AUSTRALIA – NEW ZEALAND KEEGUARD ANALYSIS SUMMARY

PREPARED FOR:

13th August 2018 www.highengineering.com

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INTRODUCTION

The KeeGuard free standing guardrail is a system which does not fasten to the roof. The system uses counterweights to provide stability to the system and resist worker applied loads and environmental loads. The system is evaluated using for the following:

- Overturning stability – to ensure the counterweights prevent the system from tipping
- Resistance to sliding – to ensure the system does not slide out of place or off the roof surface
- Component strength – to ensure the components can withstand the applied loads without breaking
- Component deflection – to ensure the system does not undergo excessive deflection that would prevent the system from properly protecting the area

The guardrail system was evaluated according to AS/NZS 1170.2 and AS 1657 together with industry best-practice and Kee Safety technical standards.

This report is a representative one and is not applicable to any particular building location. Specific location details may change the parameters and these should be verified prior to construction. For the purposes of this report, the coefficient of static friction of the roof was assumed to be 0.85.

METHODOLOGY

The guardrail systems were analysed with the following loads:

- Dead load (self weight) of the guardrail applied as a distributed load on its respective components, D = 36.7 N/m
- Uniformly distributed live load, L = 0.75 kN/m52 lb/ft
- Concentrated (point) live load based on OSHA standard 1910.29, P = 1.0 kN
- Wind loads based on the AS/NZS 1170.2 using annual probability of exceedance of 1:50 from Building Code of Australia and AS/NZ 1170.0. The representative location is in the Cook Straight and classified as wind region W and terrain category 1.5. This produces a distributed wind load of 77 N/m, representing a basic sustained windspeed of 130 kph and design windspeed of 169 kph. The wind load calculation can be seen in Appendix B.

The guardrail system was evaluated with several different load combinations to ensure the system resistance was not exceeded, according to the equation:

$$\phi R \geq \alpha_d D + \gamma\left[\left(\alpha_l L + \alpha_p P + \alpha_q Q\right)\right]$$

Where:

- ϕ is the resistance factor, 0.9
- γ is the load combination reduction factor
- α_d is the load factor for dead loads
- α_l is the load factor for live loads
- α_p is the load factor for concentrated (point) loads
- α_q is the load factor for wind loads

The system utilization is defined as the applied factored loads, divided by the resistance, as given below. A utilization greater than 1 indicates that the resistance was exceeded, and the system is not safe for use.

$$Utilization = \frac{\alpha_d D + \gamma\left[\left(\alpha_l L + \alpha_p P + \alpha_q Q\right)\right]}{\phi R}$$

Different values were used for the load factors to evaluate different conditions and components, as outlined in Table 1 below. The values for the load factors were adapted from the National Building Code of Canada, the ASCE 7-10 and then modified based on testing and computer simulations of the load sharing of between different components of the representative guardrail system. The National Building Code of Canada was used as the starting point for the development of the load combinations because it provided more combinations relating the wind load and the live loads; these are typically found combinations found in many jursidictions world-wide.

Table 1: Load combinations

Load Combination	**Loading Description**	α_d	α_l	α_p	α_q	γ
1	System Overturning: Factored point load horizontally outward at highest point with reduced wind	0	0	1.5	0.5	**0.85**
2	System Overturning: Unfettered wind load horizontally outward	0	0	0	1.	**1.0**
3	System Sliding: Factored hourly average wind	0*	0	0	1.1	**1.0**
4	Component Capacity: Factored point load horizontally outward at top of post	0	0	1.5	0	**1.0**
5	Component Capacity: Factored point load horizontally outward at top of post with reduced wind	0	0	1.5	0.5	**0.85**
6	Component Capacity: Factored point load horizontally outward at midspan of longest span	0	0	1.5	0	**1.0**
7	Component Capacity: Factored point load horizontally outward at midspan of longest span with reduced wind	0	0	1.5	0.5	**0.85**
8	Component Capacity: Point load vertically down at midspan of longest span	1.25	0	1.5	0	**1.0**
9	Component Capacity: Factored point load horizontally out at free end of top rail	0	0	1.5	0	**1.0**
10	Component Capacity: Factored point load horizontally out at free end of top rail with reduced wind	0	0	1.5	0.5	**0.85**
11	Component Capacity: Factored point load vertically down at free end of top rail	1.25	0	1.5	0	**1.0**
12	Component Capacity: Unfettered wind load horizontally outward	0	0	0	11	**1.0**
13	Component Capacity: Uniform distributed live load vertically down along full length of top rail	1.25	1.5	0	0	**1.0**

**The dead load factor shall be 0 for flat surfaces, 1.25 where the surface slopes towards the edge, and 0.9 where the surface slopes away from the edge.*

The analysis was done using static methods and assumed rigid components with minimal deflections. If excessive flexibility or deflection is permitted by the roof or building structure, or the assembly conditions, the stability of the system and the resistances may vary. The longest side of the guardrail system was designated as the front segment. The uniform live load, point load, and wind load were applied to the longest segment.

To evaluate the overturning capacity in load combinations 1 and 2, the entire system was treated as a large rigid body. The resistance was determined as the static moment caused by the weight of all the counterweights at their respective positions and the self weight of the guardrail components.

To evaluate the system sliding in load combination 3, the system was treated like a large rigid body. The resistance was determined using the coefficient of static friction, and the total weight of the system.

To evaluate the component capacity in load combinations 4 to 13, the system was treated as a single, simply supported span, or a single, cantilevered span depending on the segment of guardrail being analysed. The component resistance was determined from the material yield strength.

