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Wind loads on T-shaped and inclined free-standing walls

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Abstract. Wind tunnel measurements on T-shaped free-standing walls and inclined free-standing walls have been carried out. Mean net pressure coefficients have been derived and compared with previous research. It was observed that the high loads at the free ends are differently distributed than those derived from the pressure coefficients for free-standing walls in EN 1991-1-4. In addition net pressure coefficients based on extreme value analysis have been obtained. The lack of correlation of the wind induced pressures at windward and leeward side result in lower values for the net pressure coefficients when based on extreme value analysis. The results of this wind tunnel study have been included in Dutch guidelines for noise barriers.

Keywords: wind load; wind tunnel test; free-standing wall; mean values; extreme value analysis.

1. Introduction

The Road and Hydraulic Engineering Institute of the Public Works Department in the Netherlands (DWW) is responsible for design and maintenance of the noise barriers aside the motorways in the Netherlands. Due to increased demands for noise protection, existing noise barriers will not give sufficient noise reduction. Improvement of the behavior of these barriers is possible by increasing the height or mounting additional features on top of the screen. DWW has plans to include so-called T-tops on top of existing barriers. Both options, increasing the height and adding additional features, have been approved to increase noise reduction, but may, however, lead to increased wind loads, and therefore to higher forces and moments in the load bearing structure of the barriers.

Wind tunnel measurements on free-standing walls were carried out by Letchford and Holmes (1994). Mean pressure coefficients were determined for walls of 5 m and 10 m at the Oxford University. Mean extreme pressure coefficients based on the method proposed by Cook and Mayne as described in Cook (1990) were calculated for walls of 7.5 m at CSIRO. In both studies different aspect ratios were measured. Full scale testing on vertical walls had been presented by Robertson, *et al*. (1996, 1997) and Letchford and Holmes (1999). The effects of wind direction, Jensen number, aspect ratio, return corners, gaps and porosity, shelter and thickness/height ratio on a 2 m high wall were studied in an extensive research program. Results were presented as mean values for inclusion in design codes. A comparison with the design codes of the UK and Australia was made by Robertson,

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et al. (1995). Baker (2001) considered the unsteady wind loading characteristics of free-standing walls.

The results of these investigations have found their way into current wind loading standards, such as EN 1991-1-4 (2005). Very limited information has been found on the wind loads on free-standing walls which are equipped with additional features. Where information was available, no coefficients for T-shaped sections were given.

With the above given aspects in mind, wind tunnel measurements have been performed into the wind loading on free-standing walls of different heights, different T-tops and different inclination angles. A total of 7 configurations of free-standing walls have been tested. The results of this research are used as input for the new design and the upgrading of existing noise barriers, and will be applied in future design guidelines.

2. Experimental techniques

2.1. Atmospheric boundary-layer wind tunnel

The atmospheric boundary-layer wind tunnel of TNO has a measurement section 3 m wide and 2 m high, with a fetch length of 14 m. The measurements are made in a configuration with an upstream fetch and turntable made out of Lego board. This gives a value for the roughness length in the wind tunnel of 0.3 mm, thus giving a value for the roughness length of 3 cm in full scale. The Jensen numbers are therefore 167 and 267 for the 5 m and 8 m walls. The profiles of the mean velocity and turbulence intensity are given in Figs. 1 and 2. Typical values of the length scales at the reference heights are between 110 and 130.

2.2. Free-standing wall models

Model free-standing walls of two different heights, 5 and 8 cm, representing full scale heights of

