a relatively simple categorical site classification scheme. Approximately 90% of the calculated site-specific  $K_d$  in the urban and agricultural zoned areas fall below these specified values.

Most “open terrain” coastal sites are different in character from the flat land sites as conceived within ASCE. Most coastal sites exist in proximity to complex topography produced by the major high mountain ranges. These sites have topographic speed-up under some azimuth of approaching wind. Therefore, most “open terrain” sites with nearby topographic features do not have a circular wind environment of non-directional wind speeds, but are subject to speed-up under particular localized directions corresponding to downslope convergence acceleration from the nearby mountain range. Accordingly, a lower calculated  $K_d$  value results.

Table 2  $K_d$  Values for Oahu, Hawaii

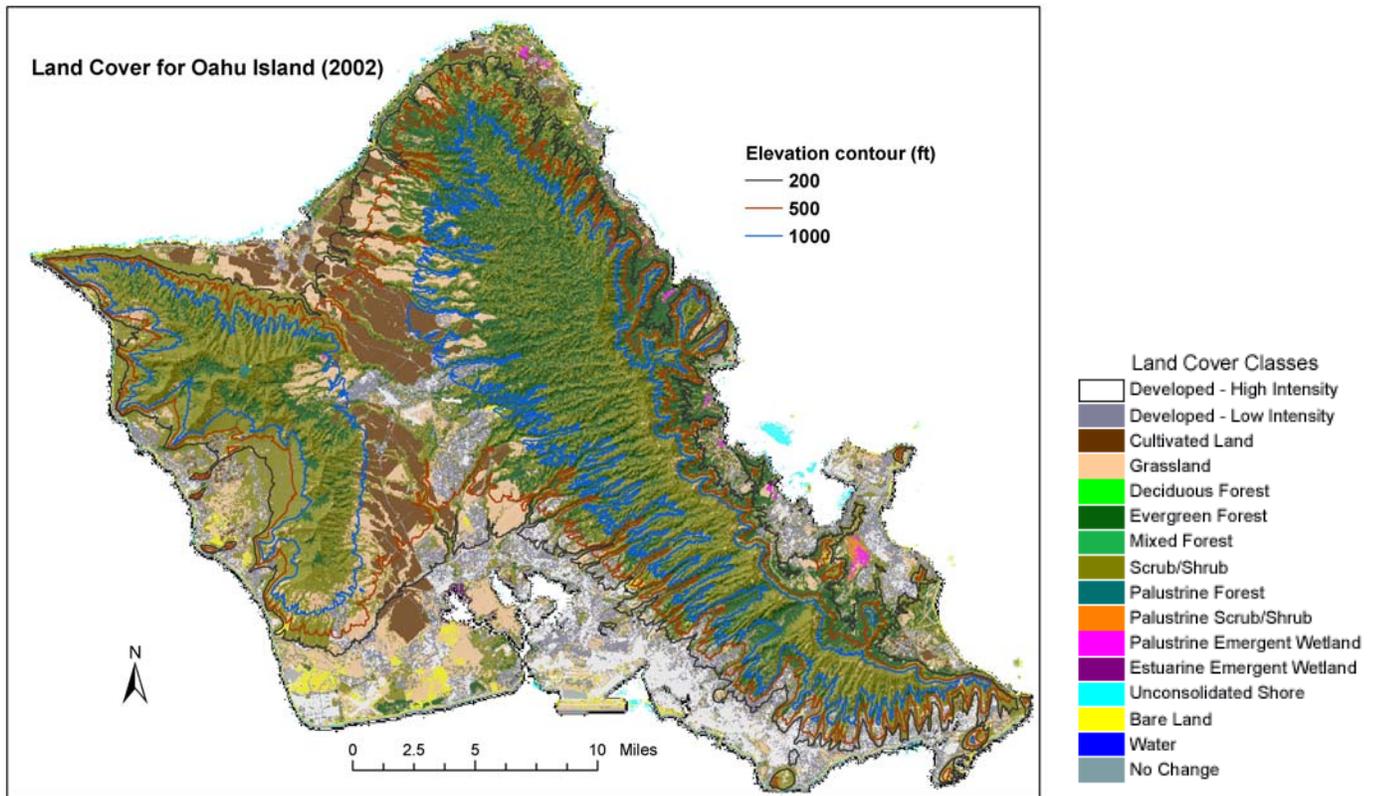
Topographic Location on Oahu, Hawaii	Main Wind Force Resisting Systems		Main Wind Force Resisting Systems with totally independent systems in each orthogonal direction		Biaxially Symmetric and Axisymmetric Structures of any Height and Arched Roof Structures
	Mean Roof Height less than or equal to 100 ft.	Mean Roof Height greater than 100 ft.	Mean Roof Height less than or equal to 100 ft.	Mean Roof Height greater than 100 ft.	
Sites within valleys at an elevation of at least 50 ft. but not greater than 500 ft.	0.65	0.70	0.70	0.75	0.85
Central Oahu above an elevation of 500 ft, the Ewa and Kapolei plains, and coastal areas with $K_{zt}$ (10m) no greater than 1.2	0.75	0.80	0.75	0.80	0.95
All other areas, including Hills, Hillsides, Ridges, Bluffs, and Escarpments at any elevation or height; coastal and inland areas with $K_{zt}$ (10m) greater than 1.2	0.70	0.75	0.75	0.80	0.90

