

# Uncertainty in wind pressure coefficients for low-rise buildings

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This paper reports on an analysis of the uncertainty in wind pressure (difference) coefficients, which are assessed on the basis of generic knowledge and experimental data rather than with a specific (wind tunnel) experiment. The analysis is carried out on time averaged pressure coefficients in a specific case, concerning a low-rise building in an urban environment. To assess the uncertainty, structured elicitation of expert judgment is employed. Method and results are described here. The acquired uncertainty is compared to an estimate of the uncertainty that could be attributed to wind pressure difference coefficients obtained in a wind tunnel experiment. This comparison serves as input to a discussion whether expert judgment studies could develop as an alternative for wind tunnel tests.

*Keywords:* wind pressure coefficients, wind tunnel, low-rise buildings, uncertainty, expert judgement.

## 1 Introduction

For the simulation of natural ventilation flows in buildings, the wind pressure distribution over the building envelope is required. In the design of low-rise buildings, wind tunnel experiments are scarcely employed to measure the wind pressures. Instead, techniques are used, which predominantly rely on inter- or extrapolation of wind pressure coefficients, measured in prior wind tunnel and full-scale experiments. Due to the complexity of the underlying physics, this is a process, which may introduce considerable uncertainty. This uncertainty, however, cannot be quantified with any of the existing techniques.

In this paper, expert judgment is used to assess this uncertainty in a specific case. The case is designed to tentatively explore the effect of the near field on the uncertainty, as well as the effect of the tap position on the building enclosure. The uncertainty is compared with an estimate of the uncertainty in pressure coefficients, obtained in a wind tunnel test. This comparison is the starting point for an evaluation under which provisions an expert judgment study could be an alternative for a wind tunnel test.

## 2 Case definition

The case under study concerns a scale 1:250 wind tunnel model of a four-story office building at the outskirts of Delft, a Dutch town. Figure 1 shows the full scale building dimensions, whereas

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Figure 2 presents the turntable layout of the building and its immediate surroundings. The building group is immersed in a simulated “urban” boundary layer. The mean velocity profile as it is measured at the center of a void turntable, is shown in Figure 3.

Due to the internal layout of the building, ventilation flows are driven by pressure differences between the long facades (cross-ventilation). Figure 1 shows four marked locations corresponding to the positions of vents in the building façade. This study focuses on two time-averaged pressure differences, i.e. between positions 1a and 1b and between locations 2a and 2b. These pressure differences are related to the mean horizontal wind speed  $U(z)$  at reference height  $z$  by the pressure difference coefficients  $\Delta C_{p1}$  and  $\Delta C_{p2}$ , where  $\Delta C_{pi}$  is defined as:

$$\Delta C_{pi} = \frac{p_{ia} - p_{ib}}{\frac{1}{2} \rho U^2(z)} \quad (1)$$

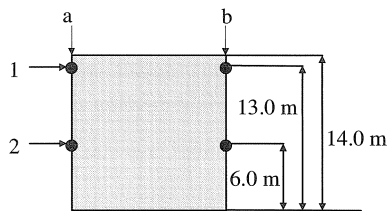


Fig. 1. Cross section of the office building, the central building in Figure 2. The full-scale building dimensions are 56 m × 14 m × 14 m. The four pressure taps are located at the centerlines of the long facades. Side a faces the built-up area (north), whereas side b is directed towards the void area (south).

