Full-Scale Wind Load Measurements on Solar Mounting Systems

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ABSTRACT

Uplift loads for the 5B MAVERICK (Ground mount, East-west ballasted solar rack structure) are a key determinant of the cost of the Maverick Solution and its competitiveness amongst other solar mounting solutions on the market. The analysis of full-scale data has shown that a) uplift peak force coefficients are independent of wind speeds and thus not reliant on wind events, and b) foundation uplift loads are half of the estimate obtained through tunnel experiments. These findings encourage the use of full-scale measurements to derive design datasets and highlight the potential limitations of current wind tunnel testing methodologies in modelling super low-rise structures (below 1 m). Our paper presents an approach for analysing full-scale structural wind loads and wind speeds close to the ground (at 1 m).

INTRODUCTION

5B MAVERICK (MAV) is a ground mount, fixed tilt east-west solar racking system whose key value propositions are prefabrication, the ability to be rapidly deployed with minimal labour and efficient aerodynamic architecture. Photovoltaic modules are supported by rails on a canopy shape, attached by hinged connections to composite steel-concrete ballast beams. The beams are tied with multiple cables along its length to ensure a fixed module tilt angle of 10 degrees and transfer lateral load. One key characteristic is that the system is self-ballasted in lower wind regions (AS1170.2 A & B), requiring extra ballast of anchorage at the periphery of the block on exposed windward edges.

Figure 1 (Left) Deployment 12MW Happy Valley Site SA; (Right) Los Andes, Chile 10MW MAV low installation height.

The design wind loads for the MAV, specifically the Beam End Uplift, were derived as force coefficients, normalised by wind speeds at 10m height, by pre-eminent wind engineering firm on their ABL Wind Tunnel. These coefficients were obtained using the Influence Coefficients extracted from structural FEA models that were developed by 5B and expert structural engineering consultants.

The full-scale test site consists of three MAVS (5P5B) in a row on open farmland (TC2, AS/NZS 1170.2-2021) at Port Pirie, South Australia. The arrays were oriented so that the site's prevalent wind directions were aligned with the structural design governing wind directions in the north and south quadrants (± 45deg), where only the southern array was instrumented.

The system was instrumented with more than 25 load cells, and strain gauges on main structural elements and foundations to collect structural loads. Wind speed measurements were taken at 10m height by a 2D Ultrasonic anemometer (WindObserver) and at 1m height by a 3D Ultrasonic anemometer (WindMaster). Directional wind speeds and load measurements were logged at 10Hz and 50Hz, respectively, using a QuantumX CX22 – HBM (DAQ) powered by the solar panels of the array.

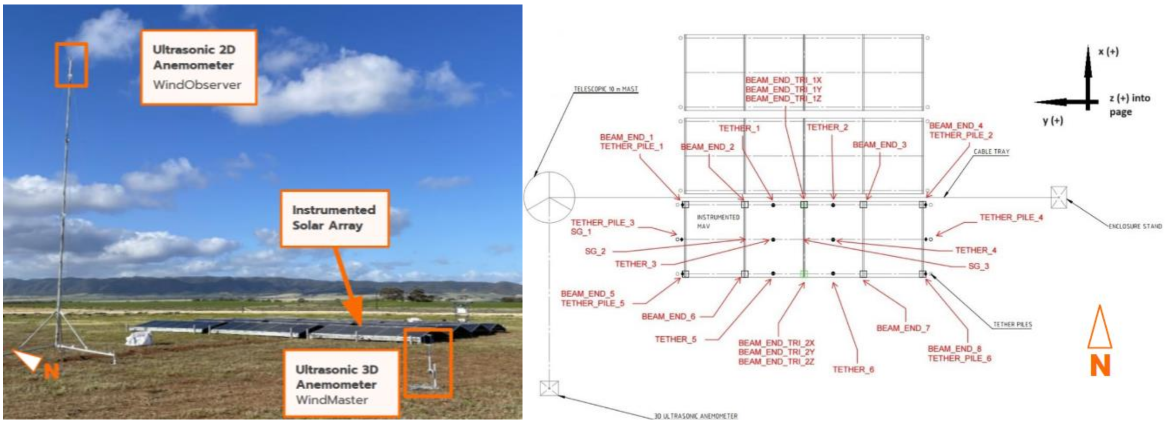

Figure 2 – (Left) Test site; (Right) Site layout describing the locations of anemometers, load cells and strain gauges

WIND PROFILE

The wind speed and turbulence intensity ratio at height (h) of 1 m versus the reference at height at 10 m, with average speeds shown in Figure 3. Also plotted are the AS 1170.2 profiles for Terrain Category 2 and the wind tunnel profile, calibrated to ASCE 49-21. The site wind measurements at height 1 m and 10 m behave "as expected" in that, the relative wind speed at 1 m aligns with the extrapolation of the AS/NZ 1170.2 profile ($\alpha = 0.185$).

