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PAPER B1

SITES FOR WIND-POWER INSTALLATIONS: PHYSICAL MODELLING OF THE WIND FIELD OVER KAHUKU POINT, OAHU, HAWAII

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Summary

Oahu Island, Hawaii, U.S.A., is known to possess a rich wind power resource due to the prevailing trade wind boundary layer. A contoured model of the Kahuku Point area was prepared to an undistorted scale of 1:3840. Measurements of wind speed and turbulence were made over the Kahuku Point model in a meteorological wind tunnel. Measurements have been compared with the results of a field program. The linear correlation between field and laboratory measurements was found to be 0.80. A correlation by rank of relative wind speeds for these data pairs revealed a simulation at a level of 0.97. Laboratory data were also used to evaluate proposed analytic methods to estimate speed-up of flow over hills. Methods examined predict values which bracket measured magnitudes.

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Nomenclature:

Symbol	Definition	Dimensions
$A(z)$	Amplification factor at height z, i.e., $\overline{U}_i(z)/\overline{U}_o(z)$	
C_f	Skin friction coefficient	
$C_{f_{10}}$	Skin friction coefficient referred to 10 m height	
D_i	Rank difference for Site i, Eq. 7	L
H	Height of hill	
k	von Karman constant	
L_d	Downwind characteristic hill length	L
L_u	Upwind characteristic hill length	L
L_{u_x}	Longitudinal integral scale	L
r	Sample correlation coefficient	
$\overline{U}(z)$	Mean longitudinal velocity at height z for Site i	LT^{-1}
U_*	Shear velocity	LT^{-1}
z	Height above ground level	L
z_o	Equivalent roughness height	L
α	Exponent for power law velocity profile	
δ	Boundary layer thickness	L
Λ_x	Integral length scale	L

Subscripts

θ^i	Test wind direction: $\theta^1 = 45°$, $\theta^2 = 66.7°$ and $\theta^3 = 90°$	
θ_i	Wind direction at Site i	
θ_{REF}	Wind direction at fixed reference site	
o	Upstream reference velocity profile	
REF	Fixed reference site	
i	Site i	

1.0 INTRODUCTION

Tropical islands such as Oahu, located in the persistent trade wind belt and adorned with ridges and hills which accelerate the surface winds, are attractive locations for WECS machines. The Kahuku Point peninsula on northern Oahu has good exposure and annual mean wind speeds near 8 m/sec (18 mph). Lindley (1977, Ref. 1) has proposed a WECS farm for the locality capable of generating 450 Megawatts. The Department of Meteorology, University of Hawaii, proposed an extensive field program in this area; hence, a parallel laboratory program was prepared to extend the measurement domain in the vertical and to survey additional sites.

Earlier studies in the wind tunnel provided fundamental understandings of flow characteristics over generic hills and ridges. The Rakaia Gorge study by Meroney et al. (1978a, Ref. 2) establishes the range of reliability to be expected between wind-tunnel and field data. For actual WECS installation the results need to be applied to real topography where windmill sites are proposed. Hence, a model study of Kahuku Point, an area proposed for WECS development, was undertaken. The data of these tests were compared with limited field measurements to verify the wind-tunnel physical modeling technique. Additional wind power rich zones were identified from a thorough wind characteristic survey made over the extended Kahuku model. Predictions, semi-empirical and analytical, by Bouwmeester et al. (1978, Ref. 3) and Hunt (1978, Ref. 4) respectively, for predicting wind amplification or speedup over ridges or obstacles were applied to the WECS sites. Calculated values were compared to the wind-tunnel test data to support the degree of reliability of those formulas in practical cases.

To be more specific, the present study objectives were:

1. To provide information for WECS installations at Kahuku Point, Oahu.
2. To confirm, validate and extend the wind-tunnel and field information.
3. To validate and reinforce the semi-empirical and analytical speedup prediction formulas.

2.0 CHARACTERISTICS OF THE KAHUKU POINT REGION

The State of Hawaii, U.S.A. with total area of 16.700 km^2 was recently estimated by Elliott (1978, Ref. 5) to possess an average mean annual wind power of more than 300 w/m^2, which is the result of a mean wind speed of 7 m/sec at 10 m Above Ground Level (AGL). Among the islands of this state, the highest average annual wind speed of 10 m/sec at 10 m AGL was obtained over Oahu island due to trade winds which prevail 80-95 percent of the time during the period May through September and 50-80 percent of the time during the period October through April.

In 1974, researchers at the University of Hawaii, Manoa, started to examine wind energy potential for Oahu. By January, 1977, they were able to identify and characterize the strong wind areas on Oahu. The strong wind areas are shown in Fig. 1 with measured annual mean wind velocity noted for each area. Among those strong wind areas, Kahuku Point is considered to provide the most promising site for wind energy generation. To pinpoint the strong wind sites over Kahuku Point, two methods of data sampling were used during the late summer and fall of 1978. For a site in a rugged and heavily populated topography, a fixed station sampling method was used to collect the long-term characteristics of local wind, such as wind direction, wind speed, turbulence intensity, etc. Four fixed stations over Kahuku Point were operated. In all these stations the instruments were placed at 10 m AGL on masts to be clear of surrounding terrain and vegetation. A mobile station sampling method was also used to provide more extended wind power surveys over accessible terrain. Three vans equipped with 10 m telescoping masts, which could be set up in 30 minutes, were used. At each site statistical properties of local wind were measured continuously during a time period of at least 24 hours.

Six-minute and hourly average values were obtained for every station and are available on magnetic tape. Properties evaluated were: mean wind direction, mean wind speed, standard deviation of wind direction, and standard deviation of wind speed. A specific site Kahuku Upper Point was selected as a reference site. Mean values of data measured during a given period of time at this reference site are used to normalize the data measured during the same period of time at other sites.

3.0 LABORATORY SIMULATION CRITERIA

Earlier efforts toward laboratory simulation of flows over complex terrains have been discussed and summarized in the report by Meroney et al. (1976, Ref. 6). The report of the Rakaia Gorge effort by Meroney et al. (1978a, Ref. 2) provided a detailed comparison between field and laboratory measurements of flow over complex terrain. The validity of physical modeling of flow over complex terrain for WECS application was initially confirmed. Subsequently, Holmes et al. (1979, Ref. 7) reported the comparison of field and laboratory measurements of maximum gust velocities over Castle Hill of 286 m height near Townsville, Australia. Linear correlation coefficients ranging from 0.68 to 0.78 were obtained in both experiments.

