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Developing the San Francisco Wind Ordinance and its Guidelines for Compliance

E. ARENS*
D. BALLANTI†
C. BENNETT‡
S. GULDMAN‡
B. WHITE§

In 1985 San Francisco adopted a wind ordinance as part of its Downtown Plan. To our knowledge, it is the first U.S. wind code containing specific legal and technical requirements for compliance. It addresses both comfort and safety criteria. The comfort criteria tend to be the critical ones in San Francisco's unusual climate, where uncomfortable sea breezes are pervasive but dangerously strong winds relatively rare. Compared to the criteria used in other codes worldwide, this ordinance uses relatively low threshold windspeeds that may be exceeded relatively large amounts of the time.

This paper discusses the development of the ordinance and its compliance guidelines by which wind testing procedures and reporting are standardized. A critical part of the effort was obtaining and generalizing an appropriate wind record for the downtown area. This is discussed, together with considerations for achieving uniformity among consultants' reports.

INTRODUCTION

SINCE 1974, the City of San Francisco has required wind studies of new highrise buildings, as part of its environmental review process. The studies, performed by a small group of consultants, were nonuniform in approach, using different weather data, wind acceptability criteria, and wind tunnel procedures. This tended to cause confusion during the review process, and raised the possibility of unequal treatment of permit applicants.

The consultants and City Planning officials began in 1983 to develop a standard wind code to be used by all wind consultants. It was completed in 1985 and incorporated in the Downtown Plan, a comprehensive law covering development in most of the city's central business district. The Plan's wind provisions are administered by the Environmental Review Office of the City Planning Department.

The code incorporates technical, planning and legal concerns. This paper describes the code, some of the history of its development and key issues encountered, and experience to date in its application.

STRUCTURE OF THE WIND ORDINANCE

The wind ordinance itself is a brief document, supported by guidelines for compliance provided by the Environmental Review Office. Together they comprise the "code", specifying how the City decides which building projects are to be tested, how the testing is to be carried out, criteria for whether the projects meet the City's requirements, and how the results are to be reported. The code is based on *acceptability criteria* obtained from the literature: windspeed limits that may not be exceeded more than a specified amount of time in a typical year to assure acceptable comfort and safety outdoors. Given acceptability criteria, it is possible to specify a procedure to test proposed projects for compliance. Within this procedure, the *weather data base* representing the City's wind climate has been standardized, and the climatic analysis procedure is embodied in a standard computer program provided to consultants by the City. The consultant has freedom in the *wind tunnel modelling* of a project and its surroundings, but is encouraged to work with the City Planning staff in selecting measurement locations. The consultant is also encouraged to work with the staff and the client in selecting appropriate alternative designs should the initial design fail to meet the requirements. The consultant's report to the City is part of a required Environmental Impact Report, and is in a standard prescribed format.

ACCEPTABILITY CRITERIA

Separate wind criteria are established for comfort in seating areas, comfort in pedestrian areas, and safety in all occupied downtown areas. The criteria each consist of a windspeed limit and a maximum amount of time per year that the limit may be exceeded.

The windspeed limits are expressed in terms of an "equivalent wind" defined to combine the effects of mean

* Department of Architecture, University of California, Berkeley, CA, U.S.A.
† Certified Consulting Meteorologist, El Cerrito, CA, U.S.A.
‡ Environmental Science Associates, San Francisco, CA, U.S.A.
§ Department of Mechanical Engineering, University of California, Davis, CA, U.S.A.

windspeed and wind turbulence on people. The definition comes from papers by Hunt *et al.* [1], and Jackson [2], summarizing extensive work in the field:

$$U_{equiv.} = U_{mean} \times [1 + 3\ (\text{turbulence intensity})],$$

where U is wind velocity, and turblence intensity is the root mean square of the instantaneous deviations from the mean velocity, divided by the mean velocity.