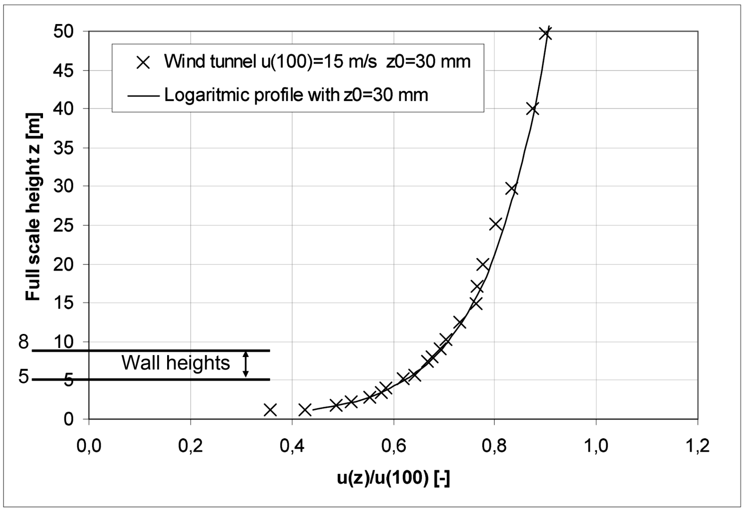


Fig. 1 Mean wind velocity from the wind tunnel

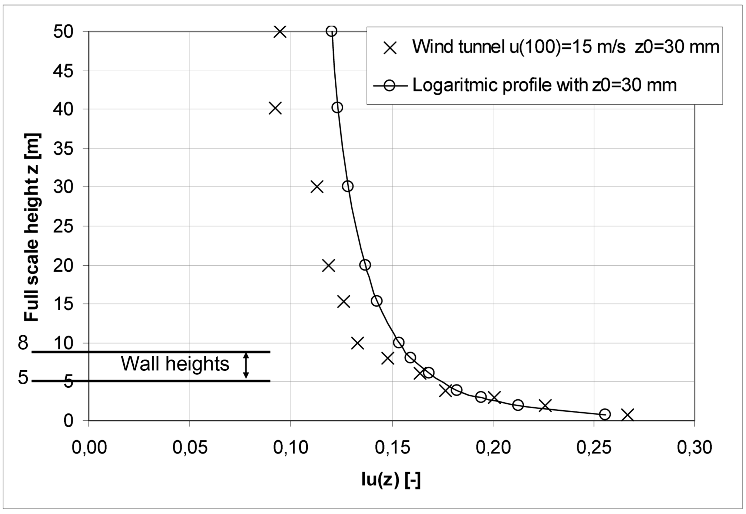


Fig. 2 Turbulence intensity from the wind tunnel

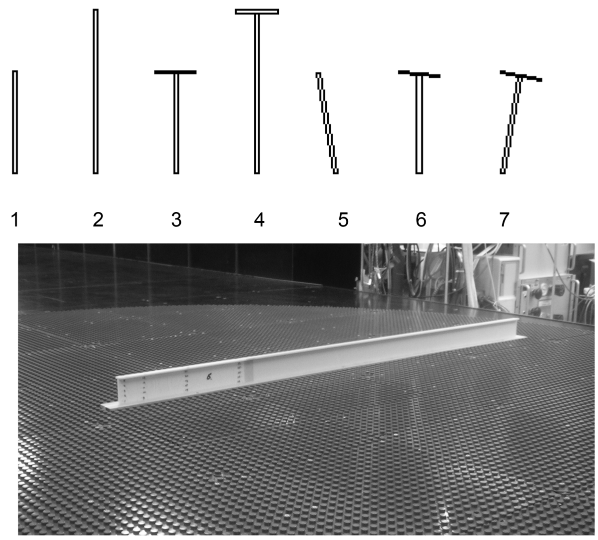


Fig. 3 Free-standing wall configurations (left); model in the wind tunnel (right)

5 and 8 m at a scaling ratio of 1:100, are used. The maximum blockage ratio is 2.6%. The ends of the free-standing walls are positioned at the centre of the turn table and the walls are extended towards the edge of the turn table. End effects can be therefore modeled adequately. Fig. 3 shows the tested free-standing wall configurations and one of the tested models inside the wind tunnel. For 7 free-standing wall configurations wind tunnel measurements are carried out:

1. Vertical free-standing wall, height 5 m, no T top applied;
2. Vertical free-standing wall, height 8 m, no T top applied;
3. As configuration 1, with a T-top;
4. As configuration 2, with a T-top;

5. As configuration 1, with an inclination of the wall of 80 degrees, and no T-top;
6. As configuration 1, with a T-top, inclined with 10 degrees;
7. As configuration 5, with a T-top, inclined with 10 degrees.

