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TNO report

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Wind Loads on Noise Barriers

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Summary

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 may not be sufficient. Improvement of the behaviour of these barriers is possible by increasing the height or mounting a so-called T-top on top of the existing barrier. Both solutions may, however, lead to increased wind loads, and therefore to increased forces and moments in the load bearing structure of the barriers.

The existing barriers have been designed according to Dutch guidelines for noise protection structures near roads (GCW) written in 1986, and updated in 2001. The wind loading provisions in this document are conservative, if compared to the new prEN 1991-1-4:2004 (Eurocode wind actions). The extra safety, gathered in the original design, would help the design of the solution with added height or added T-top. The amount of safety however, is not known explicitly.

DWW commissioned TNO to perform experimental research into the wind loading on noise barriers of different heights, different tops and different inclination angles. The wind load of 7 configurations of noise barriers is determined by wind tunnel tests. The measured pressures are analysed with two procedures. The mean pressures are analysed with procedure A of CUR recommendation 103. The extreme values are analysed with procedure B of the same recommendation.

The resulting mean pressure coefficients for zone A and C are lower than compared to the provisions given in prEN 1991-1-4:2004. The values for zone B are higher and the values for zone D are in the same order of magnitude compared to the values in prEN 1991-1-4:2004. The extreme value analysis is a more precise procedure and therefore less conservative. The values for the design net pressure coefficients are about 40% lower than the provisions of prEN 1991-1-4:2004.

The design net pressure coefficients of the 7 configurations of the noise barrier are in the same order of magnitude. In general, adding a T-top or inclination of the barrier or T-top will increase the overpressure and decrease the underpressure on the barrier. The change is at most 20%.

The design net pressure coefficients of the T-top are higher than for the barrier. Near the edge in zone A large underpressures are introduced. An inclined T-top results in higher underpressures on positive sides and lower underpressures on negative sides. The change in design net pressure coefficients is however small. The pressures on the T-top can have an important contribution to the loads on the foundation.

Contents

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 may not be sufficient. Improvement of the behaviour of these barriers is possible by increasing the height or mounting a so-called T-top on top of the existing barrier. Both solutions may, however, lead to increased wind loads, and therefore to increased forces and moments in the load bearing structure of the barriers.

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The results of this research are used as input for the new design and the upgrading of existing noise barriers.

2 Experiments

2.1 Introduction

Measurements have been performed in the Atmospheric Boundary Layer Wind tunnel of TNO in Apeldoorn. A total of 7 different models have been tested on a geometric scale of 1:100. Pressure measurements have been carried out. This chapter provides the main experimental characteristics.

2.2 Wind tunnel of TNO

The wind tunnel of TNO is designed for research in the atmospheric boundary layer. The mean wind profile and the turbulent characteristics of the flow are modelled, using specially designed aerodynamic devices. The test section is about 14 metres long. The model is placed on a turn table in the measurement section. The measurement section is 3 metres wide and 2 metres high. The wind tunnel wind speed can be applied in the range between 0.2 and 20 m/s.
This wind tunnel is in use in a wide range of research projects such as:

- Wind comfort studies around buildings;
- Wind loading on buildings and structures;
- Wind loading on off shore platforms and ships;
- Air pollution studies around motorways;
- Wind field studies in wind energy parks;
- Ventilation problems around buildings and parking houses;
- Aerodynamic resistance of sports people.

The current measurements are made in a configuration with an upstream fetch 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.

2.3 Models used

The models applied in this study are geometrically scaled on a scale 1:100. The models have been made of plastic, with the pressure taps and pressure tubes mounted inside the model. In Annex A, pictures of the models are given. A total of 7 cases have been tested, as follows:

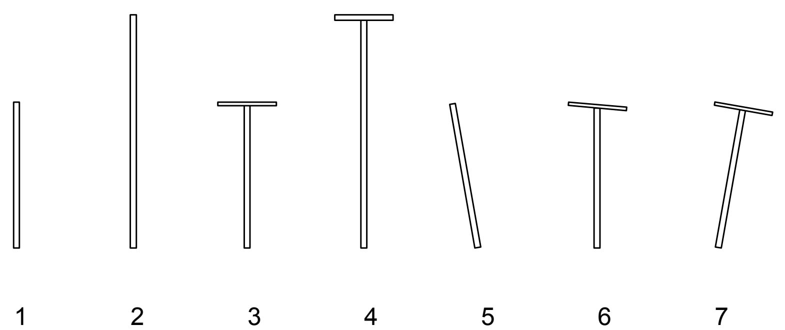


Figure 1 – Cases, which have been tested

Case 1: Vertical noise barrier, height 5 metres, no T top applied.
Case 2: Vertical noise barrier, height 8 metres, no T top applied.
Case 3: Case 1, with a T-top
Case 4: Case 2, with a T-top
Case 5: Case 1, with an inclination of the barrier of 80 degrees.
Case 6: Case 1, with a T-top, inclined with 10 degrees
Case 7: Case 5, with a T-top, inclined with 10 degrees.

The width of the T-top is for all cases 2 m. The thicknesses of the noise barrier 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 barrier and T-top is used, which represents 40 cm in full scale. Drawings of these configurations with precise dimensions are given in Annex B.

2.4 Instrumentation

Pressures are measured on the surface of the models on selected sections of the barriers. These sections have been selected, based on the zones of pressures as defined in prEN 1991-1-4:2004. Pressure taps are placed on four vertical lines. Each line corresponds to the zones A, B, C and D, as specified in prEN 1991-1-4:2004, of the barriers, with an increasing distance towards the ends of the barriers. The lines are positioned in the middle of the zones for zone A, B and C respectively. The line with pressure taps in zone D is positioned at 6h.

Per line, a total of 8 pressure taps is mounted on the barriers, 5 taps on one side and 3 taps on the other side. For the configurations with T-top 7 additional taps per T-top are installed on every measurement section. Five taps are mounted on top and two taps on the bottom of the T-top, one at each side. Figures of the positions of the pressure taps are provided in Annex B.