Additional adjacency factors were included in the calculations to account for load sharing of the point load between adjacent guardrail spans. Computer simulations found that a point load will be resisted by the entire guardrail segment and transferred to multiple post in the segment. The simplified single span analysis, described above, results in the point load only being resisted by the nearest post or two posts This results in a larger reaction force in the posts than would actually be experienced. The adjacency factor is added to account for the load sharing between multiple, adjacent spans, and provide a more accurate calculation of the maximum force resisted by the posts. The dead load, uniform live load, and wind load are applied equally to all guardrail segments, so the adjacency factors do not apply to these loads. For a point load applied to a single intermediate post with a span on each side the adjacency factor is 0.65. For a point load applied at the midspan of a rail the resulting reaction forces at the guardrail posts were determined from traditional engineering statics analysis. If there was an additional span on each side of the analysis span, the adjacency factor is 0.85, applied to the calculated reaction forces at each post. For a point load applied at the outer edge of a free (cantilevered) end the resulting reaction forces at the guardrail post were determined from traditional engineering statics analysis. The adjacency factor is 0.8, applied to the calculated reaction force at the post.

Maximum deflection criteria were specified for the component capacity analysis to ensure the guardrail did not undergo excessive deformation. The maximum allowable deflection of the top rail was 3 inches when subjected to the specified (unfactored) load combinations, and 8 inches when subjected to the factored load combinations. The specified load combinations use the same applied loads as the factored load combinations prescribed in Table 1, but the load combination reduction factor and the applicable load factors are all set to 1.0.

The load combination reduction factor, γ, provides a reduction when two or more of the uniform live load, point load, and wind load are applied simultaneously. When only one of these loads is applied, the reduction factor is 1.0. When two of these loads are applied simultaneously, the reduction factor may be 0.85. The reduction factor accounts for the fact that it is very unlikely that the maximum of two live loads will be applied at exactly the same time, so some reduction is allowed. This prevents an excessive factor of safety from applying multiple factored loads at the same time, when this loading will never actually occur.

Load combinations 1, 5, 7, and 10 analyse the factored point load and a reduced wind load. The wind load is reduced because workers are not expected to be working on the roof under the maximum wind loads, as this will pose a hazard to the workers. If the maximum wind load will cause damage to the guardrail systems, it will also likely cause injury to workers who will experience a greater force from the wind because they have a greater surface area than the guardrail segments. Workers should not work on the roof under these conditions and as a result it will be impossible for the guardrail to be loaded with the maximum wind load, and the point load. The point load will only be applied to the guardrail under intermediate to low wind conditions.

Load combinations 2 and 12 analyse the full wind load. This assumes no additional loads for the reasons described above and is only concerned with the effects of the maximum wind gust. The wind load as determined from ASCE 7-10 is the factored load due to the 3 second gust so it does not need an additional load factor for these load combinations.

Load combination 3 is concerned with sliding the entire guardrail system off the roof edge. The wind load is taken to represent sliding in a more sustained condition that the design wind load which makes for a generous load factor.The peak gust load represents a transient load, which may cause some sliding, but due to the short duration any sliding will be minimal and can be neglected as the guardrail will be expected to dampen out the effects of these gust conditions.

Load combination 3 also provides a variable load factor for the dead load based on the slope of the roof. If the roof is flat, then the dead weight will not contribute to the sliding of the guardrail and only provides sliding resistance through friction, as calculated for the system resistance, so the dead load factor is 0. If the roof is sloped towards the edge, the dead load will contribute to sliding the guardrail off the roof and a load factor of 1.25 is applied, as a standard dead load factor. If the roof is sloped away from the edge, i.e. towards an internal roof drain, then the dead load will contribute to sliding the guardrail away from the edge of the roof. This is beneficial and is given a load factor of 0.9 to match the resistance factor.

The sliding resistance is not analysed with a factored point load. A load combination identical to load combination 1 could be used to analyse the sliding. In order for this load combination to govern the system performance, the guardrail system must be very light. In this situation the system overturning, analysed in load combination 1 is always more critical, so the load combination is only relevant to the overturning analysis, not the sliding analysis.

Load combinations 4, 6, and 9 analyse the factored point load only. This may be the governing load combination in low wind regions where the load combination reduction factor results in a lower combined load in load combinations 5, 7 and 10.

Load combinations 8 and 11 analyse the dead load and a vertical point load under standard load factors.

Load combination 13 analyses the dead load and the vertical uniform live load under standard load factors.

ANALYSIS RESULTS

The KeeGuard guardrail systems in the sample were analysed. The maximum utilizations for each area can be seen below in Table 2. Detailed summaries of the calculations can be seen in Appendix C.

Table 2: Utilization results

Area	Overturning Utilization	Sliding Utilization	Bending Utilization	Deflection Utilization
Sample	0.864 Load Combination 2	0.551 Load Combination 3	0.999 Load Combination 9	0.431 Load Combination 7

The maximum overturning utilization occurred for load combination 2, with the full wind load. This is as expected as the wind load along a long section of guardrail will greatly exceed the magnitude of the point load, particularly in higher wind locations, and when the overall length of the exposed side of the system exceeds approximately 20 m.

The maximum bending utilization occurred for load combination 9 with the factored point load applied horizontally outward at the free end of the top rail. In this case there is less load sharing between adjacent posts in the guardrail, because there are only adjacent spans in one direction from the free end. As a result, the post at the free end must support a greater load than intermediate posts with spans on both sides.

The maximum deflection utilization occurred for load combination 10 with the factored point load and reduced wind load at the free end. There is less load sharing at the free end, as described above for load combination 9, so the post at the free end must support a greater load resulting in greater deflection. When analysing the deflections, the specified (unfactored) loads are used, so the deflection in load combination 10 is the deflection due to the point load, the same as load combination 9, plus the deflection due to the wind load. The load analysis uses the load factors where the reductions due to the combined loading in load combination 10 results in a lower overall load than the fully factored point load in load combination 9.

