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Wind Loads on Suspended Conical Roof Structures

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Abstract

Conical shaped suspended structures utilised for dust control off stockpiled product are used throughout Australia and the world. The action effects of wind on this style of structure lacks understanding within the engineering field and little guidance can be drawn from common standards and codes. This paper discusses wind tunnel model experiments carried out on a typical Stockpile Cover structure geometry and makes comparison against common Standards and relevant literature for the "Empty Stockpile" case. The results found substantial difference in pressure, drag and lift coefficients in comparison with AS1170.2, and similar external pressure patterns with Okamoto (1977) albeit with changing magnitudes. In addition, average lift and drag coefficients appeared to be similar with the Okamoto study.

Introduction

Many industries such as mining require stockpile covers as shown in Figure 1, for the control and mitigation of wind borne dust off the bulk product stockpiles for various reasons, including environmental and employee/public health drivers.

Figure 1. Example Ore Stockpile Cover.

Due to the economic pressure being applied to the resources sector largely from volatile mineral prices, mining companies are being led to focus on differing aspects of their business to remain viable and competitive. These include:

- Asset management whereby grasping an accurate representation of the risk leads to rationalised and strategic spending, and;
- Searching for new and economical ways to reduce costs for major project implementation and sustaining capital.

Wind Load and Stockpile Cover Design

The typical design of Stockpile Covers will follow the expected geometric shape of the bulk material being stockpiled. Of critical importance is the friction and repose angle of the material, and overall storage size requirements of the stockpile.

The structural system that makes up the Cover will typically include a series of ring beams with radial rafters spanning between them, with the lower ring beam supported by columns or other such bracing/propping arrangement that may be submerged in the stockpiled material depending on its operating volume.

Wind loading is a major consideration when assessing critical loads and load cases during the analysis of such structures. In Australia, guidance for how wind loads are applied to this shape is typically drawn from Section C5 of AS/NZS1170.2. Section C5 applies to Bins and Silos, which are completely enclosed and commonly have different aspect ratios. Therefore internal pressures are not considered, which are present for Stockpile Covers. It is important to note that the degree of blockage by the stockpiled material, and therefore internal pressures can be highly variable depending on external factors such as design volume, feed rate, reclaim rate, mining, milling, transportation or ore and processing operations.

Limited research has been undertaken on wind loading of similar themes with the most relevant by Okamoto et al (1977) who studied flow past a cone on a flat plate. This study observed external pressure coefficients, lift and drag coefficients and formations of vortex shedding that was dependent on Reynolds number. However, their experiment was for a completely enclosed structure that only considered external pressure fluctuations.

This paper analyses data from an experimental investigation that was undertaken by Peoples (2014) on a typical Stockpile Cover to determine the wind loads for designing structural components for this type of structure.

Methodology

The Cover shown in Figure 2 consists of a conically shaped roof which is supported on 14 m high columns and is comprised of 24 equal segments supported by ring beams. A 3.2 m diameter hole is located at the apex of the structure through which the ore is deposited. The overall structure has a peak roof height of 32 m and maximum roof diameter of 57m.

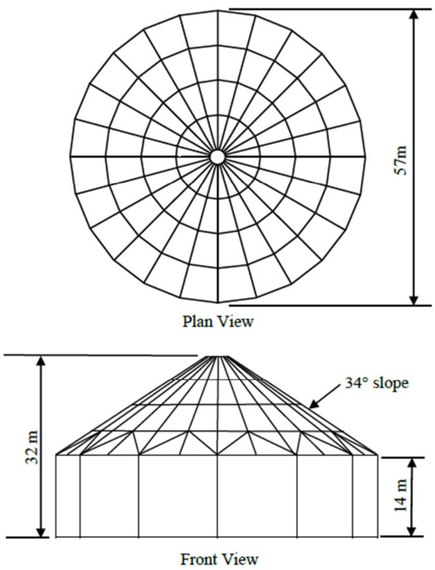

Figure 2. Stockpile Cover investigated

A wind tunnel model study was constructed at a length scale of 1/100 in the 2 × 2.5 × 22 m Boundary Layer Wind Tunnel at the College of Science Technology and Engineering at James Cook University.

An approach terrain representative of Terrain Category 2 as per AS/NZS1170.2 (2012), at a length scale of 1/100 was simulated using carpet and 40 mm cubic blocks as floor linings in the wind tunnel, and the Atmospheric Boundary Layer was satisfactorily simulated.

