Simultaneous nett wind pressures on loose-laid pavers

R.O. Denoon[1] and G.S. Wood[2]

[1] CPP Inc., 2400 Midpoint Drive, Suite 190, Fort Collins, Colorado 80525, USA, Ph: +1 970 221 3371, e-mail: rdenoon@cppwind.com

[2] Cermak Peterka Petersen Pty. Ltd., Unit 2, 500 Princes Highway, St. Peters, NSW 2044, Australia, Ph: +61 2 9551 2000, e-mail: gwood@cppwind.com

Abstract

An analysis technique has been developed to estimate the nett wind pressure acting on external loose-laid pavers. These elements are typically laid on outdoor building terraces, balconies, and rooftops. On high-rise buildings with pedestrian access, the volume of space under the pavers can be relatively high to allow for sub-floor drainage. The size of gaps between and beneath the pavers controls the filtering of the external pressure and the propagation to the underside of the paver. These gaps are too small to model at scale due to significant Reynolds Number issues and have to be considered at full-scale. A parametric experimental study has been conducted on prototype-scale samples using high-frequency simultaneous pressure measurements to determine the admittance function in the frequency domain to correct the topside pressure to the underside pressure. The appropriate transfer function for the known geometry allows for pressure time series measured on model scale terraces to be converted to a fluctuating cavity pressure, hence a time series of nett pressure on the paver. The peak nett pressure on the paver can then be extracted to determine the thickness of paver required to resist the uplift wind force.

Introduction

The majority of research in this field has been conducted on flat roofs, Bienkiewicz and Meroney (1988), Bienkiewicz and Sun (1992), Bofah et al. (1996), Gerhardt et al. (1990), Kind (1994), Mooneghi et al. (2014), and Sun and Bienkiewicz (1993). However, loose-laid pavers and other porous elements are installed on accessible balconies and terraces over the height of building, and on podium and plant levels on high-rise structures. These materials are used for practical and aesthetic reasons.

Loose laid pavers are routinely installed on the outdoor areas of medium to high rise buildings. These elements must be designed for wind loading. The wind loading on such elements is a combination of the topside pressure and the underside pressure. The topside pressure is primarily determined by the geometry of the building whereas the wind pressure developed in the common cavity below the elements is an integration of the topside pressure leaking through the gaps between pavers. This is particularly important for podium roof or mid-height terrace elements on the building where the topside pressure on various areas of the paver system could be significantly different resulting in the common cavity pressure being markedly different to the local topside pressure. The speed of pressure equalisation is a function of the spacing between, and thickness of the elements, as well as the cavity volume under the elements.

The supports for the pavers generally have vertical elements to provide efficient installation and maintain the spacing between pavers. This has the ability to offer some resistance to both a vertical uplift and an overturning failure mechanism although the magnitude of such resistance is difficult to quantify and rely upon. However, the resistance to overturning moment is expected to be greater than the resistance to vertical uplift and this is the failure mechanism which has been considered in this study.

The true nett wind load would lie between two extremes: instantaneous equalisation or no equalisation. Without knowledge of an accurate transfer function, the conservative approach would be to ignore the cavity pressure and assume that the self-weight of the paver must resist the topside wind load. Thus for a 2 kPa design wind pressure, the paver would have to be about 80 mm thick, which is evidently impractical. However, it is generally assumed in the industry that the speed of equalisation is nigh instantaneous, hence the cavity pressure is similar to the topside pressure resulting in the nett wind load being essentially zero. With this design logic, very thin elements are used and routinely removed from terraces. A typical 20 mm thick stone paver would be able to resist an uplift pressure of about 0.5 kPa, well below typical design levels.

The gap between individual elements on accessible areas is generally less than 5 mm to avoid stiletto heels being trapped, or small objects falling into the cavity. Due to the small gap, predicting the design wind load at model scale is difficult, as the physical characteristics causing equalisation become important.

To predict the nett wind load on these elements, it is beneficial to use the pressures measured during standard simultaneous wind tunnel pressure testing to measure the topside pressure. The cavity pressure would then be estimated via a transfer function based on generic testing conducted at full-scale.

Experimental set-up

A series of full-scale tests were conducted in the CPP boundary layer wind tunnel in Sydney, Australia, Figure 1. The wind tunnel test section is 3.0 m wide, by 2.4 m high with a porous slatted roof for passive blockage correction. This wind tunnel has a 21 m long test section, the floor of which is covered with roughness elements, preceded by a vorticity generating fence and spires. The generic test for balcony and terrace pavers was aimed at determining the pressure transfer function from the topside to cavity, hence the incident turbulence along the fetch was considered relatively unimportant as the size of the gaps between pavers and volume of cavity would act as a low-pass filter therefore all large scale pressure fluctuations would be transferred uniformly to the cavity. To vary the temporal and spatial higher frequency pressure distribution over the top surface, the roughness elements along the fetch and paver enclosure geometry were varied. For similar reasons the tests were conducted for a single wind direction normal to the front edge of the enclosure.