The diameter of the holes of the pressure taps is 1.5 mm. The diameter of the tubes is also 1.5 mm. The tubes have a length of 100 cm, which is corrected with the Berg and Tijdeman theory. No restrictor is used. Pressure data have been obtained with a sample frequency of 400 Hz. The total length of one sample is 20.5 seconds (8192 samples). The pressures for the individual taps are measured with the Hyscan pressure scanning equipment from Scanivalve. The accuracy of the pressure measurements is +/- 5 Pascal.

2.5 Data acquisition

Measurements were originally foreseen on a limited number of wind directions, corresponding to the most onerous directions for the wind loads on the barriers. These directions were selected based on results from earlier investigations (Robertson et. al, 1991).

Whilst preparing the tests, it appeared that measurement around the full wind rose, applying 24 wind directions, with an increment of 15 degrees, was as easy to handle. Therefore, this last option has been applied. The wind direction in relation to the noise barriers in the wind tunnel is illustrated in Figure 2.

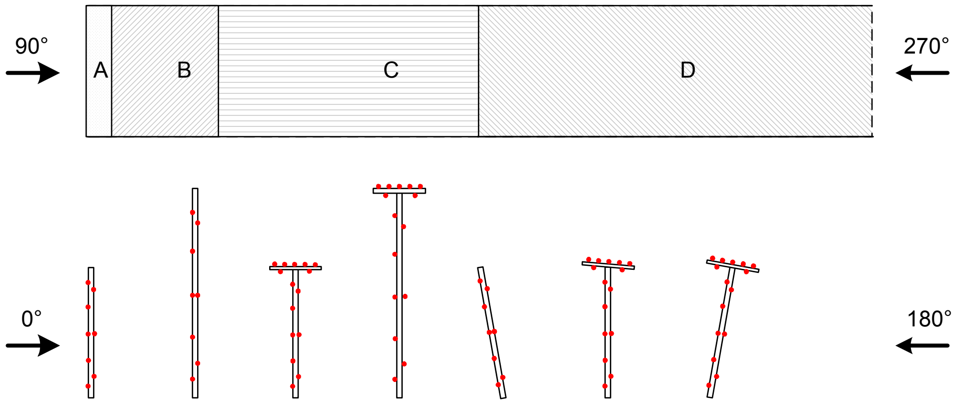


Figure 2 – Wind direction

2.6 Analyse procedures

According to CUR recommendation 103, the data can be analysed in three ways: mean pressures with method A and extreme value analysis with procedure B and C. Procedure B uses a simpler model for the design wind load. The data is analysed with procedures A and B, both the mean pressures and the extreme values are analysed. Both procedures are described below.

2.6.1 Procedure A of CUR Recommendation 103

In the first step, the measured time signals of the pressure are made dimensionless for every wind direction θ:

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

The mean values of the measured pressures $\overline{p}_{WT}(\theta)$ are used in the analysis. The wind speed v_{ref} is the mean wind velocity at reference height in the wind tunnel, in this experiment v_{ref} = 9.8 m/s at 8 metres in full scale or 8 centimetres in the wind tunnel.
The reference wind speed at 5 metres height is found by applying the following corrections in accordance with Appendix A of NEN 6702:2001:

$$v_{ref}(h=5) = \frac{\ln\frac{5}{z_0}}{\ln\frac{8}{z_0}} v_{ref}(h=8) = 0{,}92 v_{ref}(h=8)$$

The statistical distribution of the hourly mean wind velocity over the wind direction used, has to be counted for by applying the factor C_θ, or c_{dir} in the Eurocode.

Per wind direction, the representative value for the wind loading is determined from:

$$p(\theta)_{VS} = \overline{C}_p(\theta)\, p_w C_\theta^2 C_{\dim}$$

C_{dim} is taken equal to 1 for this analysis.

To obtain the appropriate value for the pressure coefficient (either a surface pressure or a net pressure), the values for $p(\theta)_{VS}$ are divided by the reference peak dynamic pressure p_w, which is derived from $v_{ref,12,5}$:

$$p_w = (1+7I)\frac{1}{2}\rho v_{ref,12,5}^2$$

$v_{ref,12,5}$ is the hourly mean wind speed at reference height h_{ref}, with a mean return period of 12,5 years, which is used as basis for NEN 6702:2001 . The reference height for the mean dynamic pressure was taken at the top of the noise barrier, 5 or 8 metres;
I is the turbulence intensity at height z.

2.6.2 *Procedure B of CUR Recommendation 103*

In the first step, the measured time signals of the pressure are made dimensionless for every wind direction θ:

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

Values for $p_{WT}(\theta,t)$ are determined from pressure measurements. The wind speed v_{ref} is the mean wind velocity at reference height in the wind tunnel, in this experiment v_{ref} = 9.8 m/s at 8 metres in full scale or 8 centimetres in the wind tunnel. For the noise barriers with a height of 5 metres a correction in accordance with Appendix A of NEN 6702:2001 is made:

$$v_{ref}(h=5) = \frac{\ln\frac{5}{z_0}}{\ln\frac{8}{z_0}} v_{ref}(h=8) = 0{,}92 v_{ref}(h=8)$$

The statistical distribution of the hourly mean wind velocity over the wind direction used, has to be counted for by applying the factor C_θ from CUR Recommendation 103 or c_{dir} in the Eurocode.

Per wind direction, the time-independent extreme value distribution of the coefficients $C_p(\theta)$, are determined as follows:

1: Per wind direction, the 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 value for the pressure coefficients are determined.

