CLIMATOLOGICAL SURVEY AND MODEL STUDY

OAKLAND-ALAMEDA COUNTY COLISEUM

PART II

WIND-TUNNEL STUDIES

by

J. E. Cermak, Professor-in-Charge, Fluid Mechanics Program
E. J. Plate, Associate Professor, Department of Civil Engineering

under contract with

Metronics Associates, Inc.
3201 Porter Drive
Stanford Industrial Park
Palo Alto, California

for

Skidmore, Owings and Merrill
1 Bush Street
San Francisco, California

Fluid Mechanics Program
Fluid Dynamics and Diffusion Laboratory
College of Engineering
Colorado State University
Fort Collins, Colorado
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ABSTRACT

Wind patterns over a 1:384 scale model of the Oakland-Alameda County Coliseum were obtained by wind-tunnel study of the proposed complex. Motion pictures of direction indicating flags and measurements of wind speed were made for three wind directions (WNW, W and WSW), for three tree plans and for two different upper-stand arrangements at a wind speed of 30 fps. Pressure distributions around the outer wall of the circular arena structure were measured for wind speeds of 30 and 55 fps.

Wind conditions over the playing field of the stadium are generally such that wind speeds are less than 60 percent of ambient air speed. Relatively high wind speeds were directed along the windward side of the arena, across the bridge connecting arena and stadium, and over the berm from left-field to right of center field.

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WIND-TUNNEL STUDIES OF THE OAKLAND-ALAMEDA COUNTY COLISEUM

I. Introduction

The Oakland-Alameda County Coliseum is to be located approximately one mile northeast of Oakland Airport. In common with many parts of the Bay Area this site is exposed to the regular diurnal sea breeze flow which predominates from late spring to early fall. Typically this flow reaches maximum velocity in the early afternoon coincident with the baseball playing period. Wind speeds are high enough to be a potential source of annoyance and discomfort to spectators and players.

A site investigation has been completed showing the meteorological conditions to be expected in and around the proposed Coliseum structure. This investigation is fully described in Part One of this report prepared by Metronics Associates, Inc. of Palo Alto, California. Results from Part One showed the need for a model study.

This wind-tunnel model study of the proposed Oakland-Alameda County Coliseum was made to determine the surface wind patterns and distributions of wind speed around the arena-stadium complex. Such information obtained for the most probable wind directions and a variety of model configurations has its utility in the identification of potential wind problems (primarily related to human discomfort) and in suggesting ways to alleviate adverse wind conditions. A secondary objective of the study was to determine the effects on wind patterns produced by various patterns of mature trees and the pressure distribution around the outer wall of the arena periphery.

II. Description of the Wind-Tunnel Model Study

In this section a brief description is given of the model, the wind tunnel-model arrangement, the model configuration and the type of data obtained during the study.

A. The Model

A model built to a scale of 1:384 (1 inch = 32 feet) was provided by the architectural firm of Skidmore, Owings and Merrill (SOM). Horizontal and vertical scales were equal. Photographs of the model are reproduced in Figs. 1a and 1b. A plan and an elevation sketch of the complex is shown in Fig. 3.

The model base was constructed from a 2 inch thick sheet of styrofoam. Plywood was used for construction of the arena and wood-cardboard construction was used for the stadium. Steel wool fastened to straight heavy pieces of wire formed the trees.

B. The Wind Tunnel-Model Arrangement

The model was mounted on a 5'10" circular turn table on the wind tunnel test-section floor at the location indicated in Fig. 2. A sloping ramp beginning at the test-section entrance at wind-tunnel floor level and terminating at the ground-level of the model provided a smooth-gradual transition for air flow onto the model. The wind-tunnel floor was built up around the circular turn table to ground level of the model to provide a continuous plane surface of test-section width which extended both upstream and downstream of the model. With this arrangement the model could be placed in any desired orientation with respect to wind direction without undesired flow interference.