The models have been made of plastic, with the pressure taps and pressure tubes mounted inside the model. The width of the T-top is for all cases 2 m in full scale (1 m to both sides of the screen). The thicknesses of the free-standing wall and the T-top are determined by the diameter of the tubes of the pressure taps in the models. The minimum possible thickness of 4 mm for both wall and T-top is used, which represents 40 cm in full scale. This is assumed representative for the usual dimensions of noise barriers, as used in the Netherlands. The aspect ratios are L/h = 12.5 for the 8 m and L/h = 20 for the 5 m walls.

2.3. Instrumentation

Pressures have been measured simultaneously on the surface of the models on selected sections of the walls. These sections have been selected, based on the zones of pressures as defined in EN 1991-1-4. Pressure taps have been mounted at four distances from the edge of the wall (0.15 h, h, 3h and 6h). Each line with pressure taps corresponds to the zones A, B, C and D, as specified in EN 1991-1-4. For the exact positions of all taps, see Fig. 4.

The pressures are measured around the full wind rose, applying 24 wind directions with an increment of 15 degrees.

2.4. Pressure measurement techniques

The diameter of the holes of the pressure taps is 1.5 mm. The diameter of the tubes is also 1.5 mm. Pressure data have been obtained with a sample frequency of 400 Hz. The pressures for the individual taps are measured with the Scanivalve-Hyscan pressure scanning equipment.

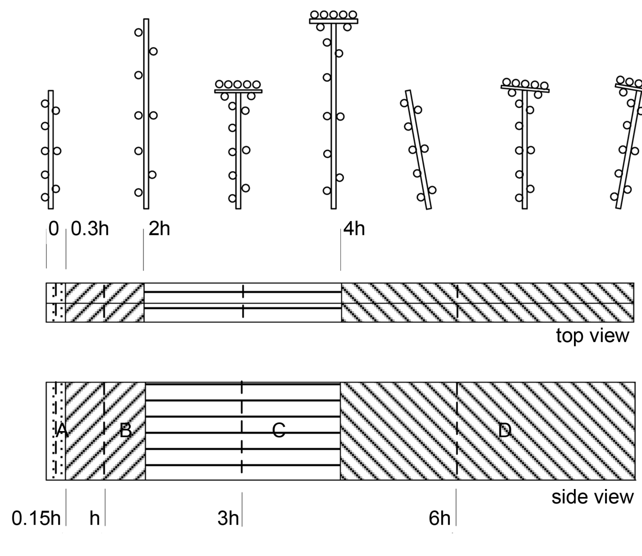


Fig. 4 Positions of pressure taps (top); position of taps in relation to zones of EN 1991-1-4 (bottom)

3. Definition of pressure coefficients

The analysis of the data has been done with two procedures: Both mean pressures as well as extreme values for the pressure coefficients have been analyzed.

3.1. Mean value analysis

The mean pressure coefficients are directly derived from the wind tunnel measurements:

$$\bar{C}_p(\theta) = \frac{\bar{p}_{WT}(\theta)}{\frac{1}{2}\rho v_{ref}^2} \tag{1}$$

where $C_p(\theta)$ = mean pressure coefficient for wind direction θ; $p_{WT}(\theta)$ = mean pressure in which the subscript $_{WT}$ stands for wind tunnel; v_{ref} = the mean wind velocity at reference height in the wind tunnel. In this experiment v_{ref} = 9.8 m/s at 8 m in full scale or 8 cm in the wind tunnel. For the lower screens, the reference wind speed at 5 m height is equal to 9.0 m/s.

