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WIND AND URBAN CLIMATES

E. J. Plate, em. Prof. Dr.-Ing.*
University of Karlsruhe, Germany (Formerly: Director of the Institute for Hydrology and Water Resources Planning, University of Karlsruhe, Germany)

H. Kiefer, Dr.-Ing.
Wacker Ingenieure, Birkenfeld/Württemberg, Germany (Formerly: Wind Engineering Division, Institute for Hydrology and Water Resources Planning, University of Karlsruhe, Germany)

J. Wacker, Dipl.-Ing.
Wacker Ingenieure, Birkenfeld/Württemberg, Germany (Formerly: Wind Engineering Division, Institute for Hydrology and Water Resources Planning, University of Karlsruhe, Germany)

ABSTRACT

A brief overview is given of wind problems in urban areas, on which the wind engineering team (WET) of the Institute of the senior author has been working for the last 25 years. After a short historical introduction we focus on investigations of wind forces on structures embedded into urban canopy layers and give a short survey of diffusion work done in atmospheric wind tunnels of the University of Karlsruhe. Wind tunnel studies were conducted of forces and diffusion for building arrangements in an urban environment. We concluded that wind tunnel results on buildings in different configurations of urban building complexes could be used to infer possible modifications of wind force codes for buildings in urban areas. Differences between free standing buildings, used for obtaining load coefficients for building standards, with the same type of building in an urban environment, were used to yield necessary corrections, if any, for modifications of design codes. We reached the conclusion that first order reliability methods need to be used for design peak pressures. Furthermore, we were able to systematize diffusion problems for urban areas by defining 4 different regions of diffusion fields, for which different modelling criteria apply, both for wind tunnel and numerical modelling.

1. INTRODUCTION (ERICH J. PLATE)

As the American Meteorological Society has kindly decided to host a session in honor of my 75th anniversary, I may be permitted to start this paper with some personal historical notes.

Corresponding author address: em. Prof. Dr.-Ing. E. J. Plate Universität Karlsruhe, Institut für Wasserwirtschaft und Kulturtechnik – Abteilung Hydrologie, Kaiserstr. 12, D-76128 Karlsruhe, E-MaiL: plate@iwk.uka.de

In 1959 I joined the staff of Colorado State University to assist Prof. J.E.Cermak in his program on wind tunnel modeling of atmospheric boundary layers, and this topic has been with me throughout my professional career of more than 40 years. It started with crude estimations of atmospheric variables, as design information for a wind-tunnel for modelling the atmosphere. The logarithmic wind profile as a modelling criterion had just been discovered, and J.E.Cermak had decided that the best way of modelling a natural boundary layer was to build a wind tunnel with a very long test section. In order to capture thermodynamic effects, the tunnel was to have humidity and moisture controlled air flow, and a section of the floor should be heated or cooled to enable the creation of thermal boundary layers (Plate & Cermak, 1963). The project was supported by the US Army, by means of a (in retrospect very limited) financial grant, and the permission to use huge amounts of Army surplus, delivered free of charge, of which we made extensive use. It was my task to build this (and a number of other) wind tunnels, and later on to use this facility for studies on atmospheric boundary layers. An outstanding first study using the capacity of the wind tunnel led to the Dissertation of Prof. Arya (Arya & Plate, 1969) on boundary layers along a smooth, heated plate, at small values of z/L, where z is the vertical coordinate and L is the Monin - Obukhov length. A number of studies of a more fundamental nature on internal boundary layers, boundary layers over water waves, effect of fences and other two dimensional building shapes on boundary layers on typical building elements followed.

In 1968, then at the Argonne National Laboratory, I summarized the state of knowledge on atmospheric boundary layers in a monograph (Plate, 1971) which became the guide for all the work that was done later on in my Institute at the University of Karlsruhe. I created a program on atmospheric research in wind-tunnels, with the express purpose of generating design information for practical applications. Much of my own work was concerned with proving the application of wind tunnel testing to a large variety of problems, exploring its limitations, and extending wind tunnel testing to different categories of problems. The result were summarized in Plate (1982). Our work naturally involved a lot of routine studies (not always really routine!) of all types of practical problems to which wind-tunnels are applied. I was ably supported by a succession of excellent junior staff members - J. Loeser, Dr. A. Lohmeyer, Dr. W.Bächlin, M.Rau and Dr. P.Kastner -Klein as group leaders. From these studies, a catalog of problems was derived that needed theoretical underpinnings leading to an extensive research program with many dissertations. Initially, most of the work was on diffusion, and diffusion in urban complexes was the first type of work on urban environments. Dissatisfaction with wind design information in standards, where pressure and load coefficients were usually taken from wind tunnel studies in air flows without appropriate boundary layers along the ground surface, led us to consider also wind loads on buildings in boundary layers and later to buildings embedded in the urban canopy layer.

The methods developed at the author´s institute were further extended and applied to numerous practical problems by private companies founded by former members of the institute, among them Ingenieurbüro Lohmeyer, specializing on environmental investigations, and Wacker Ingenieure, specializing on wind loads on structures, who built their own multi functional wind tunnel with a large cross section .

A summary of the results of these studies will be given in the remainder of the paper. A state of the art survey of wind tunnel explorations of urban environments was also presented in Plate & Kiefer, (2001).

2. THE URBAN BOUNDARY LAYER.

<u>a. The approach flow</u> The structure of the urban atmospheric boundary layer is understood as a multi-layer air flow, as schematically indicated in Fig.1 (see also Oke,1987). For neutral stratification conditions the open country surrounding the city yields a uniformly adjusted constant stress boundary layer (an equilibrium boundary layer), in which the wind velocity profile can be expressed, for modest to high (4 m/s and up) wind speed conditions, by a power law:

$$\frac{u(z)}{u_{ref}} = \left(\frac{z}{d}\right)^{\alpha} \qquad (1)$$

with α being the exponent of the power law, which reflects the roughness conditions of the surface upstream of the city. This exponent usually is of the order of 0.15 to 0.3. Wind tunnel modelling must take cognizance of this fact, and wind tunnel modelling of atmospheric flows start with showing that within the test section of the wind tunnel the power law Eq.1 also holds and has an exponent of 0.15 - 0.33, as is shown, for example in Fig.2.

When the air flow reaches the city, the wind profile has to adjust to its roughness. An internal boundary layer forms above the city, which displaces the outer boundary layer of the approach wind profile. Between internal and outer boundary layer a transition region is formed, but if the fetch of constant city roughness extends far enough, - for a 100 m thick boundary layer approximately 1000 m - the outer layer and the internal layer merge into the new, locally adjusted equilibrium boundary layer corresponding to the aerodynamic properties of the city.

