WIND EFFECTS ON PYRAMIDS

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SUMMARY

Vipac Engineers & Scientists Ltd is currently undertaking an extensive study of the wind effects on pyramid structures. The study involves the measurement of local cladding loads, global structural loads and local wind speeds around the base of the pyramid test buildings. Three basic pyramid shapes are being investigated – square base, triangular base and circular base. For each shape, a "tall": and "short" pyramid are being tested. Measurements are being taken in both open country and suburban terrain conditions. One final set of tests involves the short square pyramid placed on top of a square planform high–rise tower in an urban setting.

In this paper, some preliminary results from the study are presented.

INTRODUCTION

Relatively little documentation apparently exists as to the effects of wind loading on pyramid structures. This is perhaps an anomaly given the fact that these structures have been so prominent in the history of architecture and building.

Pyramids have been built at various times in Egypt, the Sudan, Ethiopia, western Asia, Greece, Cyprus, Italy, India, Thailand, Mexico and some Pacific islands. The most famous and probably the most remarkable are the ancient pyramids of Egypt which number over 80 and which cover a chronological time span of some 2,700 years from the beginning of the Old Kingdom to the 6th Dynasty (c. 2300 B.C.).

The most well–known are the 4th Dynasty three great pyramids of Gizeh, lying to the southwest of Cairo. The largest and oldest built by Khufu (Cheops) has an almost square base, 230m long, and measured originally 146.6m in height. Some 2,300,000 blocks of stone were used to build this pyramid, ranging from 2.5 to 16 tonnes! This masterpiece of engineering and technical skill took some 30 years to build. The road used to convey the blocks to the pyramid took by itself 10 years to finish, while the pyramid took some 20 years to construct and required the labour of 100,000 men.

We continue to see these structures in prominent locations today, e.g. I.M. Pei's famous Glass Pyramid at the Louvre; somewhat less famous is the glass pyramid located in Sydney's Royal Botanical Gardens. Most recently, there have been a spate of medium to high–rise towers both in Australia and overseas which feature pyramid roofs on the top of square and rectangular shaped buildings.

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In early 1990, the first author spent some 4 weeks working in Upper Egypt and had an opportunity to visit his birthplace in Alexandria as well as the pyramids at Gizeh. Upon returning to Australia, he determined to one day spend some time examining the effects of wind on these ancient structures.

This coincided with Vipac's recently established policy of having all core sub-groups undertake an annual research project. These projects are aimed at keeping employees in touch with academic interests and to introduce the younger engineers and scientists at Vipac to working on longer-term research oriented projects. For the 1993 project, Vipac's Wind Group chose to look at wind effects on pyramid structures.

TEST OUTPUTS

Initially the tests were designed to obtain cladding pressures and tributary area loads useful for structural load computations. However the local pressure tests revealed that for some geometries at particular angles, very high suctions were recorded at the lowest leading edge corners of the pyramids. This suggested that the local winds around the base of these models could be high for particular geometries. Consequently it was decided to extend the study to examine ground level wind effects around the base. Thus the test phases of this Vipac study are:

Phase 1: Local Cladding Loads
Phase 2: Global Structural Loads
Phase 3: Ground Level Wind Effects

The local cladding load tests have now been completed and tests are currently underway in the final two phases.

TEST GEOMETRIES

The geometries and test conditions for the model pyramids chosen for study, with a length scale of 1:400, are as follows:

Basic Shapes:	Square Base	150mm x 150mm
	Triangular Base	150mm x 150mm x 150mm
	Circular Base	150mm dia., 400mm dia.
	Building	150mm x 150mm x 285mm (ht.)
	(with short square pyramid on top)	
Pyramid Heights:	Tall	height = 1.0 x base dimension
	Short	height = 0.5 x base dimension
Terrain:	Open Country	exponent = 0.14
	Suburban	exponent = 0.24

Pressure Tap Locations

The model pyramids were made of rigid acrylic plastic and instrumented with pressure taps to measure the wind pressures. Initially 20 taps were placed on one face of each

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pyramid, with each test model rotated through a full 360° to obtain the full range of azimuthal behaviour. The test angles were at 10° increments for all pyramids with an additional tests at multiples of 45° for the square base pyramids.