3.2. Extreme value analysis

Design values for the wind loads on structures should preferably be obtained using coefficients obtained from appropriate extreme value analysis. A solid base for such analysis has been described by Cook and Mayne, which has been applied to obtain values of pressure coefficients in current codes like BS 6399 (1995) and EN 1991-1-4. Design values of the pressure coefficients may be obtained by using the so-called Cook-Mayne coefficients, which correspond to a value with a probability of non-exceedance of 78%.

$$\hat{C}_p(\theta) = \hat{U}_{p,3600} + 1.4 \cdot \frac{1}{\hat{\alpha}_p} \tag{2}$$

where $\hat{C}_p(\theta)$ = representative pressure coefficient for the maxima for wind direction θ; $U_{p,3600}$ and $1/a_p$ are the Gumbel parameters of the extreme values of the pressures belonging to full scale time series of 1 hour length. A similar equation is available for the minima.

Van Staalduinen en Vrouwenvelder (1993) have shown that statistical independency and stationarity only holds for periods with lengths of 4 to 6 hours, the typical duration of a storm in a frontal depression. When this is applied in the procedures developed by Cook and Mayne, using the wind climate statistics of the Netherlands, this yields as appropriate values for the pressure coefficients:

$$\hat{C}_p(\theta) = \hat{U}_{p,3600} + 2.9 \cdot \frac{1}{\hat{\alpha}_p} \tag{3}$$

Eq. (3) corresponds to a 90% probability of non-exceedance, which gives a (slightly) safer estimate of the design pressure coefficients, compared to the 78% fractile which has been proposed by Cook and Mayne. The procedure applied in this study is as follows:

As a first step the pressures are made dimensionless per wind direction θ:

$$C_p(\theta, t) = \frac{p_{WT}(\theta, t)}{\frac{1}{2}\rho v_{ref}^2} \tag{4}$$

The wind velocity v_{ref} is the mean wind velocity at reference location in the wind tunnel. For every wind direction, the extreme value distributions of the extremes of $C_p(\theta)$, have been determined as follows:

1: Per wind direction, the measured time series is divided in N samples with a full scale time duration of length T (in seconds).

2: Per sample, the minimum and maximum values for the pressure coefficients are determined, thus giving N maxima and N minima for every pressure tap and every wind direction.

3: For every tap, the mode $U_{p,T}$ and standard deviation a_p of the Gumbel distribution of the minima and maxima is obtained, by fitting the maximum and minimum values obtained under 2 to the general expression of the Gumbel distribution. This procedure is as follows:

· All maxima and minima are ordered according to their height: For the maxima, the highest maximum x_m gets number $m = N$. The lowest maximum has number $m = 1$. For the minima, the lowest minimum x_m gets number m = N. The highest minimum has number $m = 1$.

· For the maxima and minima, the value y_m is obtained:
y_m = -ln(-ln(m/(N+1)));

· The relation between x_m and y_m, for all values in the range $0 < y_m < 3$, is obtained by the linear expression $x_m = U_{p,T} + 1/a_p\, y_m$. This fitting procedure leads to the values for $U_{p,T}$ and a_p for both the minimum and the maximum values, per pressure tap and per wind direction.

4: Values for $U_{p,3600}$ for the extreme value distribution of the pressures within an hour are determined as follows:

$$U_{p,3600} = U_{p,T} + \ln(3600/T)/a_p \tag{5a}$$

Alternatively, when 10 minute means are used as basis for the calculation, values $U_{p,600}$ follow from:

$$U_{p,600} = U_{p,T} + \ln(600/T)/a_p \tag{5b}$$

Whilst in this study, the regulations for the Dutch wind loading code NEN 6702 have been used as basis, values for $U_{p,3600}$ have been obtained. This procedure results for each wind direction in two sets of $U_{p,3600}$ and a_p, one set for the minimum values and one for the maximum values. In this wind tunnel experiment times series with full scale equivalent duration of $T \approx 30$ seconds are applied, and a total of $N = 32$ independent extremes have been obtained.