Figure 1: Photos of wind tunnel with various test configurations

The test enclosure consisted of a fully sealed box approximately 3 m wide and 1.5 m in the direction of flow. The test allowed in excess of 15 elements to be included in each test configuration. Three elements were instrumented with up to 15 pressure tappings on both the topside and underside of the paver.

To model the influence of a rainwater outflow in the cavity pressure, a 500 mm long slot 50 mm high was introduced in the centre windward side of the test enclosure. Descriptions of the testing configurations are presented in Table 1.

Table 1: Configurations for data acquisition

Paver size (LxWxH) /mm	Cavity height /mm	Gap width /mm	Upstream slot	Incident turbulence	Leading edge
900x300x40	250	5	Open	Low	Constant
900x300x40	250	5	Closed	Low	Constant
900x300x40	250	10	Closed	Low	Constant
900x300x40	250	10	Open	Low	Constant
900x300x40	250	15	Open	Low	Constant
900x300x40	250	15	Closed	Low	Constant
900x300x40	150	15	Closed	Low	Constant
900x300x40	150	15	Open	Low	Constant
900x300x40	150	10	Open	Low	Constant
900x300x40	150	10	Closed	Low	Constant
900x300x40	150	5	Closed	Low	Constant
900x300x40	150	5	Open	Low	Constant
900x300x40	50	5	Open	Low	Constant
900x300x40	50	5	Closed	Low	Constant
900x300x40	50	10	Closed	Low	Constant
900x300x40	50	10	Open	Low	Constant
900x300x41	50	15	Open	Low	Constant
900x300x42	50	15	Closed	Low	Constant
900x300x43	50	10	Open	High	Constant
900x300x44	50	10	Closed	High	Constant
900x300x45	50	10	Open	High	Constant
900x300x46	50	10	Open	High	Constant
600x300x40	60	4	Closed	High	Stepped
600x300x40	60	4	Closed	Low	Stepped
600x300x40	60	4	Closed	High	Constant
600x300x40	60	4	Closed	Low	Constant
600x300x20	60	4	Closed	High	Constant
600x300x20	60	4	Closed	Low	Constant
600x300x20	60	4	Closed	High	Stepped
600x300x20	60	4	Closed	Low	Stepped

Simultaneous pressures were measured at each of the pressure taps. An additional transducer was used to simultaneously measure the reference pressure, q, using a Pitot-static tube mounted in the wind tunnel from which the reference velocity, U_{ref}, is calculated. A sample corresponding to five minutes at full-scale was recorded at a sampling frequency of 80 Hz for each configuration. Pressures on the top and bottom surfaces were area averaged to create a single differential pressure time series for each element and configuration.

As the failure mechanism will occur during an extreme peak event, which may not be described completely with a frequency domain approach, the results have been analysed in both the time and frequency domains. If reductions in the time and frequency domain are similar then a simple transfer function or reduction factor can be employed with measured results on small scale tests.

Typical simultaneous pressure coefficient results in the time domain are presented in Figure 2. This clearly shows that the underside pressure is similar across the whole area. It is evident that the average of the peak topside pressures is similar in magnitude to the underside pressure, but the frequency content and phase varies. These results are for configuration 23, which had a stepped leading edge to produce a large spatial pressure difference and the three panels were not on different sides of the step in the flow direction. The results for all configurations illustrated that the peak negative nett pressure received a minimum reduction of about 60% compared with the topside pressure.