For the global structural loads, advice has been received from a number of structural engineering consultants on the typical framing that would be used to support pyramid buildings of different scales. Pneumatic averaging is being used to obtain tributary area loads over these structural framing areas.

Atmospheric Boundary Layer Simulation

The models are being tested at Vipac's Boundary Layer Wind Tunnel Facility in Port Melbourne, Victoria. The wind tunnel has a working section of 3m x 2m with a fetch length of over 15m and initial trip wire fence designed to achieve a fully developed boundary layer at the downstream test section. The tunnel is powered by 10 x 10kW axial flow fans and is capable of producing mean wind speeds up to 22 m/s with correspondingly higher gust speeds.

Measured longitudinal turbulence intensities, mean wind profiles and longitudinal spectra at the pyramid apex height showed good correlation with Open Country and Suburban Terrain representative values.

Reynolds Number Similarity

In establishing pressure distributions for body shapes with an aerodynamic profile, e.g. the circular base pyramids, the requirement that Reynolds Number equality be maintained is important for dynamic similitude. The Reynolds Number, basically a product of wind speed and building typical dimension, gives the ratio of the inertial forces to viscous forces. In the case of so-called "bluff" bodies (characterised by sharp edges) the resulting flow separation and pressure distribution remain essentially unchanged over a large range **of Reynolds Number. In this case, the requirement of Reynolds Number similarity can be relaxed when determining gross reaction properties, resultant loads etc.**

The model Reynolds Number used in this study for the sharp edged pyramids is of the order of 2×10^5. To obtain a range of values for the circular base pyramids, a much larger model (400mm dia.) has been prepared to achieve a second R_E test value closer to 10^6.

Reference Pressure

The sign convention for surface pressures is **positive towards** the surface concerned and **negative away** from the surface. The initial results were normalised by the mean dynamic pressure at the reference height of the wind tunnel, corresponding to gradient height. The final presentation of the study results will use the mean dynamic pressure at the apex height of each pyramid as the reference normalising pressure.

The sampling period used in the current study was 30 seconds, and 10 x 3-second peak extreme-value analysis was used to determine the maximum and minimum values from each tap-azimuth record.

PRELIMINARY RESULTS AND DISCUSSION

Some of the local cladding results have been including in this paper.

Figure 1 shows directional pressure coefficients (angle = 0°) for the square tall pyramid in open country terrain. The maximum, mean and minimum coefficients are given in Figs.1a, 1b and 1c respectively. The mean coefficients (Fig.1b) range from 0.1 at the bottom corners to just over 0.4 in the middle of the windward face. The leeward face sees constant pressure coefficients of about −0.3. The side face pressure coefficients range from −0.2 to over −0.8 near the leading edge. The maximum (Fig.1a) and minimum (Fig.1c) values indicate that, in the extreme, the pressures can increase by more than double relative to the mean values.

Figure 2 shows the peak maximum and minimum local loads for ALL wind angles for a number of the square test pyramids.

In open country terrain (Fig.2a), the square tall pyramid (height=base dimension) exhibits maximum positive pressure coefficients ranging from just less than 0.6 to slightly over 1.0. In suburban terrain (Fig.2b), they range from 0.6 up to only about 0.8. The peak negative pressures in open country terrain range from −1.0 to just over −2.2. The corresponding range in suburban terrain is −0.8 to −1.6.

These values all reduce by about 25% for the "short" square pyramids in comparable terrain conditions (Fig.2c). Peak negative coefficients near the base of the pyramids are just over −1.6.

For the short square pyramid on top of the square building (Fig.2d), the peak positives in open country terrain are very comparable to the pyramid alone condition (no building). However, the peak negatives see a dramatic increase so that the leading edge corner pressure coefficient is just below −3.0.

Two examples are given for the peak pressure coefficients of the tall triangular base pyramid in Figures 3a,b for open country and suburban terrain. It can be seen that compared to Figs. 2a,b, the corner coefficients are generally higher, reflecting the more acute angle which the windflow must negotiate for the triangular pyramid shapes.