The wind energy site-selection laboratory method consists of obtaining velocity and turbulence measurements over a scale model of selected terrain placed in a simulated atmospheric flow. The wind characteristics of the simulated atmospheric flow are chosen to reproduce the wind profile shape and length scales of the equivalent prototype situations. Since field profiles are rarely available in advance, velocity profiles and turbulence characteristics are chosen to fit an equivalent class of conditions as recorded by earlier investigators over terrain of similar roughness.

The viability of a given simulation scenario is not only a function of the governing flow physics but the availability of a suitable simulation facility and the measurement instrumentation to be employed. When one combines operational constraints into a performance envelope, a picture appears of the performance region for typical wind tunnel facilities. Limiting criteria include model size, instrument resolution, scales of simulated turbulence, and minimum acceptable Reynolds number. Assuming an upper value of length scale of 6,000 and a useable tunnel length of 5 m, a distance of 10 km is well within the capacity of existing facilities to contain in the windward direction.

4.0 LABORATORY MEASUREMENT PROGRAM

The simulation of the atmospheric boundary layer flow over Kahuku Point, Oahu, was performed in the Environmental Wind Tunnel (EWT) at Colorado State University. This wind tunnel is specially designed to study atmospheric boundary layers. It incorporates features such as adjustable ceiling, rotating turntables, transparent boundary walls, and a long test section to permit development of adequate boundary layer thickness. Mean wind speeds of 0.2 to 50 ft/sec can be obtained in the EWT. The flexible test section roof is adjustable in height to permit the longitudinal pressure gradient to be set to zero or specific values. For the WECS study over Kahuku Point, the approach surface configuration arranged in this wind tunnel has a wind speed maximum level equivalent to 600 m height, which is similar to that for the prevailing trade wind boundary layer over Oahu Island.

4.1 Topographical Model

The area studied by means of a laboratory model is located along the northeast end of the Koolau Range on the island of Oahu, Hawaii. The primary terrain features consist of a fan-shaped set of ridges opening to the north from the mountain ridge itself. The trade wind approaches most of the year from the East or Northeast and passes over sparsely vegetated abandoned cane fields and shrub covered foothills. A model section 12,730 m in diameter centered over the northern end of the mountain ridge was constructed to a scale of 1:3840. An undistorted contour model of the Kahuku Point area was constructed from layered polyurethane foam and sanded to terrain levels. This model has a diameter of 3.66 m. The dotted circle shown on Fig. 1 indicates the area covered in the model. Fig. 2 shows a detail of this region and the location of each measurement site. Graded gravel was added to the model surface to represent orchards and forested areas noted on maps from a land use survey.

4.2 Instrumentation

Vertical, mean velocity and longitudinal turbulence intensity profiles at each WECS site were measured using a constant temperature hot-wire anemometer. These measurements were reported for three different wind directions (designated as 45°, 66.7° and 90° from true north) which encompass the predominate directions from which the Pacific trade wind blows over the Kahuku Point region. For each wind direction, 40 additional locations over the model were selected for mean velocity and turbulent intensity measurements to supplement the field designated locations. Measurements at the prespecified field sites together with the additional locations provided data for a detailed wind power contour map.

During the measurements the EWT movable carriage was positioned manually at any desired site above the model. A control unit outside the tunnel monitored the vertical movement of the probes from heights of 0.3 cm to 50 cm above the model. This actuator system provides a constant voltage change for a particular change in height. The probe support was attached to the carriage by a 0.5 m extension frame. At this length, flow distortion at a measuring location caused by the actuator system was negligible.

Measurements of power spectra at several heights were obtained at three locations for a wind direction of 45°. The locations were: Site Mill 1, Site LLL, and a location which is 8 m from the inlet of the EWT along the center-line. A System 5500 Thermal Systems, Inc. constant temperature hot-wire anemometer was used for all velocity measurements. A Hewlett Packard System 1000 digital data acquisition system was used to manage data.

The hot-wire probe was set perpendicular to the free stream direction by assuming that the local wind direction is not affected by local topography. This assumption was justified by employing local direction indicators. Small flags of 1.0 cm height were used to indicate the local wind directions. The flags were also used to identify the local flow separation zones over the topography.

5.0 TEST RESULTS

Approach flow field characteristics of the model trade-wind boundary layer, impressions from visualization experiments, and contour plots which indicate the wind power resource over the Kahuku region are presented in the following sections.

5.1 Model Boundary Layer Characteristics

The uniformity of the approach flow, boundary layer thickness and turbulent structure in the EWT were determined with and without the Kahuku Point model in place in order to properly locate the model and to define the local wind characteristics in the EWT. At a free stream velocity of about 10 m/sec, measurements were made over a rectangular grid overlapping the model location. At each location evaluated, the velocity measured at a height of 15 cm (600 m equivalent above ground) was found to be a maximum. Thus, the velocity at this height was used to normalize the vertical velocity profile for each specific loation. It was found that the boundary layer in the EWT reaches an equilibrium condition with a boundary layer thickness $\delta \simeq 15$ cm at 8 meters from the entrance nozzle. As a result of this survey, the Kahuku Point model was installed directly downstream of the 8 m line.

The approach velocity profiles have a power-law exponent of 0.18 ~ 0.15, which fit the data from an equivalent height of about 200 meters. The semi-logarithmic profile

$\bar{U}(z)/U_* = \frac{1}{k} \ln \frac{z}{z_o}$ fits the profiles from an equivalent height of 10 m to 150 m when the equivalent parameters are $z_o = 11$ cm, $U_*/\bar{U}_\delta = 0.047$ and $k = 0.40$. Resultant skin friction coefficients were $C_f/2 = (U_*/\bar{U}_\delta)^2 = 0.0022$ or $C_{f_{10}} = 2\ (U_*/\bar{U}(10))^2 = 0.0149$. The local longitudinal turbulence intensity at the surface was 17 ~ 18 percent at $z = 10$ m.