Notes:

1. The values of  $K_d$  for other non-building structures indicated in ASCE-7 Table 6-4 shall be permitted.
2. Site-specific probabilistic analysis of  $K_d$  based on wind-tunnel testing of topography and peak gust velocity profile shall be permitted to be submitted for approval by the Building Official, but  $K_d$  shall have a value not less than 0.65.

### EXPOSURE CATEGORY $K_z$ METHODOLOGY

The City of Honolulu is heavily urbanized and densely populated. Areas of south and east Oahu are also quite urbanized. Oahu land-cover data were developed by the NOAA Coastal Services Center from Landsat Enhanced Thematic Mapper satellite imagery taken in the year 2000. Processing of this imagery for land cover classification was performed within NOAA's *Coastal Change Analysis Program (C-CAP)* to provide land cover data for the coastal regions of the National Land Cover Database (NLCD), resulting in a map of the following land cover classes:



*Figure 11 Land Cover Classification Map of Oahu from the National Land Cover Database*

The NOAA land cover, the original Landsat imagery as well the current County Land Use zones were inserted into a GIS map model of Oahu. Then the map was reclassified into Exposure Categories utilizing these layers, the ASCE-7 criteria for Exposure B, and utilizing the point values of statistically fitted gust profile power law coefficients determined at the 24 representative sites by wind-tunnel measurement of mean and gust velocity profiles. The wind-tunnel velocity profiles were a key data layer in this interpretive process because the complexity and variety of rugged topography and changes in surface roughness of the island does not allow equilibrium velocity profiles to become established over a sufficiently long level fetch. As a result, the Oahu data has numerous areas where rough profiles result from the presence of upwind terrain that disturbs the wind flow so that there is a non-equilibrium boundary layer. In other words, wind flow passing over moderate to severe topography does not easily return to equilibrium, even where the terrain would normally imply a smoother velocity profile. The astute engineer should consider the directional influences of turbulence on exposure category where the approaching wind direction is downwind of a significant mountain range.

However, lower turbulence and a wind speed profile more similar to open country boundary layer flow occurs when the wind is directed up moderately sloped linear valleys in an aligned direction. The valleys where this effect is anticipated are designated with vectors to indicate the direction of flow quadrant where exposure Category C should be used up through the upland source of the valley. Also, data within the high saddle area between the two main mountain ranges does indicate that wind oriented parallel to the mountain ranges can retain smoother velocity profiles across agricultural lands.

A map reflecting these data layers and topographic effects on exposure classifications was produced to allow a quicker and more consistent basis for category determination at a building site. However, due to the variability of power law coefficients in the turbulent flow, the use of the map of Figure 12 would be limited to structures of no greater than 60 ft. height.