Given that wind loads are normalised by wind speeds at h = 10 m, it is important that structural responses are referenced to the wind speed at h = 10 m. In the following analysis, we directly measure the wind speed at h = 1 m, then apply the conservative assumption that $\alpha = 0.14$ to extrapolate to the wind speed at h = 10 m (the latter applying to the calculation of force coefficients, driving an underestimate of those coefficients since the reference wind velocity at h = 10 m will be lower than expected from standards).

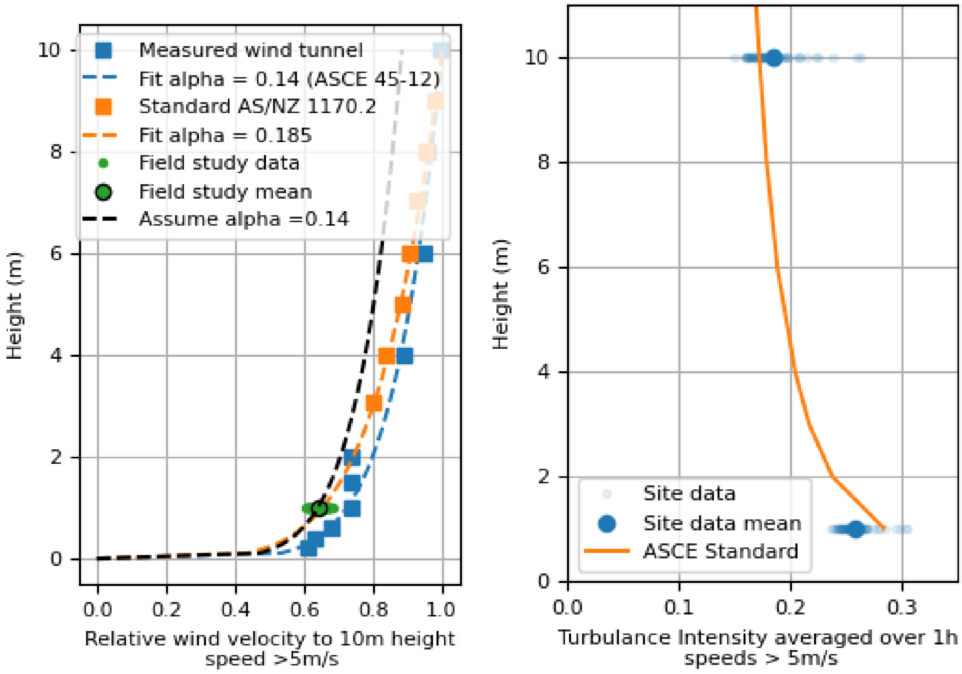

Figure 3 - (Left) Wind speed as a function of height. Comparison of the full-scale measurements with AS1170.2 TC2 and wind tunnel (ASCE49-21). (Right) Turbulence intensity is a function of height at the site according to ASCE 47-29 standards. For the data analysed in this report, the median values for the turbulence intensity were found to be 0.27 and 0.18 for h=1 m and h=10 m, respectively.

WIND EVENTS

The variation of the wind speed on-site means there are different times when a "window" matches the wind velocity profile and turbulence intensity expected from a given standard (the standards being instructions on defining relevant test conditions for structural design for wind actions). The kernel density estimate is shown in Figure 4,. The 1 m and 10 m wind measurements aggregated into 10-minute periods. Also shown, in a red box, are the time periods where the wind has a form that simultaneously fits within the AS and ASCE standards fitted profiles for the 10 m to 1 m wind speed ratio and the turbulence intensity. Note that in Figure, wind speeds below 2 m/s have been removed. Similar regions can be found that fit other requirements. The large volume of data provides sufficient input for analysing a range of such requirements.