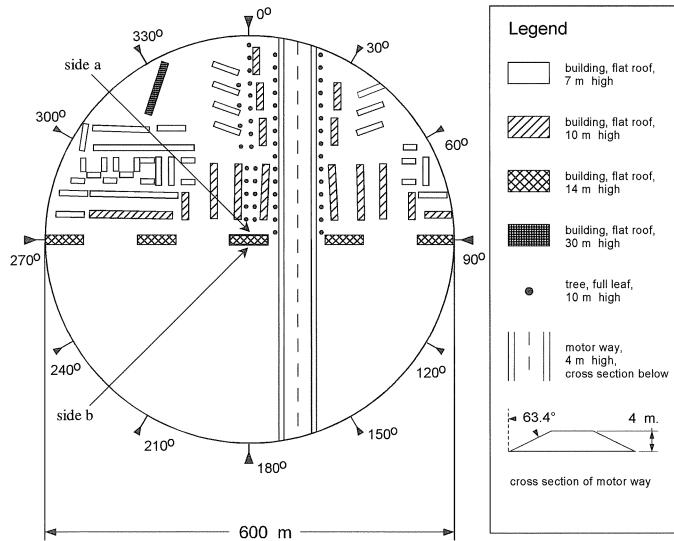


Fig. 2. Schematic layout of the turntable model. The dimensions refer to full-scale. The scale of the model is 1:250. The building in the center is the office building under study. Side a and side b are indicated.

with  $\rho$  the density of air. In this paper, all coefficients are related to the mean wind speed at building roof height in the unperturbed flow, i.e. upstream of the turntable.

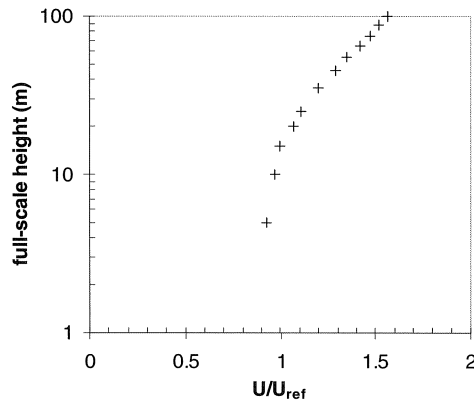


Fig. 3. Mean velocity profile in the wind tunnel at the center of a void turntable with “urban” roughness upstream of the turntable.

### 3 Existing models

A number of models are reported in literature to assist the assessment of time-averaged wind pressure coefficients on the basis of existing experimental data. These models are based on parametric analyses of selected data. Examples of this approach can be found in Allen (1984), Grosso (1992), Grosso et al. (1995), Knoll et al. (1995) and Swami & Chandra (1988). A summary of the key features of these tools can be found in De Wit (1999a).

To obtain a first impression of the uncertainties in pressure difference coefficients derived from existing data, these models were used to estimate the requested pressure difference coefficients for 7 equidistant wind angles between 0° and 180° as indicated in Figure 2. The models by Allen, Knoll et al. and Grosso allow for the assessment of the local coefficients  $\Delta C_{p1}$  and  $\Delta C_{p2}$ . Their output is shown in Figure 4 and Figure 5. Liddament, and Swami & Chandra developed models, which calculate façade averaged pressure coefficients. Figure 6 shows the results of Swami & Chandra’s model together with those of Allen and Grosso, which also allow for the assessment of façade averaged coefficients.

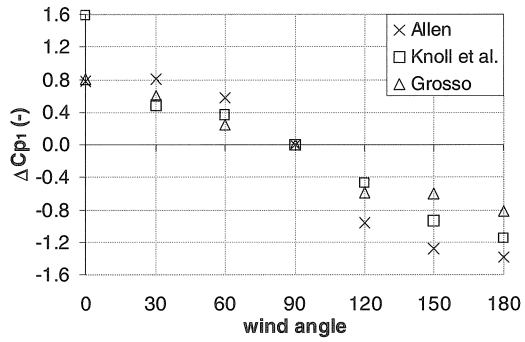


Fig. 4. Wind pressure difference coefficients  $\Delta C_{p1}$ , assessed on the basis of existing data according to three different models.