A few velocity profiles for the marine trade wind boundary layers have been reported by Augstein (1979, Ref. 8). Two typical profiles designated as BOMEX and Pacific trade wind boundary layers were used to compare with the boundary layer simulated over the Kahuku Point model. The comparison is shown on Fig. 3 wherein each profile has been normalized by the velocity maximum measured at the 600 m height. The typical trade wind boundary layer characteristics have been simulated approximately to a 1000 m equivalent height. Typical modeled sea roughness length may vary from 10^{-7} cm to 1 cm depending upon the state of the sea surface and the average surface shear stress (Roll, 1965, Ref. 9). The modeled sea surface roughness appears to be about 10 cm. Since this represents a smooth wind-tunnel floor condition, it is the minimum roughness attainable at a scale of 1:3840.

Three locations were selected for longitudinal power spectra measurements. Figure 4 shows the comparison of power spectra at the equivalent 10 m height for three locations mentioned above with the semi-universal spectrum proposed by Harris.

Overall, characteristics of flow over the Kahuku Point model are tabulated in Table 1 together with compatible full-scale atmospheric boundary layer characteristics compiled by Counihan (1975, Ref. 10).

5.2 Flow Visualization

Mean wind direction pattern and obvious separation zones over Kahuku Point for each wind direction have been observed as shown on Fig. 5. These figures indicated that the flow pattern over the model slightly altered with approach wind direction especially behind gulches. However, over regions which cover all the proposed WECS sites the wind direction remains essentially the same as that of the approach flow direction.

5.3 Wind Power Resource

Measurements at 29 proposed WECS sites were made at 45°, 66.7° and 90° wind directions from true north respectively. A free stream velocity of approximately 10 m/sec was used for each profile. Detailed contour plots of the velocities at the equivalent 10 m and 50 m heights referenced to the velocity at equivalent 600 m height are shown on Fig. 6 and 7. These contour plots were constructed from the velocity measurements, the flow visualization results, and authors' judgement concerning the extent of the local topographic influences. Data smoothing techniques were also employed to obtain the contours.

These contour plots confirm the following conclusions made by Ramage (1979, Ref. 11) regarding the field measurements of wind power in the Hawaiian Islands:

> First, near the beach a sharp acceleration between sea and land is associated with convergence and acceleration. Second, over the flat land immediately inland, the winds are frictionally slowed. Third, over gently sloping hills still further inland, distance from the corner and the sea-land discontinuity and frictional slowing are overcome by acceleration as the flow is constricted between terrain and the overlying inversion; still farther inland up the ridge distance from the corner and frictional slowing combine to overcome the hill effect resulting in less speed with land elevation.

Moreover, such maps provide a clear picture of the more promising areas over Kahuku Point area and also areas where WECS sites should be avoided.

6.0 COMPARISON WITH FIELD DATA

The field program was performed by researchers at the University of Hawaii. Summary measurements at the proposed WECS sites over Kahuku Point area from 8 August to 10 October of 1978 were provided to the authors by Dr. Anders Daniels, Department of Meteorology, University of Hawaii. The sets of data for each mobile measurement station during the test time period include: mean wind speed, standard deviation of wind speed, mean wind direction, and wind speed ratio with respect to the mean speed at a fixed reference site. The fixed reference site selected by University of Hawaii staff was Site Kahuku Upper.

Continuous hourly averaged data at each mobile station and four fixed sites (Kahuku Upper, Kahuku Road, Kahuku Oyster 90 and Kahuku Oyster 30) were also examined. An examination of the field data suggested that not all measurements were taken under circumstances comparable with the conditions chosen for physical simulation in the wind tunnel. Hence, some data sets were eliminated from the field data provided before a direct model to field comparison was attempted. Three data trends were identified for which criteria could be assigned to isolate inappropriate measurement pairs; i.e.

a) Approach and direction conditions outside the range of 45° to 90° simulated in the laboratory,

b) Periods during which local mountain-valley winds dominated the trade wind; and

c) Sites experiencing abnormally high turbulence levels in excess of values expected for well exposed anemometer conditions. Eighteen data pairs remained suitable for field/laboratory comparison.

Relative wind speeds for each site, (laboratory or field) were compared based on a normalization by an equivalent reference site at Kahuku Upper (see Fig. 2). Laboratory ratios were calculated in the following manner (assuming the same wind direction at both mobile and reference stations).

$$\left[\frac{\bar{U}_i(10)}{\bar{U}_{REF}(10)}\right]_{\theta^i,M} \cong \frac{\left[\frac{\bar{U}_i(10)}{\bar{U}_i(600)}\right]_{\theta^i,M}}{\left[\frac{\bar{U}_{REF}(10)}{\bar{U}_{REF}(600)}\right]_{\theta^i,M}} \quad , \ i=1,2,3 \qquad (1)$$

with $\theta^1 = 45°$, $\theta^2 = 66.7°$ and $\theta^3 = 90°$ respectively. In the above calculation, $\bar{U}_i(600)$ was assumed to be equivalent to $\bar{U}_{REF}(600)$. $[\bar{U}_i(10)/\bar{U}_i(600)]_{\theta^i,M}$ and $[\bar{U}_{REF}(10)/\bar{U}_{REF}(600)]_{\theta^i,M}$ were obtained directly from listed data or normalized velocity profiles.

The laboratory evaluated relative speed of each site was obtained using the following weighted average approach.

Let $\theta^1 = 45°$, $\theta^2 = 66.7°$ and $\theta^3 = 90°$ respectively.

For $\theta^3 \le \theta_i \le \theta^3 + 10°$,

$$\left[\frac{\bar{U}_i(10)}{\bar{U}_i(600)}\right]_{\theta_i,M} \cong \left[\frac{\bar{U}_i(10)}{\bar{U}_i(600)}\right]_{\theta^3,M} \tag{2}$$

For $\theta^1 \geq \theta_i \geq \theta^1 - 10°$

$$\left[\frac{\bar{U}_i(10)}{\bar{U}_i(600)}\right]_{\theta_i,M} \cong \left[\frac{\bar{U}_i(10)}{\bar{U}_i(600)}\right]_{\theta^1,M} ; \tag{3}$$

For $\theta^1 \leq \theta^i < \theta_i < \theta^j \leq \theta^3$.

$$\begin{aligned}\left[\frac{\bar{U}_i(10)}{\bar{U}_i(600)}\right]_{\theta_{i,M}} &\cong \left(1.0 - \frac{\theta^j - \theta_i}{\theta^j - \theta^i}\right) \cdot \left[\frac{\bar{U}_i(10)}{\bar{U}_i(600)}\right]_{\theta^j,M} \\ &+ \left(1.0 - \frac{\theta_i - \theta^i}{\theta^j - \theta^i}\right) \cdot \left[\frac{\bar{U}_i(10)}{\bar{U}_i(600)}\right]_{\theta^i,M}\end{aligned} \tag{4}$$

Finally, $\left[\frac{\bar{U}_i(10)}{\bar{U}_{REF}(10)}\right]_{\theta_i,\theta_F,M}$ is the relative wind speed with respect to a fixed station.