A model of the Stockpile Cover structure was constructed from Perspex at a scale of 1:100. Pressure taps were installed on the external and internal surfaces of the segments. External and internal pressures are measured on 6 panels (60 taps) simultaneously. These taps are used obtain the external, internal and net pressures on the Stockpile Cover.

Tests were carried out for three ore configurations; 1) Empty stockpile, 2) 50% Stockpile capacity and 3) 100% Stockpile capacity as shown in Figures 3, 4 and 5 respectively.

Figure 3. Case 1: Stockpile Cover Empty Model

Figure 4. Case 2: 50% Stockpile Capacity Model

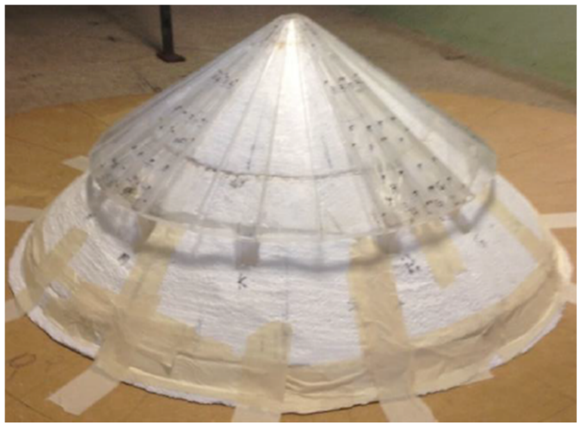

Figure 5. Case 3: 100% Stockpile Capacity Model

Results

External and internal pressures were measured for a period of 18 sec (equivalent to 10 minutes in full scale). Data collected over this time were analysed to find the mean, standard deviation and minimum and maximum pressure coefficients.

Three repeat runs were carried out, and the average of the pressure coefficients obtained from these runs; $C_p = p/(\frac{1}{2}\rho\overline{U}_h^{2})$, where, $\frac{1}{2}\rho\overline{U}_h^{2}$ is the mean dynamic pressure at height h = 32m.

The pressure acting towards the surface is defined positive and the net pressure = (external-internal) pressure.

Case1: Empty Stockpile

Figures 6, 7 and 8 show the external, internal, and net pressures measured on the cover for the Empty Case.