C. Model Configurations

The primary variables in configuration investigated were the wind direction, tree arrangement and the upper-stand geometry. These were varied as follows:

1. Wind directions chosen for investigation (based upon the climatological studies made by Metronics Associates, Inc.) were WNW, W and WSW. These directions--shown in Fig. 3 -- correspond to the prevailing wind directions at the site. To obtain the most symmetrical flow pattern possible for the pressure distribution around the arena, these measurements were taken with the wind parallel to the model axis (line connecting centers of arena and stadium). Wind speed was chosen to be 30 fps for the study excepting that one set of pressure measurements around the arena was taken with a wind speed of 55 fps to demonstrate the indifference of the flow pattern to wind speed. The reference wind speed U as used here refers to wind at a height above the model sufficiently great so that the lower boundary and model had no appreciable effect upon the air speed.

2. Three tree plans were used in the study. These are shown in Fig. 4 and are referred to as "Tree Plan A", "Tree Plan X" and "No Trees". The trees were approximately 2-1/2 in. tall (80 ft. for the prototype) and were planted sufficiently close to form a continuous

foliage excepting for a region about 1/2 in. between the ground and the lower portion of the foliage.

3. Two upper-stand geometries for the stadium were employed. The 'original' upper stand furnished by SOM extended about half-way around the stadium while the subsequently furnished upper stand extended over about one-third the periphery. These geometries are shown in Fig. 4a. Flow for the "original" geometry was studied with only tree plan A.

Configuration	Wind Direction	Wind Speed (fps)	Tree Plan	Upper Stands
1	WNW	30	No Trees	Modified
2	WNW	30	Plan X	Modified
3	WNW	30	Plan A	Modified
4	WNW	30	Plan A	Original
5	W	30	No Trees	Modified
6	W	30	Plan X	Modified
7	W	30	Plan A	Modified
8	W	30	Plan A	Original
9	WSW	30	No Trees	Modified
10	WSW	30	Plan X	Modified
11	WSW	30	Plan A	Modified
12	WSW	30	Plan A	Original
	Pressure Distribution Configurations			
1	W 36-1/2° S	30	No Trees	Modified
2	W 36-1/2° S	55	No Trees	Modified
3	W 33° S	30	No Trees	Modified

TABLE I
Configurations Studied

D. Data Obtained

General wind patterns were obtained by observing the directions taken by pivoted yarns (flags) supported on pins stuck into the model surface. Some flags were 1/4 in. above the surface while others were 1/2 in. above the surface. The directions of over fifty flags were simultaneously recorded by photographing the model with a motion picture camera. The three 100 ft reels of 16 mm film taken form a permanent data record of the surface wind patterns for all configurations studied.

Wind speeds were sensed by a Prandtl tube with the output pressure differentials being measured by a Transonic pressure transducer. Vertical profiles of wind speed were taken at six positions as shown in Fig. 3. All positions were not surveyed for each configuration. Continuous distribution curves shown in Figs. 8-13 were obtained by feeding the electrical output of the Transonic pressure transducer to one motion of an X-Y plotter and a voltage proportional to the height of the Prandtl tube relative to ground level to the second motion. The Prandtl tube was mounted on a vertical-motion carriage driven by an electrical motor.

Wind speeds obtained are estimated to have an accuracy of $\pm$ 2% and the vertical location is estimated to be within $\pm$1/32 in.

Wind speeds at a fixed distance above the surface of 1/4" (8ft) were obtained by sliding a Prandtl tube having a spacer fixed to the lower edge of the tube over the model. This was done by attaching the Prandtl tube to an 8 ft long rod which could be used by an operator standing in the tunnel to guide the tube over the model. No change in flow pattern was observed due to the presence of the operator standing downwind from the model while he was at the test-section center. Figures 14-17 show the general areal distribution of wind speeds

III. Average Surface Flow Patterns

The numerous flags placed over the model surface made directions of the wind vector visible so that at any instant the general form of the surface-flow pattern could be obtained. Detailed study of the flow patterns should be made by observing the motion picture films made of each flow configuration. Two 100 ft reels of motion picture film are provided as part of this report.