CONCLUSION

The KeeGuard guardrail systems are fit for purpose the Australia/New Zealand market. In certain very high wind conditions, it is recommended that the system be design reviewed to assure sufficient resistance is developed by the assembly of the guardrail. Client may consult with Kee Safety Technical for further assistance as required.

The end client or building owner is responsible to ensure the roof and underlying building structure/substrate can support the applied loads, including the weight of the guardrails and any bearing against parapets or other structures. The client may consult with Kee Safety Technical for further assistance as required.

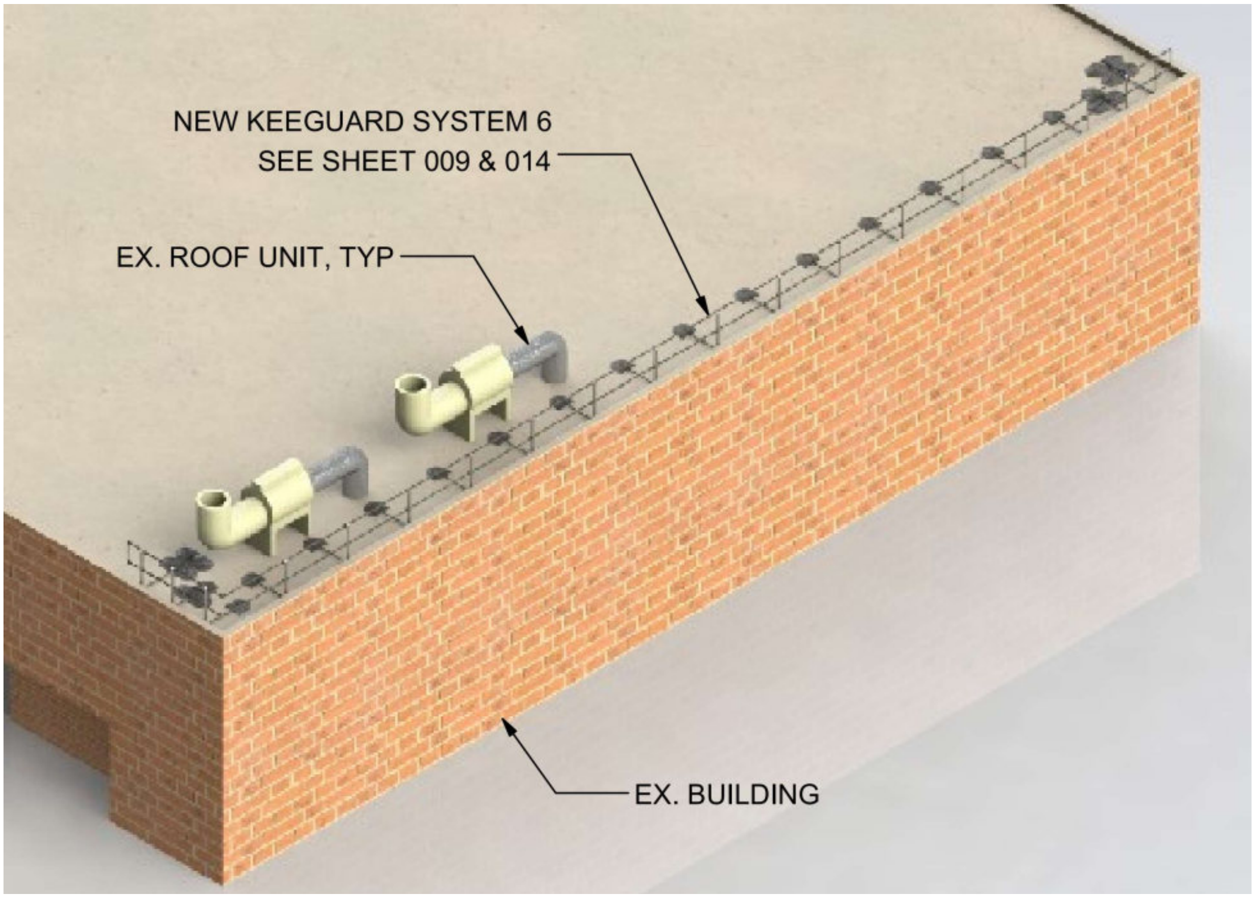
We appreciate the opportunity to be of service; please refer any questions in respect of this project to the undersigned.