The acceptability criterion for seating areas is 7 mph (3.1 m s^{-1}) equivalent wind to be exceeded not more than 10% of the time year round between the hours of 7 a.m. and 6 p.m. The windspeed criterion is based on wind effects summarized in [3–6]. The time interval of interest was chosen by officials in the Planning Department to represent the period when most of the population is exposed to the wind. The need for such an interval for comfort limits is perhaps more important in San Francisco than in other cities, in that the sea breeze climate has extremely pronounced diurnal variability. The 10% figure was also chosen by Planning Department officials. It is essentially an environmental quality decision, based on Penwarden's study [3] of wind complaints in shopping centers. Penwarden found that substantial complaints occurred when the limit of comfortable windspeed was exceeded more than 10% of the time. (It might be noted that the shopping center owners did not spend the substantial amounts of money to remedy their wind problems until the windspeed limit was exceeded more than 20% of the time. In the deliberation over this wind code, 20% was considered a limit above which economic damage would result, and 10% as a limit above which environmental quality would suffer.)

The acceptability criterion for pedestrian areas is 11 mph equivalent wind to be exceeded not more than 10% of the time year round between the hours of 7 a.m. and 6 p.m. The windspeed part of this criterion is based on the original 5 m s^{-1} (11 mph) limit used by Penwarden and Wise [5], Hunt *et al.* [1], Melbourne [4] and others. The time interval of interest and the 10% exceedence figure are based on the same logic as the criterion for seating areas.

For the two acceptability criteria described above, the averaging period for the mean velocity is on the order of a minute, the length of time over which U.S. Weather Bureau observers make their hourly observations. This interval is sufficiently close to the length of time that the wind actually takes to affect people's comfort that the Weather Bureau data can be used directly to satisfy those criteria.

The wind code criterion for safety or wind hazard is a true hourly mean of 26 mph (12 m s^{-1}) equivalent wind not to be reached or exceeded more than once a year. The full 24 h day is considered. The Planning Department officials made the decision that no more than one hourly exceedence per year should be permitted, based on political and legal considerations. The frequency associated with this criterion is thus 0.01142% (one hour per year divided by the product 365 times 24 h).

The windspeed part of the safety acceptability criterion is based on the widely used limit of 20 m s^{-1} (44 mph) equivalent wind described in Penwarden [3], Hunt *et al.* [1], Jackson [2], Melbourne [4], and others. The difference between the 26 mph of the code and the 44 mph limit of the researchers is due to the differences in the length of averaging periods associated with the two values. The mechanical forces caused by the wind at its critical limit take effect on the pedestrian on the order of three seconds. The climatological data against which this limit is tested are collected over longer intervals, typically one minute (for U.S. Weather Bureau data) or one full hour. When a 3 s limit is to be compared to climatological data collected over a longer averaging period, it must be adjusted downward to account for the greater likelihood of strong winds occurring over a short period than over a longer averaging period over which the climatological data was collected.

In the San Francisco code, this adjustment is made somewhat circuitously in that the safety windspeed limit is specified in terms of a true hourly mean windspeed as opposed to the minute-averaged windspeeds of the U.S. Weather Bureau. During the early period of developing the code, we were planning to use a source of weather data different from the Weather Bureau, one where automated equipment had accumulated true hourly-averaged records. As will be described later, we had to switch to Weather Bureau records. The safety windspeed limit formulated for hourly-averaged data remained in the code language, and is corrected in the code's compliance guidelines as follows.

The hourly-average windspeed limit of 26 mph is derived from the underlying 20 m s^{-1} (44 mph) hazard criterion by estimating the ratio between the true hourly mean velocity and the mean velocity of the highest 3 s gust expected within that hour. The value of the ratio (approximately 0.6) is taken from a figure given by Lawson [7]. 44 mph times 0.6 give the value of 26 mph. However, since the code compliance guidelines now use Weather Bureau records with one-minute averaged data, the ratio (again from Lawson) increases to over 0.8 for these records. This ratio gives a velocity limit of 36 mph (16 m s^{-1}) that is used in determining compliance with the code.

Two points might be made about the safety criterion in the San Francisco climate. First, the high winds necessary to cause exceedence of the windspeed limit almost always occur during storms, where there is no predictable diurnal variation. So it makes little difference whether the interval of interest is daytime hours or the whole 24 h period. Second, this criterion is not commonly exceeded at sidewalk level in the wind climate of San Francisco.

WEATHER DATA

Initially, the consultants performing wind studies had available to them surface observations from the weather stations at San Francisco International Airport (SFO) and at the (then) Bay Area Air Pollution Control District (BAAPCD). Upper level observations (available from nearby Oakland Airport) are not appropriate predictors of the strong low level sea breeze that causes most of San Francisco's wind climate.