For a given configuration observation of the flag directions for a period of time enables one to construct an average flow pattern. This has been done for each configuration and a qualitative sketch made for each case. Each of the flow patterns are shown in Figs. 5 through 7.

Examination of the flow-pattern sketches indicate that the wind direction is the dominant parameter in determining the flow pattern. For the wind direction WNW Figs. 5a-5d show the typical features of channelling between arena and stadium, convergence (inverse in flow speed) over the left-field berm and a rotary flow on the playing field.

Flow patterns for the W wind are shown in Figs. 6a through 6d. These patterns do not differ greatly from those for the WNW wind; however, the intensity of convergence over the left-field berm is decreased.

In Figs. 7a through 7d are shown the flow patterns for a WSW wind. The pattern is somewhat different from the previous cases in that the rotor or rotors on the playing field are apparently eliminated. The channelling across the bridge section is still intense and there is a tendency for convergence to occur on the berm just to the right of center field. This wind direction gives the most uniform flow over the entire playing field and has the general direction of WSW.

IV. Vertical and Areal Distributions of Wind Speed

Vertical profiles of the mean horizontal velocity were taken at 6 significant points around and in the stadium. The locations of these points are indicated in Fig. 3. The profiles were taken to reveal regions of high local velocities.

The result of the measurements of vertical mean-velocity profiles cannot be applied to the field situation with the same degree of accuracy possible for interpretation of wind direction from flag directions. This is due to two reasons. First, the boundary layer of the model should be modeled to the same scale as the geometry of the stadium. And secondly, the surface roughness for the model and prototype should be aerodynamically similar. If these two conditions all met, similarity of the model and prototype velocity profiles is ensured. However, in practice these conditions can be met only approximately.

Both the boundary-layer thickness at the stadium site and upwind from it, and the roughness height of the natural situation are approximately known factors and can be determined only with considerable effort - with the results not always justifying the means necessary for obtaining them. Instead, an exaggerated flow pattern in which local velocities are more severe than those encountered in reality can be obtained by keeping the boundary layer of the approaching flow upwind from the stadium thin, and by maintaining the floor on which the model is placed aerodynamically smooth. In this manner, the prototype winds estimated from the model data will be on the safe or conservative side.

Model wind speeds u_o obtained for a given ambient velocity U_o can be used to obtain corresponding model wind speeds u at different ambient speeds U by the linear relationship

$$u = u_o \frac{U}{U_o}$$

Thus, if a model wind speed at a certain elevation (say 1 inch) is measured to be 5 fps when the tunnel speed is 30 fps, the corresponding model speed at the same elevation for an ambient speed of 60 fps would be

$$u = 5 \left(\frac{60}{30}\right) = 10 \text{ fps}.$$

To translate the foregoing example of model measurement to the prototype or actual field condition it is only necessary to refer the model elevation to prototype elevation through the scale factor. Thus, for the 1 inch elevation, the corresponding prototype elevation is

$$\text{Elev}_{(\text{prot.})} = \text{Elev}_{(\text{model})} \ (384)$$
$$= 1\ (384)\ \text{in. or } 32\ \text{ft}$$

The wind speed at the prototype elevation of 32 ft would then be approximately 5 fps for a 30 fps wind or 10 fps for a 60 fps wind. For the model used in this study the reference wind speed used in the field corresponding to the model ambient velocity U_o should be measured at an elevation of approximately 50 ft at a station upwind from the Coliseum.

In the following sections, the results of the measurements will briefly be discussed. For each position, profiles obtained under a variety of different conditions are listed together.

It should be pointed out that most of the profiles which were taken with different arrangements of trees can only give a qualitative impression of the effect of the trees. The model trees resemble actual trees in their shape and general appearance. Their aerodynamic characteristics, however, are determined by such elusive features as bark configuration of the trunks and branches, leaf stiffness and leaf density which are modeled only qualitatively.

Position 1 (Fig. 8)

Velocity profiles at position 1 were measured to indicate the stability of the approach velocity, and to determine the boundary-layer thickness of the undisturbed velocity field upstream from the model. The boundary-layer thickness may serve as an indication on how little the profiles obtained in the model are affected by the flow upstream from the model.

