Micro-zoned Design Maps of Topographic Wind Effects and Exposure in the State of Hawaii Building Code

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Abstract

Hawaii is located within a hurricane hazard region, where the governing extreme winds are produced by rare tropical cyclones and not by regular wind climatology. In Hawaii, wind may govern the structural design in many cases, while seismic effects may dominate in others.

Topographic amplification of wind speed has been a significant contributing factor in the past hurricane loss experiences of Hawaii. In the Hawaiian islands, where the real terrain is often very complex or characterized by large shield mountain features, the actual magnitude and extent of speed-up can be quite different from the present ASCE/SEI 7 prescriptive calculations.

New wind speed design mapping and technical provisions have been developed as local code amendments to the International Building Code (IBC), based on requirements of the ASCE/SEI 7-05 wind load standard. Customized wind design maps were developed from computational fluid dynamics mesoscale models, and site-specific wind-tunnel tests. The methodology accounts 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.

With the adoption of these new micro-zoned wind design maps defining customized values of ASCE/SEI 7 parameters within a Hawaii State Building Code, a uniform level of protection for hurricane hazard will be specified for the structural design of new buildings in Hawaii.

Evaluation of Wind Design Parameters for Hawaii

Due to the presence of mountainous terrain and valley gorges in Hawaii, the ASCE-7 provisions, which only address the topographic speed-up influence of *isolated* 2-dimensional ridge and escarpment features and *axisymmetric* hills, do not sufficiently account for the significant effect of topographic wind speed variations caused by the highly complex three-dimensional topography in State of Hawaii. After Hurricanes Iwa (1982) and Iniki (1992) the Structural Engineers Association of Hawaii and others 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." (Chiu, 1996)

The ASCE/SEI Standard 7 (ASCE, 2006) utilizes 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,
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 700-year return period, divided by $\sqrt{1.6}$, and
I is the Importance Factor of the building or structure, based on its occupancy type.

Hawaii is making several needed technical modifications so that the data produced by island –specific model studies can be used by structural engineers in design applications through the ASCE 7 Analytical Method:

1. Verification of the appropriate design wind speed utilizing Monte Carlo simulations of the East-Central Pacific region.
2. Probabilistic wind speed hazard micro-zonation of 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.
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 exposure classification map to select the appropriate K_z , exposure coefficient.

In 2005, the National Council of Structural Engineers Associations and the American Society of Civil Engineers Structural Engineering Institute submitted joint testimony (S32-04/05) to the International Code Council, regarding the conditions when technical requirements are appropriate in a local building code rather than within the ASCE 7 Standard:

“Material that is left in the building code conforms to one of the following criteria:

Relates to local climatic, terrain, or other environmental conditions, which many building officials will wish to specify when adopting the model code by local ordinance. This includes specification of basic wind speeds, terrain, exposure and similar provisions.

Relates to enforcement of types of construction which is often set by condition so local practice, materials availability and construction industry capabilities.

Is not presently covered in an adequate manner by a national consensus standard. This includes to material covering roofing materials, hurricane protection of openings, etc.”

In 2008, the Wind Load Subcommittee of ASCE 7 also unanimously concurred that Hawaii should be defined as a Special Wind Region in Figure 6-1, i.e., as a region that has mountainous terrain that causes wind effects that cannot be addressed solely by ASCE/SEI 7 Section 6.5.7.2.

ASCE/SEI 7 (ASCE, 2006) Commentary C6.5.4.1 on Special Wind Regions. states,:

“Although the wind speed map of Fig. 6-1 is valid for most regions of the country, there are special regions in which wind speed anomalies are known to exist. Some of these special regions are noted in Fig. 6-1. Winds blowing over mountain ranges or through gorges or river valleys in these special regions can develop speeds that are substantially higher than the values indicated on the map. When selecting basic wind speeds in these special regions, use of regional climatic data and consultation with a wind engineer or meteorologist is advised.

It is also possible that anomalies in wind speeds exist on a micrometeorological scale. For example, wind speed-up over hills and escarpments is addressed in Section 6.5.7.Wind speeds over complex terrain may be better determined by wind-tunnel studies as described in Section 6.6. Adjustments of wind speeds should be made at the micrometeorological scale on the basis of wind engineering or meteorological advice and used in accordance with the provisions of Section 6.5.4.2 when such adjustments are warranted.”