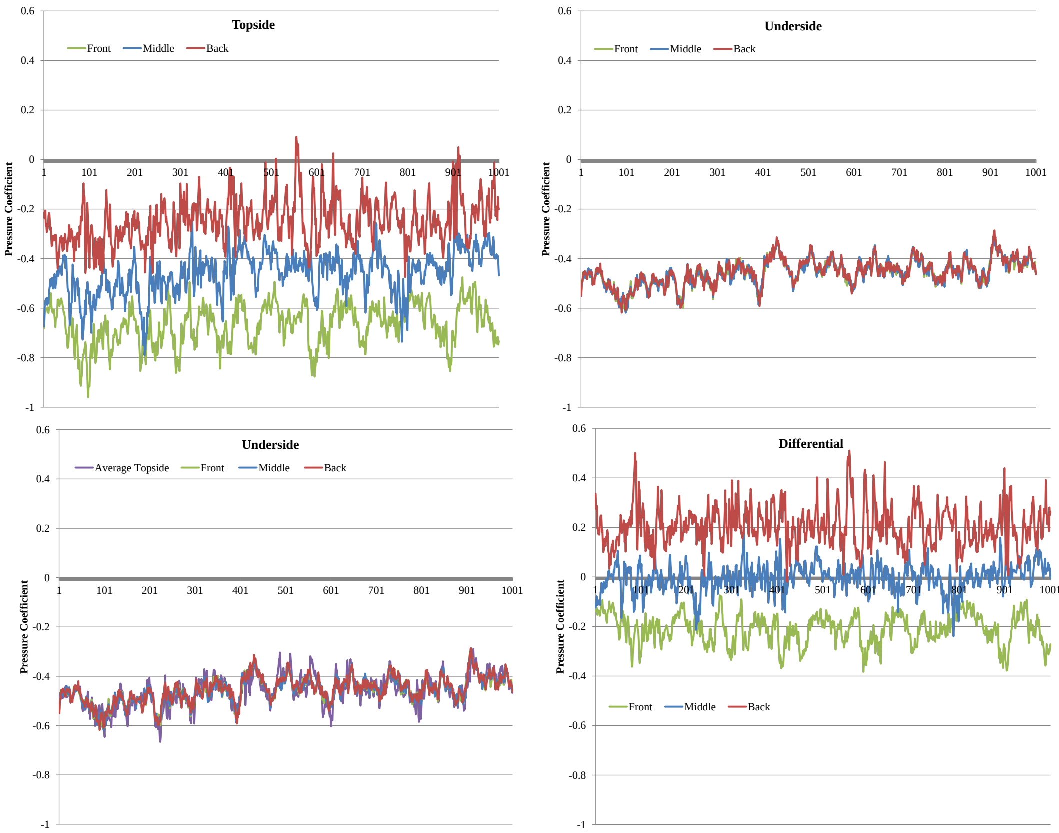

Figure 2: Typical paver pressure coefficients for configuration 23

A frequency domain analysis was conducted to determine whether the topside pressures could be used to predict the underside pressure. Topside and underside spectra for the three instrumented panels are shown in Figure 3. These spectra are for the integrated loading on a single paver surface. It is evident that for all locations the gaps between the pavers act as a low pass filter, reducing the high-frequency content in the cavity. The largest difference between the topside and underside spectra is for the front element. This would produce the highest nett dynamic load on the paver. The ratio between the cavity pressure and the topside pressure, Figure 3, is an aerodynamic admittance function for the propagation of topside pressure to the underside cavity.