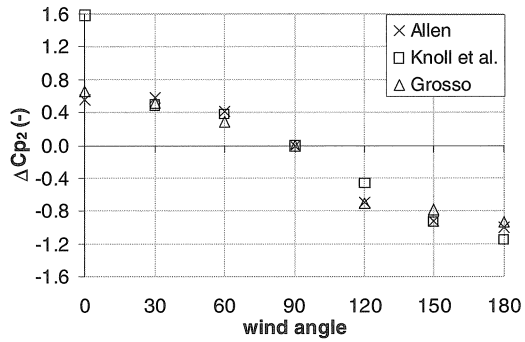


Fig. 5. Wind pressure difference coefficients  $\Delta C_{p2}$ , assessed on the basis of existing data according to three different models.

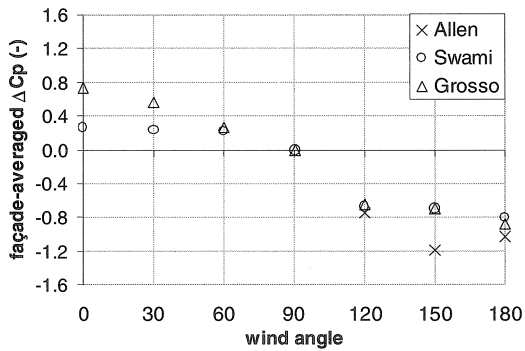


Fig. 6. Façade averaged wind pressure difference coefficients, assessed on the basis of existing data according to three different models.

Whereas the spread in the outputs from the different models for  $\Delta C_{p1}$  is considerable, they agree rather well on  $\Delta C_{p2}$  except for  $0^\circ$ . The degree of consensus on the façade-averaged coefficients strongly depends on the wind angle.

If we would consider adopting the scatter in the model outcomes as a measure of the uncertainty, it is important to contemplate which factors contribute to that scatter and, more importantly, which do not.

First, the model outcomes depend on the choices of the analyst:

- Several models require a characterization of the velocity profile in terms of  $\alpha$  or  $z_0$ . Which values most adequately represent the profile in Figure 3?
- The case at hand is out of the range of application of some of the models. Are the outcomes still appropriate?
- If the surroundings of the central building have to be classified in a “shielding” class, which class description best fits the current case?

Moreover, not all uncertainty is captured in the variation of the model output:

- The scatter in the experimental data on which the models are based is eliminated by regression or averaging. Part of this scatter may be measurement error, but part of it results from effects unexplained by the model. Models sharing the same parameters most likely ignore the same effects.
- There is considerable overlap in the data sets underpinning the different models. This overlap introduces a dependency between the model predictions.
- The majority of the data underlying the models that assess the effect of the near field were obtained in (wind tunnel) experiments with regularly arranged near field layouts. The near field in this case is irregular and consists of buildings of different heights.

Although the results of this exercise support the assumption that significant uncertainty exists in wind pressure coefficients, predicted on the basis of existing data, they do not provide a proper basis to assess this uncertainty. Wind-engineering expertise is required, both to provide reliable inputs to the models and to assess the impact of features in the case under study, which are not covered in the existing models.

Hence, the uncertainty in these pressure coefficient assessments can best be quantified by experts in the field, who, acquainted with the complexity of the underlying physics as they are, are best suited to interpolate and extrapolate the data they have available on the subject and assess the uncertainties involved. The next section reports on an experiment in which expert judgment was used to quantify the uncertainties in the wind pressure difference coefficients in the case at hand.

## 4 Expert judgment

### 4.1 Introduction

In the expert judgment study, the case described in section 2 was presented to six experts, renowned for their expertise in the field of wind pressure measurements on low-rise buildings. For each of the twelve wind angles in Figure 2 they were individually asked to assess the values of  $\Delta C_{p1}$  and  $\Delta C_{p2}$ , which would be found if this model would be examined in a wind tunnel with the velocity profile shown in Figure 3. Each expert’s assessment of a coefficient did not consist in a ‘best

estimate', but in a median value plus a central 90% confidence interval expressing his uncertainty. Probability distributions were constructed for each expert from his assessments on the basis of the principle of minimal information (Cooke, 1991).