In this paper we discuss the particular methodologies used to determine the Hawaii-specific design factors. The procedure for use of the resulting micro-zoned design maps and tables of these parameters are explained for design applications. Because most development occurs on the island of Oahu, the example map products shown in this paper will be those adopted in the current Honolulu Building Code amendments to the IBC. Unique wind conditions are produced by the complex mountainous topography in Hawaii, and each island requires individual maps of these effects for design purposes.

V Peak Gust Windspeed: Risk-Consistent Basic Design Wind Speed

ASCE 7 uses gust wind speed to characterize the winds at a location for determination of wind load. The current IBC 3-second gust value is associated with a 700-year return period divided by √1.6,. The Hawaii hazard curves for wind speeds and directional probabilities due to tropical cyclones have been established by Monte Carlo simulations (Peterka & Banks, 2002, and ARA,2001). The analysis implicitly included the historical frequency of ENSO (El Nino and La Nina) episodes, but it not include any potential effects of long-term climatic change. In summary, a 105 mph 3-second peak gust for Hawaii is considered the most appropriate to design in accordance with the ASCE provisions. The figure below illustrates that Hawaii is in a moderate hurricane hazard region.

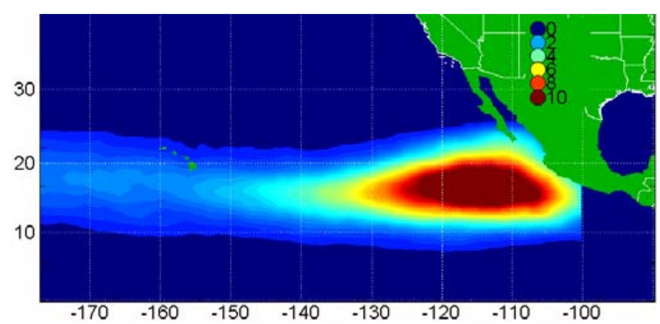

Figure1: Monte Carlo Stochastic Simulation (Peterka and Banks, 2002) Showing the number of times a hurricane passes within 75 nautical miles per 10 years in the Eastern and Central Pacific

Based on Peterka and Banks (2002), the hurricane wind speed (for Honolulu) with certain return period can be approximately predicted using the following equation for the wind hazard curve:

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

in which T (in years) is return period and V_T is hurricane wind speed with the return period of T .

Topographic Speed-up Factor K_{zt}

Prior topographic wind effects parametric methods include the terrain factor incorporated into the national wind load standard ASCE 7-02. These provisions utilize simple parametric formulations, which may work for some areas characterized by an isolated axisymmetric hill, continuous two-dimensional low ridge or continuous two-dimensional escarpment where the wind does not have an upwind influencing feature. 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, Kzt 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.

NASA, FEMA, and NOAA-sponsored projects performed by Martin & Chock, Inc. produced new methodologies pertaining to modeling of wind speeds and 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. Modeling of the wind flow over terrain or about a structure requires special consideration of flow conditions to obtain similitude between the model and the prototype. In general, the requirements are that the model and prototype be geometrically similar, that the approach mean velocity and turbulence structure at the modeled site have a vertical profile shape similar to the full-scale flow, and that the Reynolds number for the model and prototype be within a higher range of magnitude ($>2 \times 10^4$). These criteria were satisfied by constructing a scale model of the terrain or structure, and performing the tests in a wind tunnel specifically designed to model atmospheric boundary layer flows. The wind-tunnel testing was performed in the natural boundary-layer wind tunnel of Cermak Peterka Petersen, Inc. (CPP, Inc.), Fort Collins, Colorado. This wind tunnel has a 68-ft (21-m) long test section. All data collection was performed in accordance with the American Society of Civil Engineers (ASCE) Standard 7-05 on wind loads and ASCE /SEI 49-07 *Wind Tunnel Model Studies of Buildings and Structures*.

Wind speedups or reductions were measured at several hundred locations for 16 directions of wind at each site. Then a phenomenological modeling technique based on terrain profiles was formulated to statistically fit the measured data (Chock and Cochran, 2006). The predictive model formulations for peak gust, mean speed, and peak/mean ratio considered site membership in landform position categories of principal high mountain ridges, secondary ridges, mid-ridge, narrow valleys, wide valley, low hills, and open terrain. The topographic scale digital terrain parameters considered in the predictive model included: distance-weighted near-field and far-field terrain upwind slopes, distance-weighted near-field slope downwind of the site, the degree of alignment of the principal slope (i.e., the aspect) of a site's upwind terrain relative to directional alignment with the site, terrain curvature perpendicular to the upwind terrain slope, projected upwind line of sight visibility (a means of windward/leeward identification), height of obstructions upwind of the site above a standardized line of sight, and a power transformation of site elevation.