3: Per sample, the mode U_p and standard deviation a_p of the Gumbel distribution 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:

1. All maxima and minima are ordered according to their height:
   a. For the maxima, the highest maximum x_m gets number m = N. The lowest maximum has number m = 1.
   b. For the minima, the lowest minimum x_m gets number m = N. The highest minimum has number m = 1.
2. For the maxima and minima, the value is obtained of $y_m = -\ln(-\ln(m/(N+1)))$;
3. The relation between x_m and y_m, for all values in the range $0 < y_m < 3$, is obtained by the linear expression $x_m = U_p + 1/a_p\, y_m$. This fitting procedure determines the values for U_p en a_p for both the minimum and the maximum values

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

$U_{p,3600} = U_{p,T} + \ln(3600/T)/a_x$

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.

The relation between reference wind speed in the wind tunnel, scaled to full scale, and the potential wind speed is defined by the factor C_v, defined as follows:

$$C_v = \frac{v_{ref,12,5}}{v_{12,5}}$$

$v_{ref,12,5}$ is the hourly mean wind speed at reference height h_{ref}, with a mean return period of 12,5 years, which is used as basis for NEN 6702:2001 ;
$v_{12,5}$ is the potential wind speed with a mean return period of 12,5 year. The value for $v_{12,5}$ is derived from Table 1.

Table 1 Values for $v_{12,5}$ to determine the factor C_v

Wind climate area	$v_{12,5}$ [m/s]
I	27,5
II	25,0
III	22,5

The hourly mean wind speed at reference height h_{ref} with a mean return period of 12,5 year is determined from:

$$v_{ref,12,5} = 2{,}5u * \ln\left(\frac{h_{ref} - d_w}{z_0}\right)$$

Using the parameters in Table 2:

Table 2 Parameters needed to calculate $v_{ref,12,5}$

	Flat terrain			Urban terrain		
	I	II	III	I	II	III
u*	2,25	2,30	2,25	3,08	2,82	2,60
z_0	0,1	0,2	0,3	0,7	0,7	0,7
d_w	0	0	0	3,5	3,5	3,5

The value for C_v is equal to 0,74 and 0,85 respectively for a height of 5 metres and 8 metres.

Per wind direction, the representative values for the loading are determined from:

$C_p(\theta) = U_{p,3600} + 2{,}9 \cdot 1/a_p$, for maximum values;
$C_p(\theta) = U_{p,3600} - 2{,}9 \cdot 1/a_p$, for minimum values.

Per wind direction, the representative value for the wind loading is determined from:

$$p(\theta)_{VS} = C_p(\theta)\frac{1}{2}\rho v_{12,5}^2 C_v^2 C_\theta^2 C_{\dim}$$

C_{dim} is taken equal to 1 for this analysis.

To obtain the appropriate value for the pressure coefficient (either a surface pressure or a net pressure), the values for $p(\theta)_{VS}$ are divided by the reference peak dynamic pressure, as given in NEN 6702:2001 . The reference height in these cases is the barrier height. For the analysis, the wind speed of area II in the Netherlands is applied. The reference dynamic pressures in NEN 6702:2001 for 5 metres and 8 metres are respectively 0.68 and 0.81 kN/m^2.

2.7 Data analysis

The mean pressure analysis is carried out according to procedure A of the CUR recommendation 103. The results are included in Annex C.

The extreme value analysis is carried out according to the procedures described in CUR Recommendation 103, procedure B. The extreme value distribution of the pressure coefficients has been determined and fitted to the Gumbel distribution. The design value of the pressure coefficient has been chosen as the 90% fractile of the maximum and minimum values respectively. The value for the pressure coefficient obtained has been 'calibrated' against the procedures in the wind loading codes (NEN 6702:2001 and prEN 1991-1-4:2004), yielding the value for the so-called pseudo steady pressure coefficients.

The analysis has been done in three steps:

- At first, all individual taps have been analysed according to the procedure B. This gives for every tap a design value for the maximum and minimum pressure to occur. Pressures are obtained on every side of the noise barriers individually, for all wind directions measured (see figure 3a). The minimum and maximum pressure coefficients for each tap of all cases are given in Annex D.

- Secondly, time traces of pressures on both sides of the barrier have been combined to new time traces of the pressure differences over the barrier. Combinations have been made with 1 or 2 taps on either side of the barrier, thus obtaining three time traces of pressure differences over the height and two at the T-top, if present (see figure 3b). These time traces have been analysed separately according to method B of CUR 103. The resulting minimum and maximum net pressure coefficients are given for the combined positions for all cases in Annex E.

- Thirdly, the time traces of the pressures on the noise barrier have been combined in time domain to single time traces for the barrier and the T-top. These time traces of forces and moments have been analysed separately according to procedure B (see figure 3c). Both the net pressure coefficients of the barriers and T-tops for all cases are given in Annex F.

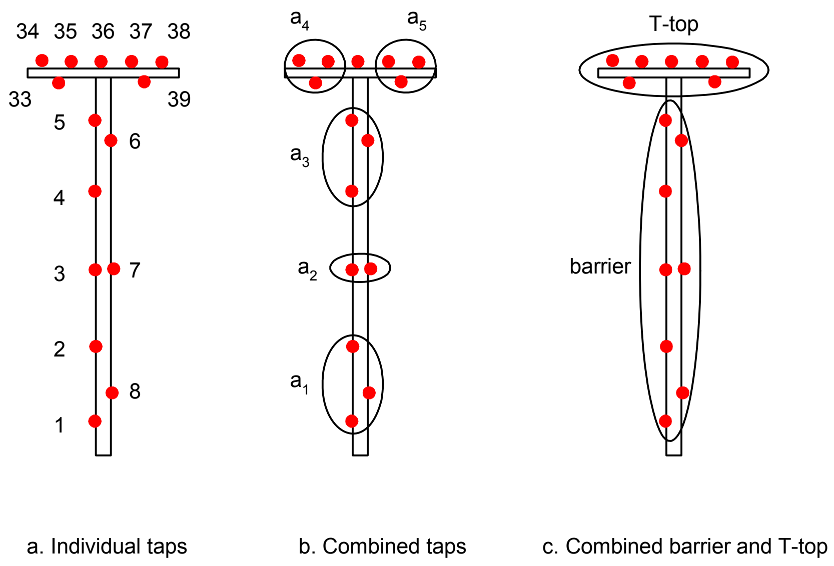


Figure 3 – Pressure combinations for zone A, used in extreme value analyses

3 Results

3.1 Introduction

The results are presented for every zone on the barrier. Mean pressure coefficients, as well as design pressure coefficients, determined according to the procedures described in chapter 2 are given in annexes C to F. Corresponding figures are given in Annex G to J. This chapter gives a comparison between the configurations. The conclusions on the mean pressure coefficients are used as indication for the phenomena that occur on the different cases studied in qualitative way. Quantitative conclusions will only be made for the design pressure coefficients, obtained from extreme value analysis.