As expected, the profiles measured at position 1 are consistently the same, with a boundary-layer thickness of 1.25 in.

Position 2 (Fig. 9)

At position 2 the mean-wind direction changes significantly with height. The lower part of the profile is essentially in the wake of the arena but also in the zone of retardation of the flow due to the stadium. As a result, the velocity direction at bridge level is almost perpendicular to the bridges.

At a large distance from the ground, above the arena, the velocity must be directed parallel to the ambient wind, and, therefore, the wind direction at distances from the ground approximately equal to the height of the arena must change rapidly. Therefore, two profiles were taken: one, valid for the upper part of the profile, was taken with the Prandtl tube placed parallel to the ambient wind vector. In the lower parts, the Prandtl tube was oriented parallel to the direction indicated by the flags.

For the case of original upper stands the Prandtl tube was placed upstream from the bridge on the south side, facing north. For the W and the WNW winds, the velocity changes only little with height. The profiles show a jet passing under the bridge with a maximum speed of about 18 fps, a decrease in speed downwind from the bridge structure at bridge level, and then a rapid increase with height. This picture is consistent for all configurations studied, even for the WSW wind data with no trees which indicates a different trend altogether at elevations above 1 inch. However, if the change in direction is considered, then the profile would probably look more nearly as shown by the dashed curve.

The trees in arrangement X seem to have little effect on the flow below and just above the bridge. A large influence is seen higher up, where the velocity is actually initially decreasing. This effect depends strongly on the actual shape of the trees and no conclusions should be drawn on this part of the profile.

Position 3 (Rings I and III) (Figs. 10 and 11)

The velocity profiles at position 3 are probably the most significant in terms of spectator and player comfort. This station was chosen directly in front of the lower-level entrance for the first series of flows with unmodified upper stands so that an impression could be obtained on the effect of the doors on the velocity distribution. In all the other configurations position 3 was located midway between the bridge location and the first lower-level entrance on the windward side. An increase in wind speed is indicated near the entrance at the lower level as compared to the wind speed at the second location of position 3 (Ring I). The magnitude might in the actual situation be more pronounced because of larger negative pressures downwind from the stadium and less friction in the prototype entrance hall than in the model entrance hall.

The main observations on wind speed for position 3 are listed briefly as follows:

Modified rim, ring I

a. direction of flow changes with height

b. for all cases, in the lower 2 in. (64 ft) the wind magnitude of 5 fps is not exceeded

c. above 64 ft the wind increases rapidly to ambient, with the smallest increase seen for tree plan X and a WNW wind.

Modified rim, ring III

a. a jet of air at 15 - 20 fps flows through the gap under the upper stand

b. tree plan X and a WNW wind show an upward shift of the profile above the rim, but other cases are about the same.

Unmodified rim, ring I

With a tree plan A only and WNW and W wind the air speed is about the same as with modified rim but a larger speed exists in the lower ring (about 10-12 fps) reflecting the effect of the lower-stand opening.

Position 4: Modified rim (Fig. 12)

Position 4 is the center of the stadium. Here, the wind directions are only insignificantly different from the directions of the ambient air above the model, and by aligning the Prandtl tube with its axis half way between the wind direction of the ambient air and the ground-wind direction as indicated by the flags, a velocity profile is obtained which is true in magnitude.

The results are essentially similar for all wind directions and tree arrangements. Over the first 2 in. (64 ft) the velocity does not increase to more than 5 fps, with the increase somewhat more rapidly for the WSW direction than for the others. Above the stadium height, the ambient velocity is obtained over a distance of about 3 to 5 inches (100 to 180 ft).

Position 5 (Fig. 13)

Position 5 is located downwind from the stadium. The profiles obtained here are to some extent developed from profiles taken at positions 3 and 4. At position 3 the near-discontinuity in the velocity profile is evident which was caused by the separation of the flow on the edge of the grandstand rim. The large velocity gradient tends to be smoothed out downwind due to the action of turbulence and pressure recovery, with the result that the velocity in lower regions is increased and the velocity gradients are flattened. Position 5 still shows a large deficiency of the profile as compared with the profile at position 1, but the wind level is considerably higher than at position 4.