For the islands of Maui and Hawaii, the existing topographic wind speed-up techniques used for Oahu and Kauai could not fully capture the wind flow over the terrain of the island because of thelarger-scale (mesoscale) impact of Haleakala and Puu Kukui, Mauna Loa, and Mauna Kea. The height of the terrain is sufficient and the area of the island is large enough that they have a significant impact on the wind flow over and around this high terrain. The height and size of the shield volcanoes required a different technique to quantify their impact on wind speed-up, using state-of-the art mesoscale computational fluid dynamic (CFD) numerical simulations. The CFD model WRF (Weather Research and Forecast Model) wind flow simulations were combined with wind tunnel tests of selected regions for validation.

The assembled data for mean and 3-second gust were then normalized relative to a 10-m wind speed over open, coastal, flat terrain or offshore aroused ocean. Contour maps were then created from the individual point converted data by gridding interpolation. The contoured values of K_{zt} represent the square of the wind speed-up relative to the speed at a coastal site on open flat terrain.

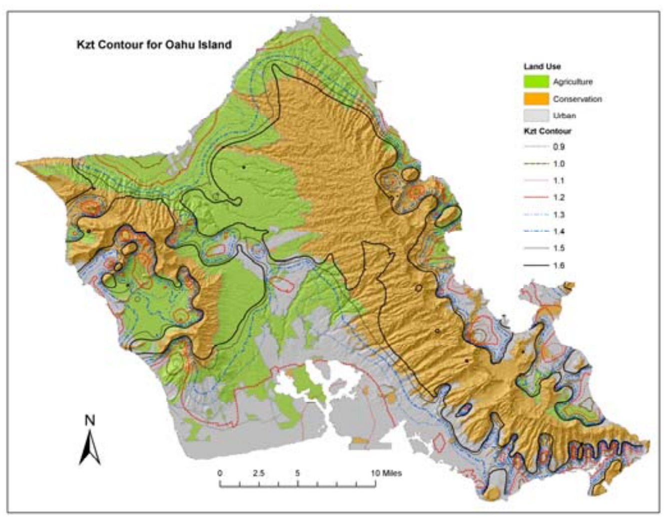

Figure 2: Topographic Effect Factor K_{zt} Map for Oahu

The current ASCE 7-05 provisions would theoretically require the assessment of up to 8 different wind loadings, each with a directionally specific K_{zt} (θ) value. This would be considered entirely impractical for design purposes. Use of a single map for design representing the maximum K_{zt} value of topographic speed-up squared from any direction is the simplest to apply, although overly conservative if not adjusted for directionality. Fortunately, 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

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 Hawaii were found to be approximately uniform within about 5% (Peterka & Banks, 2002), 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, the probability is less than 1 that the wind direction will impact the structure or a structural component in its 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. Effect 3 is incorporated in the determination of the K_z velocity pressure exposure coefficient for the direction of analysis.
4. The possibility that topography creates significant effects at a local site resulting in a site-specific directional dependency of wind speeds. The effect of topographic speed-up directional dependence is not currently considered in the ASCE default values of K_d .

The ASCE 7 Commentary provides a basis for making an adjustment of wind load by means of the directionality factor K_d. The default factor is currently based on flat terrain conditions without site-specific effect 4. The procedure 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 generally has more significance than effect 2 in Hawaii. A conceptual explanation of the calculation process follows.

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, 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, Cp(θ), will be very similar to the shape of the directional mean pressure coefficient. In general, the response function shape V_R is related to the directional pressure coefficient, Cp(θ), 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 diagrammatically illustrated below:

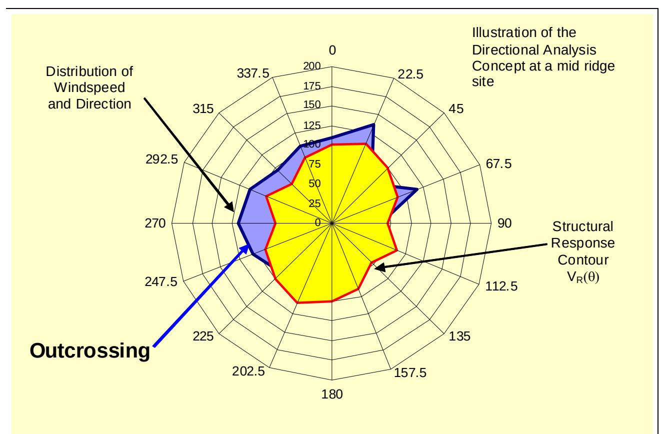

Figure 3: Illustration of a Structural Response Function and Wind Speed Variation by Wind Direction