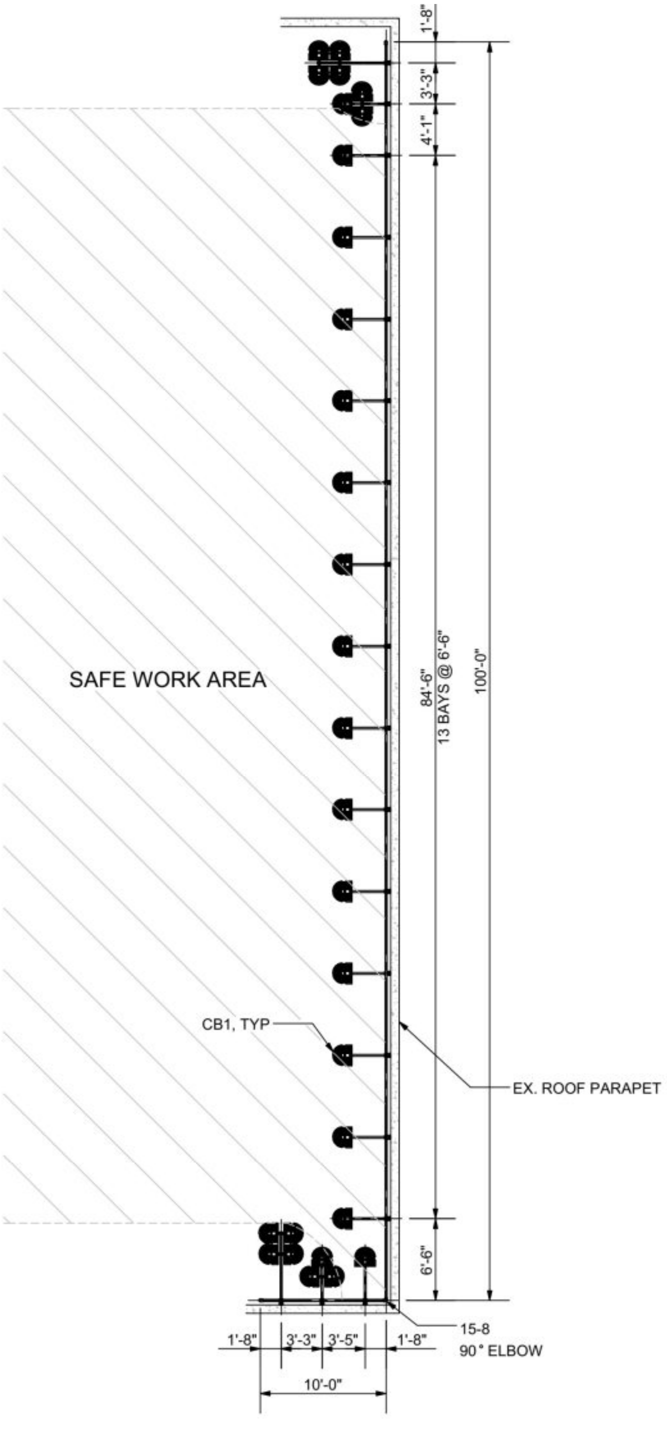
Respectfully submitted,

PROFESSIONAL ENGINEER ALBERTA
WILLIAM R. PARSONS

William R. Parsons, P.Eng.
Principal Engineer AB Lic# 14381 13-Aug-1

APPENDIX A: SAMPLE SYSTEM DRAWING





1
009
PLAN: KEEGUARD SYSTEM 6
SCALE: 1:150

APPENDIX B: WIND LOAD CALCULATIONS

Project Info

Client:
Building Name:
Project Title: Representative project for information only.

Background

Calculations performed in accordance with the AS/NZ 1170.2:2011 Structural Design Actions: Wind Actions.

The load combinations are set out in Kee Safety Technical Standard.

Wind Loads

Static procedure for wind loading is assumed to be applicable and was used.
Neglecting effects of speed up over hills and escarpments.
Neglecting effects of impact from windborne debris.
AS/NZS 1170.2 uses the peak gust wind speed as the input wind speed. The annual probability of exceedence is variable and prescribed in the Building Code of Australia and AS/NZ 1170.0.

System Description

KeeGuard guardrail installed on ___________________

The building guardrail is treated as Normal importance.

The building address is ________________. It is located on the Cook Strait and is classified as wind region W and terrain category 1.5.

System Definition

System Configuration

$l := 36\ m$	Total length of front guardrail segment (segment being loaded)
$l_{long} := 2.4\ m$	Length of longest span
$l_{Dreturn} := 0.5\ m$	Length of longest D-return
$n_{int} := 14$	Number of intermediates
$l_2 := \begin{bmatrix} 0.508\ m \\ 1.575\ m \\ 2.565\ m \end{bmatrix}$	Position of posts and weights on left return
$l_3 := \begin{bmatrix} 0.0\ m \end{bmatrix}$	Position of posts and weights on right return
$n_2 := 6$	Number of extra bases at left end
$n_3 := 0$	Number of extra bases at right end
$l_4 := 1.575\ m$	Position of back segment
$n_4 := 7$	Number of posts and weights in back segment
$Elev := 50\ m$	Building elevation (at ground) above sea level
$H := 8\ m$	Height of roof
$\theta := 0\ deg$	Slope of roof (positive towards edge, negative away)
$h_{TR} := 1.1\ m$	Height of top guardrail above roof surface
$h_{MR} := \frac{h_{TR}}{2} = 0.55\ m$	Height of mid guardrail above roof surface
$h := H + h_{TR} = 9.1\ m$	Height of guardrail above ground
$d := 1.9\ in = 48.26\ mm$	Rail outer diamater
$d_{in} := d - 2 \cdot 0.109\ in = 42.723\ mm$	Rail inner diameter
$I_{rail} := \frac{\pi}{64}\left(d^4 - {d_{in}}^4\right) = 102733.865\ mm^4$	Rail area moment of inertia
$S_{rail} := 2\ \frac{I_{rail}}{d} = 4257.516\ mm^3$	Rail section modulus
$W_{singlebase} := (29\ lbm + 5\ oz) \cdot g = 130.388\ N$	Weight of one KeeGuard base
$n_{base} := 1$	Number of bases at each post
$W_{base} := n_{base} \cdot W_{singlebase} = 130.388\ N$	Total base weight at each post
$l_{base} := 62\ in = 1.575\ m$	Minimum moment arm of KeeGuard base
$\mu := 0.85$	Coefficient of static friction

Loading

$\phi := 0.9$	Resistance factor
$D := 2.72\ \frac{lbf}{ft} = 39.695\ \frac{N}{m}$	Dead load (self weight)
$L := 0.75\ \frac{kN}{m}$	Uniformly distributed live load
$P := 1.0\ kN$	Concentrated (point) live load