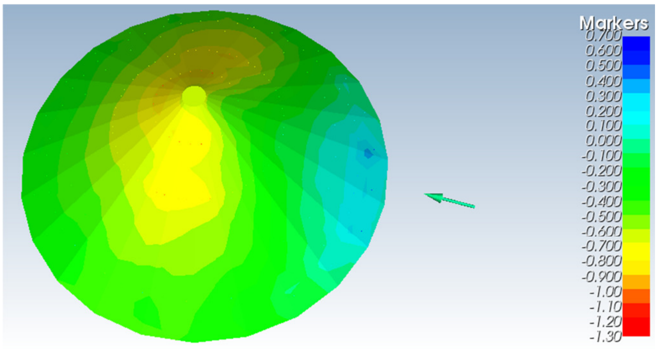

Figure 6. Case 1: Mean External Pressure Coefficients

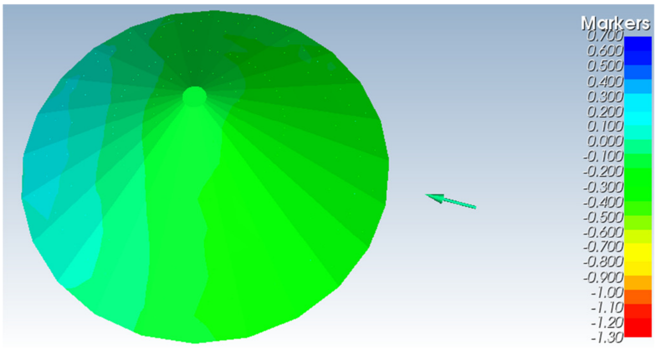

Figure 7. Case 1: Mean Internal Pressure Coefficients

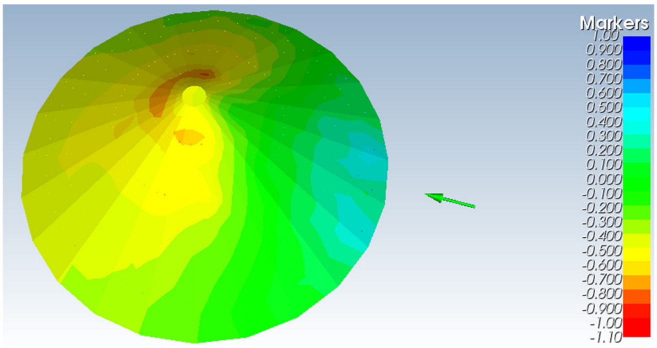

Figure 8. Case 1: Mean Net Pressure Coefficients

The mean external pressure coefficient distribution in Figure 6 shows positive pressures being induced on the lower-mid part windward side of the structure which gradually reduce as the wind moves laterally around the structure. The positive pressures extended around the front on the structure before peaking as negative pressure at the sides of the structure in the separation region. The pressures then gradually decrease around the leeward side (wake region) of the structure.

It can also be seen that in each panel/section of the structure, the magnitude of negative pressure increases as the wind passes up the cover, culminating with the largest negative pressures of each panel near the apex. The negative pressures occur at the apex on all sides structure, including the windward part. The leeward side of the structure generally experiences negative pressure.

The mean internal pressure coefficient distribution shown in Figure 7 produced a distinguishable pattern. It shows that the large negative pressures were induced at the windward edge of the structure as the flow separates, which then decrease around the sides of the structure until becoming positive in the middle of the inside leeward side. These positive pressures extended up the most of the roof height, except near the apex where the pressures were found to be negative.

The net mean pressure distribution produced similar patterns to the external pressure distribution, and resulted in positive pressures acting locally around the windward edge of the structure and part way towards the apex, with the majority of the rest of the structure experiencing negative pressures.

Discussion

An engineer would typically refer to the most relevant standard to seek information in regards to the loading applicable, in this instance, AS/NZS1170.2 Section C5. At best, this could be used as a guide to understand external pressure coefficients acting on conical roof structures, albeit completely enclosed underneath. This Standard indicates external pressure coefficients of -0.8 for the windward edge to -0.5 at the apex.

From Figure 6, it can be seen that the external pressure for the Stockpile cover varies across the surface of the roof, with positive pressures at the windward side and higher negative pressures in the region of the apex. These results do not match Section C5 of AS/NZS1170.2. The experiments show a reversal in the windward pressure direction (comparing negative pressure in the Standard, to positive pressure measured in the experiment).

Internal pressure coefficients as shown in Figure 7 indicate the majority of the internal roof surface is experiencing a suction effect, perhaps likely due to flow separation that commences at the windward lower edge of the roof. A positive pressure region was observed in the leeward 1/3rd of the roof area. This suggests that the most turbulence inside the roof occurs directly behind the windward edge and the turbulence intensity drops towards the leeward edge.

Okamoto et al (1977) found external pressure coefficient patterns on a cone placed on a flat plate, with a surface incline angle of 30^{o}, that appear to resemble patterns shown in Figure 6. Their study found that positive pressures coefficients existed from the windward edge of 0.4, then progressively becoming negative in value at approximately 2/3 the distance towards the apex from the windward edge. The study also found peak negative pressures occurring around the sides of the surface in the separation region. The study supports the finding of wind shear flow separation occurring at the sides and apex of the surface in the current experiment. However, the magnitude of mean pressures are generally higher than that found in the Okamoto study. This is perhaps due to differing incline angles between the two experiments, surface texture, unknown turbulence intensity profile, and the impacts of the cone sitting on a flat plate.

Lift and Drag

Drag and Lift force coefficients C_D and C_L based on the experimental data described here are derived using the following Equations 1 and 2 respectively.

$$C_D = \frac{F_D}{0.5\rho U_h^{\,2} A} \qquad (1)$$

$$C_L = \frac{F_L}{0.5\rho U_h^{\,2} A} \qquad (2)$$

Here F_D is the drag force, F_L is the lift force and A is the reference area.

The external and internal pressures measured at each tap within each patch were averaged to obtain net pressure acting on each patch. The lift and drag force from each segment are given by the Equations 3 and 4 and Figure 9.

$$F_L = \sum_{j=1}^{4} p_j A_j \cos\alpha \quad (3)$$

$$F_D = \sum_{j=1}^{4} p_j A_j \sin\alpha \cos\theta \quad (4)$$

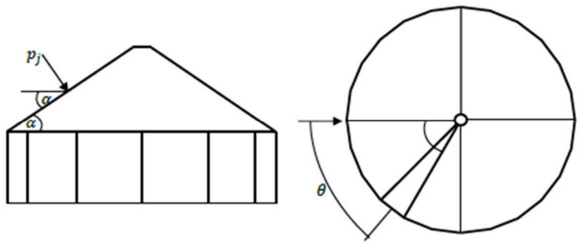

Figure 9. Reference Angles for Equations (3) and (4)

These values are then combined with the applicable reference areas for lift and drag as shown in Figure 10.