These values were calculated by using

$[\bar{U}_i(10)/\bar{U}_i(600)]_{\theta_i,M}$ and $[\bar{U}_{REF}(10)/\bar{U}_{REF}(600)]_{\theta_F,M}$

obtained from equation (2) or (3) or (4), i.e.

$$\left[\frac{\bar{U}_i(10)}{\bar{U}_{REF}(10)}\right]_{\theta_i,\theta_F,M} \cong \frac{\left[\frac{\bar{U}_i(10)}{\bar{U}_i(600)}\right]_{\theta_i,M}}{\left[\frac{\bar{U}_{REF}(10)}{\bar{U}_{REF}(600)}\right]_{\theta_F,M}} \tag{5}$$

where $\bar{U}_i(600) \cong \bar{U}_{REF}(600)$ was again assumed.

By assuming the laboratory test data as an "independent" variable x and the field data a "dependent" variable y, the sample correlation coefficient r between a set (x, y) was calculated as

$$r = \frac{n \Sigma x y - \Sigma x \Sigma y}{\{[n \Sigma x^2 - (\Sigma x)^2]\ [n \Sigma y^2 - (\Sigma y)^2]\}^{\frac{1}{2}}} \tag{6}$$

where n is the total number of (x, y) pairs used. If the sample regression line for 26 data pairs are used in the above relation, excluding data belonging to eliminating Category a), the sample correlation coefficient r calculated for these data is 0.57. This value of correlation is lower than would be desired.

If all the questionable sites are excluded, the sample correlation coefficient obtained for the remaining 18 data pairs is 0.80. Figure 8 shows the scatter diagram and the sample regression line for these data pairs.

An alternative way to compare field data and laboratory data is the correlation of the site rank, when both sets of data are ordered according to the relative wind speed magnitude. The correlation by rank was calculated by

$$r = 1.0 - \frac{6 \sum_{i=1}^{n} D_i^2}{n(n-1)} \tag{7}$$

where $D_i = \mathrm{Rank}_{\substack{\mathrm{FIELD} \\ \mathrm{STATION}}} - \mathrm{Rank}_{\substack{\mathrm{MODEL} \\ \mathrm{STATION}}}$

n = total number of data pairs used.

For a relative wind speed rank test for the 18 Kahuku Point data, calculated rank correlation is $r = 0.970$.

7.0 COMPARISON WITH AMPLIFICATION PREDICTION RELATIONS

One of the goals of this study was to evaluate some of the techniques which have been proposed to make a quantitative prediction of the effects of topography upon the wind flow. Various techniques which include numerical, semi-empirical and analytical methodologies have been proposed by researchers such as Jackson and Hunt (1975, Ref. 12), Hunt (1973, Ref. 13), Hunt (1978, Ref. 4), Britter et al. (1979, Ref. 14), Bouwmeester et al. (1979, Ref. 3), Derickson and Meroney (1977, Ref. 15) and Lavoie (1974, Ref. 16). As might be expected, different assumptions were used, which lead to various degree of accuracy and computational complication.

This study provides an opportunity to evaluate some of these techniques as they may be applied to actual hill modified flow fields. Comparison of the laboratory data to values obtained by various techniques could justify their assumptions and, hopefully, provide further information which may be used for improvement. In this study, the semi-empirical and the analytical techniques proposed by Bouwmeester et al. (1979, Ref. 3) and Hunt (1978, Ref. 4), respectively, were chosen to compare with our laboratory results.

7.1 Bouwmeester's Semi-empirical Technique

From studies of the flow over two-dimensional ridges, Bouwmeester et al. (1979, Ref. 3) proposed a semi-empirical speed-up prediction technique. Detailed explanation of this technique is given in Bouwmeester's doctoral thesis (1979, Ref. 3) and a report by Meroney et al. (1978b, Ref. 17). The predictions were derived for isolated and smooth two-dimensional ridges immersed in an atmospheric boundary layer which has a constant velocity profile exponent.

The Bouwmeester algorithm for topographical amplification suggests

$$A_i(z) = f(L_u/H,\ L_d/H, \text{ and } z_o) \tag{8}$$

where L_u/H and L_d/H are upward and downward average hill slope from crest and z_o is approach fetch surface roughness. To apply the technique, vertical sections of the subject hill along the approach and direction were sketched, slopes determined, and empirical correlations consulted.

7.2 Hunt's Analytical Approximations

In a recent review paper about the wind over hills, Hunt (1978, Ref. 4) proposed an analytical approximation relation for the wind speed-up prediction. The relation is simply a modification of the inviscid potential flow theory for a uniform airstream over an obstacle when $H/L_o \ll 1$ and $H/b \ll 1$.

The amplification factor at hill crest $A_i(z)$ can be evaluated simply as

$$A_i(z) \simeq 1 + \frac{H}{L_o}\frac{1}{\pi}\int_{-\infty}^{\infty}\frac{df(\xi)/d\xi}{\xi}\,d\xi \qquad (9)$$

where $f(x)$ is hill height versus longitudinal distances when the origin of the x axis is the hill crest. The integral in Equation (9) was evaluated by applying a simple graphical integration technique to the hill sections discussed earlier.

7.3 Amplification Factor Comparison

Amplification factors are summarized in Table 2 for the convenience of direct comparison. Individual deviation from the laboratory results for both techniques are also presented. It is obvious that Bouwmeester's technique tends to overpredict, while Hunt's analytical formula tends to underestimate the amplification factors. Overall average deviations from our laboratory results are + 16% and - 18% respectively.