Eq. (3) gives the appropriate values for the pressure coefficients $\hat{C}_p(\theta)$ when related to a mean dynamic pressure. Current wind loading standards, such as the Eurocode EN 1991-1-4, use a peak dynamic pressure as basis for calculation. Therefore, the resulting coefficients from the wind tunnel should be rewritten in a form suitable for use in codes and standards. This requires a ‘calibration’ of the results into what Cook has called ‘pseudo-steady’ coefficients. In conformity with the Dutch guideline on wind tunnel studies CUR 103 (2005), the $\hat{C}_p(\theta)$ values have been transformed into pressure coefficients $\hat{C}_{p,NEN}$ for inclusion in the Dutch code for wind loads NEN 6702 (2005). First, the representative values for the loading are calculated, using:

$$\hat{p}(\theta)_{rep} = \hat{C}_p(\theta)\frac{1}{2}\rho v_b^2 C_v^2 \tag{6}$$

Where v_b is the basic wind velocity applied, and C_v is a coefficient taking into account the influence of reference height and roughness in the wind tunnel. The values for $\hat{C}_{p,NEN}$ are simply found by dividing $\hat{p}(\theta)_{rep}$ by the peak dynamic pressure (p_w), as defined in NEN 6702:

$$\hat{C}_{p,NEN} = \hat{p}(\theta)_{rep}/p_w \tag{7}$$

A similar procedure is used for the minima.

4. Results

4.1. Mean value analysis

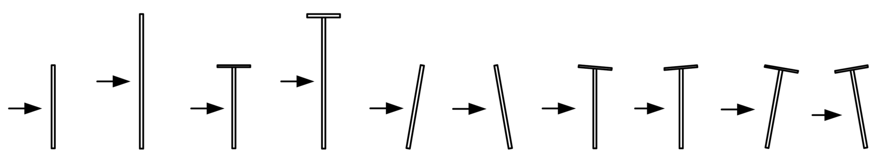
The pressure coefficients based on mean values are given in Table 1. For every pressure tap, a series of 24 values is available. The maximum and the minimum values of the series have been used to obtain the mean net pressure coefficient of the vertical part of the free-standing wall and for the T-top. For the symmetric configurations the net pressure coefficient is taken as the maximum of wind from left and wind from right. For the other configurations the net pressure coefficients are given for both wind directions. The mean net pressure coefficient of the T-top is determined by adding the maximum overpressure at the underside to the maximum suction at the upper side. Since not all configurations are symmetric both halves of the T-top are treated separately and the more onerous value is chosen.

The net pressure coefficient of the vertical part of a wall with a T-top is lower than for a similar wall without T-top. Although the overpressure at windward side is higher compared to a single free-standing wall, the underpressure at leeward side is smaller. The latter effect dominates, resulting in a smaller net pressure coefficient. The effect is mostly emphatic for zone A. The extent of decrease is related to the ratio width T-top over height wall.

An inclined wall with the inclination towards the wind results in a higher net pressure coefficient. An inclination in the direction of the wind has the opposite effect. An inclination towards the wind

Table 1 Mean net pressure coefficients and EN 1991-1-4 values for free-standing walls

Configuration



	Zone	EN	1	2	3	4	5a	5b	6a	6b	7a	7b
Vertical part	0.15h	3.4	3.0	3.0	2.6	2.8	2.8	3.4	2.8	2.6	2.7	2.6
	h	2.1	2.9	3.1	2.5	3.0	2.9	3.2	2.4	2.5	2.3	2.5
	3h	1.7	1.5	1.5	1.6	1.5	1.5	1.5	1.5	1.5	1.5	1.4
	6h	1.2	1.3	1.2	1.4	1.3	1.3	1.3	1.4	1.3	1.3	1.3
T-top	0.15h	-	-	-	5.2	5.4	-	-	5.4	4.3	5.4	3.6
	h	-	-	-	3.1	3.0	-	-	3.1	3.1	2.9	2.9
	3h	-	-	-	2.3	2.0	-	-	2.3	2.3	2.3	2.2
	6h	-	-	-	1.7	1.4	-	-	1.6	1.7	1.5	1.8

gives higher overpressures at the windward side, while an inclination in the direction of the wind leads to smaller underpressures at the leeward side. The effect is only significant for zone A.