Several characteristic structural response shape functions for cladding and components as well as main wind resisting systems were used for analysis of the wind directionality factor. These response functions were derived from wind-tunnel and full-scale test data and Main Wind Force Resisting System (MWFRS) structural analysis in the recognized literature (Dalgliesh, 1975, and Iverson, 1990), representing roof components, wall components, and uncoupled and fully coupled main wind force resisting systems. For main wind-force resisting systems, wind-tunnel and full-scale testing of buildings have measured the directional dependence of forces and overturning moments. In the context of this derivation, an uncoupled MWFRS 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 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.

Probabilistic calculations have been performed so that the designer will not have to derive the net directionality value (Chock, Peterka, and Yu, 2005). The basic calculations consisted of determining the likelihood of occurrence of the wind speed exceeding the aerodynamic boundary of structural capacity defined by the response function. 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, and at the same time are risk-equivalent to the intent of ASCE-7 as typically used at sites in the continental United States. The heightened directionality of the wind environment results in values of K_d that are typically less than the default value of 0.85.

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 Kzt (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 Kzt (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.

Table 1: Directionality Factors K_d for Oahu MWFRS

Exposure Category K_z

Land-cover data were developed by the NOAA Coastal Services Center from Landsat Enhanced Thematic Mapper satellite imagery beginning 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 land cover classes. The NOAA land cover, the original Landsat imagery as well the current County Land Use zones of each island were inserted into GIS map models. Then the map was reclassified into Exposure Categories utilizing the ASCE-7 criteria for Exposure B, and compared to the point values of statistically fitted gust profile power law coefficients determined at representative sites by measurement of gust velocity profiles. The wind-tunnel velocity profiles on Oahu were a key data layer in this interpretive process because the complexity and variety of rugged topography and changes in surface roughness of this island does not allow equilibrium velocity profiles to become established over a sufficiently long fetch. In other words, turbulent wind flow passing over mountainous topography does not easily return to equilibrium, even where the local terrain roughness would normally imply a smoother velocity profile.

A GIS map reflecting these exposure classifications was produced to allow a quicker and more consistent basis for category determination at a building site. Due to the variability of power law coefficients in the turbulent flow, there are some limiting conditions for use of these maps.

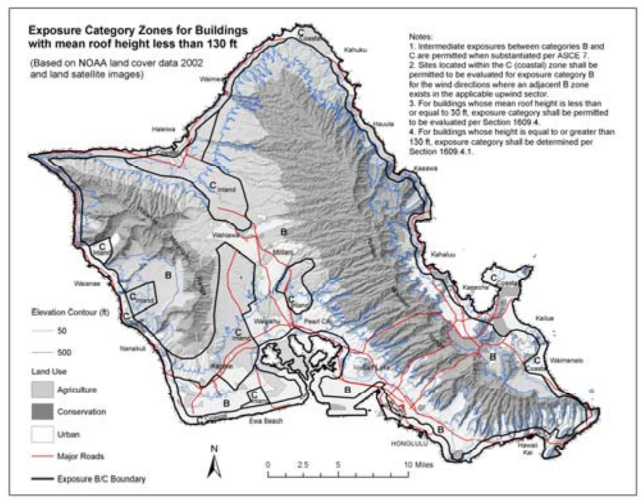

Figure 4: Exposure Category Map of Oahu

Application to Wind Design in Hawaii

The design methodology in the new Hawaii Building Code for velocity pressure will be based on utilizing a single non-directional map of K_{zt} at10 meters, providing contours of the square of topographically influenced wind speed-up. A single map representative of the maximum topographic speed-up effect on velocity pressure is used since it is the simplest to apply. Since it represents the maximum K_{zt} value of topographic speed-up squared from any direction, there is an adjustment of velocity pressure by means of the directionality factor K_d, which normalizes the risk by computing the probability that the predominant extreme wind speed-up may not coincide with the least favorable orientation of a structural component or system. The specified K_d factors account for the directional probabilities of windspeed, determined to provide a level of safety consistent with wind load exceedence probabilities inherent in flat land open terrain sites. GIS maps for use in local building code amendments to the International Building Code are embodied in maps of K_{zt} contours and Exposure Category. These GIS maps are then rendered for detailed use as hyperlinked pdf mapbooks that provide enlarged map windows from a master key map. K_d is usually furnished as a supplemental tabular amendment.