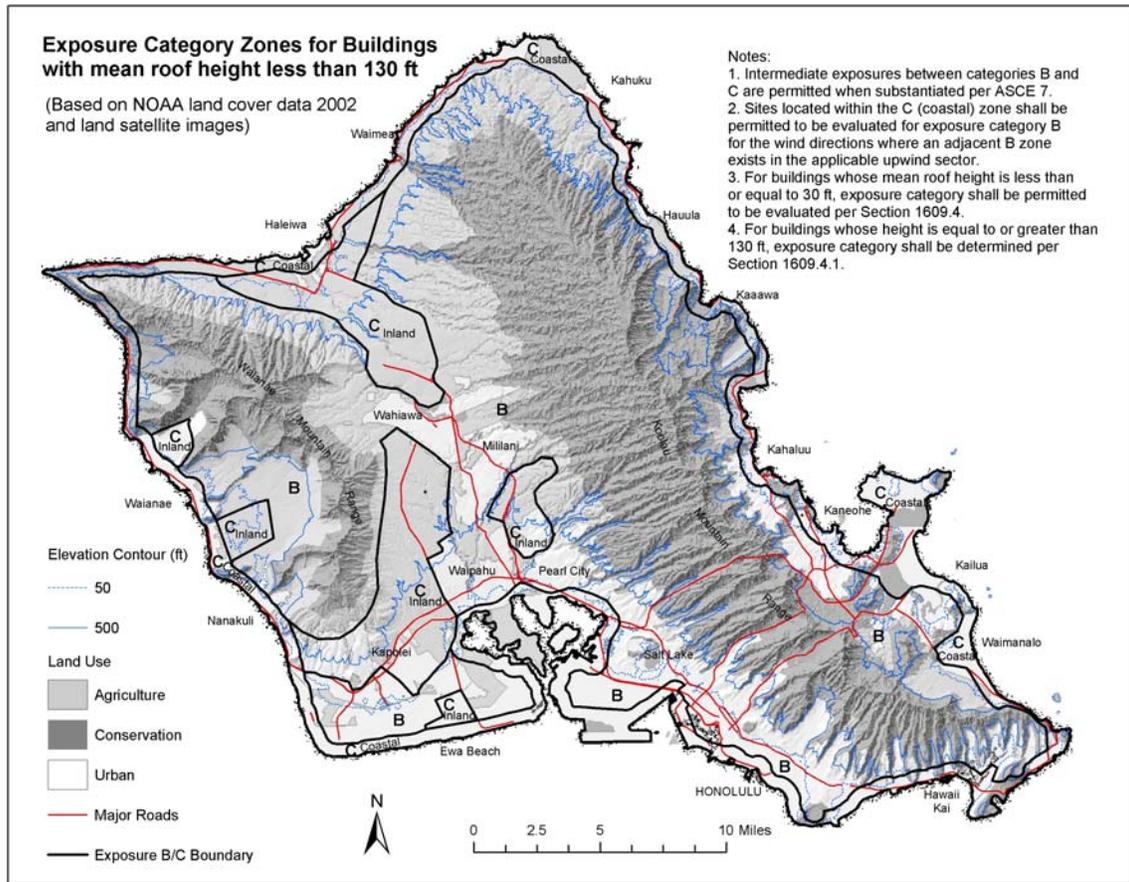


Figure 12 Exposure Category Map of Oahu

### APPLICATION TO THE WIND DESIGN PROVISIONS FOR THE CITY OF HONOLULU

The governing extreme winds for Hawaii are produced by rare tropical cyclones that have no direct relationship with a parent population of regular wind climatology. Monte-Carlo simulations have found that the basic wind speed was underestimated in the UBC by approximately 10 mph, and a 105 mph 3-second peak gust for Oahu is considered appropriate for design in accordance with the ASCE-7 provisions.