The SFO and BAAPCD stations yielded substantially different records of wind speeds and directions. SFO was recognized to be far from the city and affected by local topographic channeling that converts synoptic westerly winds to northwest winds. Initially, the BAAPCD

records seemed promising because they were taken on a tall building within the city. However, inspection of the BAAPCD anemometer in 1984 showed it to be sheltered both by surrounding buildings and by the parapet of the building upon which it was mounted (Fig. 1). Neither set of records was suitable for a technically defensible code.

It might be noted that each of these problems is very common with urban wind data. The weather database is probably the key element to any wind code. One lesson worth repeating here is that it is essential to personally inspect wind recording facilities, no matter how professionally maintained they may be. In the case of the BAAPCD, numerous staff meteorologists used their weather station observations on a daily basis for forecasting pollution levels, but most had never climbed to the roof to inspect the station, and those responsible for the station were unaware of building aerodynamics.

We then discovered an opportunity to resurrect an old wind record of high quality. Between 1945 and 1951, the Weather Bureau had maintained a first order weather station in downtown San Francisco. The anemometer was mounted on a 25-foot high, well-exposed platform on the then-freestanding old Federal Building. The platform is still standing, and a visit confirmed that it had had excellent exposure above the city at the time the anemometer was in operation (Fig. 2). The record from this anemometer was available only in the form of monthly means in old Weather Bureau climatologies, but inquiry showed that the National Climatic Center (NCC) had six years of hourly record. The first three years were on magnetic tape, with every third hour digitized.

The second three years were on the original logging forms, with every hour available. The total number of observations were thus 32,795, adequate to provide a reliable estimate of future climatic conditions in San Francisco. Funds were obtained to pay the NCC to digitize the wind data, group it into 3 h bins, and summarize it by time of day and month using their standard SMOS or RUSSWO format [8].

The wind frequency distribution for each wind direction was determined from the data by entering the summarized bin data into a computer file and fitting the high-end speeds of the wind speed bins against the number of observations exceeding those speeds. A log–log fit proved accurate when fitted over intervals equal in length to the interval of each bin. The result is a continuous curve of straight line segments predicting the number of hours any given speed is exceeded at the old San Francisco Federal Building.

Because the NCC summaries group the weather data into three-hourly intervals, it was necessary to use the interval 6 a.m. to 8 p.m. to represent the daytime hours specified in the code (7 a.m. to 6 p.m.). The effect of this approximation is conservative because the two evening hours added are more windy than the one morning hour added. It would have been preferable if the periods for which weather data was available matched the times of concern for the code, but as with the 26 mph criterion, the code language was fixed before the weather data base had been determined.

In the San Francisco weather record, four of the sixteen measured wind directions contain the greatest frequency of occurrence as well as the majority of strong wind occurrences. These are NW, WNW, W, and WSW, with daytime occurrence frequencies of 10%, 14%, 35%, and 2%, respectively. The remaining 12 wind directions comprise the remaining 36% of wind occurrences. Calm conditions occur 2% of the time.

For the same major wind directions, the individual daytime windspeed values exceeded 10% of the time are:

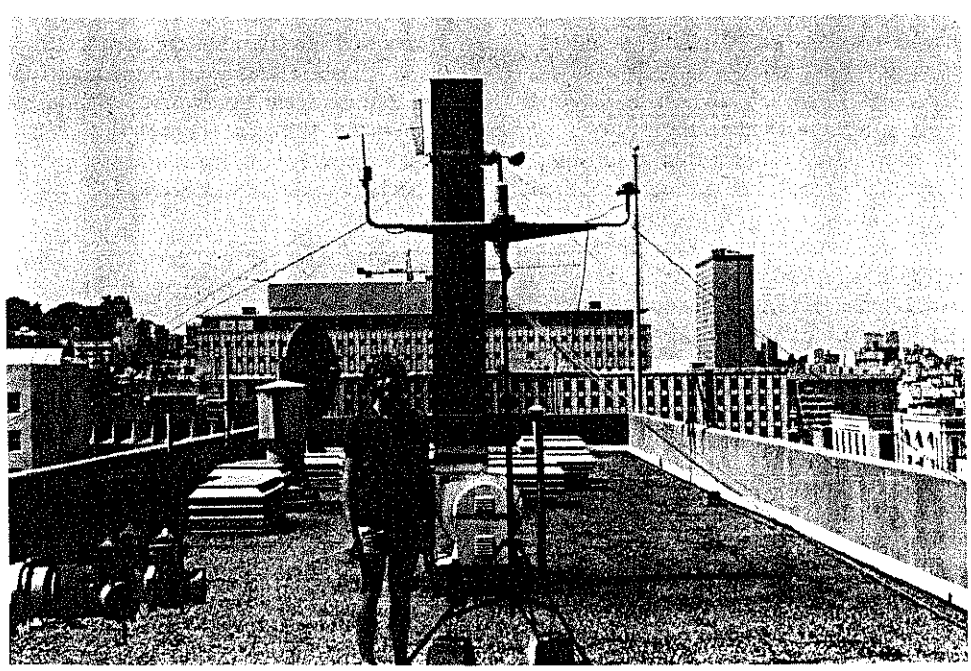

Fig. 1. Building-influenced BAAPCD anemometer.

Fig. 2. Unobstructed Weather Bureau anemometer.

21, 25, 21, and 18 mph. The value for the 12 remaining wind directions is 15 mph.

The fitted windspeed distributions were incorporated in a program prepared by Bennett and Guldman for analysing the wind criteria against the winds predicted for proposed projects. It is basically a distillation of the climatological data base for use in complying with the wind code. The program is made available to wind consultants and its use in wind studies is required in order to standardize test results.

WIND TUNNEL PROCEDURE

Wind tunnel measurements are normally conducted for the major wind directions mentioned above. Should the design of a particular building suggest that strong wind accelerations within pedestrian areas could be expected for other wind directions, the compliance guidelines require tests for that direction to be carried out to see whether the hazard criterion is exceeded.

The ground-level measurement locations are chosen by the wind consultant, who makes a general evaluation of the model environment before measurements begin. City staff consider the consultant responsible for identifying and testing public areas that could be adversely affected. The staff determine which areas are to be considered as seating areas and oversee the location selection process.

The reference velocities for the wind tunnel tests originate at the Weather Bureau anemometer height of 132 feet above ground level. The anemometer is assumed to be in a boundary layer with a power law of 0.25. Although the anemometer was in a well-exposed location, wind tunnel tests were made to account for effects caused by the building and its surrounds. The tests used a model of the city as it existed in 1945–51, and compared the wind velocity measured at the anemometer location to a velocity measured at the same height in the same boundary layer but over an open area away from the influence of buildings. The tests provided a set of correction factors by which wind data from the Federal Building should be multiplied: NW:1.02; WNW: 1.00; W: 0.96; WSW: 0.85.

The wind tunnel test procedures are otherwise conventional for this type of work. The appropriate profiles for the atmospheric boundary layer in the vicinity of specific proposed projects are left to the discretion of the consultant, and are usually based on typical urban roughnesses described in the literatures.

The wind velocity ratios coming from the wind tunnel tests are then analysed using the standard computer program containing the frequency distributions of San Francisco winds. The ouput pages of this program (Tables 1 and 2) indicate how it works for the comfort criteria and the safety criterion, respectively.

ENVIRONMENTAL IMPACT REPORTING PROCESS

The wind tunnel work is done as part of the environmental impact review (EIR) process. This process includes study of the effects of alternatives to the project, as well as of the effects of the project as it is being proposed by the developer. Some of the alternatives may be designs still under consideration by the developer, while others are chosen by City staff, covering a range of feasible uses of the site. Each of the alternatives is tested in the wind tunnel. Each model is measured and photographed, and preserved in the event that retesting is needed.