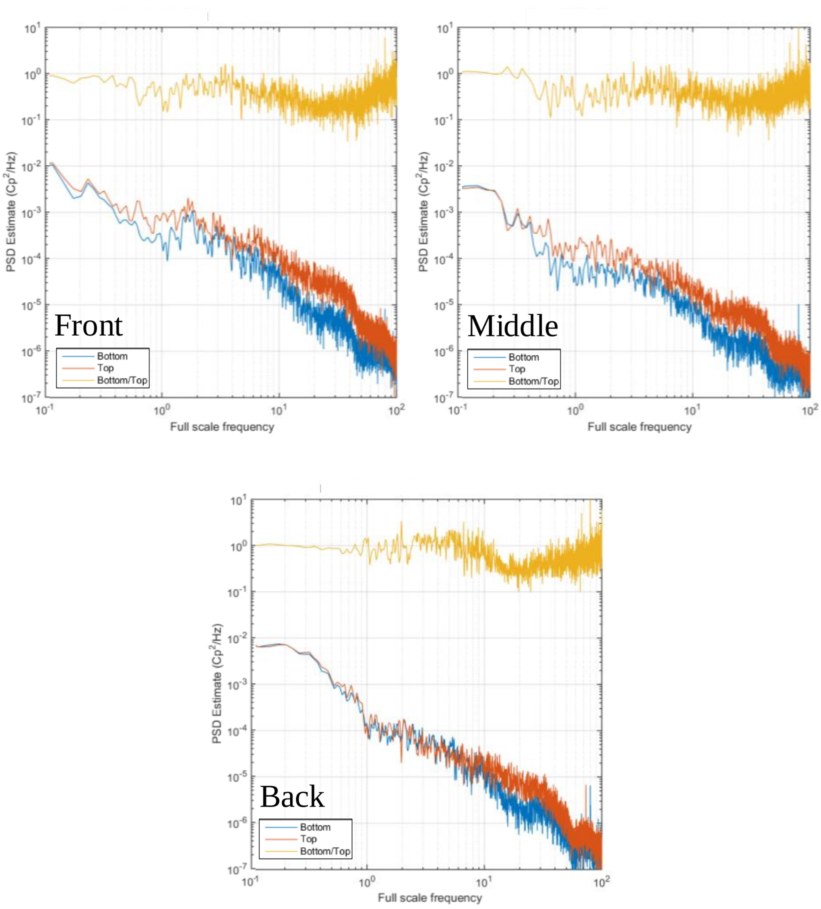

Figure 3: Spectra of integrated surface pressure coefficients

The results from the testing with an open slot on the front wall did not significantly change the peak differential pressure on an individual sample, nor the pressure spectra. The reason for this is that the total area of the gaps between the pavers is about three times that of the slot area for a 5 mm gap between pavers on the test box, hence the underside pressure is more dominated by the topside open area. As the paved area increased in size, the influence of any slot would decrease.

Although the gap size and cavity volume influence the peak results in the full-scale test, the aerodynamic admittance function was similar with the propagation frequency of the topside pressure to the cavity being filtered at a similar frequency band. The shape of this function was relatively constant for all configurations tested with the low frequency content being fully transmitted to the underside and starting to reduce from about 0.3 Hz full scale for the front paver extending to about 10 Hz for the rear paver. It should be noted that if the admittance function was equal to unity for all frequencies, the dynamics of the underside pressure would be the same as the topside and the nett load would approach zero.

Area averaging the topside pressure over all panels and applying a worst case enveloped transfer function to the large-scale measurements provided a conservative response compared with the simultaneous time domain approach. The reduction in peak nett pressure was about 50% compared with the topside pressure.

Discussion

The relatively constant spectral results permits an effective low-pass filter duration of turbulence to be developed, which allows the time series of surface pressure coefficient results from small scale tests to predict the simultaneous underside cavity pressure coefficients and thereafter the differential pressure coefficient on the pavers.

For ease of installation, it is considered unlikely that the thickness of paver would vary across a paved area. For any open paved area, the worst case nett loading will occur on elements where the topside pressure is significantly different to the average topside pressure. For paver uplift this will occur where the topside pressure is lower, which will tend to occur at the exposed edges of terraces, roofs, or balconies. Once the paver has been lifted, the differential pressure on the surfaces of the paver will be dictated by the local wind speed and direction and will govern the flight path of the paver. If the paver is behind a balustrade on a small balcony or terrace, or a significant parapet, the local wind speed would be expected to be relatively low and although the paver may be dislodged, it would not necessarily be removed from the building.

Model Scale

Extrapolating the results to model scale requires care with the frequency scale. The technique described was used to investigate the wind loads on loose laid paver areas on a medium-rise building. A 1:400 scale model of the development was tested for design cladding pressures. The external pressure for a typical balcony location is presented in Figure 4 along with the enveloped aerodynamic admittance function at model scale.

A Fast Fourier Transform was conducted on the time series to convert to the frequency domain. This was factored by the admittance function to estimate the cavity pressure under the small balcony area and then converted back to the time domain. A comparison of the top, underside, and nett pressure coefficient on the balcony area is presented in Figure 5. It is evident that for a small area represented by a single tapping location there is a significant reduction in design pressure on the paver.

Estimating the cavity pressure using two pressure tappings on a single face of a building and combining with the single topside pressure resulted in only a marginal increase in the peak differential pressure. The reason for this is that the low frequency component of the pressure fluctuation is well correlated over the façade, while the high-frequency component is filtered out of the cavity pressure. The peak nett pressure only changes by about 5%.

Estimating the cavity pressure using surface pressures on different faces of a building, representing a corner balcony terrace resulted in a more significant increase in the peak differential pressure, due to the significant difference in the mean and low frequency pressure on the two building faces.

The ultimate limit design topside pressure would have resulted in a paver having a thickness of about 140 mm assuming a constant cavity pressure. With the confidence of the transfer function the thickness of the paver reduced to about 30 mm using two pressure tappings to predict the cavity pressure. For corner balconies this increased to about 70 mm and therefore the cavity should be segmented to ensure propagation of an equalising pressure.