To implement empirical control, two independent wind tunnel tests were carried out to actually measure the values of the requested wind pressure differences for the twelve wind angles. From a comparison of the experts' assessments with the measured data, a performance score could be calculated for each expert.

Finally, a single (marginal) probability distribution was obtained for each pressure difference coefficient at each wind angle by calculation of a weighted average of the experts' distributions. The weights in this process were based on the experts' performances.

In expert judgment terminology, this resulting distribution for each variable is referred to as the distribution for the decision-maker, or simply the DM.

The most important aspects of the procedure, which was followed to obtain and process the experts' judgments, is outlined in the next section. It is based on Cooke (1991) and Cooke & Goossens (1995). Similar approaches in civil engineering applications can be found in Van Elst (1997) and Ter Haar et al. (1998).

#### 4.2 *Selection of the experts*

A pool of candidates for the expert panel was established by screening recent literature. From the many candidates resulting from the screening, a panel of 7 experts was established on the basis of the following criteria:

- access to relevant knowledge
- recognition in the field
- impartiality with respect to the outcome of the experiment
- familiarity with the concepts of uncertainty
- diversity of background among multiple experts
- willingness to participate

One of the selected experts withdrew in the elicitation stage, as he did not appreciate the concept of subjective probability. Table 1 lists the experts, who participated in the study.

The team of W. de Gids, B. Knoll and H. Phaff worked together and produced one single set of assessments. They will be referred to as a single expert.

Table 1. List of substantive experts in the experiment.

|                                |             |
|--------------------------------|-------------|
| W. de Gids, B. Knoll, H. Phaff | Netherlands |
| J.-A. Hertig                   | Switzerland |
| B. Lee                         | UK          |
| D. Surry                       | Canada      |
| A. Vrouwenvelder               | Netherlands |
| E. Willemsen                   | Netherlands |

#### 4.3 *Expert training*

None of the experts but one had ever participated as substantive expert in an experiment involving structured elicitation of expert judgment, so they were unacquainted with the motions and underlying concepts of such an experiment. Moreover, acting as a substantive expert entails the assessment subjective quantile values and subjective probabilities, a task the experts were not familiar with.

Hence the experts received a concise training with the aim to:

- provide an overview of the process
- develop confidence
- introduce the experts to the task they must perform
- instill awareness and control of biases
- practice making probabilistic judgments

#### 4.4 *Elicitation*

In the elicitation stage, the core of the experiment, the experts made their judgments available to the analyst. In this experiment, individual meetings with each expert were arranged. The experts were specifically asked not to discuss the experiment with each other. In this way, the diversity of viewpoints would be minimally suppressed.

The elicitation took place in three parts. Prior to the elicitation meeting, each expert prepared his assessments e.g. by looking up relevant literature and making calculations. During the meeting, these assessments were discussed with the analyst, who avoided giving any substantive comments, but merely pursued clarity, consistency and probabilistic soundness in the expert's reasoning. On the basis of the discussion, the expert revised and completed his assessments if necessary. To ascertain traceability of the results, the elicitation was completed with the writing of the rationale, a report documenting the reasoning underlying the assessments of the substantive expert. The experts' rationales can be found in De Wit (1999b).

#### 4.5 *Wind tunnel tests*

To implement empirical control, two wind tunnel tests were carried out once the experts' assessments had been compiled. The aim of these experiments was to obtain experimental data on which the performances of the experts could be scored.

The first experiment took place in the low speed German-Dutch wind tunnel (DNW-LST), located at the facility of the Dutch Aerospace Laboratory (NLR) in The Netherlands. This is a closed-loop wind tunnel with a closed test section of 8.75 m long and a cross-section of 3.00 m × 2.25 m at the position of the turntable. The other test was performed in a boundary layer wind tunnel of the University of Western Ontario in Canada (UWO-BLWT1). This is an open-return tunnel with a test section of 28.7 m length and a cross section of 2.4 m × 2.1 m.