The net pressure coefficients of the T-top itself are high compared to the pressure coefficients of the vertical part of the free-standing wall. The contribution to the moments acting on the foundation is significant. An inclination of the T-top can reduce the net pressure coefficients, but mainly for zones A and B and only if the T-top has an inclination in the direction of the wind. A combination of an inclined wall and an inclined T-top reduces the net pressure coefficient for the vertical part of the free-standing wall. The reduction for wind from left and wind from right is almost equal. The net pressure coefficient of the T-top reduces for wind from right and is unchanged for wind from left. The reduction is more significant for zones A and B.

Looking at the differences between zones, zone B is rather conspicuous. The net pressure coefficients are in the same order as the values in zone A for all wind directions (see also Fig. 5). Compared to EN 1991-1-4, the values for zone A and C are lower, D is of the same order of magnitude and B is higher. Configurations 1 and 2 are also compared with the mean pressure coefficients of the wind tunnel experiments in Oxford and at CSIRO (1994) and the full scale measurements at Silsoe (1996-1997). The results are given in Table 2. The results of the Oxford and CSIRO tests are the maximum values of the oblique wind direction (45°) and perpendicular wind (0°). The Silsoe and TNO values are the maximum values over all wind directions.

Resulting values are in the same order of magnitude. However, some differences are clear. It seems that the values given in EN 1991-1-4 for zone B may be too optimistic. Not only the measurements reported here, but also the other sources give indications that at least to a distance equal to the height, the coefficients may be in the order of 3. Values in zones A and C are

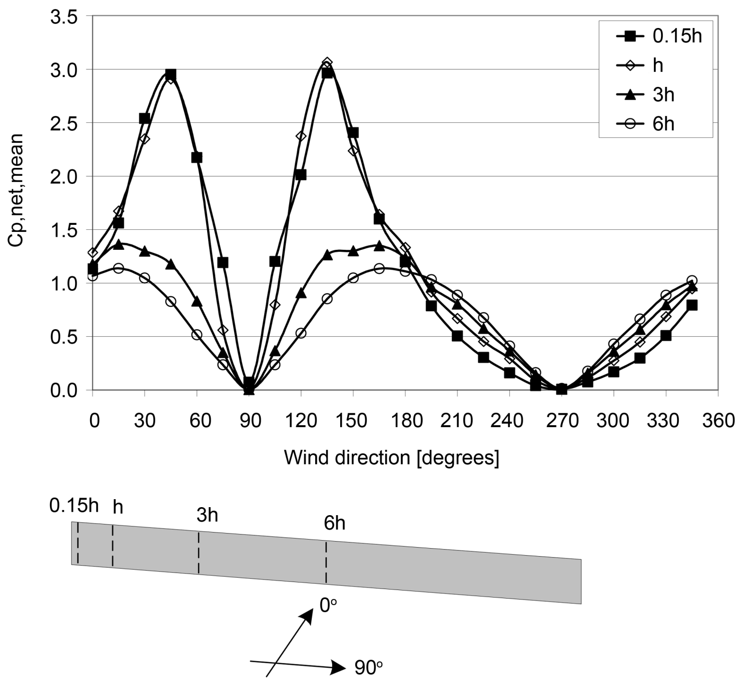


Fig. 5 Mean net pressure coefficients for configuration 2, vertical wall of 8 m without T-top

Table 2 Mean net pressure coefficients of different researches compared to EN 1991-1-4

Zone	TNO		Oxford		CSIRO		Silsoe		EN 1991-1-4	
A	0.15h	3.0	0-0.3h	3.33	0-3h/4	2.82	0-h	2.8	0-0.3h	3.4
B	h	3.0	0-h	3.24	0-1.5h	2.30	h-2h	2.0	0.3h-2h	2.1
			0-2h	2.59						
C	3h	1.5	3h-4h	1.32	1.5h-3h	1.29	2h-3h	1.5	2h-4h	1.7
D	6h	1.3	3h-5h	1.27	1.27-1.38	1.15			>4h	1.2

sufficiently conservative in EN 1991-1-4, and the values for zone D, which is the most relevant zone in the design of free-standing walls, are all around 1.2.