<u>b.The layered flow above the city.</u> The fully developed equilibrium boundary layer above a city consists of four layers. The lowest is the urban canopy layer, in which houses, streets and other urban features are embedded. The flow in this region is governed mainly by the form drag on individual buildings, i.e. by pressure differences between front and rear of structures. Its height is approximately equal to the average building height (but see below). For the canopy layer, no reasonable models of the velocity field can be given, because the local arrangements of streets and trees, topographic features, highways and rivers lead to a complicated three dimensional flow field.

At some distance above the canopy layer, the flow field is two dimensional and a constant stress layer exists, in which momentum is transmitted to the ground by horizontal shear stresses, and in which the velocity distribution is described by the famous logarithmic law:

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \frac{z-d}{z_o} \qquad (2)$$

where κ is v.Karman´s constant, usually taken to be 0.4, z_o is the roughness height, and d the displacement height, and $u_* = \sqrt{\tau/\rho}$, where τ is the horizontal shear stress, and ρ is the density.

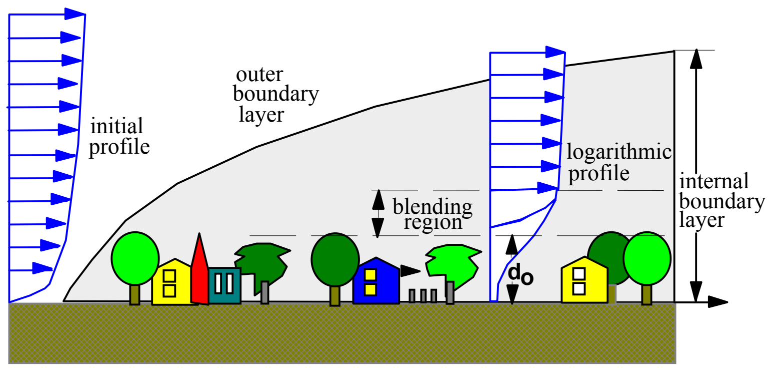


Fig.1: Schematic development of an urban boundary layer.

The major difference between canopy layer and logarithmic layer is that the horizontal force on the flow in the canopy is composed of drag forces on the individual roughness elements - i.e. by pressure forces, resulting in a highly three-dimensional flow velocity distribution - whereas in the logarithmic region, the vertical momentum flux is carried by a constant shear τ only, as is indicated by parallel streamlines of the mean velocity field. Consequently, between canopy layer and logarithmic layer there exists a blending layer in which the highly three-dimensional canopy flow pattern is converted into a basically two-dimensional flow field with constant (atmospheric) pressure, which forms the logarithmic layer. Experience has shown that the thickness of the blending region can be expressed roughly as a fraction of the distance D between elements, with an added effect coming from the shape of the roughness elements. It is not unreasonable to expect that the roughness of the surface carries its effect through the blending region, and that coefficients d and z_0 of the logarithmic law are quantities which are determined by the building configurations.

The literature reports many different expressions for a relationship between the parameters of Eq.2, and
characteristics of the canopy layer. The earliest ones (see Plate, 1971) assumed a simple relationship between d and z_0 and average roughness height H, such as:

$$z_0 = 0.15\,H, \quad \text{and} \quad d = 0.85\,H \qquad (3)$$

However, this equation is too simple, and is based on experiences with low growing crops, and a few early experiments. Much more detailed analyses have shown, that z_0 depends also on the arrangements of the roughness elements. Its value must be considered a measure of the drag exerted on the roughness arrangement. Empirically, it seems reasonable to expect that the more roughness elements or buildings there are, the higher will be the drag. Two parameters are found (Theurer et al., 1992) to be important for classifying roughness in terms of building arrangements. These are the coefficient λ_{ar} and λ_{fa}, defined as:

λ_{ar} = sum of all areas covered by build ings/total urban area

λ_{fa} = sum of average building areas normal to the wind/ total urban area.

Eq.3 is valid for fairly dense vegetative covers, where roughness elements cover about 60% of the area. Kondo and Yamazawa (1986) found that for Japanese cities z_0 and λ_{ar} are linearly related. For different lower fractions λ_{ar} they show that:

$$z_o = 0.25H \cdot \lambda_{ar} \qquad (4)$$

fits observed data quite well for $0.4m<z_0<2.5m$. For $\lambda_{ar} = 0.6$, Eq.4 reduces to Eq.3.

Under certain conditions, when the building density is not too high, a more detailed model for describing z_0 and d, was given by Bottema and Mestayer (1997), based on the drag of the canopy on the air flow. At this time, a more general model does not exist. It should reflect the fact that with increasing building density the flow becomes not rougher, but smoother. Hussain & Lee, (1980) identified three different types of flows for groups of buildings, which are aligned in parallel rows perpendicular to the wind, and which are of equal height and flat roofed.

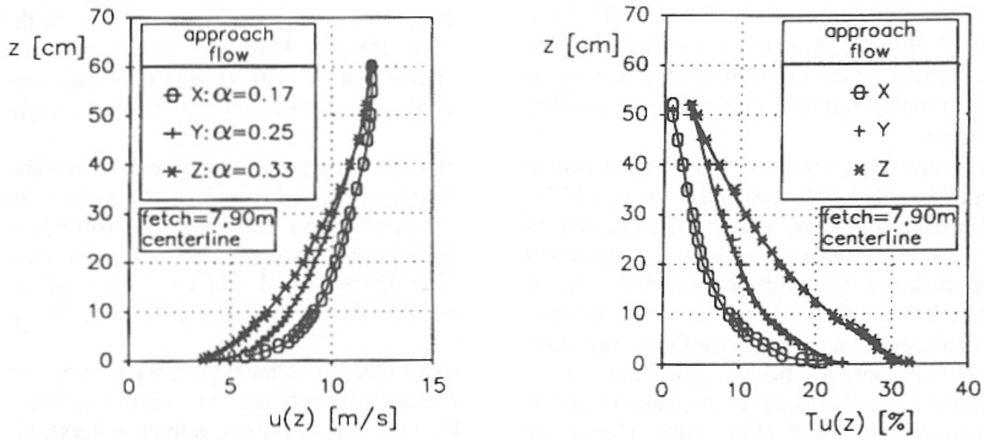


Fig.2: Wind profiles in a wind tunnel: mean velocity distributions for different exponents of Eq. 1 caused by different roughness (left) and turbulent intensity (right).

By varying the distance between the rows, one finds two minimum values of u_*. The first one (isolated roughness flow IRF) occurs when the distance between rows is large, i.e. building density λ_{ar} is small, so that the contribution of the few individual buildings is a small fraction only of the total shear force on the surface area. The other one occurs when the building density λ_{ar} approaches 1, i.e. the distance between the rows is very small. All roughness effects disappear and an elevated flat and smooth surface is generated.