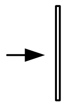
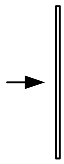
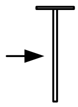
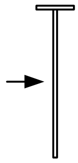
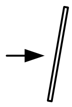
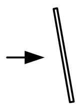
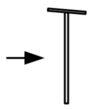
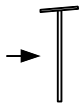
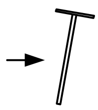
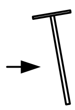
3.2 Mean pressure coefficients

The mean pressure coefficients have been analysed according to procedure A of CUR recommendation 103. The mean pressure coefficients are given in C and G. The mean pressure coefficients of the individual taps are used to investigate five effects:

- The height of the barrier;
- The influence of a T-top;
- The influence of an inclined barrier;
- The influence of an inclined T-top;
- The influence of both inclined barrier and inclined T-top.

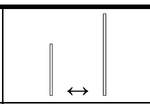
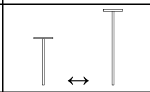
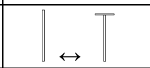
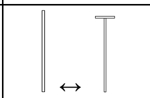
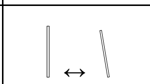
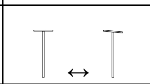
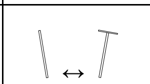
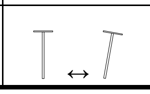
To determine the effect, the differences between 7 configurations on underpressure and overpressure on the barriers and T-tops are evaluated in Table 4. For the noise barriers with an inclination, two situations are evaluated: a positive and a negative inclination. The definition of the inclination is based on the position of the barrier in relation to the wind. A positive inclination means an inclination, which is directed in line with the wind and a negative inclination is directed towards the wind. The elaboration of the inclination angles for the 7 cases is given in Table 3.

Table 3 Elaboration of inclination angles

Case	Wind	Height	Inclination barrier	Inclination T-top	Description
1		5 m	--	--	Symmetric configuration
2		8 m	--	--	Symmetric configuration
3		5 m	--	--	Symmetric configuration
4		8 m	--	--	Symmetric configuration
5p		5 m	+10°	--	Symmetric configuration, positive inclination
5n		5 m	-10°	--	Symmetric configuration, negative inclination
6p		5 m	--	+5°	Symmetric configuration, positive inclination of T-top
6n		5 m	--	-5°	Symmetric configuration, negative inclination of T-top
7p		5 m	+10°	+10°	Symmetric configuration, positive inclination of both barrier and T-top
7n		5 m	-10°	-10°	Symmetric configuration, negative inclination of both barrier and T-top

NOTE:
Arrow indicates the direction of the wind

Table 4 *Qualitative comparisons of configurations*

	Influence	Comparison of cases		Angle	Overpressure		Underpressure	
					Barrier	T-top	Barrier	T-top
1	Higher barrier	1-2		s	Equal		Higher	
		3-4		s	Equal	Equal	Higher	Higher Lower
2	Horizontal T-top	1-3		s	Higher		Lower	
		2-4		s	Higher		Lower	
3	Inclined barrier	1-5		p n	Higher Equal		Equal Higher	
4	Inclined T-top	3-6		p n	Equal Equal	Equal Equal	Equal Higher	Higher Lower
	Inclined T-top	5-7		p n	Higher Higher		Lower Lower	
5	Inclined barrier and inclined T-top	3-7		p n	Equal Equal	Equal Equal	Lower Higher	Higher Lower

NOTES:
s Symmetric configuration, no angle
p Positive angle as given in Table 3
n Negative angle as given in Table 3

1: Comparing cases 1 and 2, and also cases 3 and 4, the pressure at windward side is unaffected by the height of the barrier. However, the value for the underpressure increases with 5 to 10%. The overpressure of the T-tops is as well not influenced by the height. The results show that in zone A the underpressure on the T-top can either increase or decrease. In zone B, C and D this effect is faded out.

2: Comparing cases 1 and 3, and also cases 2 and 4, it shows that adding a T-top will increase the overpressure (maximum values) at windward side, but leads to a decrease in the underpressures found at leeward side. The decrease is dependent on the ratio width T-top over height barrier. The influence of the T-top is relatively high in zones A and B. For the zones C and D, only very slight differences are found. The resulting, mean pressure coefficients will be roughly the same with T-top compared to the situations without.

3: Comparing cases 1 and 5 shows that small differences are found when the barrier is inclined with an angle of 10 degrees to the vertical. The overpressure is higher when the inclination angle is positive (the inclination is towards the wind), while the underpressure is roughly the same. The opposite holds for a negative inclination angle (when the inclination is in the direction of the wind). The overpressure does not change dramatically, about 10 %.