4.2. Extreme value analysis

As a second step, the time series measured have been used to analyze the extremes. Extreme value analysis of the data has been carried out in a number of steps: All taps have been analyzed individually. Additionally, time series have been used to construct new time series of the overall load. From the original data, a more or less uniform distribution of the pressures over the height was found. The tributary area for every pressure tap was assumed to be evenly distributed.

Fig. 6 shows which set of pressure data were combined into one set. For the loading on the T-top itself, both the resulting moment as well as the overall uplift has been analyzed. The net pressure coefficients are given in Tables 3 and 4.

Table 3 gives the values for the wall itself, both as modified Cook-Mayne coefficients, following from Eq. (3), and in the pseudo-steady format, related to the Dutch wind loading code NEN 6702, as described in 3.2. The coefficients of Table 4 are only given in the pseudo-steady format.

For the walls without T-tops, the pseudo-steady coefficients, which are obtained from the extreme value analysis, are significantly lower than obtained from mean value analysis. The lack of correlation of the wind induced pressures at windward and leeward side is the main cause for this difference. The difference is largest for the pressure taps near the ends of the walls, zones A and B. The relevant wind directions for the wind loading correspond with an oblique angle of attack, for which the leeward side pressures are dominated by structure-induced turbulence, which is a very non-stationary process, which is very poorly correlated with the windward side pressures.

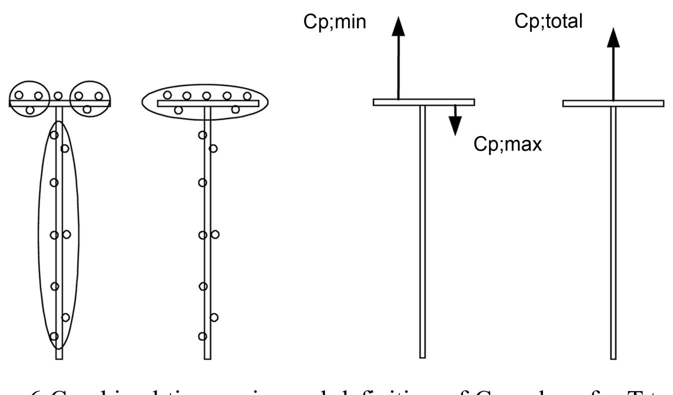
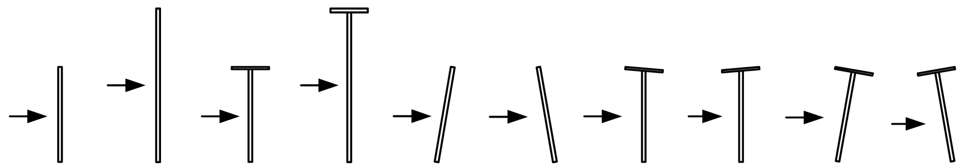


Fig. 6 Combined time series and definition of Cp-values for T-tops

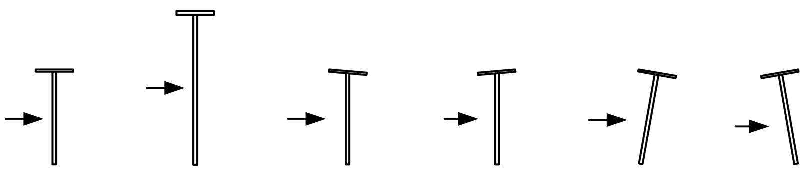
Table 3 Net pressure coefficients based for the free-standing wall on extreme value analysis