Some of the more interesting azimuthal variations in the tests data obtained to date will be discussed showing varying cases of re−attachment of the flow on the different pyramids and other unique loading characteristics.

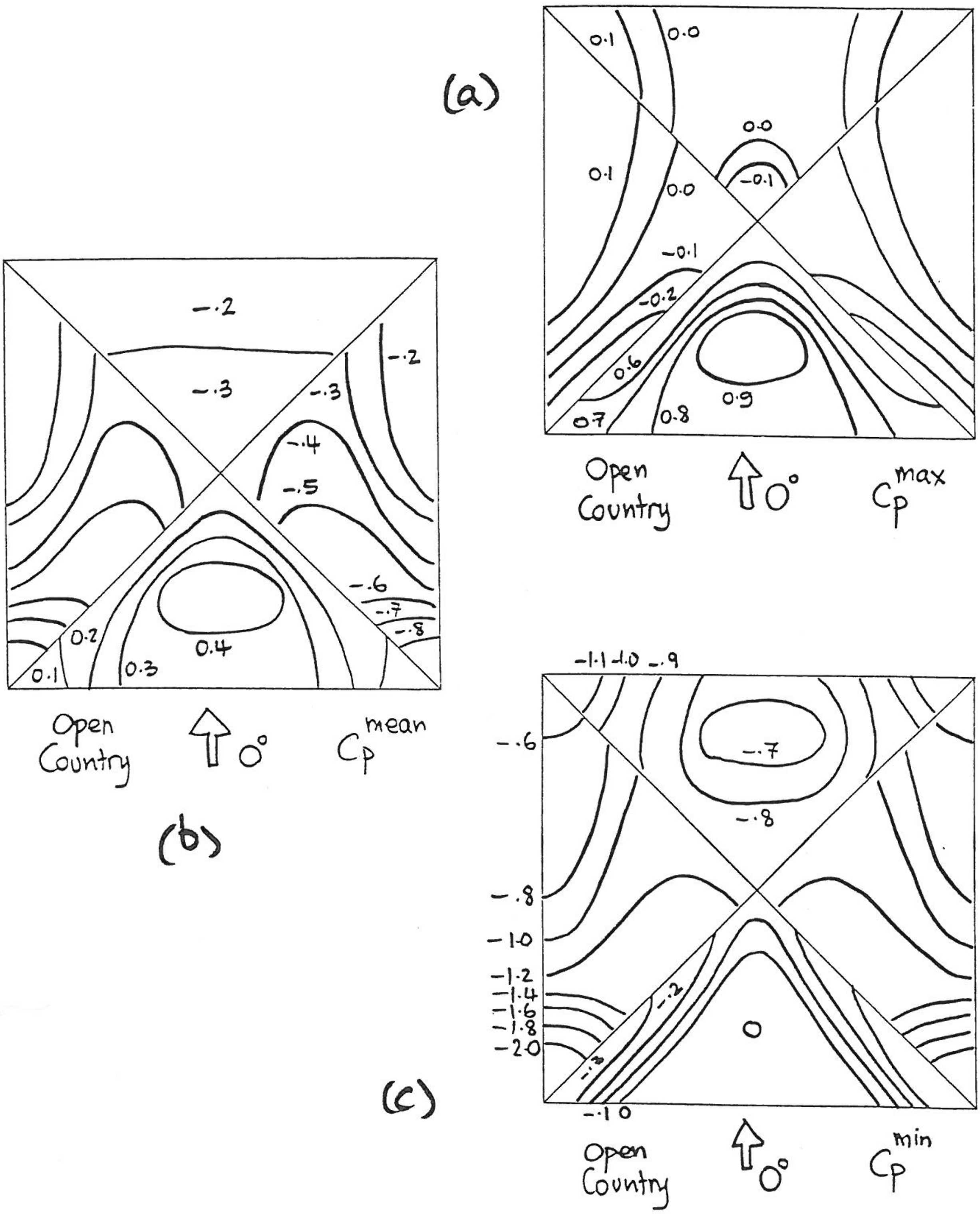

Figure 1 Directional Local Pressure Coefficients
for the Square Tall Pyramid in Open Country Terrain
(a) Maxima (b) Means (c) Minima