Material Properties and System Constraints

$F_Y := 345\ MPa$	Yield strength
$E := 200\ GPa$	Elastic modulus
$\delta_{max} := 75\ mm$	Maximum displacement of top rail for specified (unfactored) loading
$\delta_{maxfact} := 200\ mm$	Maximum displacement of top rail for factored loading

Wind Load Parameters

$WindRegion := \text{“W”}$	See Figure 3.1(A) and 3.1(B) to determine the wind region
$R := 50$	Average recurrence interval (years) (>5 years) refer to the Building Code of Australia or AS/NZS 1170.0 for information on values of annual probability of exceedence appropriate for the design of structures
$TerrainCategory := 1.5$ Terrain Categories 1 - Very exposed terrain 1.5 - Midway between category 1 and 2 2 - Open terrain 2.5 - Midway between category 2 and 3 3 - Numerous, small obstructions 4 - Numerous, large obstructions	Terrain category (see section 4.2.1) (select the worse case) for a more precise calculation terrain averaging could be used (see section 4.2.3)
$E_h := Elev + h = 59.1\ m$	Elevation of guardrail above sea level

Wind Load Analysis

Regional Wind Speeds

$WindRegion = \text{"W"}$ See Figure 3.1(A) and 3.1(B) to determine the wind region

$$Regions := \begin{bmatrix} \text{"A"} \\ \text{"W"} \\ \text{"B"} \\ \text{"C"} \\ \text{"D"} \end{bmatrix} \qquad ind_R := \text{match}\left(WindRegion, Regions\right)_0 = 1$$

$R = 50$ Average recurrence interval (years) (>5 years) refer to the Building Code of Australia or AS/NZS 1170.0 for information on values of annual probability of exceedence appropriate for the design of structures

$$F_C := \begin{array}{l} \text{if } R \geq 50 \\ \quad \| \; 1.05 \\ \text{else} \\ \quad \| \; 1.0 \end{array} = 1.05$$

Uncertanty factor for wind speed predictions in Region C (see section 3.4)

$$F_D := \begin{array}{l} \text{if } R \geq 50 \\ \quad \| \; 1.1 \\ \text{else} \\ \quad \| \; 1.0 \end{array} = 1.1$$

Uncertanty factor for wind speed predictions in Region D (see section 3.4)

$$V := \text{round}\left(\begin{bmatrix} 67 - 41\ R^{-0.1} \\ 104 - 70\ R^{-0.045} \\ 106 - 92\ R^{-0.1} \\ F_C \cdot \left(122 - 104\ R^{-0.1}\right) \\ F_D \cdot \left(156 - 142\ R^{-0.1}\right) \end{bmatrix}\right) \frac{m}{s} = \begin{bmatrix} 39 \\ 45 \\ 44 \\ 54 \\ 66 \end{bmatrix} \frac{m}{s}$$

Calculated wind speed for each region (see section 3.2)

$V_R := V_{ind_R} = 45\ \frac{m}{s}$ Regional gust wind speed

Wind Directional Multiplier

$M_d := 1.00$ Wind directional multiplier (for any direction, any region)

Terrain/Height Multiplier

$TerrainCategory = 1.5$

Terrain category (see section 4.2.1) (select the worse case) for a more precise calculation terrain averaging could be used (see section 4.2.3)

$$M_{cat} := \begin{bmatrix} 3\ m & 0.99 & 0.91 & 0.83 & 0.75 \\ 5\ m & 1.05 & 0.91 & 0.83 & 0.75 \\ 10\ m & 1.12 & 1.00 & 0.83 & 0.75 \\ 15\ m & 1.16 & 1.05 & 0.89 & 0.75 \\ 20\ m & 1.19 & 1.08 & 0.94 & 0.75 \\ 30\ m & 1.22 & 1.12 & 1.00 & 0.80 \\ 40\ m & 1.24 & 1.16 & 1.04 & 0.85 \\ 50\ m & 1.25 & 1.18 & 1.07 & 0.90 \\ 75\ m & 1.27 & 1.22 & 1.12 & 0.98 \\ 100\ m & 1.29 & 1.24 & 1.16 & 1.03 \\ 150\ m & 1.31 & 1.27 & 1.21 & 1.11 \\ 200\ m & 1.32 & 1.29 & 1.24 & 1.16 \end{bmatrix}$$