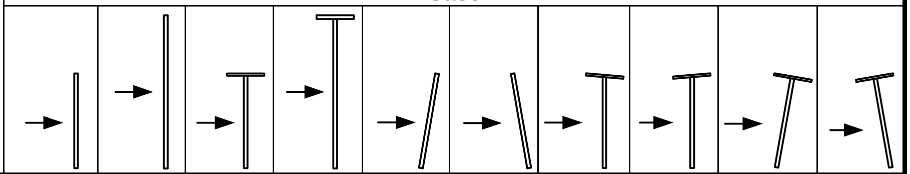
4: Comparing cases 3 and 6, the angle of the T-top hardly influences the values of the mean pressure coefficients on windward and leeward side. There is a small effect of the angle on the leeward side pressures obtained, in the order of 5%. Comparing case 5 and

7, the values for overpressure increase and for underpressure decrease. The effect on the T-top depends on the direction of the angle. If the angle is positive, the underpressure at the T-top increases. If the angle is negative, the underpressure is lower. The overpressure hardly changes in both situations. In zone C and D the effect of the inclined T-top on the barrier is fractional.
The pressure distribution over the T-top varies over the zones. A horizontal T-top has peaks near the edges at zone A and equally distributed pressures over the T-top in the other zones. The inclined T-top shows the same distribution over the zones, apart from zone D. Zone D has a lower pressure at the positive side and a higher pressure at the negative side. In contrary, zone A has a higher peak at the positive side.

5: Comparing case 3 and 7, the effect of the inclination of the T-top on the inclined barrier is relatively small on the mean pressures. The overpressure at the T-top is not affected. The influence on the underpressure depends on the side of the T-top, as explained by point 4.

Combinations of the most onerous value for overpressure on one side and underpressure on the other side give the following values for the mean net pressure coefficients over the noise barriers (rounded to 1 decimal).

Table 5 Mean net pressure coefficients per zone: most onerous values on barrier

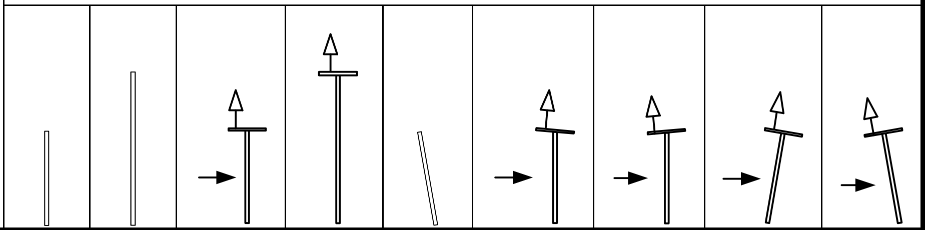
	Case									
										
Zone	**1**	**2**	**3**	**4**	**5 p**	**5 n**	**6 p**	**6 n**	**7 p**	**7 n**
A	3.0	3.0	2.6	2.8	2.8	3.4	2.8	2.6	2.7	2.6
B	2.9	3.1	2.5	3.0	2.9	3.2	2.4	2.5	2.3	2.5
C	1.5	1.5	1.6	1.5	1.5	1.5	1.5	1.5	1.5	1.4
D	1.3	1.2	1.4	1.3	1.3	1.3	1.4	1.3	1.3	1.3

NOTES:
p Positive angle as given in Table 3
n Negative angle as given in Table 3

The above given values are lower for zones A and C, compared to the provisions given in prEN 1991-1-4:2004 (3.4 and 1.7). The values of zone D are in the same order of magnitude (1.2). The values for zone B are higher for all cases studied here (2.1).

In table 5 the values for the T-tops are given. The values are for all relevant cases (3, 4, 6 and 7) in the same order of magnitude over the zones. The peaks are significant in zone A near the edges.

Table 6 Mean net pressure coefficients per zone: most onerous values on T-top

	Case								
									
Zone	1	2	3	4	5	6 p	6 n	7 p	7 n
A			5.2	5.4		5.4	4.3	5.4	3.6
B			3.1	3.0		3.1	3.1	2.9	2.9
C			2.3	2.0		2.3	2.3	2.3	2.2
D			1.7	1.4		1.6	1.7	1.5	1.8

NOTES:

p Positive angle as given in Table 3

n Negative angle as given in Table 3

down Pressure downwards for calculation of moments as defined in Figure 5

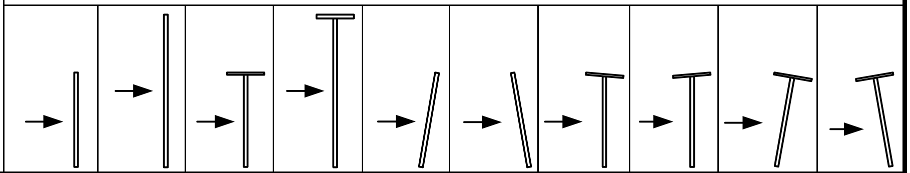
up Pressure upwards for calculation of moments as defined in Figure 5

3.3 Design net pressure coefficients

The net pressure coefficients have been analysed according to the procedure B of CUR recommendation 103. Three extreme value analyses are made. Firstly, the individual taps are analysed. The results of the extreme value analysis of the individual taps are presented in annexes D and H. Secondly, the values are analysed in three sectors over the height of the barrier and two sectors on the T-tops. The values for the net design pressure coefficients found in this analysis are summarized in annex E and annex I. Thirdly, all pressure taps on the barrier are combined to one new. The net pressure coefficients are included in annexes F and J.

The analyses result in net pressure coefficients for barrier and T-top in the 7 cases. The resulting net pressure coefficients are given in Table 6 and Table 7. In Table 6 the most onerous net pressure coefficients on the barriers derived from step 3 are summarized.