	Configuration										
	Zone	1	2	3	4	5a	5b	6a	6b	7a	7b
$\hat{C}_p$ [a]	0.15h	6.9	5.5	6.4	5.9	6.0	6.9	6.3	6.1	6.2	5.6
	h	5.6	4.8	5.3	5.2	5.0	5.4	4.8	4.6	4.5	4.4
	3h	3.5	3.1	4.4	3.4	3.6	3.8	3.7	3.9	3.7	3.0
	6h	3.4	3.0	3.5	3.0	3.3	3.6	3.3	3.6	3.5	3.8
C_p [b]	0.15h	2.5	2.0	2.1	2.1	2.1	2.5	2.3	2.1	2.3	2.2
	h	2.0	1.7	1.9	1.8	1.8	1.9	1.9	1.6	1.6	1.7
	3h	1.3	1.1	1.6	1.2	1.3	1.4	1.4	1.4	1.2	1.2
	6h	1.2	1.1	1.3	1.1	1.2	1.3	1.2	1.4	1.3	1.3

Notes
[a]Cp-values based on modified Cook-Mayne coefficients, calculated with Eq. (3)
[b]Cp-values related to NEN 6702

Table 4 Net pressure coefficients for the T-top based on extreme value analysis for use in NEN 6702



	Configuration						
	Zone	3	4	6a	6b	7a	7b
$C_{p;min}$ [a]	0.15h	-3.7	-3.4	-3.6	-3.4	-3.2	-2.7
	h	-2.7	-2.3	-2.9	-2.7	-2.2	-2.8
	3h	-2.4	-2.2	-2.4	-2.4	-2.2	-2.0
	6h	-2.3	-1.7	-1.8	-2.2	-1.6	-2.9[d]
$C_{p;max}$ [b]	0.15h	0.9	1.0	1.1	0.8	1.1	0.9
	h	0.5	0.5	0.6	0.5	0.6	0.5
	3h	0.2	0.2	0.2	0.2	0.2	0.1
	6h	0.2	0.2	0.2	0.2	0.2	0.2
$C_{p;tot}$ [c]	0.15h	-1.7	-1.5	-1.4[e]	-1.4[e]	-1.4[e]	-1.4[e]
	h	-1.7	-1.4	-1.5[e]	-1.5[e]	-1.4[e]	-1.4[e]
	3h	-1.4	-1.5	-1.6[e]	-1.6[e]	-1.4[e]	-1.4[e]
	6h	-1.4	-1.1	-1.2[e]	-1.2[e]	-1.4[e]	-1.4[e]

Notes
[a]Minimum values of averaged time series of one side of the T-top (3 taps, see Fig. 4)
[b]Maximum values of averaged time series of one side of the T-top (3 taps, see Fig. 4)
[c]Minimum values of averaged time series of the complete T-top (7 taps, see Fig. 4)
[d]Unreliable value, no explanation has been found
[e]Minimum value taken over all wind directions, one value for 6a and 6b, 7a and 7b

5. Conclusions

Wind tunnel research on free-standing walls with T-tops shows that the net pressure coefficient of the wall itself may decrease due to the application of a T-top. The complete structure with T-top is subjected to a higher wind load than a single free-standing wall, since the T-top has a large contribution to the forces and moments acting on the foundation. An inclined wall with the inclination towards the wind results in a higher net pressure coefficient. An inclination in the direction of the wind has the opposite effect.

The measured mean values are similar to the net pressure coefficients for free-standing walls in EN 1991-1-4. However, there is a difference for the values in zone B, near the end of the wall. The values of zone B are similar to those in zone A, close to the edge. Previous research on free-standing walls have also shown that the difference in mean net pressure coefficients for zone A and zone B is small. This indicates that the net pressure coefficient for zone B given in EN 1991-1-4 is probably too low.

Values obtained from the extreme value analysis, given in the pseudo-steady format, are lower than the mean values. This indicates that for these structures, the quasi-steady assumption is a safe approximation of the net pressures.

The mean net pressure coefficients will be included in Dutch guidelines for noise barriers. This is assumed to be a safe estimate. Values for zone B will be chosen higher than those in the EN 1991-1-4.

Acknowledgements

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