Areal distributions of mean-wind speed are given by Figs. 14-17. Measurements for these distributions (as previously indicated) were taken at a height of 1/4 inch. (8 ft) above the surface.

The significant features of the distribution are of course the areas of relatively high speed compared to ambient air speed. In general, three regions show wind speeds which are a high percentage of the ambient. These are as follows:

1. The windward walkway near the arena
2. The bridge region

3. The windward berm extending from left field to right of center field.

A shift in wind direction from WSW (Fig. 14) to WNW (Fig. 15) has the primary effect of shifting the high wind speed on the berm from just to right of center field to left-field.

Tree plan X produces no major change in areal wind-speed distribution. Figs. 16 and 17 indicate that the high-speed regions have been reduced in speed by about 10% compared to the corresponding speeds without trees.

V. Pressure Distribution Around Arena

The difference in pressure between points on the arena exterior wall and the undisturbed static pressure (measured at a point two feet above the model arena) was measured at intervals of 11-1/4^0 and 22-1/2^0 around the entire periphery of the arena. A pressure tap consisting of a 1/16 in. inside diameter brass tube was inserted in a hole drilled through the model wall and adjusted so that it was flush with the outside surface at a point midway between ground level and the upper edge of the arena. Similar pressure taps were located at approximate quarter points between the ground level and the upper edge but complete measurements around the arena were not made using these after several sets of readings indicated no significant difference from the center tap reading. Pressure differences were read directly in mm of mercury on a "Transonic" pressure gage.

Two complete sets of pressure differences were measured with the axis of the model (line joining centers of the arena and stadium) parallel to the wind-tunnel axis. These sets of measurements were made at ambient wind speeds of 30 fps and 55 fps with no trees on the model. In this orientation the flow direction across the bridge joining the arena and stadium was generally in the direction of "project" south. The distributions for this orientation are shown in Fig. 18 and are seen to be similar for the two wind speeds.

One set of measurements was taken with the model axis rotated clockwise (looking down on top of the arena) 3.50° with respect to the tunnel axis. Only a wind speed of 30 fps was used in this case and no trees were planted on the model. Air flow across the bridge was in this case in the direction of "project north." Fig. 19 shows the distribution obtained in this case. This distribution shows the same characteristic variations as do the pressure distributions obtained in the initial orientation.

An attempt was made to orient the model with respect to the wind tunnel axis so that flow over the bridges immediately downwind from the arena would be symmetrical. However, this flow pattern was not stable but would always revert to flow either in the direction of "project" north or south.

The pressure coefficient (dimensionless) shown in Figures 18 and 19 is given by the following expression:

$$C_P = \frac{p_{wall}}{\rho \frac{U^2}{2}}$$

Here p_{wall} is the pressure above (positive) or below (negative) atmospheric pressure on the wall, ρ is the mass density of air and U is the ambient wind speed. When the unit of p_{wall} is desired in lbs/ft², ρ is to be introduced in slugs/ft³ (approximately 0.0023 at sea level for ordinary temperatures) and U is to be introduced in ft/sec.

For the data in Fig. 18 the minimum pressure coefficient occurs at about 280° and has a value -0.71. Assuming atmospheric pressure inside the arena the pressure difference across the wall in a mean wind speed of 80 mph would be

$$p_{wall} = -0.71\,(0.0023)\ \frac{(80 \times 1.46)^2}{2}$$

$$= 11 \text{ lbs/ft}^2$$

Similarly, the maximum positive pressure based on a positive coefficient of 0.60 would be 10 lbs/ft².