Table 7 Design net pressure coefficients: most onerous values on barrier

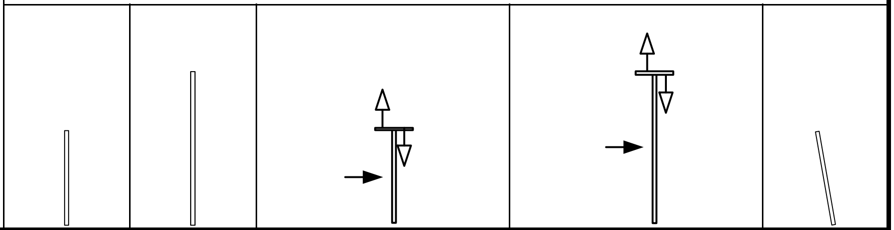


	Case									
Zone	**1**	**2**	**3**	**4**	**5 p**	**5 n**	**6 p**	**6 n**	**7 p**	**7 n**
A	1.8	1.4	1.5	1.5	1.6	1.8	1.6	1.6	1.7	1.6
B	1.5	1.3	1.4	1.3	1.3	1.4	1.3	1.2	1.2	1.2
C	0.9	0.8	1.2	0.9	0.9	1.0	1.0	1.0	0.9	0.8
D	0.9	0.8	0.9	0.8	0.9	1.0	0.9	1.0	0.9	0.9

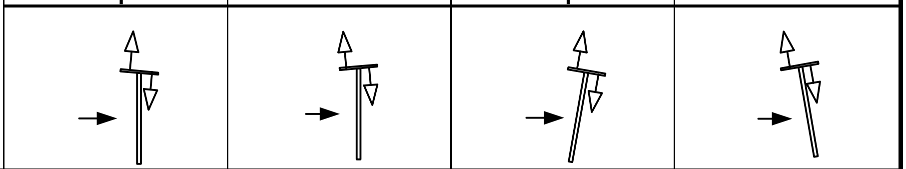
NOTES:
- p Positive angle as given in Table 3
- n Negative angle as given in Table 3

Table 7 and 8 give the most onerous values on the T-tops from step 2 and step 3 of the calculation, respectively. The values in table 7 are used in the calculation of the resulting moments. The maximum uplift or downlift are derived from Table 8.The calculation of the forces and moments is treated in paragraph 3.4.

Table 8 Design pressure net coefficients: most onerous values on T-top(moments)



Zone	Case 1	2	3 down	3 up	4 down	4 up	5
A			0.6	-2.7	0.7	-2.5	
B			0.3	-2.0	0.3	-1.7	
C			0.2	-1.8	0.2	-1.6	
D			0.1	-1.6	0.1	-1.2	

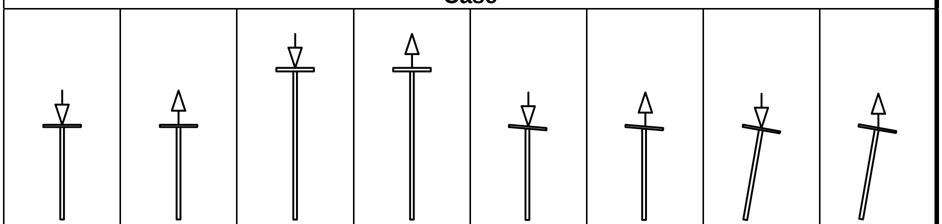


	Case 6 p		6 n		7 p		7 n	
Zone	6 down	6 up	6 down	6 up	7 down	7 up	7 down	7 up
A	0.6	-2.6	0.8	-2.4	0.7	-2.3	0.8	-2.0
B	0.4	-2.1	0.4	-2.0	0.4	-1.6	0.4	-2.0
C	0.2	-1.7	0.2	-1.8	0.1	-1.6	0.1	-1.4
D	0.1	-1.3	0.1	-1.6	0.1	-1.2	0.1	-2.1

NOTES:

p Positive angle as given in Table 3
n Negative angle as given in Table 3
down Pressure downwards for calculation of moments as defined in Figure 5
up Pressure upwards for calculation of moments as defined in Figure 5

Table 9 Design pressure coefficients: most onerous net values on T-top (forces)



Zone	Case 3 down	3 up	4 down	4 up	6 down	6 up	7 down	7 up
A	0.5	-1.2	0.4	-1.1	0.5	-1.0	0.5	-1.0
B	0.1	-1.3	0.1	-1.0	0.1	-1.1	0.1	-1.0
C	0.1	-1.0	0.1	-1.1	0.0	-1.2	0.1	-1.0
D	0.1	-1.0	0.1	-0.8	0.1	-0.9	0.1	-1.0

NOTES:

down Pressure downwards for calculation of forces as defined in Figure 5
up Pressure upwards for calculation of forces as defined in Figure 5

The following conclusions are drawn:

- Using extreme value analysis results in lower values for the pressure coefficients. The pressure coefficients obtained with the more precise procedures are decreased with 40%.

- The design values of the net pressure coefficients are lower than in prEN 1991-1-4:2004. This is a consequence of the analyses procedure. The values in prEN 1991-1-4:2004 are based on mean pressures. The mean pressure coefficients derived in chapter 3.2 are lower for zone A and C compared to the provisions given in prEN 1991-1-4:2004. The values for zone B are higher and the values for zone D are in the same order of magnitude than the values in prEN 1991-1-4:2004. Other research on vertical walls, including the study on which the values in the Eurocode are based on, will be discussed in chapter 4.

- The influences of the configurations on the pressure coefficients are similarly. The T-top reduces the pressure coefficients on the barrier. However, the difference is not very great.

- The pressure coefficients on the T-tops are higher than on the barriers.

- The differences in pressure coefficients between the zones A and B are small. Zone C and D also have comparable pressure coefficients. Their values are about 50% of the pressure coefficients in zone A and B.

- A noise barrier consists of 90% percent or more of zone D. The effects of the configurations are mainly relevant for zone A. Zone D shows even less difference in pressure coefficients for the configurations studied.

3.4 Forces and moments

The forces and moments in the noise barrier and on the foundation can be calculated with the design net pressure coefficients of Table 6 and Table 7. The barrier and T-top will be discussed separately.

The forces and moments introduced are caused by wind from all directions. The forces and moment on the barrier are derived from the design net pressure coefficients in Table 7 by multiplying them with the height of the barrier. The point of application is at 50% of the height. The design net pressure coefficients should be placed on both sides of the noise barrier (see Figure 5). If the noise barrier has an inclination, the p-value has to be used for the positive side and the n-value for the negative side. The definition of a positive and negative side is given in Table 3.