The above comparison not only indicates the trends of both techniques, but also reveals the importance of upstream effects on the predictions of speed-up over a complex terrain. In addition to the lack of isolation, smoothness and two-dimensionality of hills, the assumption of a constant approach flow velocity profile was distorted by the topography features upstream and the associated turbulence structure. If further experimental work could provide some information about the above effects on speed-up, this technique may be modified to provide a more satisfactory prediction method.

8.0 CONCLUSIONS

A 1:3840 model of Kahuku Point was tested in the Colorado State University, Environmental Wind Tunnel. The model was placed at a location 8 meters from the wind tunnel inlet, where an equilibrium boundray layer was established. Boundary layer thickness, and turbulent structure were similar to the observed trade wind boundary layer. Local modeling of the roughness features of the topography were also included in the study.

Wind speed, turbulence, and spectral scales were measured and found compatible with an average adiabatic wind profile condition as modified by trade wind characteristics.

Thirty-two field test site measurements were made available by the University of Hawaii. Of these field measurements, eighteen were found to correspond to the conditions modeled in the wind tunnel. Direct correlation of the laboratory and field measurements for the 18 sites produced a linear correlation coefficient of $r = 0.80$. The value of the correlation by rank for the 18 sites was .970. The remaining 7 sites did not correspond to the test conditions in the wind tunnel.

Additional measurements at locations evenly selected over the Kahuku Point model together with flow visualization studies provide information that may be used to identify likely WECS site locations. Contoured maps were prepared which indicate the wind-power resource distributions over Kahuku Point.

By applying the semi-empirical and the analytical relations, which were proposed by Bouwmeester and Hunt respectively, to several WECS sites, the two methods were found to bracket typical topography amplification. Bouwmeester's analysis tends to overpredict the wind amplification, whereas Hunt's method predicted too small an amplification. Evidently, the methods suffer from the lack of internal specification of the turbulent structure due to the upstream topography features. Improvement in prediction of the approach flow would appear to be a first step in reducing the uncertainty of the predictions.

9.0 ACKNOWLEDGEMENTS

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Table 1. Comparison of Approach Boundary Layer in the EWT with Atmospheric Boundary Layer Compiled by Counihan (1975).

	Length Scale 3840:1	
Parameters	Boundary Layer in the EWT	Neutral Stability Atmospheric B.L.
Roughness Height (z_o)	0.11 m	0.11 m
Power Law Coefficient α_o	0.13 - 0.15	0.14 ± 0.02
Boundary Layer Thickness δ	600 m	600 m ± ?
Turbulence Intensity at 10 m $\sqrt{\overline{u'^2}}/\bar{U}$	17 ~ 18%	15 ± 5%
C_f at 10 m	0.0149	0.0128
$\sqrt{\overline{u'^2}}/U_*$ at 10 m	2.78	2.5 ± 5
Λ_x at 10 m	167 m	100 - 170 m

Table 2. Comparison of Measured Amplification Factors with Values Predicted by Applying Bouwmeester's and Hunt's Techniques for Several Selected WECS Sites.

Site	$A_i(10)$ Laboratory	$A_i(10)$ Bouwmeester	$A_{i_B} - A_L/A_{i_L}$ (%)	$A_i(10)$ Hunt	$A_{i_H} - A_{i_L}/A_{i_L}$
3	1.15	1.268	+10	--	--
6	1.43	1.677	+17	1.18	-17
10	1.41	1.892	+34	1.065	-24
LLL(11)	1.35	1.43	+ 6	1.225	- 9
14	1.40	1.445	+ 3	1.08	-24
15	1.52	1.822	+19	1.08	-29
16	1.68	1.627	- 3.5	10.2	-39
17	1.18	1.66	+40	1.03	-13
23	1.20	1.567	+30	1.03	-14
24	1.19	1.445	+21	1.03	-13
30	1.29	1.724	+33	1.09	-15
32	1.38	1.54	+11	1.43	+ 3.6
33	1.15	1.687	+25	1.02	-11
35	1.35	1.548	+10	1.05	-22
Mill 2	1.40	1.29	- 8	1.11	-21
Opana Amb.	1.36	1.52	+11	1.01	-26
		Overall Average	+16%	Overall Average	-18%

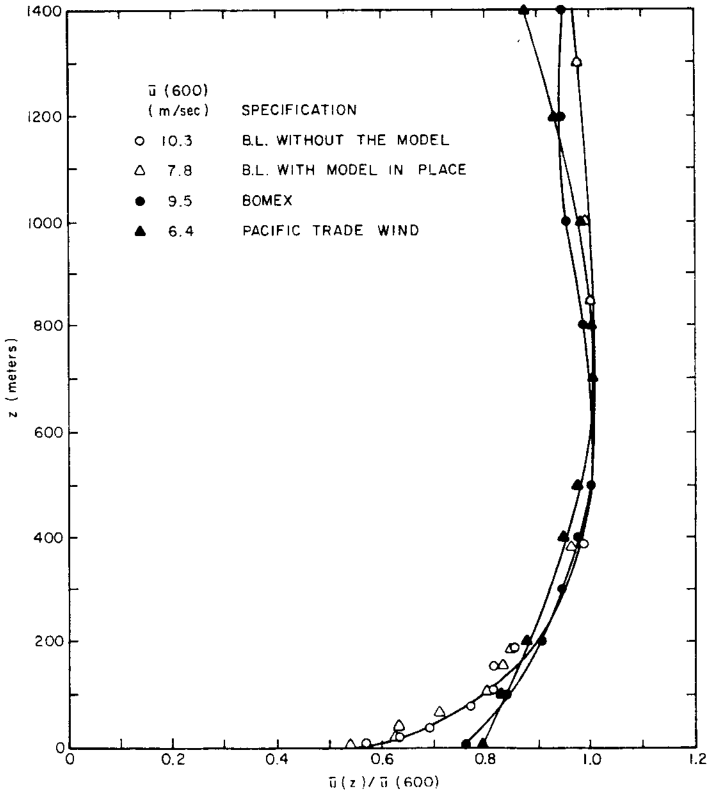

FIG. 3. COMPARISON OF SIMULATED TRADE WIND BOUNDARY LAYER IN EWT WITH MARINE TRADE WIND BOUNDARY LAYER REPORTED BY AUGSTEIN (1979).

