Wind Engineering Science and its Role in Optimising the Design of the Built Environment

by

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Dissertation presented for the Degree of Doctor of Engineering in the Faculty of Engineering, at Stellenbosch University

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March 2016

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DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the authorship owner thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

March 2016

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Abstract

Wind Engineering and Building Aerodynamics constitutes a relatively recent technical science (spanning the last sixty years or so), which integrates three principal domains and the related pools of knowledge – namely wind physics and statistics, the wind's action on the built environment and analyses of its consequences (e.g. loading, deformation or damage). The overarching aim and reason for the science is to gain an understanding and to quantify a largely unpredictable stochastic weather phenomenon and its effects on the built environment, including people. The information which is derived permits the researcher to proliferate and implement modern findings, mainly in the structural engineering but also environmental and architectural design domains.

This dissertation presents an overview of wind-engineering research activities and outputs of the author, which span more than thirty years of his professional career. During that time the author has been privileged to work and interact with a number of prominent wind-engineering experts and has been exposed to a diverse spectrum of research topics and studies. These involved wind-tunnel modelling, scientific analyses of wind damage and disasters, full-scale measurements, development of predictive models, design guides and standards, as well as consulting inputs to the industry.

Apart from personal research, the author was involved in a number of local and international activities, committees, conferences, lectures, presentations, and has provided editorial inputs to journals and conferences, as well as co-supervisions of postgraduate studies.

Extensive referencing is made to a range of published outputs. Furthermore, technically challenging and unpublished information of scientific significance is highlighted. The benefits of a comprehensive and multifaceted research process, involving a team of committed and talented people, are demonstrated.

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Oorsig:

Wind Ingenieurswese en Gebou-Aerodinamika verteenwoordig ŉ relatief jong tegniese wetenskap, met ŉ lewensspan van ongeveer 60 jaar. Dit verteenwoordig die integrasie van drie hoofkennisvelde, naamlik wind fisika en statistiek, die oordrag van kragte na die bou-omgewing en analise van die gevolge hievan (te wete belasting, vervorming of beskadiging). Die oorsigtelike doelwit wat met hierdie wetenskap beoog word, is die verwerwing van kennis en insig, asook die kwantifisering van grootliks onvoorspelbare stogastiese weerverskynsels en die effekte daarvan op die bou-omgewing, insluitend op mense. Die inligting wat so verwerf word, vind toepassing hoofsaaklik in struktuuringenieurswese, maar ook op gebiede van omgewings en argitektoniese ontwerp.

Hierdie verhandeling verteenwoordig ŉ oorsig van navorsingsaktiwiteite en uitsette op die gebied van Wind-Ingenieurswese deur die outeur oor ŉ bestek van meer as dertig jaar van sy professionele loopbaan. Die outeur was bevoorreg om gedurende hierdie periode interaksie te hê met ŉ aantal vooraanstaande Wind-Ingenieur spesialiste en was ook blootgestel aan ŉ diverse spektrum van navorsingonderwerpe en studies. Hierby word onderwerpe ingesluit soos windtonnel modellering, die wetenskaplike ontleding van windskade en rampe, volskaalse metings van belastings, voorspellings-modellering, ontwerp-riglyne en standaarde sowel as raadgewende insette aan die bedryf.

Benewens sy navorsingsaktiwiteite was die outeur ook betrokke by nasionale en internasionale aksies, met insluiting van komitees, konferensies, lesings en aanbiedings, verskaffing van redaksionele insette aan joernale en konferensie verhandelings, sowel as mede-studieleiding van nagraadse studies.

Omvattende sitering word na ŉ stel van gepubliseerde uitsette in die verhandeling gemaak. Daarbenewens word tegnies uitdagende en ongepubliseerde inligting wat van wetenskaplike belang is, beklemtoon. Die voordele van ŉ omvattende en multidissiplinêre navorsingsproses waarby ŉ span van toegewyde en talentvolle lede betrokke is, word gedemonstreer.