More information on the experiments can be found in De Wit (1999a) and in Willemsen (1998) for the DNW-experiment and in Soerensen (1998) for the experiment in the UWO-tunnel.

#### 4.6 *Analysis of the data*

The analysis of the data focuses on the assessment of the experts' performances and the combination of their judgments to calculate the distributions for the decision-maker, the DM. To accomplish this, the classical model is used as developed by Cooke (1991). This section briefly addresses this model.

##### *Expert performance*

An expert's performance  $w_e$  is calculated from a comparison of his assessments with measured realizations. It is the product of two measures, calibration  $C_e$  and information score  $I_e$ :

$$w_e = C_e I_e \quad (2)$$

Loosely stated, calibration measures the degree to which the realizations support the expert's assessments. In scoring calibration, an expert is regarded as the statistical hypothesis: "the realizations are samples, drawn independently from distributions corresponding to the expert's quantile assessments". The calibration score can be interpreted as the minimum significance level at which this hypothesis would not be rejected. Ergo, a calibration score has a value between 0 and 1 and higher scores are better.

The information score indicates how 'tight' the expert's distributions are. It is calculated per variable as the relative information of the expert's distribution with respect to the uniform distribution on a suitably chosen intrinsic range for that variable. It expresses what we learn from the expert's assessments if we initially believe that the variable is uniformly distributed on the intrinsic range. Information scores are always positive and higher scores are preferred.

The fact that an expert's performance is the product of two scores, calibration and information, suggests that he could compensate a low calibration by being highly informative. This is only possible to a limited extent. An expert's performance is dominated by his calibration, as this score may range over five orders of magnitude, whereas the information score rarely varies more than a factor five between experts. Hence, the information score serves to modulate between more or less equally calibrated experts.



### Combination of the experts' assessments

For each variable, the experts' assessments must be combined to obtain the DM for that variable. Combination of the experts' assessments according to the classical model uses linear pooling, which means that the DM is a weighted average of the experts' distributions.

Basically, an expert's weight is his normalized performance. The normalization serves to ascertain that the sum of weights for each variable equals 1. However, if an expert's calibration score is below a suitably chosen value of the significance level, the expert, considered as a hypothesis, is "rejected" and his weight is set to zero. The significance level receives the value that optimizes the performance of the DM, which is calculated in the same way as the performance of individual experts.

It can be shown that this method of scoring experts is 'asymptotically strictly proper', which means that experts on the long run receive the highest weights if they state assessments according to their true beliefs (Cooke, 1991).

## 5 Results

Figure 7 and Figure 8 show the results of both wind tunnel experiments and the experts' assessments.

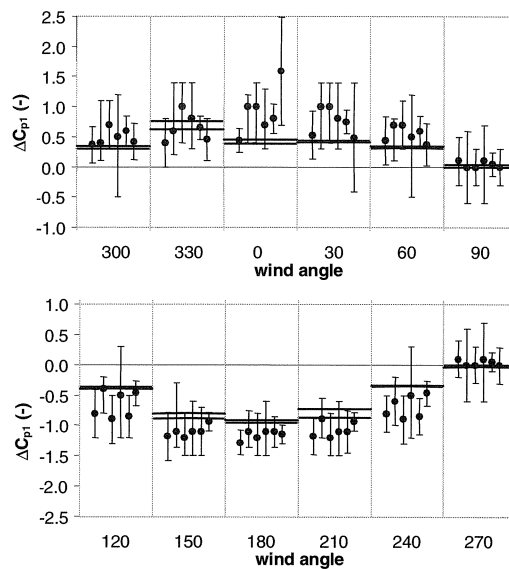


Fig. 7. Assessments of the 6 experts for  $\Delta C_{p1}$ . The dots are their median values, the error bars represent their central 90% confidence intervals. The drawn horizontal lines show the results from the two wind tunnel tests. For each wind angle, the results of experts 1 through 6 are shown from left to right.