Arrangements with building densities in between these extremes will have larger values of u_*. With increase in building density , the individual buildings interfere with one another, and the case of wake interference begins. Theurer (Theurer et al., 1992) found a linear relationship of parameters d and z_o with form parameters λ_{ar} and λ_{fa} respectively, for small values of the order of 0.1 -0.25. For larger building densities or frontal area ratios the data show a tendency to decrease with large values, although the scatter becomes large. The relationship between building geometry and roughness parameters becomes less well defined, and at this time no systematic relationships has been found relating parameters z_o and d to parameters derived from geometric configurations of urban complexes. Therefore, the best way of obtaining operational values of z_o and d for urban areas is obtained from experiments on built up areas, or on their models in a wind tunnel. If this information is not available, we prefer to use the empirical collection of data from Theurer (see Theurer, et al., 1992) and Badde (Badde & Plate, 1994) who summarized what is known about these parameters in Table 1.

3. WIND FORCES ON STRUCTURES IN URBAN AREAS.

As design quantities of forces in urban areas are caused by extreme winds, it can be assumed without loss of generality that these forces are modelled in the wind tunnel. Disputable is the question of the Reynolds number necessary for getting beyond a critical value Re_{crit}. At Reynolds numbers higher than Re_{crit} the flow field and its turbulence become independent of Reynolds number, except possibly for buildings with shapes for which local Reynolds numbers are significant. In order to prove without doubt that modelling is indeed accomplishable, numerous studies with parallel measurements on full size buildings and their wind tunnel models have been made by the author´s team. Blohm (Blohm & Plate, 1975) and Schnabel (1981) studied wind forces on circular light house towers under ideal conditions. These towers have been built into the ocean many kilometers offshore. The wind profile developed over the ocean, therefore had practically infinite fetch, in particular when the wind velocity was so low that only small water surface waves were generated. These studies were important also as Schnabel´s results yielded excellent vertical and lateral coherencies of the pressures on the towers. Maier - Erbacher (Maier-Erbacher & Plate, 1991) extended the study to towers in varying topographies, finding to our surprise that even a fairly steep embankment behind the tower hardly affected the forces, and not at all the drag coefficient of the tower.

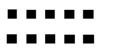
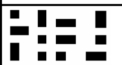
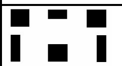
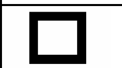
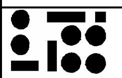
Configuration		Characteristics	Roof Shape	z_0	$\overline{H}$	$\sigma_H/\overline{H}$	$\overline{L}/\overline{B}$	$\overline{L}/\overline{H}$	λ_{ar}	λ_{fa}
1		New district, one family buildings 1 - 2 storeys	Mainly gable roofs, rarely flat roofs	0.1 - 0.3 (1.3)	8 - 10	~ 0	~ 1	~ 1.5	0.1 - 0.2	~ 0.1
2		Residential area 1 - 3 storeys	Mainly gable roofs, rarely flat roofs	0.1 - 0.3 (1.4)	8 - 12	< 0.2	~ 1	~ 1.5 - 2.5	0.15 - 0.25	~ 0.1
3		Residential blocks regularly aligned 3 - 5 storeys	Mainly gable roofs, rarely flat roofs	~ 0.3 (1.5)	12 - 20	< 0.2	< 0.5	~ 1 - 2	0.1 - 0.25	0.1 - 0.25
4		Residential area high-rise buildings and residential blocks 4 - 15 storeys	Gable roofs, flat roofs	> 0.5	> 15	0 - 0.5	< 0.5	~ 0.7 - 1.5	0.1 - 0.2	0.15 - 0.3
5		Cultural facilities churches, schools, etc.in residential areas	Gable roofs, flat roofs	0.3 - 1.5 (2.4)	> 8	> 0.5	0.5 - 2.0	~ 2 - 5	0.1 - 0.3	0.05 - 0.15
6		Block of buildings in City Centers 3 - 6 storeys	Mainly gable roofs, rarely flat roofs	~ 0.7 (2.1)	15 - 25	< 0.3	~ 1	~ 0.7 - 0.9	0.3 - 0.7	-
7		City Center areas including parks, ,high-rise buildings and public facilities	Gable roofs, flat roofs	0.3 - 0.7 (>2)	>15	< 0.4	~ 1	~ 1.5 - 2	< 0.5	0.1 - 0.2
8		Commercial and industrial area 2 - 5 storeys	Mainly flat roofs or gable roofs	~ 0.3 (0.6)	5 - 15	< 0.5	< 1	~ 2 - 5	0.3 - 0.4	0.05 - 0.2
9		Industrial plant with tanks	Mainly flat roof	~ 0.5 (1.6)	10 - 25	< 0.5	~ 1	~ 0.5 - 1.5	0.1 - 0.4	0.1 - 0.2
10		Industrial area 1 - 4 storeys	Mainly flat roofs, rarely gable roofs	0.3 - 0.5 (1.6)	5 - 15	0.3 - 0.5	~ 1	~ 2 - 7	0.2 - 0.4	0.05 - 0.2

Table 1: Typical building configurations and their geometric and aerodynamic parameters found in German cities (Badde & Plate, 1995). $\overline{H}$ is the mean building height, σ_H is the standard deviation of the building heights, $\overline{L}, \overline{B}$ are mean length and mean width, resp. of buildings

Bächlin (1987) investigated the forces on a tennis hall with an elliptic roof, and verified that not only the pressure distribution on the roof, but also the internal pressure in the building were properly modelled in the wind tunnel. We then turned to look at forces on structures in urban complexes. Initial studies were concerned with different building shapes in smooth and uniformly rough boundary layers.

The influence of different wind profiles and approach flow conditions from Fig.2 on rectangular shaped test buildings of different side ratios and heights according to Table 2 was investigated by Wacker et al. (1990a, 1991, 1992, 1993). Model tests on a family of test buildings provided an extensive data base for wind induced loads as function of approach flow conditions and building geometry. Furthermore, the data sets enabled checks of the general design rules given in codes. The commonly accepted quasi-steady approach which relates the pressure fluctuations to the wind velocity fluctuations by use of gust factors ($G(z) = 1 + 2 \cdot k \cdot \sigma_u(z)$, with $\sigma_u =$ rms value of u(z), and k = 3.5) is compared with results of model scale tests in Fig. 3. The ratio of the peak pressure coefficients to the time averaged mean values of the pressure time series is plotted against the turbulence intensity $T_u(z) = \sigma_u(z)/\overline{u}(z)$ for the stagnation point at the front wall (Fig. 3 A) and the roof centreline (Fig. 3 B).

The wind tunnel data showed that peak pressures averaged over a 0.5 sec time period in full scale (this corresponds to small tributary areas of approximately 1 m² in size, typical for small façade elements or roof pavers) may be underestimated by the classical approach for elements corresponding to this size. Wacker (1994) also compared standard assessment methods for local peak wind pressures with a reliability-based assessment method, which combined second moment reliability (SMR) principles with wind pressure data from wind tunnel study. Peak pressure coefficients, based on the simplified Cook-Mayne method were calculated on a consistent safety level (Wacker, 1994).