The design methodology in the Honolulu Building Code for velocity pressure can be based on utilizing a single *non-directional* map of  $K_{zt}$  at 10m contouring the topographically influenced wind speed-up. A single map representative of the maximum topographic speed-up effect would be the simplest to apply, although over-conservative since it represents the maximum  $K_{zt}$  value of topographic speed-up from any direction. ASCE provides a basis for making an adjustment of wind load by means of the directionality factor  $K_d$ , which can reduce this over-conservatism by taking into account the probability that the predominant extreme wind speed-up may not coincide with the least favorable orientation of a structural component or system. Specification of customized  $K_d$  factors for Oahu then account for the *directional* probabilities of windspeed, based on extensive probabilistic calculations of individual site wind rose data for Oahu that define the directional dependencies of windspeed. The values of probabilistically derived  $K_d$  are determined to provide a level of safety consistent with wind load exceedance probabilities inherent in flat land open terrain sites. GIS maps for use in local building codes and risk assessments are embodied in contour maps of  $K_{zt,10m}$  and **Exposure Category**.  $K_d$  is furnished as a supplemental table in the Honolulu amendment to the International Building Code wind provisions for the design of new buildings and structures of up to 60 feet height. The proposed maps can be utilized in conjunction with the latest analysis of hurricane probabilities to furnish wind velocity pressures

consistent with the ASCE-intended ultimate return period. The designer may then work with a single velocity pressure value and adjust it with height based on the terrain exposure windward of each quadrant determined from an island map of Exposure Categories.

A uniform level of protection (or risk) for hurricane hazard can then be achieved in structural design throughout the City and County of Honolulu. The map-based Honolulu code provisions for use with the ASCE-7 Analytical Method could be easier to use than the current provisions for the  $K_z$ ,  $K_{zt}$ , and  $K_d$  factors. For the International Residential Code and ASCE-7 Simplified Method, a single map of “ $V_{effective}$ ”, i.e.,  $V$  multiplied by  $\sqrt{(K_{zt} \times K_d / 0.85)}$  would allow implicit consideration of topographic effects. An example of a map of  $V_{effective}$  for components and cladding is shown in Figure 13.

Site-specific wind studies can be done for more refined wind loads. For example, special design consideration would be recommendable for structures at the edge of escarpments, which would be subject to vertical components of wind flow not fully determined in this project. Special building-specific investigations, including wind-tunnel tests, are advised for tall structures located near significant topographic features.

This customized approach has been applied where the governing extreme winds are produced by rare tropical cyclones and not by regular wind climatology. In particular, the tabulated  $K_d$  values were calculated from the Oahu wind hazard curve and directional wind data at hundreds of Oahu sites. Similar applications of this methodology to estimate  $K_d$  and derive mapping of  $K_{zt}$  and Exposure Categories for other tropical cyclone-prone locations would need to be based on regional wind hazard curves and representative directional wind spatial data.

Implementation of the topographic and directionality factors in the Honolulu Building Code would fulfill recommendations made by structural engineers after Hurricanes Iwa (1982) and Iniki (1992). In particular, *Chiu* and others [13] recommended that “topographic effects must be considered when designing to resist wind effects. Microzonation is necessary for the individual islands in order to provide information about the dramatic variation of wind speeds with topography.” Utilizing the data analysis techniques presented in this paper, similar mapping products based on wind data can be developed for the other Hawaiian islands in the future.