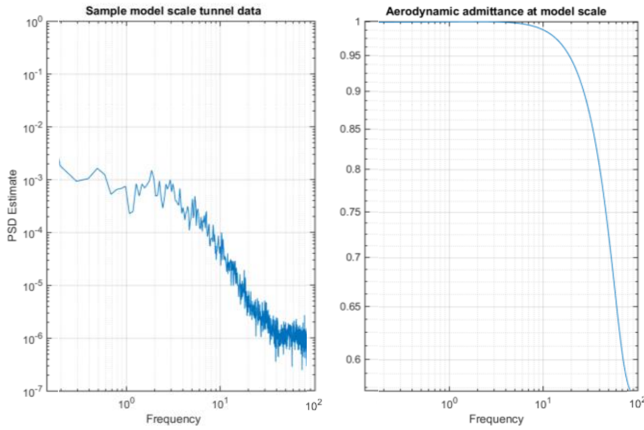

Figure 4: Spectrum of surface pressure and aerodynamic admittance function at model scale

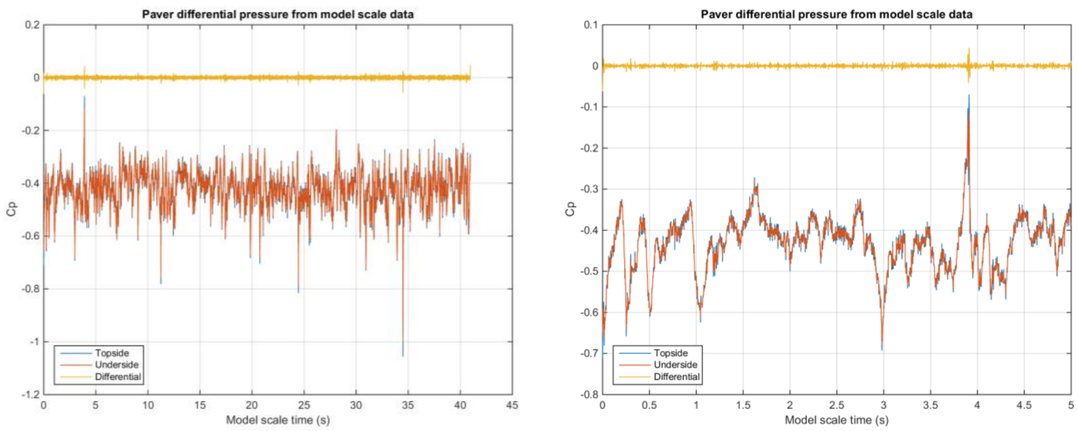

Figure 5: Pressure time series from test location

Conclusions

A technique has been developed to estimate the cavity pressure beneath loose-laid pavers using wind-tunnel measurements on full-scale samples. For the standard range of pavers tested from 600-900 x 300 mm pavers, 20-40 mm thick, the transfer function to estimate the cavity pressure from the topside measurements was similar for a wide range of incident wind conditions, external opening configurations, and cavity volumes. As the area of paver coverage increases, the low-pass filter characteristics would be expected to remain the same.

An enveloped aerodynamic transfer function was developed to allow the cavity pressure to be estimated from the topside pressure measurements thereby allowing the design differential pressure to be conservatively estimated from surface pressure measurements on a small scale sample.

For large areas the cavity volume under an area wrapping around different facades of a building should be compartmentalised to minimize high pressure deviations from the mean topside pressure. This is particularly the case for mid-height terraces around the building perimeter when the peak differential pressure can be in excess of the topside pressure. This essentially requires the cavity to be compartmentalised into areas of relatively constant pressure, which is generally easy to achieve to match drainage areas.

REFERNCES

Bienkiewicz, B., and Meroney, R.N., 1988. Wind effects on roof ballast pavers. J. Eng. Struct. 114, 1250–1267.

Bienkiewicz, B., and Sun, Y., 1992. Wind-tunnel study of wind loading on loose-laid roofing system. J. Wind Eng. Ind. Aerodyn. 43, 1817–1828.

Bofah, K.K., Gerhardt, H.J., and Kramer, C., 1996. Calculations of pressure equilibration underneath loose-laid, flow permeable roof insulation boards. J. Wind Eng. Ind. Aerodyn. 59, 23–37.

Gerhardt, H.J., Kramer, C., and Bofah, K.K., 1990. Wind loading on loosely laid pavers and insulation boards for flat roofs. J. Wind Eng. Ind. Aerodyn. 36 (Part 1), 309–318.

Kind, R.J., 1994. Predicting pressure distribution underneath loose laid roof cladding systems. J. Wind Eng. Ind. Aerodyn. 51, 371–379.

Mooneghi, M.A., Irwin, P., and Chowdhury A.G. 2014, Large-scale testing on wind uplift of roof pavers. J. Wind Eng. Ind. Aerodyn. 128, 22–36

Sun, Y., Bienkiewicz, B., 1993. Numerical simulation of pressure distributions underneath roofing paver systems. J. Wind Eng. Ind. Aerodyn. 46–47, 517–526.