Furthermore, the data provided useful results concerning the spatial correlation of the wind induced pressure field at the building surface and leads to the definition of tributary areas and corresponding wind load coefficients. Also, the analysis in the frequency domain gives evidence about vortex shedding phenomena due to different approach flow conditions and building dimensions (Wacker, 1995)). A study by Wacker & Plate (1990a) used wind tunnel data to infer fatigue loads for cladding elements - with the result that buffeting of cladding elements did not lead to any significant dynamic loads on the surfaces, -fatigue loads to be expected at most for the fastening elements. The study, which used experimental data in conjunction with the classical fatigue model of Miles, and of Miner´s cumulative damage function, proved to be an excellent direct application of wind tunnel results in a fatigue analysis, but it also yielded a nice application example for stochastic design, for a book on "Statistics and Applied Probability Theory for Civil Engineers" (Plate, 1993).

We then addressed the problem of wind forces on structures in urban areas (Kiefer and Plate (1998, 1999)). Until now design codes are based on wind-tunnel experiments on free-standing building models. However, the free-standing building is a very rare case in reality. In densely populated areas buildings are grouped together and arranged in characteristic configurations due to their function or location in the urban area. In some design codes the effect of the surrounding is taken into consideration by adjusting the wind profile, and using a modified reference velocity in combination with pressure coefficients of the isolated building case.

	model type									
	A	B	C	D	E	F	G	H	I	K
L [cm]	15	5	15	10	15	10	8	12	7.5	15
B [cm]	15	15	5	15	10	10	12	8	15	7.5
H [cm]	for all models: 5,10,20,30									

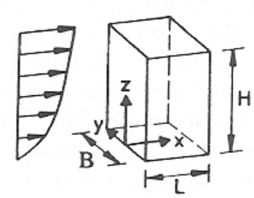


Table 2: Model types and their dimension used by Wacker (Wacker , 1995)

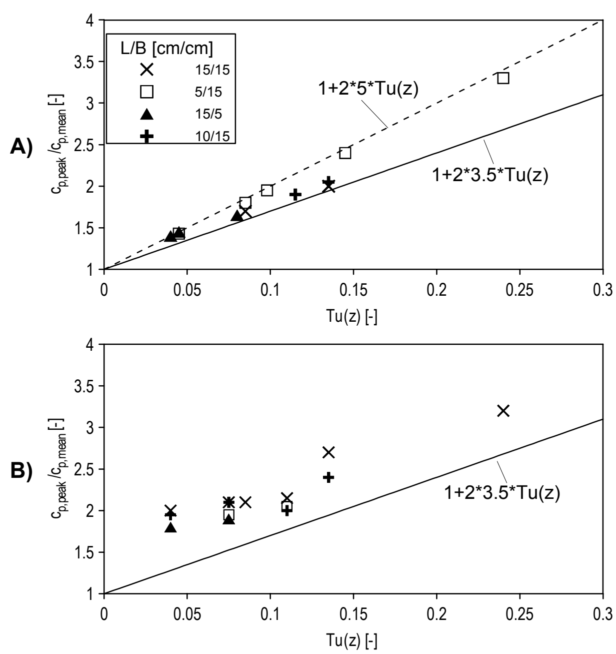


Fig. 3 Local pressure gust factors and comparison with those resulting from linear quasi-steady theory

A) front wall; B) roof; (Wacker & Plate, 1993)

The main reason for not explicitely accounting for the effect of the surroundings is the lack of data. The Study of Hussain & Lee (1980) provided some data, but their regularly arranged roughness configurations are not representative for most of the building arrangements found in reality. Ho et al. (1991) investigated the effect of a typical North American industrial area on wind loads. Their study was limited to low-rise structures. Hertig & Alexandrou (1995) also presented some first results of measurements in two models of characteristic urban areas in Switzerland. The influence of neighbouring buildings on the wind induced loads is evident in the results of these studies, but the results are not sufficient to infer general design rules for wind loads on structures in built-up areas. To improve the data base extensive investigations were carried out at the IHW, including classification of representative building layouts, wind-tunnel experiments, and full-scale measurements. The building classes of Theurer were collected into three basic types of building arrangements which were built to scale for experiments for wind loads on buildings in built-up areas (see Fig. 4):

- Type I: Homogeneous row pattern - constant building dimensions and distances between the buildings
- Type II: Variable building dimensions and distances just like in industrial areas
- Type III: Buildings are arranged in blocks just like in city centers

Type I consisted of buildings with dimensions identical to the lowest rectangular shaped test building and the distance s between the building rows was varied according to the three flow regimes of Fig.1. The mean building height of the other types was nearly the same as the constant building height of type I (H = 16m in full scale). The type II building arrangement is representative for a large number of existing built-up areas. The pressure measurements on the test buildings inside the industrial area (Type II) were made at different locations in order to determine the influence of the immediate surroundings. The wind directions were varied for all investigated configurations. Flat-roofed test buildings of different heights (H = 16m, 32m, and 64m in full scale) and aspect ratios (W = 16m, L/W = 1 and L/W = 3.3) were used for systematic measurements. Overall forces and local peak pressure coefficient were determined for the test buildings.

The study yielded a large data base for wind loads on buildings of the same height or lower or exceeding the mean height of the surroundings. Among the results was the finding that the immediate surroundings or the near field around an individual building strongly reduces wind induced forces for buildings deeply embedded into the city canopy, whereas for taller buildings the forces increase, reaching force coefficients nearer to those on free standing buildings. Because near field conditions will not remain constant during the lifetime of a building due to modifications of neighboring structures, and because large variability of loads caused by different near field conditions we determined design loads by means of second moment reliability analysis (SMR) to obtain design wind loads on a defined safety level (Kiefer, 2003).

SMR-based local peak wind load coefficients on the same level of safety for freestanding buildings and buildings embedded in built-up areas are compared in Fig. 5. The reduction of local wind load coefficients found for buildings as high or lower as the surroundings corresponds approximately to the reduction of design wind speed and the resulting design dynamic wind pressure given in the wind profile model of the Eurocode (1994) for urban areas. This means the design procedure of the Eurocode leads to a sufficient level of safety and an economic design. However, the Eurocode approach for the wind model in built-up areas is not fully included in the new formulation of the German wind load code.

In addition to the systematic wind tunnel study measurements on two test buildings on the University Campus embedded in complex surroundings were carried out in full-scale, paralleled by wind tunnel tests on the scaled models of these test buildings embedded in their surroundings were conducted (Kiefer.& Plate (1998b)). The comparison of the results in full and model scale shows good agreement (see Fig. 6), if the loads are determined as function of tributary area and are based on statistically defined peak load coefficients (Cook-Mayne-method). The results in the frequency domain (Fig. 7) show that the fluctuating wind induced pressure field was properly modelled in the wind tunnel and represents the characteristic features in time and space.