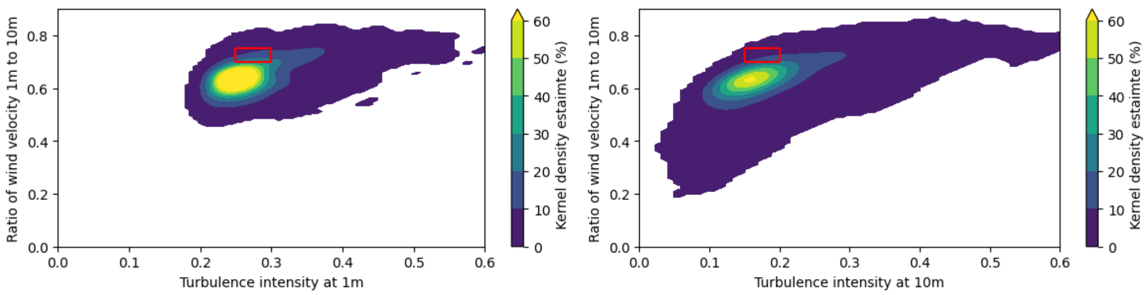

Figure 4 - Representation of the on-site data as a function of key wind metrics, being the ratio of the 1m to 10m wind velocity and the turbulence intensity at (top) 1 m and (bottom) 10 m. The red box represents the region which is expected from standards. The white area is empty.

BEAM UPLIFT FORCE COEFFICIENTS (C_F)

The Beam uplift force coefficient C_F was defined within a time window (w). In this analysis, the size of the window was varied from 10 to 30 minutes For a given interval, we define

$$\hat{C}_{F,w} = \frac{2F_{\text{lift},w}}{\rho v_w^2} \qquad (1)$$

To resolve a value of, $\hat{C}_{F,w}$ we must define:

i. The window size (T_w) is varied between 10 and 30 min. Where the maximum force $F_{\text{lift},w}$ is determined
ii. v_{gust} as different gust durations between 3 and 30 s
iii. The statistic to aggregate the wind speed time series from gust duration to the windows period. For a given window, the maximum gust velocity is taken to insertion into Equation 1. Possibly not simultaneous with Uplift Force.

RESULTS

For a period of 37 days in 2024, we examine the h = 1 m instantaneous wind speed, *v*, and the instantaneous beam end force, *F* (per Equation 1). Determining a force coefficient requires a 10 m wind speed. To fulfil this, the 1 m wind speed data was scaled to an assumed 10 m wind speed using the standard power law relationship for wind with height and an exponent of 0.14, resulting in

$$v_{10m} = v_{1m}\left(\frac{1}{10}\right)^{-0.14} \qquad (2)$$

This provides that the 10 m wind speed is expected to be 1.38 times faster than the 1 m wind speed for a TC2 AS 1170.2

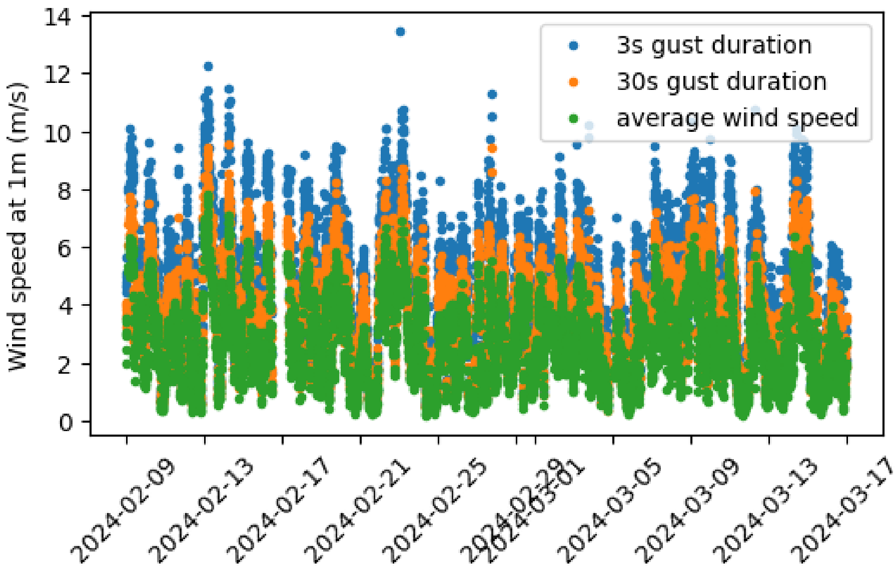

Figure 5 - The time series of the wind analysed in this report shows the 3 s gust, 30 s gust, and average wind speed in a 10-minute period for a height of 1 m.

Force Coefficients Is Not Sensitive to Wind speed

The beam force coefficient C_F was determined for Beam End 7 when the wind approached from the SSW. Similar results (with respect to convergence, as opposed to the absolute scale of response) are seen from other beams and directions. C_F is constant and independent of wind speed. The value of C_F is significantly below the results obtained from the wind tunnel. The data below 2 ms^{-1} shows significant variance and is expected to arise from a low signal-to-noise ratio. The dip of C_F at higher wind speeds is related to a lack of events at these wind speeds, shown in the following figure; very few events are above a 3 s gust speed of 12 m/s.