Occasions may arise when the pressure inside the building is above atmospheric. The most extreme case can be computed from Fig. 19 which shows the greatest difference between positive and negative coefficients. Assume that an opening in the wall occurs where the pressure coefficient has a maximum value of +0.63 (22.5°). In this event the pressure difference across the wall where the largest negative coefficient occurs (-0.78 at 90°) would be for an average wind of 80 mph.

$$p_{wall} = (0.63 + 0.78)\ (0.0023)\ \frac{(80 \times 1.46)^2}{2}$$

$$= 22\ lbs/ft^2$$

It should be noted that the above applications of the pressure coefficient to calculate pressure drop are based on an average wind speed. Gusts in excess of the average speed will cause greater peak pressure differences than given above.

VI. Summary of Findings and Recommendations

Results of this brief summary general study of wind over a model of the Oakland-Alameda County Coliseum are summarized in the following statements.

1. The flow pattern as indicated by the similar pressure profiles around the arena obtained at two wind speeds is independent of wind speed. This result justifies interpretation of prototype winds in terms of model winds.
2. With or without trees the airflow pattern within the stadium changes markedly with wind direction. For a WNW wind the flow is in the ambient direction in the outfield and also in the left field, outfield and right-field stands. In the upper stands and in the infields the flow direction is reversed. For a W wind the flow direction is variable on the field but generally W in all the stands. For the WSW wind the flow is WSW on the field and in the stands.
3. With or without trees the flow between the arena and stadium is across the bridge and is consistently from left to right

(30-50° N of W) at each wind direction.

4. Without trees wind speeds within the stadium except for specific locations are generally 60% of ambient speed or less. Highest stadium speeds are associated with a WNW wind; lowest with a W wind. Specific locations where speeds may exceed 60% of ambient are:

   a) Approximately 90% of ambient on berm beyond left-field end of upper stands for wind direction WNW and approximately 85% of ambient in stands below berm at this location.

   b) Approximately 95% of ambient on outfield berm and 70% in outfield stands for a WSW wind.

   c) Ambient wind speed is expected in the slot between upper and middle stands particularly in the windward direction. Ambient wind speeds in the back rows of the middle stands are expected as a result.

5. Without trees and at each direction wind speeds of 90-100% of ambient are expected on the bridge; similar speeds are expected beneath the bridge.

6. Tree plan A has no effect on stadium wind speeds for WNW direction.

7. Tree plan X does not materially change the flow patterns but does produce a measureable reduction in wind speed. Thus in 4a above speeds are reduced from 95% and 85% to 70%

respectively. In 4b from 95% and 70% to 85% and 60% respectively. In 5 above speeds on the windward side of the arena are reduced to about 70% and speeds above and below the bridge to about 65% of ambient. Trees in plan X located south of the stadium do not contribute to the control of wind within the stadium.

Based on the results obtained, the following general conclusions and recommendations can be made:

1. As presently designed the stadium structure will reduce the expected ambient wind speeds to acceptable levels on the playing field and throughout most of the seating area with the following exceptions. Left-field and outfield seating areas will be adversely affected by WNW and WSW winds respectively. In addition, flow between the upper and middle stands on the westerly side of the stadium will be objectionable and will adversely affect at least part of the seating area in the middle stands.
2. Outside the stadium the two most critical areas are the bridge and windward side of the arena.
3. Trees and dense shrubbery can be used more effectively than proposed in plan X. Planting should be as close to the stadium as possible. For example, a protective tree screen is recommended on top of the berm from the bridge

to a point due north of the stadium center. This screen will reduce flow through the slot and will protect the left-field stand area for the most prevalent wind direction, namely WNW. An extension of the tree screen to a point south of stadium center will give protection for the less frequent direction WSW.

4. A wind screen extending approximately 12 feet above bridge level should be placed along the northerly side of the bridge. The screen may be either dense shrubbery, trees or constructed elements and should have not more than 50% porosity. Similar protection should be considered for the area under the bridge if it is a major traffic zone.

5. If the walkway around the arena is to be used as a principal traffic route, it should be protected with a screen as suggested in Recommendation 4, particularly from the bridge around the northerly side to a point SW of the arena center.

LIST OF FIGURES

LIST OF FIGURES--Cont'd

Figure