If the test shows that the project would violate the acceptability criteria, the project sponsor is encouraged

Table 1. Pedestrian-level wind speeds (mph). At each measurement location, the comfort criterion speed established in Section 148 of the Downtown Plan (11 mph for pedestrian and seven mph for public seating areas, not to be exceeded more than 10% of the time) is given. For each configuration, the wind speed, in mph, exceeded at pedestrian level for 10% of the time is shown. If the comfort criterion for the location is violated, the percentage of time which the comfort criterion is exceeded is stated

		Existing Setting		Project	
Location	Criterion speed (mph)	10% Exc. speed (mph)	% Time criterion exceeded	10% Exc. speed (mph)	% Time criterion exceeded
No. 1	11	7		7	
No. 2	11	11		15	10%
No. 3	7	18	41%	10	21%

to modify the design to try to correct the problem. The best results occur when the project architect attends the wind tunnel tests and works with the wind consultant to come up with design changes that eliminate the violation. Such sessions also reveal situations where the City might be inclined to grant an exception. In one example, an 18 storey office tower proposed on an especially windy site, more than 20 design variations were tested in a one-day working session. Only one design met the wind criteria, but the City staff judged that aesthetically unacceptable. The staff recommended, and the Planning Commission approved, a design that exceeded the wind comfort criterion at one measurement location. The evidence of how difficult it was to meet the criteria supported their decision to grant the exemption.

The results of the tests are presented in the wind con-

Table 2. Wind hazard evaluation. The ratios of pedestrian-level wind speeds to the 132-ft. height reference wind speeds are shown in the first line of output for each location. The second line of output shows the pedestrian level wind speeds in miles per hour (mph) which would be exceeded one hour per year (0.011416% of the time) for each measurement location shown. The wind ordinance establishes that a one-minute average speed of 36 mph not be reached or exceeded one hour per year. The third line of output for each location shows the hazard speed and what percentage of the time it would be exceeded. The rows labeled CONTRIB tabulate the percentage contribution to the exceedances from each direction

Existing setting, September 1986

		Criterion			Wind Direction				
Location	1 h yr^{-1} Speed (mph)	Speed (mph)	% Time Exceeded		NW	WNW	W	WSW	Other
No. 1				Ratios	0.5478	0.3298	0.2188	0.3655	0.3655
	17.29			Contrib.	96.9%	0.0%	0.0%	3.1%	0.0%
		36	0.0000%	Contrib.	0.0%	0.0%	0.0%	0.0%	0.0%
No. 2				Ratios	0.4622	0.5972	0.4996	0.5197	0.5197
	23.00			Contrib.	0.0%	48.1%	0.0%	51.9%	0.1%
		36	0.0000%	Contrib.	0.0%	0.0%	0.0%	0.0%	0.0%
No. 3				Ratios	1.1846	1.0084	0.4102	0.8677	0.8677
	38.82			Contrib.	7.8%	45.3%	0.0%	46.8%	0.1%
		36	0.0865%	Contrib.	61.0%	29.9%	0.0%	8.2%	0.8%

Project, September 1986

		Criterion			Wind Direction				
Location	1 h yr^{-1} Speed (mph)	Speed (mph)	% Time Exceeded		NW	WNW	W	WSW	Other
No. 1				Ratios	0.5618	0.2952	0.1982	0.3517	0.3517
	17.72			Contrib.	99.9%	0.0%	0.0%	0.1%	0.0%
		36	0.0000%	Contrib.	0.0%	0.0%	0.0%	0.0%	0.0%
No. 2				Ratios	0.7816	0.9316	0.4496	0.7209	0.7209
	34.82			Contrib.	0.0%	98.9%	0.0%	1.1%	0.0%
		36	0.0044%	Contrib.	0.0%	99.7%	0.0%	0.3%	0.0%
No. 3				Ratios	0.8398	0.3964	0.3846	0.5403	0.5403
	26.56			Contrib.	99.6%	0.0%	0.0%	0.4%	0.0%
		36	0.0000%	Contrib.	0.0%	0.0%	0.0%	0.0%	0.0%

sultant's report to the City. These results are summarized in the EIR, a document available to the public, and which is carefully read by the City Planning Commission in approving or denying the project. The language used in the EIR is prescribed in highly standardized format. The format assures that all pertinent information is presented that the report focuses on compliance with code criteria, and that the length and complexity of the EIR is limited.