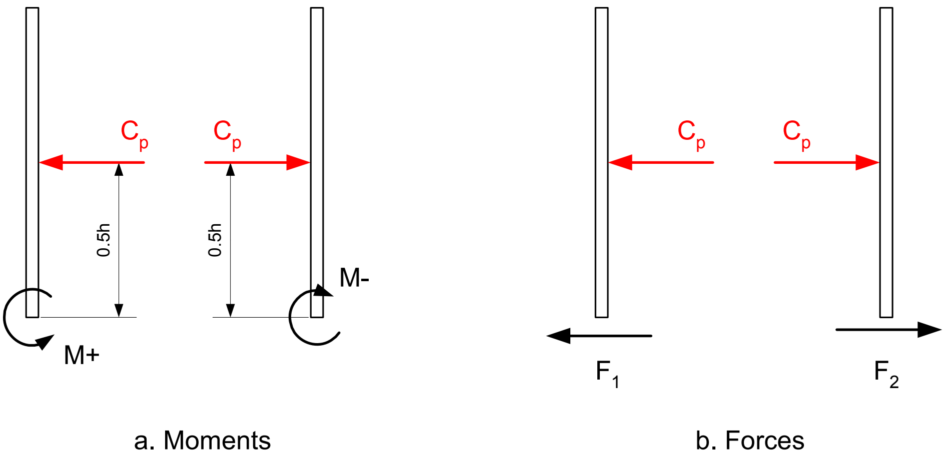


Figure 4 – Load combinations barrier

The load combinations for the forces and moments on the T-top are illustrated in Figure 5.

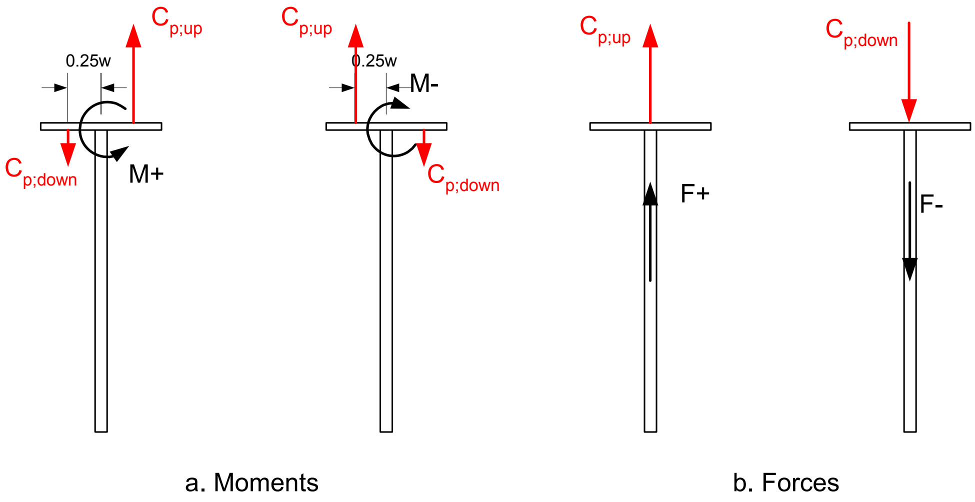


Figure 5 – Load combinations T-top

The calculation of the moments is similarly to the barrier. The design net pressure coefficients in Table 7 multiplied with the loaded area, half width of T-top, leads to the design forces. The point of application is at ¼ width of the T-top, so in the middle of one half. The moments have to be calculated with combinations of downward and upward forces. If the T-top has an inclination, the p-value has to be used for the positive side and the n-value for the negative side. Check all possible combinations. The definition of a positive and negative side is given in table 3.

The maximum tensile forces (uplift) on the foundation are found with the upward design net pressure coefficients in Table 8. The coefficients multiplied with the loaded area, whole width of T-top, leads to the design forces. The pressure forces (downlift) are similarly calculated with the downward design net pressure coefficients.

The net pressure coefficients are design values. The load factor should still be applied.

4 Other research on vertical walls

The research carried out by TNO is compared with results from experiments available from the ‘free’ literature and information received from contact persons elsewhere. Three sources of data have been compared with the results of this wind tunnel research:
-measurements conducted in full scale at Silsoe Research Institute in the UK, published in a number of papers and reports;
-wind tunnel data measured at Building Research Establishment in de UK, with restricted availability, through personal communication with Dr. Paul Blackmore;
-wind tunnel data measured in wind tunnels in Oxford, UK and CSIRO, Australia, and published in a joint paper.

These data sources where all used as basis for our current design rules, as published in prEN 1991-1-4:2004, as well in e.g. the Australian Standard, and the ESDU design data.

4.1 Full scale measurements at Silsoe Research Institute

The measurements in Silsoe were performed on a wooden test wall, 2 m high and 215 mm thick. It represents a typical masonry wall. The wall was constructed of a modular panel size of 2 metres square. Different lengths of walls have been studied, up to a length of 26 metres. Also measurements with sheltered walls have been measured. Measurements have been carried out of the forces on the panels, as well as pressure distributions. The wall has been studied on a flat undisturbed terrain.

View of the test wall at Silsoe Research institute

Force coefficients have been published, defined as mean force coefficients. The focus of the research was mainly at the end panels. Main observations were:

-Forces on the end panels are highest for the 26 metres long wall. No longer walls have been tested, so no results for longer walls are available. The wind direction at which this highest value occurs is at an angle of attack of about 30 degrees. Values in the order of 2.8 are published.
A provisional design force coefficient distribution was published, with values depending on the wall length.

For long walls, the values in zone A where about 3.0 or higher (longer walls than 13 x h have not been tested, so no final values have been reported).
In zone B, a value of 2.6 was reported for the longest wall
In zone C, a value of 1.6 is recommended
For zone D, a value of 1.1 has been recommended.