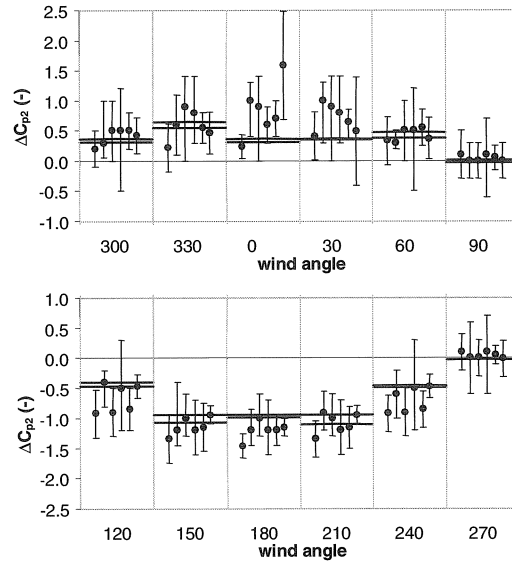


Fig. 8. Assessments of the 6 experts for  $\Delta C_{p2}$ . The dots are their median values, the error bars represent their central 90% confidence intervals. The drawn horizontal lines show the results from the two wind tunnel tests. For each wind angle, the results of experts 1 through 6 are shown from left to right.

Figures 7 and 8 refer to the experts by number. These numbers were randomly attributed to the experts in Table 1 and will be used throughout this paper.

## 6 Analysis

The experts' performance scores, calculated with the classical model on the basis of 2 realizations for each variable (i.e the wind tunnel results), are listed in Table 2. The last row of the table shows the scores of the DM.

As in Figures 7 and 8, each expert is referred to by his number, which was randomly attributed. The experts' scores were not directly calculated from their assessments as shown in Figure 7 and Figure 8. From their rationales it became clear that, for each wind angle, the experts first assessed the pressure differences between windward and leeward side. Subsequently they adjusted the sign to obtain the requested pressure differences between side a and side b. Hence, it was considered more appropriate to score the experts on their initial assessments of the pressure difference coefficients between windward and leeward side. In this way, possible systematic tendencies of any of the experts to over- or underestimate would not be masked.

Table 2. Experts' performances, calculated with the classical model and scaled to an effective number of 10 seed variables. The last row shows the score of the optimized DM.

| Expert | Calibration<br>$C_e$ | Information<br>$I_e$ | Performance<br>$w_e$ |
|--------|----------------------|----------------------|----------------------|
| 1      | $3.0 \cdot 10^{-2}$  | 0.65                 | $2.0 \cdot 10^{-2}$  |
| 2      | $3.6 \cdot 10^{-1}$  | 0.55                 | $2.0 \cdot 10^{-1}$  |
| 3      | $1.0 \cdot 10^{-2}$  | 0.46                 | $4.6 \cdot 10^{-3}$  |
| 4      | $1.0 \cdot 10^{-3}$  | 0.17                 | $1.7 \cdot 10^{-4}$  |
| 5      | $1.0 \cdot 10^{-4}$  | 0.81                 | $8.1 \cdot 10^{-5}$  |
| 6      | $3.0 \cdot 10^{-1}$  | 0.73                 | $2.2 \cdot 10^{-1}$  |
| DM     | $3.6 \cdot 10^{-1}$  | 0.55                 | $2.0 \cdot 10^{-1}$  |

Calibration scores can only be interpreted in relation to the number of variables from which they were calculated. The expert scores in Table 2 are based on 24 variables, i.e. the  $\Delta C_{p1}$ 's and  $\Delta C_{p2}$ 's for 12 wind angles. However, the scores have been scaled to an effective number of 10 seed variables, a common number in expert judgment studies, by adjusting the power of the test.

Experts 2 and 6 are almost equally well calibrated. The calibration scores of the other experts are lower by an order of magnitude or more, which is significant.