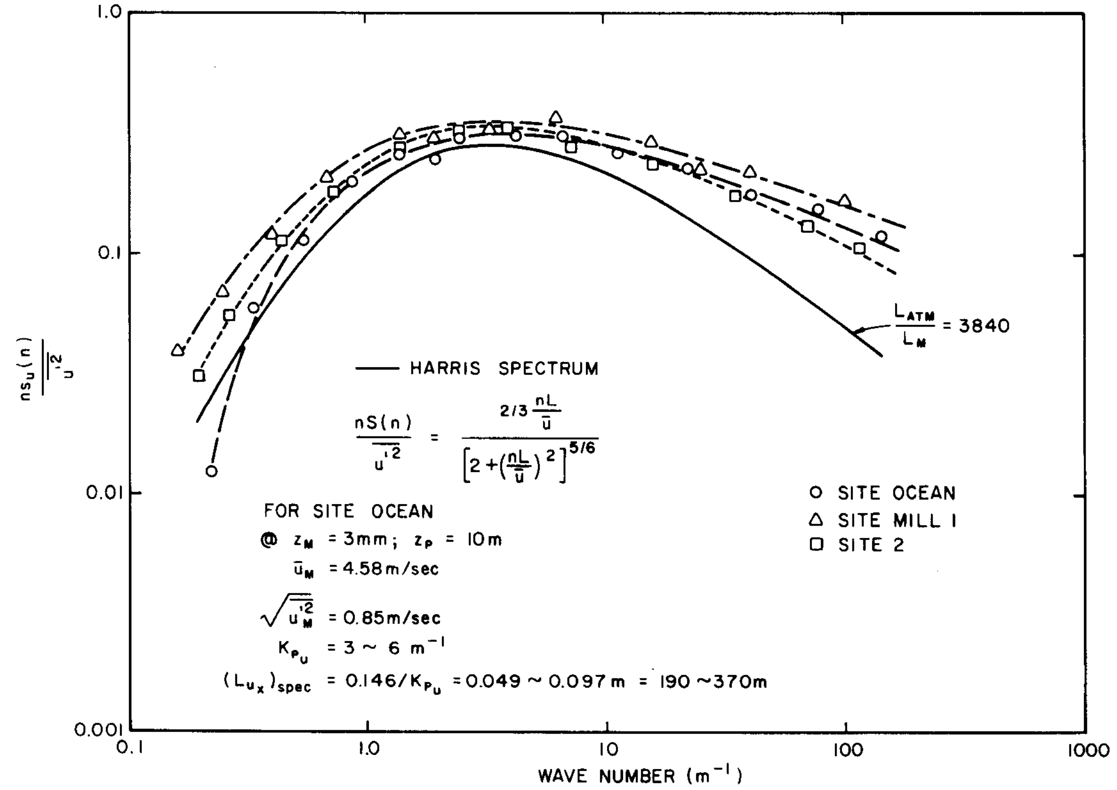

FIG. 4. COMPARISON OF LONGITUDINAL POWER SPECTRA MEASURED AT THREE SITES OVER THE KAHUKU MODEL WITH HARRIS SPECTRUM AT 10 m HEIGHT.

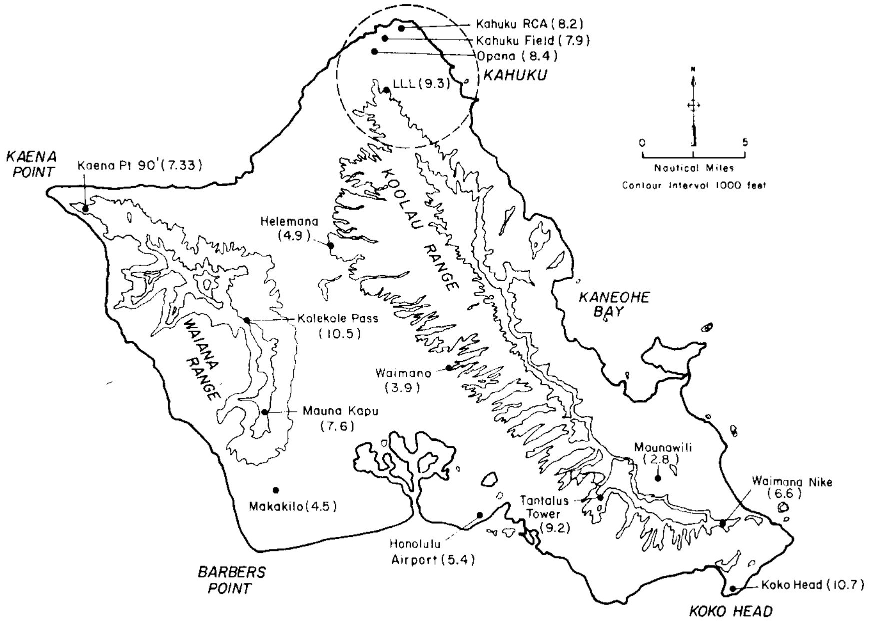

FIG. 1. ANNUAL MEAN WIND VELOCITY (m/sec) AT SITES OVER OAHU ISLAND AND THE AREA COVERED IN THE MODEL TEST.

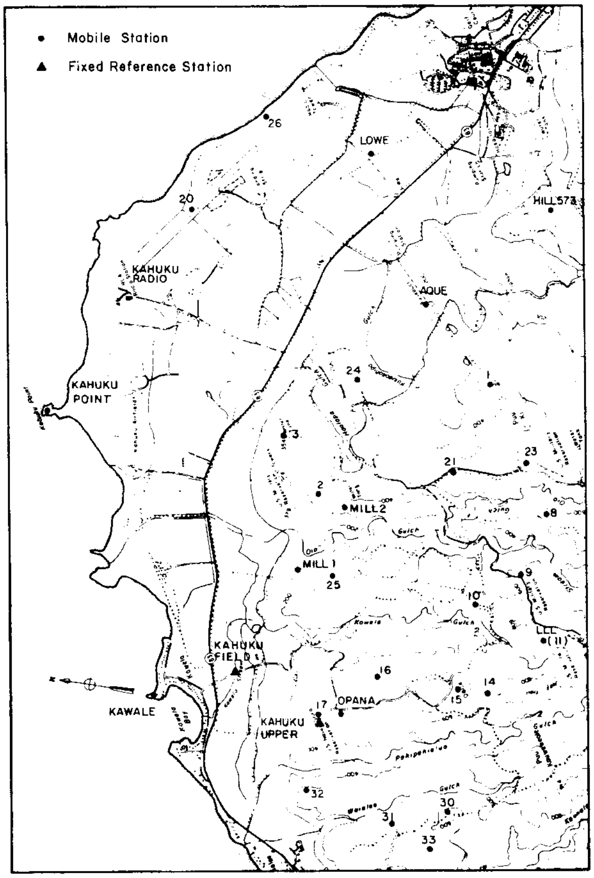

FIG. 2. CONTOURED MAP FOR KAHUKU POINT AREA AND LOCATIONS OF WECS SITE IN THIS AREA.