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Acknowledgments

Throughout my professional career I have had the privilege of interacting with a vast number of people who supported and influenced me and, importantly, contributed to my personal growth and goals. For that I am grateful. I feel especially indebted towards:

- my dear Father, a brilliant structural engineer of the 'old school', who realised the importance and challenges of quantifying wind actions on structures, and who encouraged and greatly supported my initial steps into the science of Wind Engineering (in the course of my MSc research).
- Drs Rodney Milford and Louis Waldeck for being my role models in wind engineering and Tersius van Wyk for his continual support and encouragement in stressful times.
- Profs Johan Retief and the late Peter Dunaiski for noticing the academic value of my activities.
- Prof Johan Retief and Dr Celeste Viljoen, promotors of the current dissertation.
- Drs Brian Lunt and Tony Williams for their fairness and for sharing their engineering knowledge.
- Dr Jeffrey Mahachi and Mike Stylianakis for sharing their insights into the structural performance of housing stock and for their friendship.
- Profs Alan Davenport and Hans-Jürgen Niemann for continual international support for the CSIR's Wind Engineering activities and their friendship.
- The CSIR and its management for allowing and enabling me to grow and follow my professional career.
- Several of my colleagues and supervisors for their peer interactions, friendliness and understanding.
- Mr Theuns Knoetze and Dr Joe Maparivana for their enthusiastic support and interest in the current effort.
- Prof Marian Gizejowski for our long-term fruitful interactions in terms of the South Africa / Poland Science Cooperation Programme.
- Numerous engineers, architects, developers, town planners and other professionals with whom I interacted over the years – for their professionalism and fairness.
- Overseas peer researchers across the world.
- Last, but not least, my dearest family for their unconditional love and acceptance of my long working hours.

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Wind Engineering science and its role in optimising the design of the Built Environment

1. Outline of wind engineering and its context

Wind Engineering and Building Aerodynamics constitutes a relatively recent technical science (spanning the last 60 years or so) which integrates three principal domains and the related pools of knowledge – namely wind physics and statistics, the wind's action on the built environment and analyses of its consequences (e.g. loading, deformation or damage).

Research into wind engineering was triggered by the spectacular collapse of the Tacoma Narrows Bridge in the USA in November 1940 (Figure 1.1). Under a fairly typical (for the geographic area) magnitude of wind flow, the bridge developed excessive, dynamically induced, deformations leading to its collapse. At that stage engineers realised that the traditional wind loading design paradigm, based on an occurrence of high magnitude uniform flow, was not applicable to the built environment – in particular to long or tall structures (especially those dynamically sensitive) in which the organisation of wind flow (most importantly its correlation in time and space domains) plays a significant role in the loading response.

Figure 1.1: Deformation and collapse of the Tacoma Narrows Bridge (7 November 1940)

The initial and significant foundations for the science, in terms of the understanding of boundary-layer principles, were laid by Professor Martin Jensen of Denmark. It was then rapidly expanded by several prominent international contributors across Europe and North America, most remarkably by Canada's late Professor Alan Davenport.

The overarching aim of (and the reason for) a wind engineering science is to gain an understanding of and to quantify a largely unpredictable stochastic weather

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phenomenon and its effect on the built environment. In that sense, wind engineering can be seen as the science of bridging the atmospheric and civil engineering domains by translating the action of wind into design implications, as demonstrated in Figure 1.2. The information derived enables the integration of modern findings into procedures and standards implemented mainly in the structural engineering but also the environmental and architectural design domains.

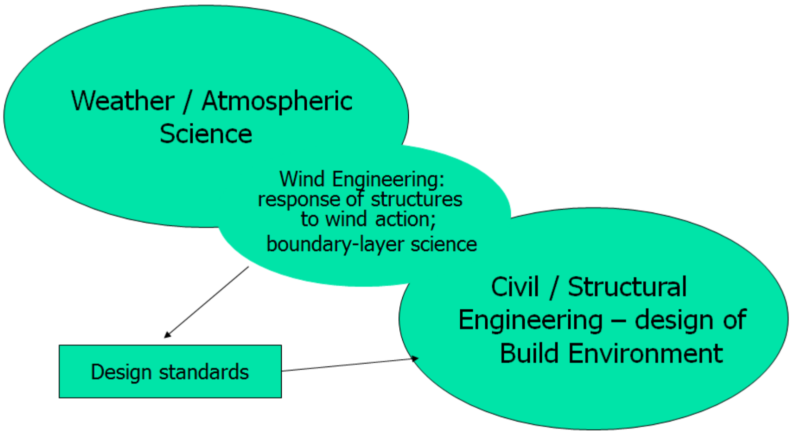

Figure 1.2: The role of wind engineering

As demonstrated schematically in Figure 1.3, wind engineering science overarches and integrates the input and expertise of the mechanical, structural and environmental engineering fields, as well as those of weather sciences and architecture. The stochastic nature of wind occurrence and action also requires continuous statistical inputs by means of implementing modern IT and electronic technology and processes.