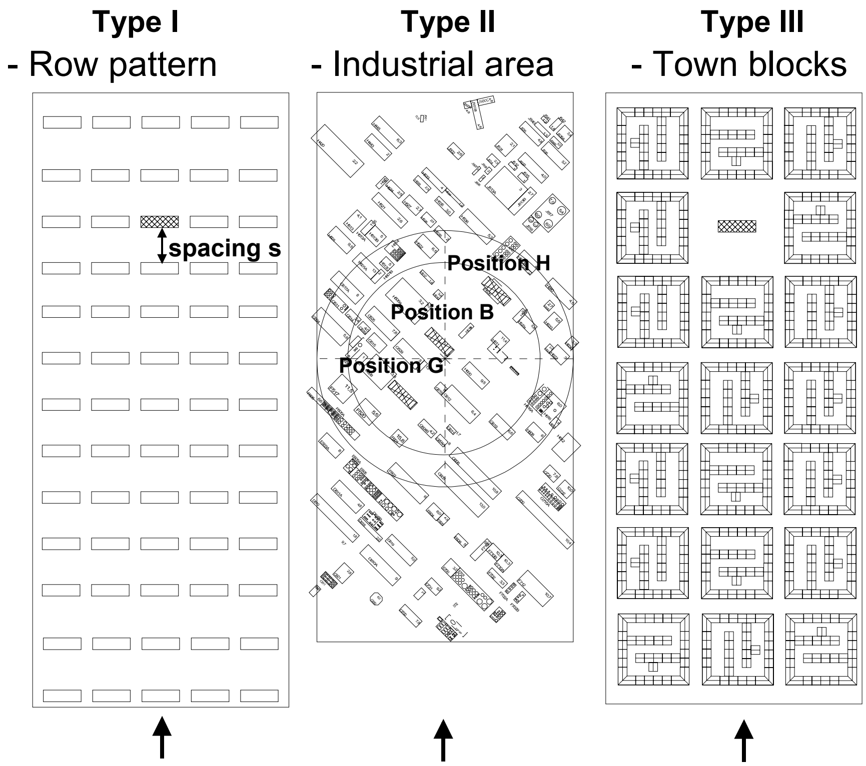


Fig.4 Different fundamental types of built-up areas used for the systematic wind tunnel investigations (Kiefer, 2003)

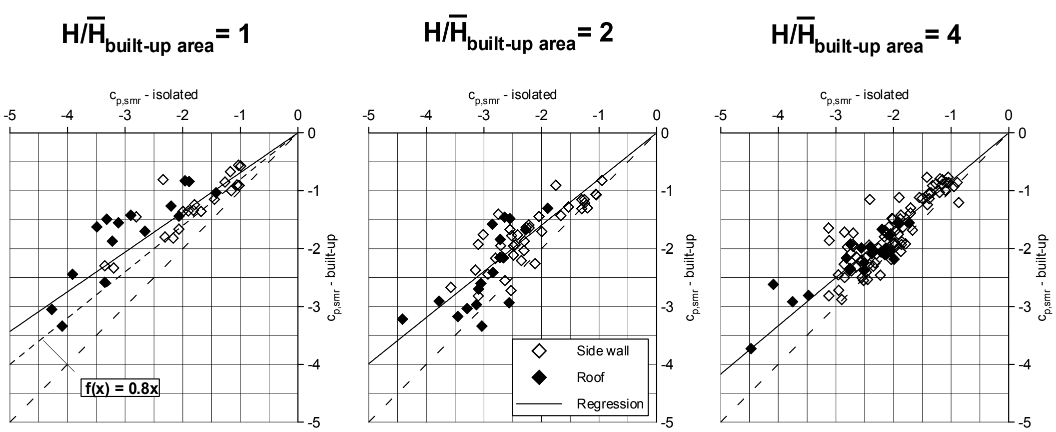


Fig.5 Comparison of local peak pressure coefficients based on SMR-principles for test buildings of different heights (Kiefer, 2003)

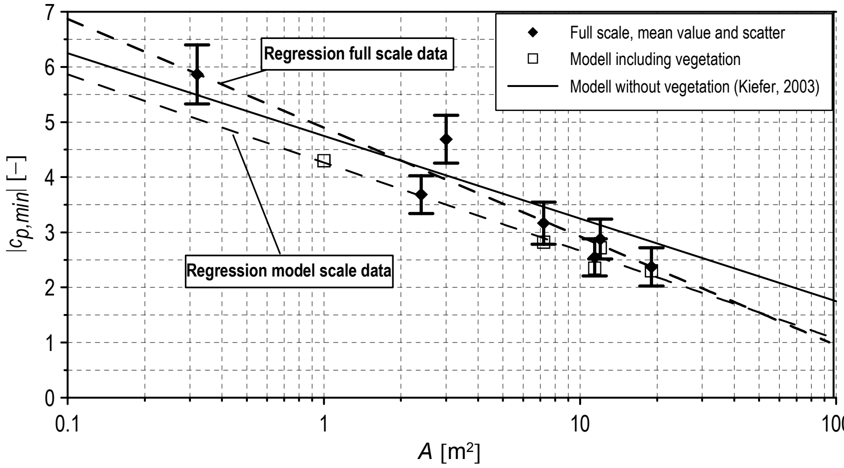


Fig.6 Comparison of local peak pressure coefficients for different tributary areas at the roof corner in full and model scale

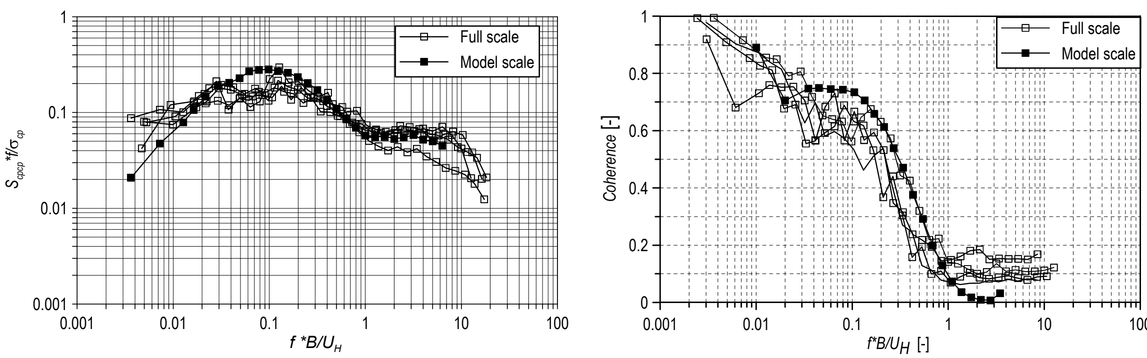


Fig.7 Comparison of spectra and coherence of the pressure fluctuations at the roof corner taps in full and model scale