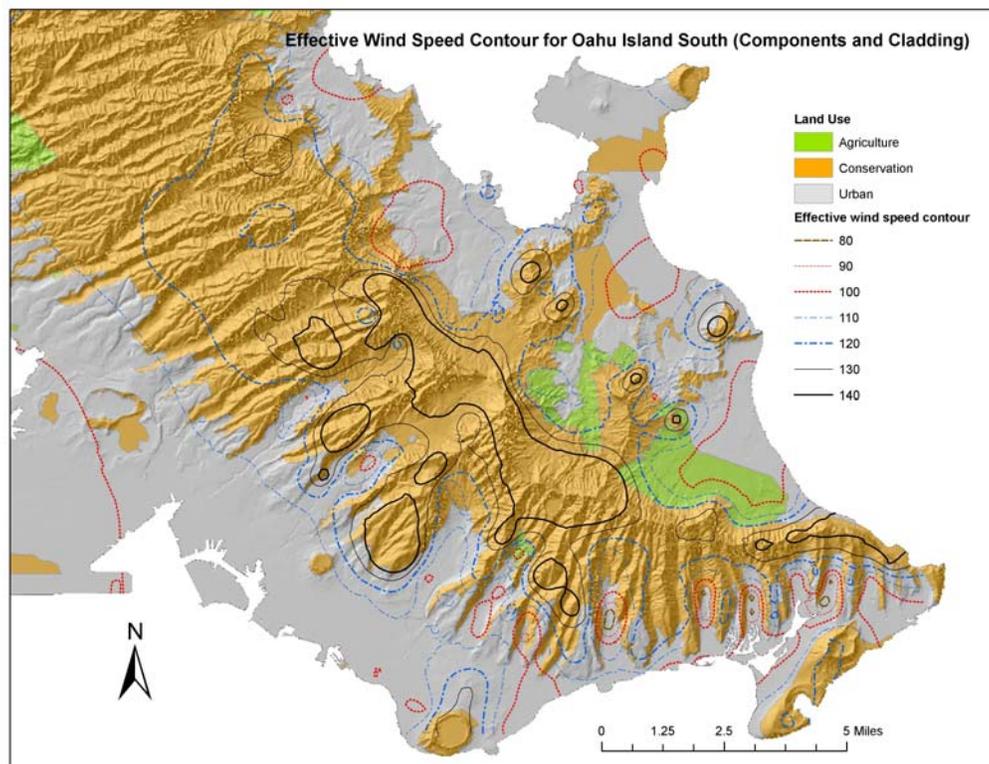


Figure 13 Example of  $V_{effective} [= V \sqrt{(K_{zt} K_d / 0.85)}]$  Map of Southeast Oahu

## REFERENCES

- [1] American Society of Civil Engineers, Minimum Design Loads for Buildings and Other Structures ASCE 7-02, Reston, VA, USA, 2002.
- [2] Peterka, Jon A., Design Wind Speeds for Honolulu, Hawaii, CCP, Inc. Report, Ft. Collins, CO, USA, 1993.
- [3] Peterka, Jon A. and Banks, David, Wind Speed Mapping of Hawaii and Pacific Insular States by Monte Carlo Simulation – CCP, Inc. Final Report 99-1773, NASA Contract NASW-99046, Ft. Collins, CO, USA, 2002.
- [4] Banks, D, Peterka, J., Tropical Storm Track Prediction Using Autoregressive Time Series Analysis, Americas Conference on Wind Engineering, Clemson University, SC, USA, June 2001.
- [5] ARA, Inc., Hazard Mitigation Study for the Hawaii Hurricane Relief Fund, ARA Report 0476, Raleigh, NC, USA, 2001.
- [6] Chock, G. and Cochran, L., Modeling of Topographic Wind Effects in Hawaii, Journal of Wind Engineering and Industrial Aerodynamics, 2005 (*in publication*).
- [7] Davenport, A.G., The Prediction of Risk Under Wind Loading, Proceeding of the 2<sup>nd</sup> International Conference on Structural Safety and Reliability, Munich, Germany, September 1977.
- [8] Davenport, A.G., Ho, T.C.E., and Surry, D., The Codification of Low Building Wind Loads, Proceedings of The 7<sup>th</sup> U.S. National Conference on Wind Engineering, Los Angeles, CA, USA, June 1993.
- [9] Holmes, J.D., Reduction Factors For Wind Direction for Use in Codes and Standards, Symposium on Designing with the Wind, Nantes, France, June 1981.
- [10] Dalglish, W.A., Comparison of Model/Full-Scale Wind Pressure on High-Rise Building, Journal of Wind Engineering and Industrial Aerodynamics, Vol.1, No.1, 1975, pp. 55-66.
- [11] Iverson, R., Levitan, M., Full-Scale Point Pressure Test Data from Texas Tech University Field Experiments for Wind Loads, [www.wind.ttu.edu](http://www.wind.ttu.edu), 1990.
- [13] Chiu, N.L., et al, Hurricane Iniki's Impact on Kauai, National Science Foundation, National Technical Information Service PB96-175351, 1995.