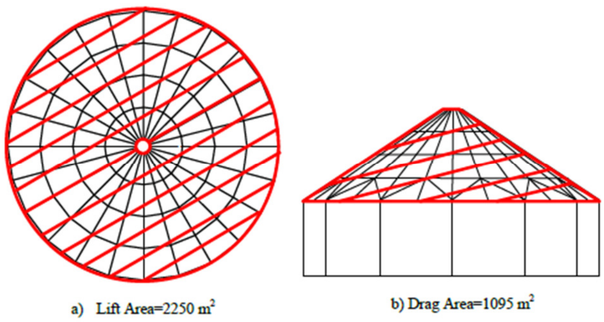

Figure 10. Reference areas for Lift and Drag

The mean for lift and drag are presented in Table 1, along with comparison of typical shapes previously studied (Hoerner, 1965), along with results by Okamoto et al (1977).

Table 1. Lift and Drag Coefficients from experiments and comparison with Hoerner, (1965) and Okamoto (1977).

	Experiment	Hoerner Conical Shape	Okamoto Cone incline angle 30°
Lift (net)	-0.265	NA	-0.324
Drag (net)	0.309	0.7	0.320

The sign convention for the Lift is positive in the vertical direction towards the ground, and for Drag positive in the wind direction.

It can be seen that the Drag coefficient based on the experimental data is substantially less than that found by Hoerner (1965), albeit the aspect ratios of the structures between the two varied substantially.

Okamoto et al (1977) found that as the angle of a conical surface decreased, the Drag coefficient also decreased, however the Lift coefficient increased.

It was also found that the localised Drag coefficient on the conical surface varied from 0.5 at z/H = 0 then linearly decreasing to -0.05 for z/H = 1.0, for a surface incline angle of 30°. Overall height of the cone from the floor plate is designated as H, and z is the local distance between the floor plate to any elevation on the cone. Analysing this data, the approximate average Drag coefficient is 0.32, which appears to closely correlate with the results in the current study. The texture of the conical surface used by Okamoto et al (1977) was not able to be determined.

Okamoto et al (1977) found that as the angle of a conical surface decreased, the Lift coefficient increased. For a surface incline angle of 30°, the localised Lift coefficient on the conical surface varied from 0.1 to 0.3 for z/H of 0 to 1.0. Analysing this data, the approximate average Lift coefficient is 0.324, which appears in similar magnitude with the current study. The sign convention used in the Okamoto study is opposite to that used herein.

Comparative values for the Lift coefficient from Standards and Codes were not evident, however it is noted that the experimental results indicate a substantially smaller value than that which could be derived from adapting Section C5 of AS/NZS1170.2.

Further Work

The research of this topic is ongoing, along with the analysis of experimental data in relation to Case 2 and 3 relating to the variable blockages under the roof structure.

Conclusions

This study to- date has concluded the following:

- There is little information or design data regarding open structures of this geometry. When compared to design data from similar shapes and structures, there were few which represented the pressure coefficients determined for the Stockpile Cover.
- Okamoto et al (1977) suggests that the lift and drag coefficients for an empty under Stockpile Cover are similar to that for flow past a conical shape on a flat plate.
- Pressure coefficients over the roof surface vary dramatically and differ substantially with AS/NZS1170.2 Section C5.
- It is unclear how designers of this type structures in the past have determined wind loadings based on the standards, codes and literature available prior to this work.

Acknowledgments

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References

Hoerner, S.F. (1965). Fluid-Dynamic Drag: Practical Information on Aerodynamic Drag and Hydrodynamic Resistance. United States of America: Published by the author.

Okamoto, T., Yagita, M., Kataoka, S. (1977) Flow past cone placed on flat plate. Bulletin of Japan Society of Mechanical Engineers, Issue 141, pp 329-336

Standards Australia. (2012). AS/NZS1170.2 Structural design actions - Wind actions. Standards Australia International Ltd.

Peoples, B (2014) Wind Loads on Coarse Ore Stockpile Covers BE Thesis, School of Engineering & Physical Sciences James Cook University, Australia