4. DIFFUSION IN URBAN AREAS

Pollutant loads in urban areas depend on many factors, climate among them. Obviously, for zero wind without convection either self induced turbulence from the sources themselves, or from vehicles moving through city canyons of urban areas will be the only agents for mixing of pollutants. Critical pollution cases occur when the wind velocity is practically zero, and when an inversion inhibits the spreading of pollutants beyond some minimum height. In these cases, the profiles of temperature and heat flow are as shown in Fig.8

In convective situations thermal convection contributes to the mixing, However, even at small wind velocities, the urban complex takes a high degree of mixing energy from the wind flow and combines with thermal mixing to produce a field of practically constant temperature, and also of strong mixing within the urban streets. It is not yet fully determined at which conditions shear induced turbulence starts to overcome convective turbulence. We suspect that beyond some critical conditions convective turbulence is overcome by mechanical turbulence. This conditions is likely to occur at some critical value of u_*/w_*, where w_* is the Deardorf velocity:

$$w_* = (\beta \cdot Q \cdot h)^{1/3} \quad (5)$$

where $\beta = 1/T$ is the buoyancy parameter for mean temperature T, $Q = \overline{T' \cdot w'}$ is the turbulent heat flux, and h is the height of the mixing layer. In order to find this critical number (likely of the order of 0.35), and more generally , to study convective flows by means of experiments. We built a wind tunnel having a test section with a heatable floor, and a return duct consisting of ten ducts on top of one another, each of which can be heated or velocity controlled individually (Rau et al., 1991). One of its primary purposes is to model convective flows in urban environments: is convection really completely suppressed by wind shear, or else, how does convection in combination with wind shear affect turbulent transport? Unfortunately, for a variety of reasons these experiments have not yet been done.

Our research on diffusion in urban areas in neutrally stratified boundary layers has been concerned with two categories. The primary concern was with safety of people living in neighborhoods of chemical factories, in which toxic substances are stored or handled. Accidental releases are of foremost concern in such situations, and warning systems in case of an accident are of the utmost importance, in particular in Germany with its large concentrations of chemical factories in the Rhine - Main area and in the Ruhr district. The second category concerns traffic pollution. The growing traffic density has compensated technical reductions of exhaust contaminants. In almost all cities, extreme traffic pollution can occur. We envisioned the generation of traffic control systems in which traffic is re-routed whenever the toxicity level in a street reaches levels critical to human health.

As a framework for studying these problems, it is useful to distinguish four regions of applications of different modelling techniques, which are shown schematically in Fig.9:

Region 1:source dominated region. This is the initial region, extending over a few tens of meters close to the source, involving the building under consideration or its direct surroundings. Modeling in this and in the near field region is the traditional scope of wind tunnel studies, as it is unlikely that numerical models can well cover the complex flow field induced by the local arrangement of buildings of different heights, sizes, and orientation. Numerous studies of this kind have been made by the author and his team, as have been in many other laboratories in the world.

It can be argued that for such models there always exists a need to model a large part of the upstream surroundings, as the initial wind profile over the city very much influences exchanges between urban canopies and the blending region. We contend that the upstream region has to be modelled far enough to reestablish a fully developed boundary layer to replace the internal boundary layer forming over the edge of building complexes (Plate, 1971, Garratt, 1990), as schematically shown in Fig.1. Of special interest were effects of secondary turbulence created by traffic. We developed a criterion for modelling the turbulence introduced by moving traffic, and generated a method for moving traffic modelling, which was successfully used both for modelling traffic situations, for example in the neighborhood of tunnel in- and outlets, (Bächlin, 1994) and for basic studies of wind and traffic combinations on diffusion in city canyons (Kastner - Klein & Plate, 1999)

Region 2: Near field region . A near field region, extending up to a few hundred meters, in which the exact location of the source is not important, because the buildings downstream of the source strongly influence the wind field and cause strong mixing, which obscures the initial conditions. The outer edge of this region is formed by the "radius of homogenisation", which obtains its name because beyond this distance the concentration plume can be modelled as if it were in a field of homogeneous turbulence. The circle with this radius denotes the border between near and far field.

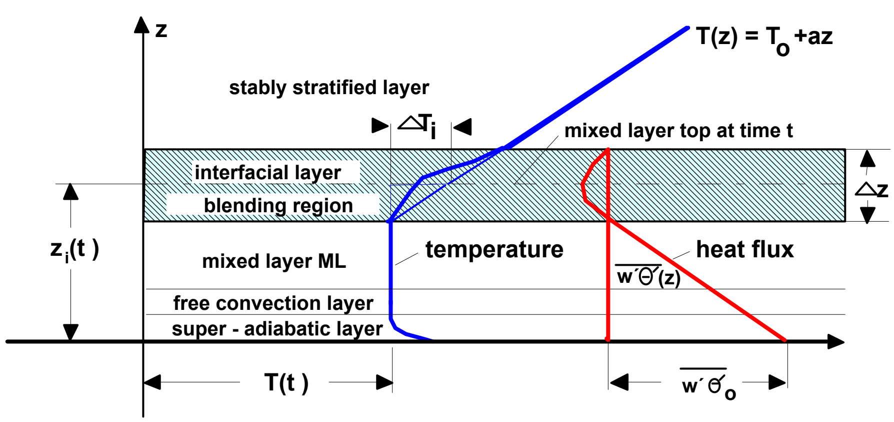


Fig. 8: Idealized temperature profiles in convective conditions

Region 3: Far field region . The far field region extends up to 4 to 5 km downstream of the source. It is mainly of interest for long range air pollution studies, where simple models of the Gaussian plume type can be used to calculate concentration fields from different urban sources. Concentration fields in the far field are characterized by a vertically constant concentration in city streets, and by a Gaussian plume extending from the ground to heights z. Consequently, the far field concentration field resulting from a continuous source located at point $P(x_0, y_0, z_0)$ can be represented approximately by a concentration field c(x,y,z) emanating from a virtual continuous source located at point $P(x_0+\Delta x, y_0+\Delta y,\ 0)$ at ground level:

$$c(x,y,z)=\frac{q_m}{\rho\pi\sigma_y\sigma_z}\cdot\exp\left\{-\frac{(y+\Delta y)^2}{2\sigma_y^2}-\frac{(z)^2}{2\sigma_z^2}\right\} \qquad (6)$$

where q_m is the mass of pollutant (with density ρ) released per unit of time. For this equation, diffusivities D_z and D_y are assumed constant. They yield spreading coefficients σ_y^2 and σ_z^2 which are linear function of x:

$$\sigma_y^2=\frac{2D_y}{\bar{u}}(x+\Delta x) \quad \text{and} \quad \sigma_z^2=\frac{2D_z}{\bar{u}}(x+\Delta x). \qquad (7)$$

where $\bar{u}$ is a (constant) reference velocity. Mass conservation is also possible if the spreading coefficients are non-linear in x, as often used in empirical formulas (depending on Pasquill stability classes). Due to mixing in the near field, the apparent source location is different from the actual source location by an offset of Δx parallel to the wind direction, and an offset Δy horizontally perpendicular to the wind direction. The apparent height of the virtual source is z = 0.