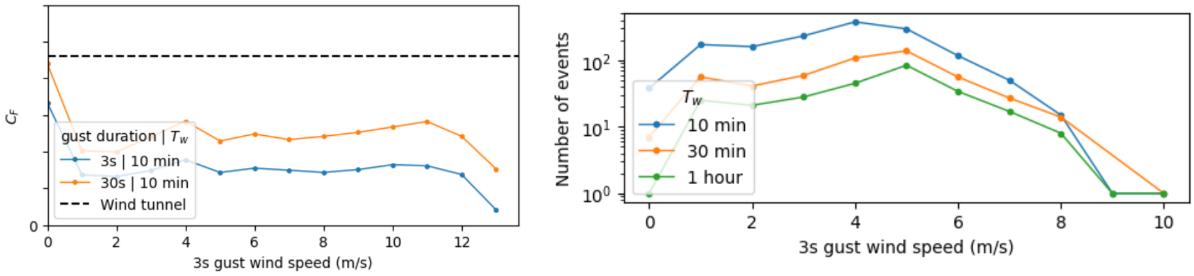

Figure 6 - (Left) C_F determined as a function of 3 and 30-second gust speed, using the 1 m data scaled to 10 m. (Right) Number of events used in the analysis of the top. Data is for wind direction from south-southwest on beam end 7.

Force Coefficient is sensitive to the gust duration but not to window size (Tw)

C_F is sensitive to the gust duration but insensitive to the window duration. The determined C_F for beam end 7 is shown in the following figure. The data is limited to the wind coming from SSW and shown as a function of the window width (T_w). Based on the conclusions of its insensitivity to wind speed, we limited the range of 3-second gust speeds that were analysed to be between 2 m/s and below 12 m/s. The lower limit is to remove values with low signal-to-noise, and the upper limit is to remove events with a low number of events where the wind speed was not sufficiently sampled.

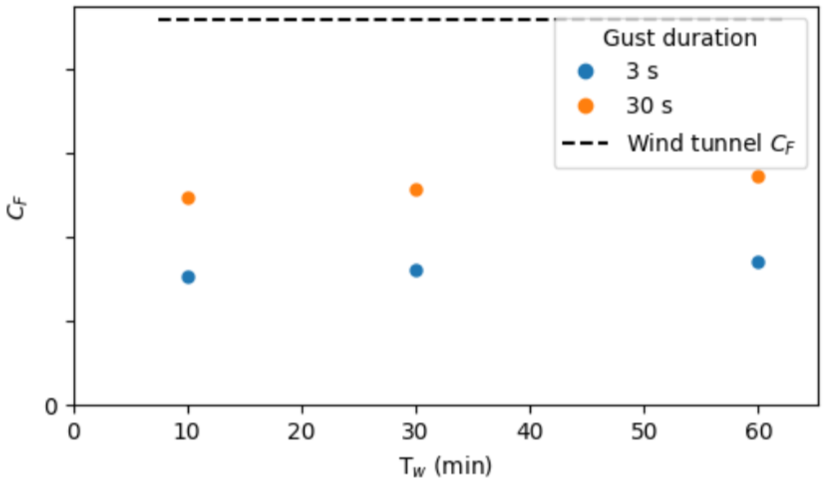

Figure 11: Mean force coefficient determined as a function of the window, for different gust durations for wind speeds greater than 2 m/s, less than 12 m/s and wind coming from SSW, over a 37 day period.

CONCLUSION

In summary:

i. C_F is consistent between different window sizes (T_w).

ii. C_F increases with gust duration, as expected. This is because an increased gust duration has a lower gust velocity, leading to a higher C_F.

iii. C_F is independent of wind speed for wind speeds above 2 m/s for a given gust duration. This confirms that the system is reacting quadratically with wind speed. Therefore, The system is in the convergent regime, and the findings may be extrapolated to higher wind speed events. There is no indication that any change in the spectral content of the excitation with wind speed will result in a different mode(s) of response from the structure. Hence, design wind loads can be contained without the requirment for a "high wind event".

iv. C_F for beam end uplift determined from full-scale data was less than half of what was estimated from wind tunnel experiments.

Further investigation is being undertaken with a pre-eminet wind engineering firm on the sources of the discrepancy between full-scale and wind tunnels.

REFERENCES

Standards Australia, (2021), "Structural design actions. Part 2 Wind actions", Australian/New Zealand Standard, **AS/NZS 1170.2:2021.**

American Society of Civil Engineers (2021), "Minimum Design Loads and Associated Criteria for Buildings and Other Structures", **ASCE 7-22**

American Society of Civil Engineers (2021), "Wind Tunnel Testing for Buildings and Other Structures", **ASCE 49-21**