CONSIDERATIONS ENCOUNTERED IN PRACTICE

The code contains a provision that, in situations where the existing wind exceeds the comfort criteria, the proposed building must be designed to reduce wind until the criterion is met. This provision makes the selection of measurement locations particularly important, for in general a building has decreasing influence on the wind at more distant locations. In some cases, there may be nothing the proposed building can do. This is handled in practice by observing the range of wind influences possible with the full range of possible building shapes. This sensitivity testing gives the distances to which the building can have an effect on the surroundings, and allows the selection of a fair set of measurement locations. It is important that the City staff be involved with this part of the process.

In general, experience has shown that the effects of a new 350 foot building in the downtown area will require measurement at locations on both sides of the street around the city block that contains the site, along sidewalks outward to the next distant intersections downwind and crosswind, and halfway up the block on streets to windward. In the event of uncertainty, or patterns revealed in the early sensitivity testing, measurements are taken further away.

Although it may not appear to be strictly in the developer's self interest to uncover every possible wind problem, it is clear from previous development experience in San Francisco that buildings with serious wind problems also have "image" problems. Because of this, and because active participation is encouraged between developer, consultant, and city staff, developers have not seriously challenged the code, the criteria, or the testing process. On the contrary, a number of them have taken pains to explore the potential for design improvements implicit in the process.

The code allows exemptions to the comfort criteria. We feel that exception provision (1) is necessary, and that the City's procedure for working with the developer and consultant to examine difficult cases is exemplary. The exception provision (2) contains an exception based on the "limited amount by which the comfort level is exceeded". This provision is not relevant and should not have been included in the wording, since the code's comfort criteria are based on the amount of time during which comfort levels are exceeded. The other two provisions are technically correct. In practice, the exception provisions have not affected the fair implementation of the code. They provide the Planning staff considerable discretionary power over exemption decisions, but given the staff's involvement in the wind testing procedure, it is advantageous to the City that the staff has flexibility to deal with unusual or difficult cases such as the one mentioned earlier.

CONCLUSIONS

A code and supporting documentation has been developed in San Francisco. Its objective was to standardize the treatment of ground-level winds in the environmental review process. The code development required a surprising amount of development work and much discussion with the Planning Department.

From a technical standpoint, the standardized weather data base is perhaps the most significant concern. The wind prediction depends entirely on the quality of the data source, and how the records have been processed. After that, consistency of approach by the consultants and by the city staff is the most important thing.

This paper describes the guidelines for compliance adopted by the City and the consultants. These operational procedures are an integral part of the code, and are equally important as the code provisions themselves. The process depends on the active cooperation of the City, consultants, and developer to obtain maximum benefit. To date, our experience with the process has been very good.

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APPENDIX 1: WORDING OF THE WIND ORDINANCE

Sec. 148. *Reduction of ground level wind currents in C-3 districts*

(a) *Requirement and Exception.* In C-3 districts buildings and additions to existing buildings shall be shaped, or other wind baffling measures shall be adopted, so that the developments will not cause ground level wind currents to exceed, more than 10% of the time year round, between 7 a.m. and 6 p.m., the comfort level of 11 m.p.h. equivalent wind speed in areas of substantial pedestrian use and 7 m.p.h. equivalent wind speed in public seating areas.

When pre-existing ambient wind speeds exceed the comfort level, or when a proposed building or addition may cause ambient wind speeds to exceed the comfort level, the building shall be designed to reduce the ambient wind speeds to meet the requirements. An exception may be granted, in accordance with the provisions of Section 309, allowing the building or addition to add to the amount of time that the comfort level is exceeded by the least practical amount if: (1) it can be shown that a building or addition cannot be shaped and other wind baffling measured cannot be adopted to meet the foregoing requirements without creating an unattractive and ungainly building form and without unduly restricting the development potential of the building site in question; (2) it is concluded that, because of the limited amount by which the comfort level is exceeded, the limited location in which the comfort level is exceeded, or the limited time during which the comfort level is exceeded, the addition is insubstantial.

No exception shall be granted and no building or addition shall be permitted that causes equivalent wind speeds to reach or exceed the hazard level of 26 miles per hour for a single hour of the year.

(b) *Definition.* The term "equivalent wind speed" shall mean an hourly mean wind speed adjusted to incorporate the effects of gustiness or turbulence on pedestrians.

(c) *Guidelines.* Procedures and Methodologies for implementing this section shall be specified by the Office of Environmental Review of the Department of City Planning.