The initial conditions are determined by the characteristics of the urban area. The application of these equations requires the determination of 5 parameters, coefficients $2D_z/\bar{u}$ and $2D_y/\bar{u}$, and coefficients Δx and Δy and since Eq. 7 is valid only for x > R, where R is the radius of homogenization, this quantity also becomes an unknown. Sets of parameters for different types of urban complexes have been collected and reported by Theurer (Theurer et al., 1996, see also Plate & Kiefer, 2001).

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6. CONCLUSION.

A long series of experiments, in our and other institutes, interpreted in the light of existing and newly developed theories have created a state of the art on urban wind problems, whose first results were discussed in a NATO Advanced Study Institute in Karlsbad, Germany.(Cermak et al., 1995). The knowledge accumulated allows to solve practical applications with great confidence. We have identified and studied the urban boundary layer as the region in which buildings and building arrangements interact with the atmospheric wind field.

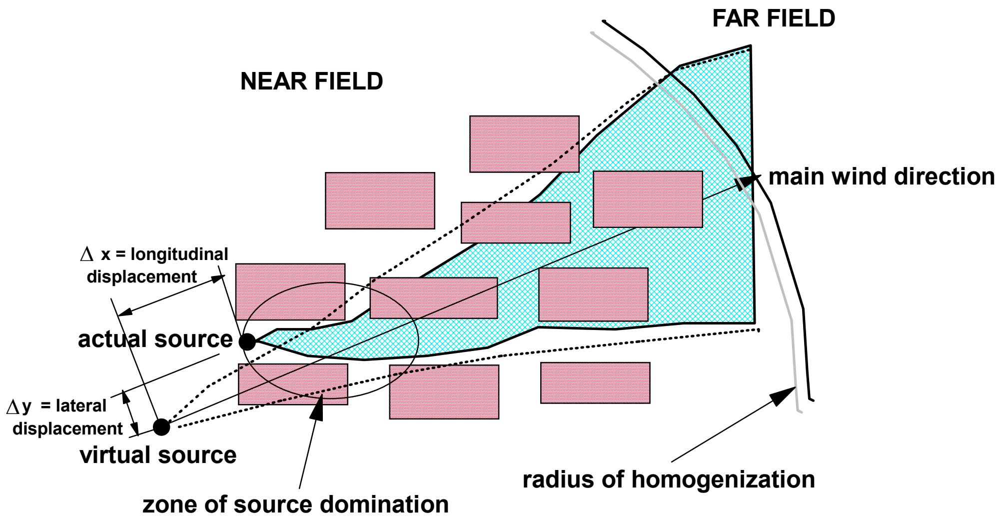

Fig.9: The zones of the diffusion field downwind of a point source (schematic map of an urban area)

A categorization is possible both through the characteristics of the urban canopy as it interacts with the external flow field, as well as with the scale of the problems to be considered. For wind forces, the scale is determined by the building under consideration and its surroundings, and for diffusion we can extend the scale to three regions: source area, near field, and far field.

We may increase the number of regions to be considered from three regions of diffusion categories to a fourth one, the region of meso- scale meteorology. Meso-scale meteorological processes and Coriolis forces dominate, gaseous releases from all sources, as calculated from far field models, are superimposed and can only be determined by means of meso-scale atmospheric transport models. This region is beyond the interest of local urban climate modelling. However, the meso scale meteorological field sets the dynamic boundary conditions for the flow field which has to be considered. The statistical variability of wind field and climate is directly transferred into design criteria for the wind loads, which obtain a large degree of uncertainty from the uncertainty of the atmospheric processes. Two conclusions can be drawn: the first is to consider in more detail the stochastic nature of design loads due to wind (Plate & Davenport, 1995). The second is that the necessity exists of close cooperation of meteorologists and experts on building aerodynamic.

6. REFERENCES:

Arya, S.P.S., E.J.Plate, 1969: Modeling of the stably stratified atmospheric boundary layer. Journal of the Atmospheric Sciences Vol.26, 1969, No.4, pp.656-665

Bächlin, W., 1987: Pressure inside buildings - A dominant parameter for calculating effective natural ventilation.In:Indoor Air '87. Proc. 4th Intern. Conf. on Indoor Air Quality and Climate, Berlin, 17-21 Aug. 1987, Vol.3,pp.337-341

Bächlin, W., Theurer, W., Plate, E.J., 1992: Dispersion of gases released near the ground in built up areas: Experimental results compared to simple numerical modelling. In: Journal of Wind Engineering and Industrial Aerodynamics Vol. 44, 1992, pp. 2721 - 2732

Bächlin, W., P.Klein, 1994: Diffusion problems near tunnel portals in built-up areas. The Science of the Total Environment, vol. 146/147, 1994, pp. 377 - 385

Badde, O., E.J.Plate, 1994: Einfluß verschiedener Bebauungsmuster auf die windinduzierte Gebäudebelastung. Abschlußkolloquium Strömungsmechanische Bemessungsgrundlagen für Bauwerke", lagen für Bauwerke", Sonderforschungsbereich 210, Univ. Karlsruhe, 24./25. Nov. 1994

Blok, O., Plate, E. J., 1975: Wind, wave and windpressure investigation at the lighthouse 'Alte Weser' (for prototype and model). In: 2nd National Conference on Wind Effects on Buildings and Structures,June 1975,Fort Collins,Col.,USA

Bottema, M. and P.G. Mestayer (1997) Urban roughness mapping techniques and some first results. Proc. 2nd European - African Conference on Wind Engineering, Genova, pp.197

Cermak, J.E., A.G.Davenport, E.J.Plate, and D.X.Viegas, (eds.),1995: Wind Climate in Cities. (u.a.): Kluwer Dordrecht 1995 (NATO ASI Series E vol.277)

Garratt ,J.R. (1990) "The internal boundary layer: a review" Boundary Layer Meteorology, Vol.50, pp.171-203

Hertig + Alexandrou, (1995): The influence of surroundings on pressure distributions around buildings, F. Cermak et al. (eds.), Wind Climate in Cities, 293-317, Kluwer Academic Publishers....