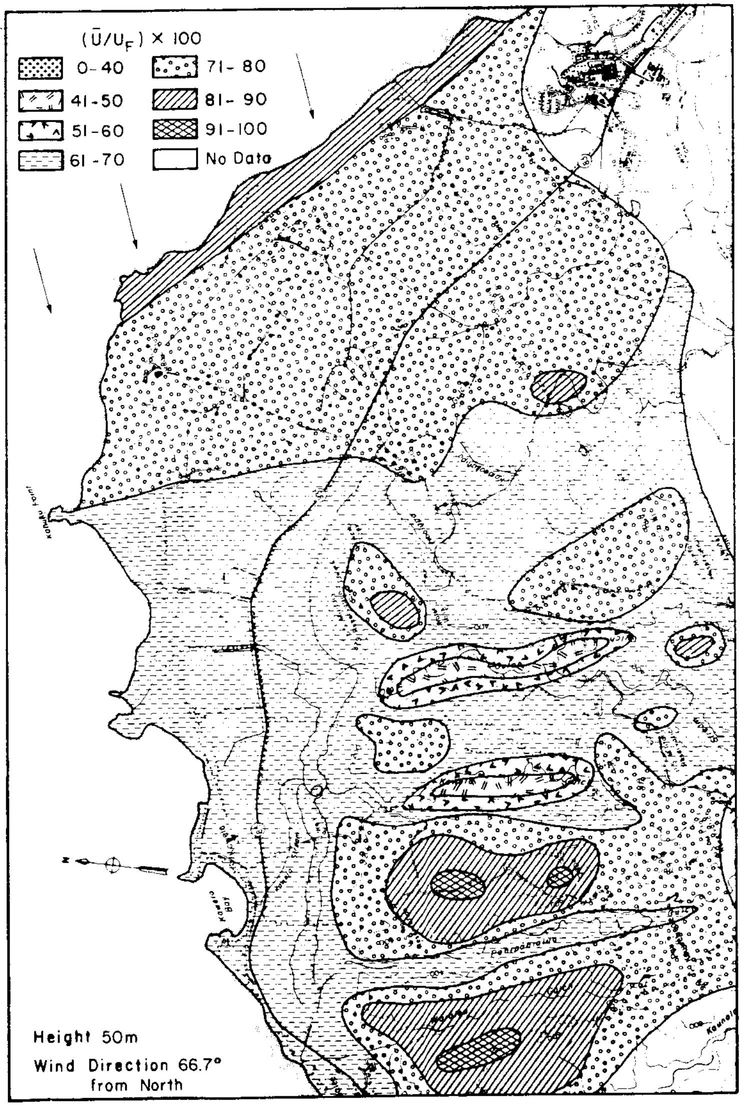

FIG. 7. CONTOUR PLOT OF RELATIVE VELOCITIES OVER THE KAHUKU POINT MODEL AT EQUIVALENT 50 m HEIGHT FOR WIND DIRECTION OF 66.7° FROM NORTH.

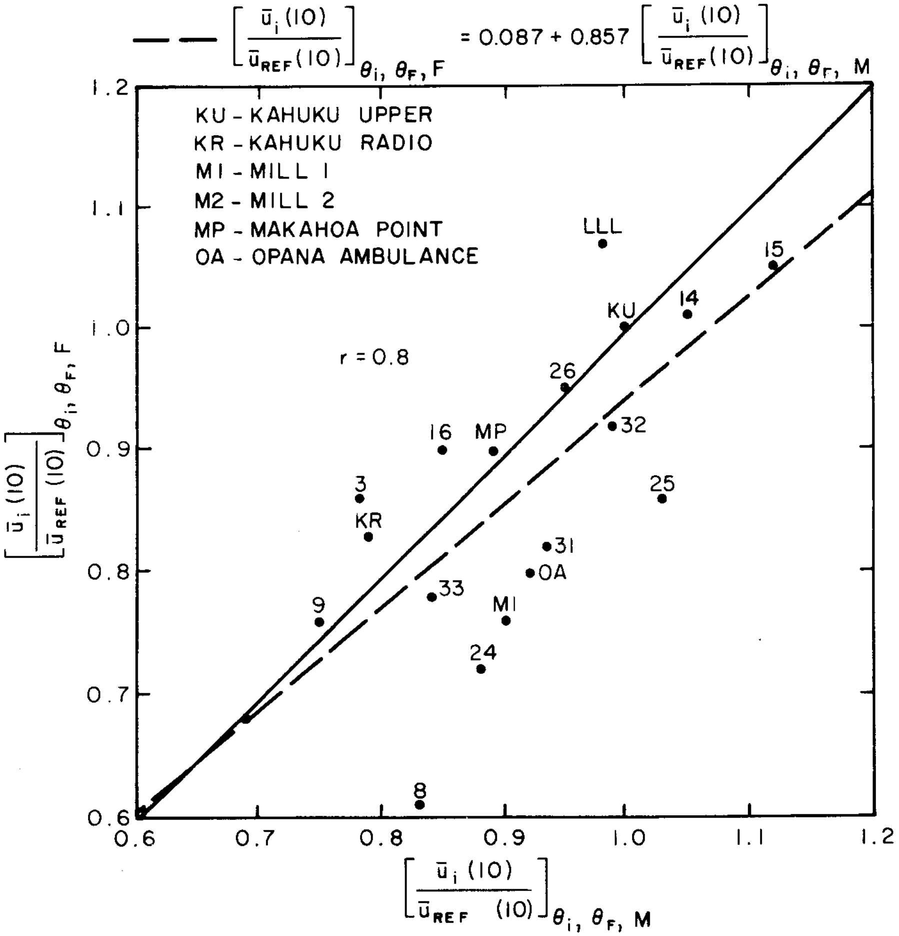

FIG. 8. SCATTER DIAGRAM AND SAMPLE REGRESSION LINE FOR 18 DATA PAIRS.