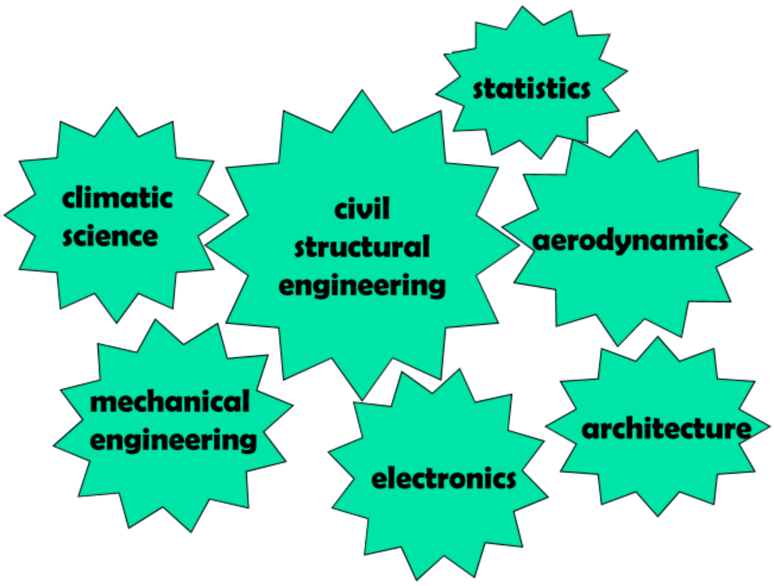

Figure 1.3: Interaction with various disciplines of science

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There are several specialised areas of wind engineering which can broadly be grouped into the following:

- categorisation of types and characteristics of strong and extreme wind events,
- determination of the related magnitude of wind speeds/direction and their statistical description,
- analyses of wind loading response (in the static and dynamic domains) of various types of structures, and/or their elements,
- development of loading requirements, processes and manuals,
- various types/disciplines of wind-tunnel modelling (e.g. topographical influences, unusual forms of structures or localised impacts),
- environmental wind studies within the built environment,
- analyses of wind-induced damage, and
- compliance and vulnerability analyses; and identification of remedial measures.

Like in any other science, each of the above areas of research comprises a large volume of related pools of knowledge, factors, analytical methodologies, statistical interpretations and implementation procedures.

It is important to stress that in South Africa:

- *in the absence of snow and ice loading,*
- *in combination with southern continental coastal exposure to trade and frontal winds, and*
- *significant convective activity inland of the country,*

wind action constitutes the critical environmental loading that affects structural design – i.e. the safety of most of the built environment. (Only for specific types of structures or their components – e.g. tall buildings or innovative materials/elements – earthquake or temperature loading may become comparable or more precarious.)

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2. Wind engineering career of the author

2. 1 Overview

Throughout his professional career the author has been privileged to work and closely interact with a number of committed, talented and prominent wind-engineering experts in South Africa and across the world. The full list of people would be exhaustive but it would unfair not to mention a few (in alphabetical order):

- Prof Alan Davenport
- Prof Chris Guerts
- Prof Jacques Hertig
- Dr John Holmes
- Prof Kishor Mehta
- Dr Rodney Milford
- Prof Hans-Jürgen Niemann
- Prof Hans Ruscheweych
- Prof Giovanni Solari
- Prof Ted Stathopoulus
- Prof Dave Surry
- Prof Yukio Tamura
- Dr Louis Waldeck
- Prof Jacob Wisse
- Prof Jerzy Zuranski

It is of interest to mention that Canada's Prof Alan Davenport, the undisputed pioneer of wind engineering science, retained strong South African family connections and on several occasions visited the country, the CSIR and the author (Figure 2.1).