$$M_{cat0.5} := \begin{bmatrix} 3\ m & \mathrm{mean}\left(M_{cat_{0,1}}, M_{cat_{0,2}}\right) & \mathrm{mean}\left(M_{cat_{0,2}}, M_{cat_{0,3}}\right) \\ 5\ m & \mathrm{mean}\left(M_{cat_{1,1}}, M_{cat_{1,2}}\right) & \mathrm{mean}\left(M_{cat_{1,2}}, M_{cat_{1,3}}\right) \\ 10\ m & \mathrm{mean}\left(M_{cat_{2,1}}, M_{cat_{2,2}}\right) & \mathrm{mean}\left(M_{cat_{2,2}}, M_{cat_{2,3}}\right) \\ 15\ m & \mathrm{mean}\left(M_{cat_{3,1}}, M_{cat_{3,2}}\right) & \mathrm{mean}\left(M_{cat_{3,2}}, M_{cat_{3,3}}\right) \\ 20\ m & \mathrm{mean}\left(M_{cat_{4,1}}, M_{cat_{4,2}}\right) & \mathrm{mean}\left(M_{cat_{4,2}}, M_{cat_{4,3}}\right) \\ 30\ m & \mathrm{mean}\left(M_{cat_{5,1}}, M_{cat_{5,2}}\right) & \mathrm{mean}\left(M_{cat_{5,2}}, M_{cat_{5,3}}\right) \\ 40\ m & \mathrm{mean}\left(M_{cat_{6,1}}, M_{cat_{6,2}}\right) & \mathrm{mean}\left(M_{cat_{6,2}}, M_{cat_{6,3}}\right) \\ 50\ m & \mathrm{mean}\left(M_{cat_{7,1}}, M_{cat_{7,2}}\right) & \mathrm{mean}\left(M_{cat_{7,2}}, M_{cat_{0,3}}\right) \\ 75\ m & \mathrm{mean}\left(M_{cat_{8,1}}, M_{cat_{8,2}}\right) & \mathrm{mean}\left(M_{cat_{8,2}}, M_{cat_{8,3}}\right) \\ 100\ m & \mathrm{mean}\left(M_{cat_{9,1}}, M_{cat_{9,2}}\right) & \mathrm{mean}\left(M_{cat_{9,2}}, M_{cat_{9,3}}\right) \\ 150\ m & \mathrm{mean}\left(M_{cat_{10,1}}, M_{cat_{10,2}}\right) & \mathrm{mean}\left(M_{cat_{10,2}}, M_{cat_{10,3}}\right) \\ 200\ m & \mathrm{mean}\left(M_{cat_{11,1}}, M_{cat_{11,2}}\right) & \mathrm{mean}\left(M_{cat_{11,2}}, M_{cat_{11,3}}\right) \end{bmatrix} = \begin{bmatrix} 3\ m & 0.95 & 0.87 \\ 5\ m & 0.98 & 0.87 \\ 10\ m & 1.06 & 0.915 \\ 15\ m & 1.105 & 0.97 \\ 20\ m & 1.135 & 1.01 \\ 30\ m & 1.17 & 1.06 \\ 40\ m & 1.2 & 1.1 \\ 50\ m & 1.215 & 1.005 \\ 75\ m & 1.245 & 1.17 \\ 100\ m & 1.265 & 1.2 \\ 150\ m & 1.29 & 1.24 \\ 200\ m & 1.305 & 1.265 \end{bmatrix}$$

$$M_{hcat} := \left[\begin{array}{l}
\dfrac{min\,(\text{vlookup}\,(h, M_{cat}, 1, \text{“gt”})) - \max\,(\text{vlookup}\,(h, M_{cat}, 1, \text{“leq”}))}{min\,(\text{vlookup}\,(h, M_{cat}, 0, \text{“gt”})) - \max\,(\text{vlookup}\,(h, M_{cat}, 0, \text{“leq”}))} \cdot (h - \max\,(\text{vlookup}\,(h, \\
\dfrac{min\,(\text{vlookup}\,(h, M_{cat0.5}, 1, \text{“gt”})) - \max\,(\text{vlookup}\,(h, M_{cat0.5}, 1, \text{“leq”}))}{min\,(\text{vlookup}\,(h, M_{cat0.5}, 0, \text{“gt”})) - \max\,(\text{vlookup}\,(h, M_{cat0.5}, 0, \text{“leq”}))} \cdot (h - \max\,(\text{vlookup}\,(h, \\
\dfrac{min\,(\text{vlookup}\,(h, M_{cat}, 2, \text{“gt”})) - \max\,(\text{vlookup}\,(h, M_{cat}, 2, \text{“leq”}))}{min\,(\text{vlookup}\,(h, M_{cat}, 0, \text{“gt”})) - \max\,(\text{vlookup}\,(h, M_{cat}, 0, \text{“leq”}))} \cdot (h - \max\,(\text{vlookup}\,(h, \\
\dfrac{min\,(\text{vlookup}\,(h, M_{cat0.5}, 2, \text{“gt”})) - \max\,(\text{vlookup}\,(h, M_{cat0.5}, 2, \text{“leq”}))}{min\,(\text{vlookup}\,(h, M_{cat0.5}, 0, \text{“gt”})) - \max\,(\text{vlookup}\,(h, M_{cat0.5}, 0, \text{“leq”}))} \cdot (h - \max\,(\text{vlookup}\,(h, \\
\dfrac{min\,(\text{vlookup}\,(h, M_{cat}, 3, \text{“gt”})) - \max\,(\text{vlookup}\,(h, M_{cat}, 3, \text{“leq”}))}{min\,(\text{vlookup}\,(h, M_{cat}, 0, \text{“gt”})) - \max\,(\text{vlookup}\,(h, M_{cat}, 0, \text{“leq”}))} \cdot (h - \max\,(\text{vlookup}\,(h, \\
\dfrac{min\,(\text{vlookup}\,(h, M_{cat}, 4, \text{“gt”})) - \max\,(\text{vlookup}\,(h, M_{cat}, 4, \text{“leq”}))}{min\,(\text{vlookup}\,(h, M_{cat}, 0, \text{“gt”})) - \max\,(\text{vlookup}\,(h, M_{cat}, 0, \text{“leq”}))} \cdot (h - \max\,(\text{vlookup}\,(h,
\end{array}\right.$$

$$\begin{array}{l}
M_{zcat} := \text{if } TerrainCategory = 1 \\
\quad \Vert\, M_{hcat_0} \\
\text{else if } TerrainCategory = 1.5 \\
\quad \Vert\, M_{hcat_1} \\
\text{else if } TerrainCategory = 2 \\
\quad \Vert\, M_{hcat_2} \\
\text{else if } TerrainCategory = 2.5 \\
\quad \Vert\, M_{hcat_3} \\
\text{else if } TerrainCategory = 3 \\
\quad \Vert\, M_{hcat_4} \\
\text{else if } TerrainCategory = 4 \\
\quad \Vert\, M_{hcat_5}
\end{array} = 1.046$$