As explained in section 4.6, in calculating the decision-maker, the significance level is assigned a value, which maximizes the performance of the DM. In this case, maximum performance of the decision-maker was found at a significance level of  $3.6 \cdot 10^{-1}$ . In other words, all experts except expert 2 received a zero weight, as their calibration scores are lower than the calibration level. Hence, the assessments of the DM with optimized performance are equal to those of expert 2. Figure 9 and Figure 10 show these assessments separately.

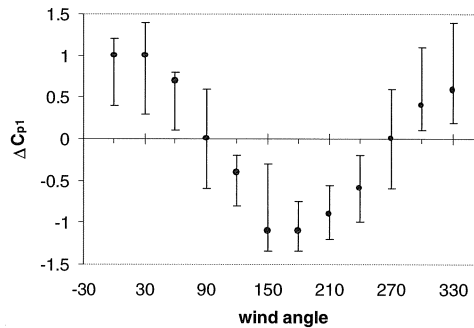


Fig. 9. DM's assessments for the  $\Delta C_{p1}$ 's.

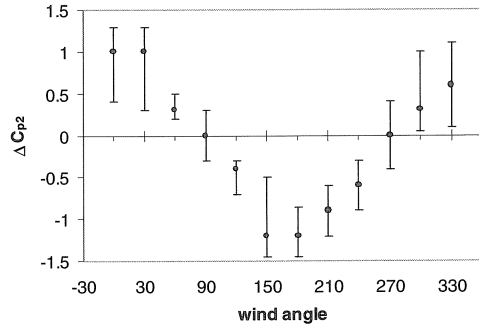


Fig. 10. DM's assessments for the  $\Delta C_{p2}$ 's.

A more detailed analysis of the experts' assessments can be found in De Wit (1999a).

## 7 Discussion

Figure 9 and Figure 10 show the median values plus a central 90% confidence intervals for the pressure difference coefficients considered in this case study. These values result from an optimal combination of the experts' assessments as explained in section 4.6 and can be interpreted as the uncertainties that should be considered in  $\Delta C_{p1}$  and  $\Delta C_{p2}$  when their values are assessed from existing data.

It is interesting to compare these results with the uncertainties in pressure difference coefficients, obtained from a wind tunnel experiment. This reveals the extra information we gain by doing a specific wind tunnel experiment instead of an assessment on the basis of existing data.

As each sound wind tunnel test, compliant with the case description in section 2 yields valid realizations of the wind pressure difference coefficients, the spread in the outcomes of such tests would be a suitable estimator for the uncertainty. In a recently completed study (Hoelscher, 1997), twelve wind tunnel laboratories measured the surface pressures at a floor-mounted cube, corresponding to 50 m height in full-scale. They were asked to perform the measurements in a simulated boundary layer flow at neutral stratification corresponding to urban terrain with a profile exponent of  $\alpha = 0.22 \pm 0.02$ . Apart from a few basic constraints, the participants were free to perform the tasks according to their own judgement and standards.

Figure 11 shows the 90% confidence intervals for pressure difference coefficients between front and back of the cube, measured at the façade centerline at  $0.93H$  and  $0.5H$  respectively, where  $H$  is the obstacle height. These measuring locations are comparable to those of  $\Delta C_{p1}$  ( $0.93H$ ) and  $\Delta C_{p2}$  ( $0.43H$ ) respectively. Figure 11 shows that the width of the confidence intervals is on average 0.2 and does not significantly depend on the wind angle.

To explore if these results obtained for an isolated cube of 50 m full-scale height make sense in the current case, a virtual expert was created. His median values were chosen equal to the outcomes of the uwo wind tunnel test. The 95% and 5% quantile values were set to the median value  $\pm 0.1$  to obtain 90% confidence intervals of width 0.2. Subsequently, the performance of this virtual expert

was scored on the results of the test in the DNW tunnel along with the other experts. Table 3 lists the performance score of this virtual expert.