In addition, algebraically-normalized maps of "$V_{effective}$", i.e., V multiplied by $\sqrt{(K_{zt} \times K_d / 0.85)}$ allow implicit consideration of topographic effects. An example of a map of $V_{effective}$ for components and cladding is shown in Figure 5. The $V_{effective}$ values can be used for performance-specified building components and cladding, as well as when using prescriptive design tables and existing reference standards and simplified methods based on wind speed tables.

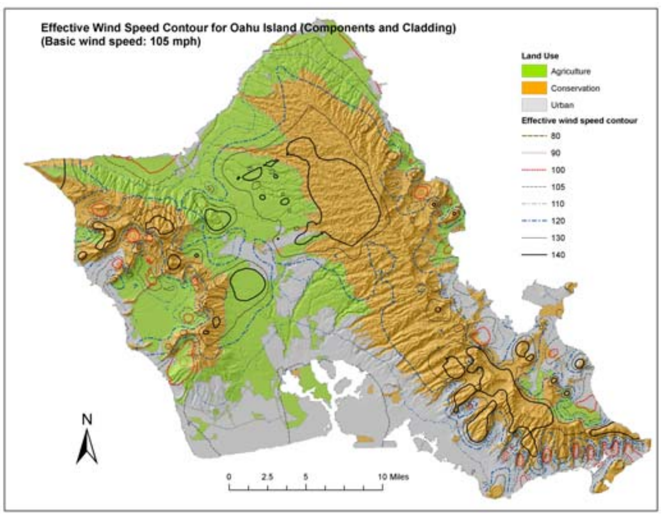

Figure 5: Effective Velocity $V_{effective}$ Map for Oahu

Differentiation of Scale and Site-Specific Analysis

Spatial resolution scales for digital modeling, including terrain effects, are conventionally described in the recognized literature as follows:

Scale	Spatial Resolution
Toposcale	10 – 200 m
Mesoscale	200 m – 5 km
Macroscale	5 - 500 km

Table 2 Scale Terminology

The Hawaii studies have considered toposcale and mesoscale effects of the terrain and surface roughness, but not the effects of the immediate proximity of the built environment. The effects of adjacent structures and the aerodynamic characteristics of a proposed building are typically studied by site-specific wind-tunnel tests.

Special building investigations including wind-tunnel tests and site-specific directionality analysis are advised for tall structures in particular. The exact proximity radius for the surrounding building environment is determined on a case-by-case basis, but should be not be less than a minimum of 250m (ASCE/SEI, 2007). These proximity models would therefore not typically address the mesoscale effects of topographic wind speed-up given in the Hawaii maps. Accordingly, the use of wind-tunnel building model tests would not qualify for a waiver of these provisions. However, site-specific probabilistic analysis to derive more-refined topographic speed-up K_{zt} and directionality K_d factors based on wind-tunnel data is permitted when submitted and approved by the Building Official. This analysis would need to demonstrate risk equivalence and not neglect the technical basis of the Hawaii maps.

Conclusions

Due to the presence of mountainous terrain and valley gorges in Hawaii, the ASCE/SEI 7 provisions, which only address the topographic speed-up influence of *isolated* 2-dimensional ridge and escarpment features and *axisymmetric* hills, do not sufficiently account for the significant effect of topographic wind speed-upcaused by complex three-dimensional topography in State of Hawaii. The topography in Hawaii creates speed-up effects that cannot be adequately portrayed by a single statewide value of windspeed.

The State of Hawaii is developing wind maps for each populated island. The primary maps are based on the application of topographic effect adjustments to a 105 mph peak gust Basic Wind Speed. Special wind regions near mountainous terrain and valleys are accounted within the Topographic Factor defined in these micro-zonation maps.

The final local Special Wind Region maps will be completed in 2008. Wind micro-zonation maps defining K_{zt} and the equivalent net effective wind speeds will be incorporated into the Hawaii State Building Code. These are formulated as "uniform-risk" wind speed maps reflecting the same probability of exceedance regardless of topographic location. The authorities having jurisdiction will thus define through local amendment the local K_{zt} , K_d , and K_z adjustments necessary to the Basic Wind Speed of 105 mph. Concurrently, a proposal to designate Hawaii as a Special Wind Region within ASCE/SEI 7-10 is proceeding.

Acknowledgements

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