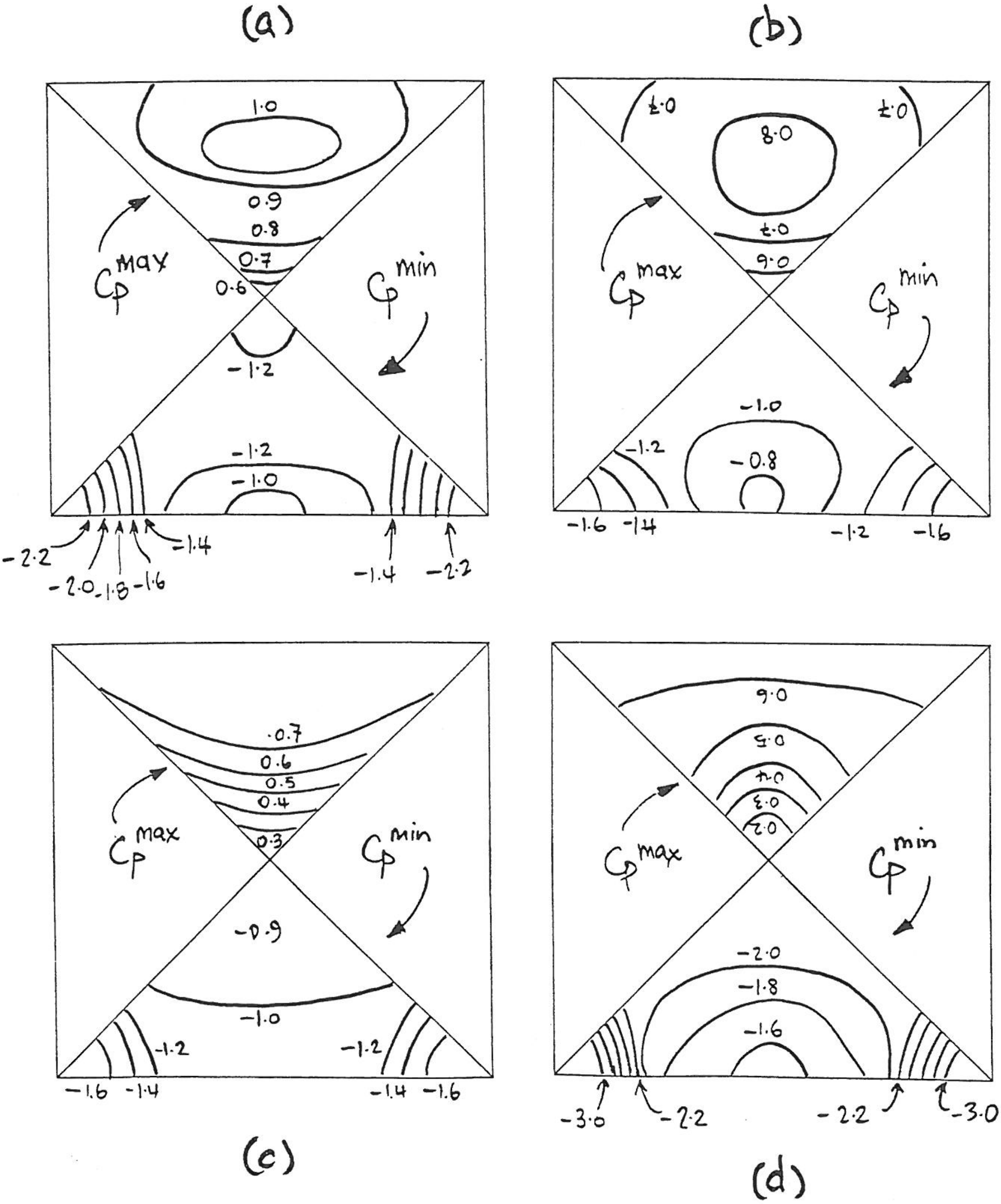

Figure 2 Worst Case Peak Pressure Coefficients
for Square Pyramids
(a) "Tall", Open Country (b) "Tall", Suburban Terrain
(c) "Short", Open Country (d) "Short", plus Building, Open Country