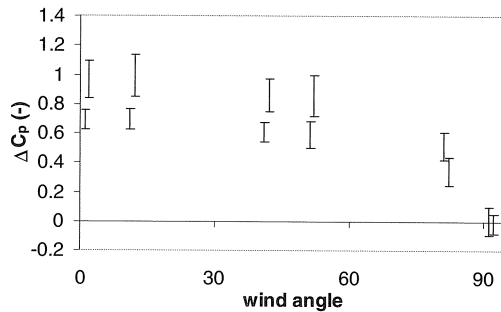


Fig. 11. Spread in wind pressure difference coefficients, measured in twelve different wind tunnels on an isolated cube (Hoelscher, 1997). The error bars represent the 90% confidence intervals. The upper error bars are obtained at a level of 0.5 of the cube height, the lower bars were found at 0.93 of the cube height.

Table 3. Performance of a virtual expert, created on the basis of the data from the UWQ-test and scored on the results of the experiment in the DNW-tunnel.

|                | $C_e$               | $I_e$ | $w_e$               |
|----------------|---------------------|-------|---------------------|
| Virtual expert | $3.8 \cdot 10^{-1}$ | 1.65  | $5.2 \cdot 10^{-1}$ |

Comparison of the numbers in this table with Table 2 shows that the virtual expert, created on the basis of wind tunnel data, has a calibration score, which is similar to that of the DM, calculated from the expert judgments. However, the information score of the virtual expert is 3 times higher than the information score of the DM. Or, alternatively, the confidence intervals of the virtual expert are 3–6 times narrower than the confidence intervals of the DM. This can be interpreted as the extra information, which is gained by doing a wind tunnel experiment in this case.

Wind pressure coefficients, assessed on the basis of existing data in this study have an uncertainty, which is large compared to both their median values, and to the (estimated) uncertainty in wind tunnel results. This suggests that the output of models and tools, based on a parametric analysis of prior wind tunnel and full-scale data, have little meaning unless the uncertainty in this output is quantified. This study shows that an expert judgment study is an adequate method to perform this quantification. In the form it was implemented here though, it is also a very expensive approach, far more expensive than a wind tunnel study.

The most obvious measure to cut back the costs, i.e. by reducing the number of experts in the panel to e.g. 1 or 2, is not an attractive one at this stage. Indeed, the experts in this study show little agreement in their assessments. This is expressed in their rationales, which underpin their assessments

with different and sometimes even conflicting arguments. Moreover, the experts' calibration scores show a large scatter and only two out of six experts receive a fair calibration score.

Thus, at this stage it should be concluded that an expert judgment study is not an attractive alternative for a wind tunnel experiment. However, this tentative conclusion is moderated by the following consideration. If expert judgment studies would be as common as wind tunnel studies are today, experts would be better trained to make subjective probability assessments, which might allow for a reduction of the number of experts in the study. Moreover, experts would probably be better equipped to estimate wind pressure coefficients on the basis of available data, which might lead to a reduction of their uncertainty without a loss of calibration.

Hence, it seems worthwhile to dedicate further research efforts to the exploration of the perspectives of expert judgment in this field.

## 8 Conclusions

Expert judgment was successfully employed to quantify the uncertainty in wind pressure difference coefficients for a low-rise building in an urban environment. The uncertainty was measured in the situation that the coefficients are assessed on the basis of existing experimental data and knowledge rather than with a specific (wind tunnel) experiment. The observed uncertainty is large, both compared to the median values of the coefficients, and compared to the (estimated) uncertainty in wind tunnel results. This suggests that point estimates on the basis of existing data do not give useful information. In stead, probability distributions for the coefficients as obtained from an expert judgment study, might be valuable for certain applications, e.g. concerning serviceability limit state evaluations.

However, in the form it was implemented in this study, elicitation and processing of expert judgments is much more expensive than a wind tunnel experiment. Further study is required to investigate to which extent the costs (and possibly the uncertainties) would be reduced if experts would become more familiar with and skilled in the assessment of subjective probabilities.

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