Ho, T.C.E., D.Surry, and A.G.Davenport, (1991): Variability of low building wind loads due to surroundings. Journal of .Wind Engineering and Industrial Aerodynamics, (Elsevier Science Publisher),Vol.38, pp.297-310

Hussain, M. & B.E.Lee (1980): A wind tunnel study of the mean pressure forces acting on large groups of low-rise buildings. Journal of Wind Engineering and Industrial Aerodynamics, (Elsevier Science Publisher), Vol.6, pp.207-225

Oke, T., 1987: Boundary layer climates, 2nd ed. , Routledge, London

Kastner-Klein, P., E.J. Plate, 1999: Wind-tunnel study of concentration fields in street canyons. Atmospheric Environment Vol 33, 1999, No. 24 - 25, pp. 3973 - 3980

Kiefer, H., Plate, E.J., 1998a: Modelling of mean and fluctuating wind loads in built-up areas. Journal of Wind Engineering and Industrial Aerodynamics, Vol. 74-76, 1998, pp. 619 - 629

Kiefer,H., E.J.Plate, 1998b: Wind loads on buildings in built-up areas - results from full-scale and wind-tunnel measurements. 2nd East European Conference on Wind Engineering, 7-11 Sept. 1998, Prague, Czech Rep., Proc. Vol. 1, Eds.: M. Pirner et al., pp. 263 - 269

Kiefer, H., E.J.Plate, 1998b: Winderzeugte Bauwerkslasten in bebauten Gebieten. Baukonstruktionen unter Windeinwirkung, U. Peil,(ed): 5. Dreiländertagung D-A-C-H ’97, WTG-Berichte Nr. 5, Aachen: Windtechnol. Ges. 1998, pp. 51 - 63

Kiefer, H., E.J.Plate, 1999: Mean and fluctuating wind loads in built-up areas. Wind Engineering into the 21st Century, : A. Larsen et al. (eds.), Balkema 1999, Vol. 3, pp. 1813 – 1818

Kiefer, H., 2003: Windlasten auf quaderförmige Gebäude in bebauten Gebieteten, Dissertation, Institute for Hydrology and Water Resources Planning, University of Karlsruhe, Germany

Kondo,J. H.Yamazawa, 1986: Aerodynamic roughness over an inhomogeneous ground surface, Boundary Layer Meterorology, Vol. 35, pp. 331 - 348

Maier-Erbacher, J., E.J.Plate, 1991: Measurement of velocity near and pressure on a cylindrical tower located in irregular terrain. Journal of Wind Engineering and Industrial Aerodynamics, Vol. 38, 1991, pp. 167 - 184

Plate, E.J., 1971: Aerodynamic Characteristics of Atmospheric Boundary Layers. Oak Ridge, Tenn. : USAEC 1971.

Plate, E.J., 1982: Wind tunnel modelling of wind effects in engineering. In: Engineering Meteorology, ed.:E.J.Plate, Amsterdam:Elsevier 1982, Studies in Wind Engineering and Industrial Aerodynamics 1,pp.573-639

Plate, E.J., 1993: Statistik und angewandte Wahrscheinlichkeitslehre für Bauingenieure. Berlin: Ernst & Sohn, 1993

Plate, E.J., J.E.Cermak, 1963: Micrometeorological Wind Tunnel Facilities: Description and Characteristics. Final Report, Contract No. DA-36-039-SC-80371 with U.S. Army Electronic Research and Development Activity, Fort Huachuca, Arizona, February 1963, CER63EJP-JEC9

Plate, E.J., Davenport, A.G., 1995: The risk of wind effects in cities. J.E.Cermak, A.G. Davenport, E.J.Plate, D.X.Viegas (eds). Wind Climate in Cities, Kluwer Dordrecht 1995 (NATO ASI Series E Vol.277) pp. 1 - 20

Plate, E.J., H. Kiefer, 2001: Wind loads in urban areas. Journal of Wind Engineering and Industrial Aerodynamics Vol. 89, pp. 1233-1256

Rau, M., W. Bächlin, E.J. Plate, 1991: Detailed design features of a new wind tunnel for studying the effects of thermal stratification. Atmospheric Environment, Vol. 25A, 1991, No. 7, pp. 1257-1262

Schnabel, W., 1981: Field and wind-tunnel measurements of wind pressures acting on a tower. Journal of Wind Engineering and Industrial Aerodynamics,Vol.8, 1981 pp.73 - 91

Theurer, W., W.Bächlin, E.J.Plate, 1992: Model study of the development of boundary layers above urban areas. Journal of Wind Engineering and Industrial Aerodynamics Vol. 41, 1992, pp. 437 - 448

Theurer, W., E.J.Plate, K.Hoeschele, 1996: Semi-empirical models as a combination of wind tunnel and numerical dispersion modelling. Atmospheric Environment Vol. 30, 1996, No. 21, pp. 3583 - 3597

Wacker, J., 1994: Towards reliability-based local design wind pressures for simple rectangular-shaped buildings. Journal of Wind Engineering and Industrial Aerodynamics Vol. 53, No.1-2, 1994, pp. 157 - 175

Wacker, J., R.Friedrich, E.J.Plate, U.Bergdolt, 1991: Fluctuating wind loads on cladding elements and roof pavers. Journal of Wind Engineering and Industrial Aerodynamics, Vol.38,1991, pp.405-418

Wacker, J., E. J.Plate, 1990a: Fatigue caused by wind pressure buffeting on surface elements of high rise buildings. Structural Dynamics, Proc. of the European Conf. on Structural Dynamics, Eurodyn '90,5-7 June 1990,Bochum,Germany, Eds.: W.B.Krätzig et al. Rotterdam: Balkema 1991, pp. 1133 - 1138

Wacker, J., Friedrich, R., Plate, E.J., Dorsch, F., 1990b: Drag and lift on rectangular bluff bodies immersed in deep boundary layer flow over rough surfaces. Journal of Wind Engineering and Industrial Aerodynamics Vol.33,1990,No.1/2,pp.113-122

Wacker, J., E.J.Plate, 1992: Correlation structure of wind pressure buffeting on cuboidal buildings and corresponding effective area wind loads. Journal of Wind Engineering and Industrial Aerodynamics Vol. 43, 1992, pp. 1865 - 1876

Wacker, J., E.J.Plate, 1993: Local peak wind pressure coefficients for cuboidal buildings and corresponding pressure gust factors. Journal of Wind Engineering and Industrial Aerodynamics, vol. 50, pp. 183 - 192

Wacker, J., E.J.Plate, 1994: Reliability-based local design wind pressures for simple rectangularly-shaped buildings. Structural Safety and Reliability, Eds.: Schueller et al. Rotterdam: Balkema 1994, pp. 1689 - 1696

Wacker, J. (1995): "Local wind pressures for cubical buildings in turbulent boundary layers", in: Wind Climate in Cities, Cermak et al., 1995, Kluwer Academic Publlisher, London