Terrain/height multiplier (see section 4.2)

Shielding Multiplier

$M_s := 1.0$

Shielding multiplier (see section 4.3) (assumed 1.0 to be conservative, calculation requires information on the size and spacing of neighbouring buildings)

Topographic Multiplier

$E_h = 59.1\ m$ Site elevation

$M_h := 1.0$ Hill shape multiplier (taken as 1.0 to neglect effect of hills) (see section 4.4.2)

$M_{lee} := 1.0$ Lee multiplier (1.34 for sites within the New Zealand lee zones, otherwise 1.0) (see section 4.4.3)

$$M_t := \begin{array}{l} \text{if } E_h > 500\ m \\ \quad \left\| M_h \cdot M_{lee} \cdot \left(1 + 0.00015\ E_h\right) \right. \\ \text{else} \\ \quad \left\| \max\left(M_h, M_{lee}\right) \right. \end{array} = 1$$

Topographic multiplier (see section 4.4)

Wind Speed

$V_{sit\beta} := V_R \cdot M_d \cdot \left(M_{zcat} \cdot M_s \cdot M_t\right) = 47.052\ \dfrac{m}{s}$ Site wind speed (see section 2.2)

$V_{min} := 30\ \dfrac{m}{s}$ Minimum design wind speed

$V_{des\theta} := \max\left(V_{sit\beta}, V_{min}\right) = 47.052\ \dfrac{m}{s}$ Design wind speed (see section 2.3)

Aerodynamic Shape Factor

Individual Members

$$K_{arMat} := \begin{bmatrix} 8 & 0.7 \\ 14 & 0.8 \\ 30 & 0.9 \\ 40 & 1.0 \end{bmatrix}$$

Aspect ratio correction factor (see table E1)

$$\frac{l_{long}}{d} = 49.731$$

Aspect ratio

$$K_{ar} := \text{if } \frac{l_{long}}{d} > \max\left(K_{arMat}^{\langle 0 \rangle}\right)$$

$$\Big\|\, K_{arMat_{\text{length}\left(K_{arMat}^{\langle 0 \rangle}\right)-1,1}}$$

$$\text{else}$$

$$\Bigg\|\, \frac{min\left(\text{vlookup}\left(\frac{l_{long}}{d}, K_{arMat}, 1, \text{“gt”}\right)\right) - \max\left(\text{vlookup}\left(\frac{l_{long}}{d}, K_{arMat}, 1, \text{“leq”}\right)\right)}{min\left(\text{vlookup}\left(\frac{l_{long}}{d}, K_{arMat}, 0, \text{“gt”}\right)\right) - \max\left(\text{vlookup}\left(\frac{l_{long}}{d}, K_{arMat}, 0, \text{“leq”}\right)\right)} \cdot \left(\frac{l_{long}}{d} - \max\left(\text{vlooku}\right.\right.$$

$$K_i := 1.0$$

Factor for angle of inclination of the wind (take as 1.0 for wind normal to member)

$$h_r := 150 \cdot 10^{-6}\ m$$

Average height of surface roughness (typical value for galvanized steel)

$$C_d := \text{if } d \cdot V_{des\theta} < 4\ \frac{m^2}{s}$$

$$\Big\|\, 1.2$$

$$\text{else if } d \cdot V_{des\theta} > 10\ \frac{m^2}{s}$$

$$\Big\|\, \max\left(1.0 + 0.033 \cdot \log\left(V_{des\theta} \cdot h_r\right) - 0.025 \cdot \left(\log\left(V_{des\theta} \cdot h_r\right)\right)^2, 0.6\right)$$

$$\text{else}$$

$$\Bigg\|\, \frac{1.2 - 0.6}{4\ \frac{m^2}{s} - 10\ \frac{m^2}{s}} \cdot \left(d \cdot V_{des\theta} - 4\ \frac{m^2}{s}\right) + 1.2$$

$$= 1.2$$

Drag force coefficient (see Appendix E3)

$$C_{fig1} := K_{ar} \cdot K_i \cdot C_d = 1.2$$

Aerodynamic shape factor (see Appendix E2.1)

Single Open Frame

$$\delta := \frac{d \cdot 2 \cdot \left(l_{long} + h_{TR}\right)}{l_{long} \cdot \left(h_{TR} + \frac{d}{2}\right)} = 0.125$$

Solidity ratio (solid area/total area)

$\delta_e := 1.2\ \delta^{1.75} = 0.032$ Effective solidity ratio for circular cross-section members

$C_{fig2} := 1.2 + 0.26 \cdot \left(1 - \delta_e\right) = 1.452$ Aerodynamic shape factor (see Appendix E2.2)

$$C_{fig} := \begin{array}{l} \text{if } \left(0.2 < \delta_e < 0.8\right) \wedge \left(\frac{1}{3} < \frac{l}{h_{TR}} < 3\right) \\ \quad \| C_{fig2} \\ \text{else} \\ \quad \| C_{fig1} \end{array} = 1.2$$

Aerodynamic shape factor

Dynamic Response Factor

$C_{dyn} := 1.0$

Dynamic response factor (see section 6.1) (assume natural frequency >1Hz, short (h<200m) buildings)

Wind Load

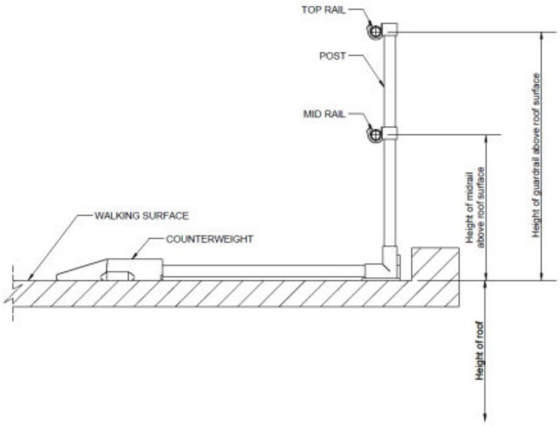
$p_{air} := 1.2\ \frac{kg}{m^3}$ Density of air