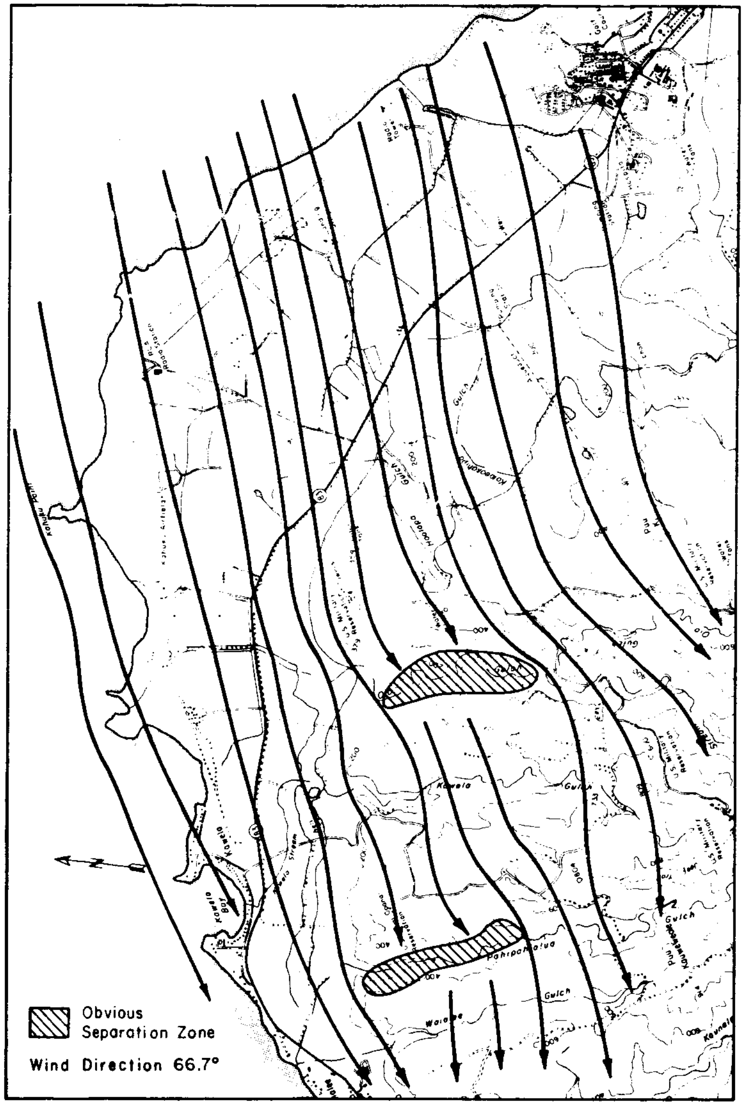

FIG. 5. FLOW PATTERN OVER THE KAHUKU POINT MODEL FOR APPROACHING WIND DIRECTION OF 66.7° FROM NORTH.

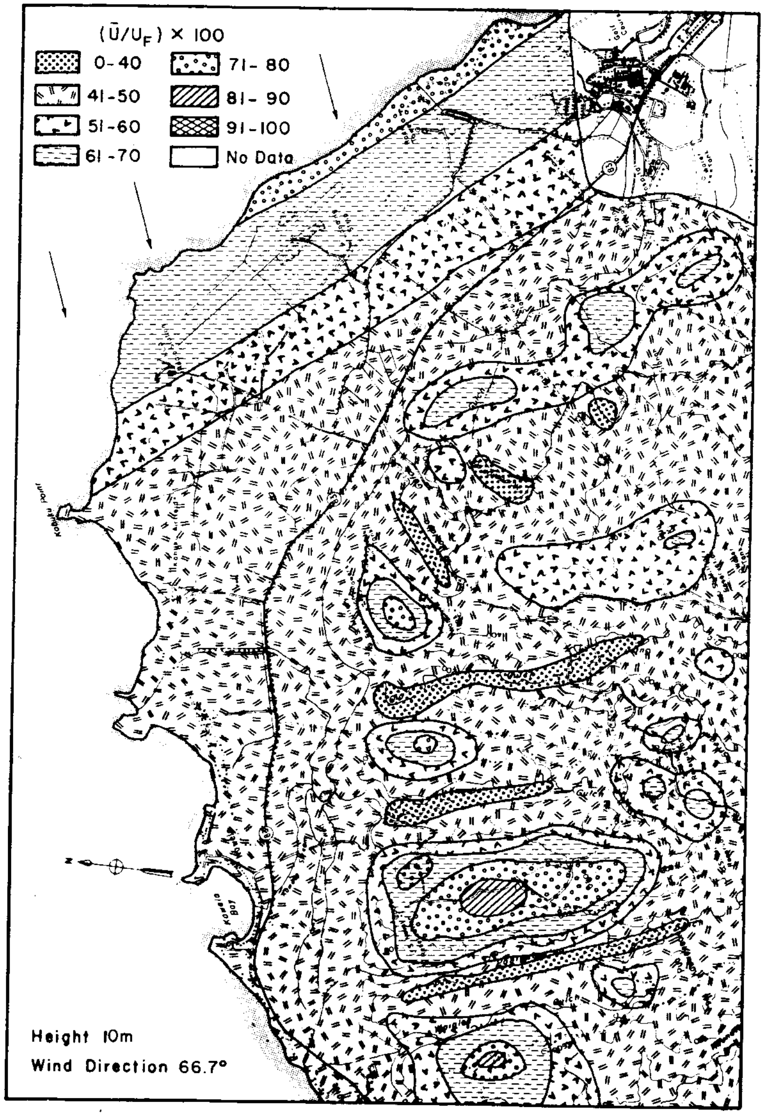

FIG. 6. CONTOUR PLOT OF RELATIVE VELOCITIES OVER THE KAHUKU POINT MODEL AT EQUIVALENT 10 m HEIGHT FOR WIND DIRECTION OF 66.7° FROM NORTH.