These values have not been included in our current standards. The values of zone A, C and D in the prEN 1991-1-4:2004 are in the same order of magnitude. Values in zone B in prEN 1991-1-4:2004 are smaller. This is in line with the observations made in the TNO wind tunnel, where higher values for zone B have been given.

Table 10 Mean pressure coefficients per zone: comparison with Silsoe results

Zone	Case		Silsoe results	prEN 1991-1-4:2004
	1 (5 m)	2 (8 m)	wall length 13 h	without return corners
A	3.0	3.0	2.9	3.4
B	2.9	3.2	2.6	2.1
C	1.5	1.5	2.6	1.7
D	1.3	1.2	1.1	1.2

4.2 Wind tunnel measurements at BRE

In 1993 and 1999, BRE conducted wind tunnel measurements at a range of configurations of noise barriers. The results have been published in reports, which are confidential. Chris Geurts and Carine van Bentum of TNO has had personal communication with Paul Blackmore of BRE.
In the 1993 series, tests where made at a scale of 1:50 on 8 metre and 2 metre high walls (full scale sizes). Wall thickness was 4 mm in the wind tunnel. Different geometries of so-called diffractors have been tested. The results have been presented as so-called pseudo static coefficients, which correspond to coefficients given by method B in the measurements by TNO.

Results from the plain vertical walls have been presented as a function of wind direction. The values of the 8 metre wall are higher than for the 2 metre wall. Values of the 8 metre wall where 3.13, 2.93, 1.58 and 1.20 respectively for the zones A, B, C and D. Values for zone B are higher than reported in prEN 1991-1-4:2004. These values are generally higher than the results reported from the analysis of the peak net pressures in the TNO tests.

The measurements at BRE have been conducted in an approach flow corresponding to built-up terrain. This is different from the TNO tests, where a roughness of flat grassland has been applied. It is not known how big the differences may be because of this difference in flow conditions.

In 1999, BRE conduced a second series of tests, focusing only at zone D of the noise barrier, on 25 different barrier configurations. Again a scale of 1:50 has been applied, using an approach flow of urban terrain, applying a smooth turntable. Wall heights of 3, 6 and 8 metres have been tested. Design values have been obtained for the plane barriers, between 1,13 and 1,22, where the lowest wall gives the higher values.
Also, an estimate of the height of the centre of pressure has been given. For a plane wall this height is at around 52% of the total height. For cranked walls (half T-tops), this height is increased. For a wall with height 6 metres, and a 2 metres extension, this height is at 53% of the overall height, which is not a significant difference.

The results for the louvered structures, cranked barriers, sheltered barriers etcetera, tested by BRE, have not been given here, since they do not compare to the measurements carried out by TNO.

4.3 Wind tunnel measurements at Oxford and CSIRO

In a joint paper, Chris Letchford and John Holmes present measurements in two wind tunnels on freestanding walls. They present measurements on infinite walls and semi-infinite walls, i.e., walls spanning the wind tunnel width or ending at the wind tunnel wall. Also, finite walls have been studied.

The effects of different turbulence content in the approach flow have been studied as well.

In their conclusions they state that ‘Walls are going up, not going down’, referring to the increasing demands for noise barriers and other sheltering structures. Not design values have been given directly. Values in the order of 3 in the end zones, and 1.2 in the central zones are reported, which correspond well with the results presented before from the Silsoe and BRE reports, and corresponding with the mean pressure coefficients in the TNO tests. Wind loads at the ends are higher for approach flow in the order of 45 degrees. Wind loads in the centre are higher when wind is normal to the barriers.

5 Conclusions

The wind load of 7 configurations of noise barriers is determined by wind tunnel tests. The measured pressures are analysed with two procedures. The mean pressures are analysed with procedure A of CUR recommendation 103. The extreme values are analysed with procedure B of the same recommendation.

The resulting mean pressure coefficients for zone A and C are lower than compared to the provisions given in prEN 1991-1-4:2004. The values for zone B are higher and the values for zone D are in the same order of magnitude than the values in prEN 1991-1-4:2004. The extreme value analysis is a more precise procedure and therefore less conservative. The values for the design net pressure coefficients are about 40% lower than the provisions of prEN 1991-1-4:2004.

The design net pressure coefficients of the 7 configurations of the noise barrier are in the same order of magnitude. In general, adding a T-top or inclination of the barrier or T-top will increase the overpressure and decrease the underpressure on the barrier. The change is at most 20%.

The design net pressure coefficients of the T-top are higher than for the barrier. Near the edge in zone A large underpressures are introduced. An inclined T-top results in higher underpressures on positive sides and lower underpressures on negative sides. The change in design net pressure coefficients is however small. The pressures on the T-top can have an important contribution to the loads on the foundation.

The results of these measurements will be incorporated in a proposal for a new text for the Dutch GCW, which will be presented in a separate report.

6 References

A.P.Robertson, R.P. Hoxey, J.L. Short, W.A. Ferguson, P.A. Blackmore ‘Wind loads on boundary walls: full-scale studies’. Journal of Wind Engineering and Industrial Aerodynamics 69-71 (1997) p. 451-459

C.W. Letchford, J.D. Holmes, ‘Wind loads on free-standing walls in turbulent boundary layers’ Journal of Wind Engineering and Industrial Aerodynamics 51 (1994) p. 1-27

prEN 1991-1-4:2004 ‘Eurocode 1: Actions on structures, part 1-4 Wind Actions’, 2004

NEN 6702:2001 ‘Technische grondslagen voor bouwconstructies - TGB 1990 – Belastingen en vervormingen’, december 2001, inclusief wijzigingsblad NEN 6702:2001 /A1, juli 2005

Richtlijnen Geluidbeperkende constructies langs wegen (GCW-2001), CROW, 2001.