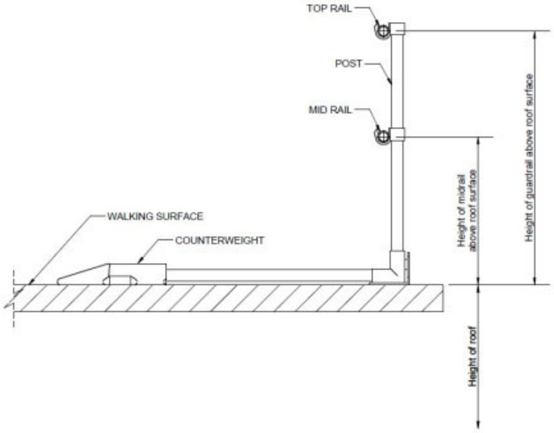
$p := 0.5\ p_{air} \cdot V_{des\theta}{}^2 \cdot C_{fig} \cdot C_{dyn} = 1594.001\ Pa$ Design wind pressure (see section 2.4)

$Q := d \cdot p = 0.0769\ \frac{kN}{m}$ Wind load on guardrail pipe

APPENDIX C: DETAILED CALCULATION SUMMARIES

System Configuration





$l=36\ m$	Total length of front guardrail segment (segment being loaded)
$l_{long}=2.4\ m$	Length of longest span
$l_{Dreturn}=0.5\ m$	Length of longest cantilever span
$n_{int}=14$	Number of intermediates
$l_2=\begin{bmatrix}0.508\\1.575\\2.565\end{bmatrix}\ m$	Position of posts and weights on left return
$l_3=\begin{bmatrix}0\end{bmatrix}\ m$	Position of posts and weights on right return

Note: additional segment lengths are not considered tocontribute to the longest run and are omitted here

$n_2=6$	Number of extra bases at left end
$n_3=0$	Number of extra bases at right end
$l_4=1.575\ m$	Position of back segment
$n_4=7$	Number of posts and weights in back segment
$H=8\ m$	Height of roof
$\theta=0$	Slope of roof (positive towards edge, negative away)
$h_{TR}=1.1\ m$	Height of top guardrail above roof surface
$h_{MR}=0.55\ m$	Height of mid guardrail above roof surface
$h=9.1\ m$	Height of guardrail above ground
$W_{singlebase}=130.388\ N$	Weight of one KeeGuard base
$n_{base}=1$	Number of bases at each post
$W_{base}=130.388\ N$	Total base weight at each post
$l_{base}=1.575\ m$	Minimum moment arm of KeeGuard base

Applied Loads

$D=39.695\ \frac{N}{m}$	Dead load (self weight)
$L=0.75\ \frac{kN}{m}$	Uniformly distributed live load
$P=1\ kN$	Concentrated (point) live load
$Q=0.077\ \frac{kN}{m}$	Wind load

Limiting Conditions

Overturning Limiting Case

$Case_{O_{ind_O}}$ = "Load Combination 2: Unfettered wind load horizontally outward"

$M_{O_{ind_O}}=5.743\ kN \cdot m$	Factored overturning moment
$\phi \cdot R_O=6.65\ kN \cdot m$	Factored overturning resistance
$Overturn_{ind_O}=0.864$	Overturning utilization

Sliding Limiting Case

$Case_{S_{ind_S}}$ = "Load Combination 3: Factored hourly average wind"

$P_{S_{ind_S}}=7.396\ kN$	Factored sliding force
$\phi \cdot R_S=13.416\ kN$	Factored sliding resistance
$Sliding_{ind_S}=0.551$	Sliding utilization

Bending Limiting Case

$Case_{BD_{ind_B}}$ = "Load Combination 9: Factored point load horizontally out at free end of top rail with reduced wind"

$M_{BPost_{ind_B}} = 1320\ N \cdot m$	Factored bending moment in post
$M_{BRail_{ind_B}} = 750\ N \cdot m$	Factored bending moment in rail
$\phi \cdot M_{RBend} = 1321.959\ N \cdot m$	Factored bending resistance
$BendPost_{ind_B} = 0.999$	Bending utilization of the post
$BendRail_{ind_B} = 0.567$	Bending utilization of the rail

Deflection Limiting Case

$Case_{BD_{ind_D}}$ = "Load Combination 7: Factored wind with reduced point load horizontally outward at midspan of longest span"

$\delta_{ind_D} = 32.348\ mm$	Displacement
$\delta_{fact_{ind_D}} = 41.244\ mm$	Displacement under factored loading
$\delta_{max} = 75\ mm$	Maximum displacement for specified loading
$\delta_{maxfact} = 200\ mm$	Maximum displacement for factored loading
$Deflection_{ind_D} = 0.431$	Deflection utilization
$DeflectionFactored_{ind_D} = 0.206$	Factored deflection utilization

Conclusion (Representative)

The configuration is suitable and safe for use.

All of the load combinations result in utilizations less than 1.

Notes:

1. The end client or building owner is responsible to ensure the roof and underlying building structure/substrate can support the applied loads, including the weight of the guardrails and any bearing against parapets or other structures.
2. This analysis uses static methods and assumes rigid components with minimal deflections. If excessive flexibility or deflection is permitted by the roof or building structure, or the assembly conditions, the stability of the system and the resistances may vary.