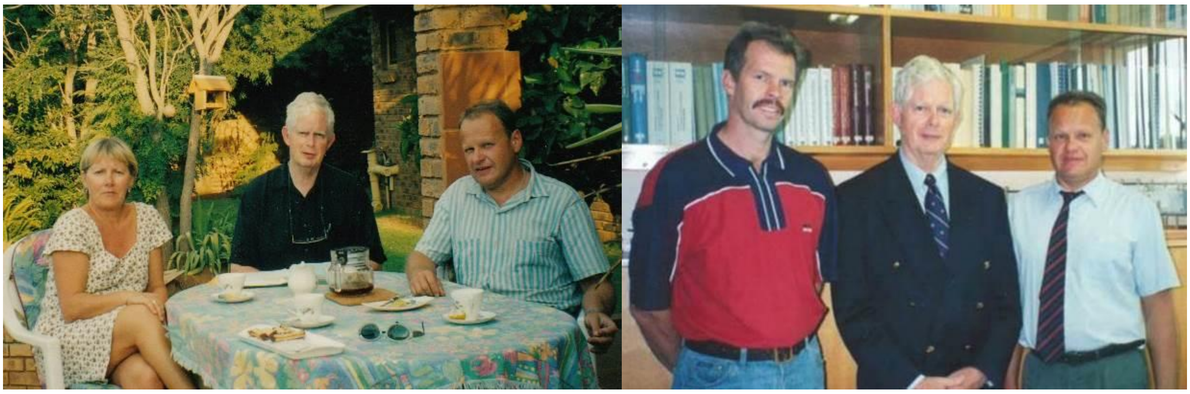

Figure 2.1: Prof Alan Davenport (centre) during his visits to South Africa and the CSIR in 1994 and 1999 (also included: Barbara Goliger, Tersius van Wyk and the author)

Another stimulating aspect of the author's wind engineering career is its diversity. Across the world, the science of wind engineering involves research inputs from a few hundred established scientists (typically structural/mechanical engineers or climatologists) and, at times, several hundred postgraduate researchers. Most of them, especially in the developed economies, specialise and concentrate on specific and limited aspects of wind engineering only.

The author's civil engineering studies (at Warsaw Technical University) were directed at structural engineering, bridge and underground structures. The MSc research project was aimed at an optimisation of the wind loading dynamic response of a deck of a cable-stayed bridge, envisaged across one of the major European rivers, the Vistula (Wisła) River (Goliger, 1974). *(It is of general interest that, at the time of developing the current dissertation, the water level of the river was less than 0,5m. This resulted from an unprecedented drought experienced in Europe - ever recorded since the time of Napoleonic Wars.)* Several years later the author's specific expertise, which was gained during his MSc research, was utilised in analyses and design inputs for a few dynamically sensitive bridges developed in South Africa (Figures 2.2a to 2.2d).

a) b)

Figure 2.2: a) Truss arch bridge in Menlyn, over the N1 in Pretoria; b) cable-stayed Blackburn bridge over the N2, near Umhlanga

c) d)

Figure 2.2: c) Ribbon pedestrian bridge near Umkomaas, KwaZulu-Natal; d) proposed cable-stayed Sandton bridge over the N1

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Throughout his professional career in wind engineering (spanning 30 years) the author has had the advantage of being exposed to, and involved in, a large spectrum of research topics/problems and studies. Broadly speaking, these included wind-tunnel modelling (structural and environmental), analyses of wind damage and disaster, full-scale measurements, consulting to the industry and the development of design guides and standards. *(This was due mainly to the limited extent of the South African economy and related needs which were not able to support a large number of specialist researchers. Broadening the scope of the author's involvement and associated responsibilities became particularly acute during the latter part of his career.)*

Apart from personal research commitments, the author was involved in a number of local and international research activities and committees. These were related to:

- local and international scientific activities and steering committees (including coordination of two substantial international initiatives),
- inputs/exposure to the development of international wind-related manuals,
- lectures and presentations,
- standard-development committees,
- input to the organisation of conferences and review of their submissions, and
- editorial boards and reviews for international journals.

These will be listed in sections that follow.

Of general interest is the unique (and memorable from a South African perspective) consequence of one of his research outcomes which relates to the publishing of a book on South African tornadoes (Goliger *et al*; 1997). A copy of this book was presented to the then South African President Nelson Mandela, who personally experienced one of the tornadic events in KwaZulu-Natal. (See Figure 2.3.) (Coincidentally, the wind-induced collapse of a large-scale temporary canopy roof also affected the succeeding president, Mr Thabo Mbeki, and the author was appointed to investigate that incident.)

In the following sections an overview of the most important aspects of the author's wind engineering activities, projects and outcomes is presented. Extensive references are made, where relevant, and a few unpublished details (of specific technical interest) are also included. The dissertation is clustered around the following:

- Section 2 (the current) gives an overview of the professional career and outlines the involvement in reviews of peer contributions;
- Section 3 relates to wind-tunnel modelling and structural testing which, over the years, absorbed a substantial amount of the author's involvement.
- Section 4 describes environmental engineering wind-tunnel studies.
- Section 5 summarises investigations into wind damage, which evolved into a comprehensive research project on South African tornadoes. *These activities*

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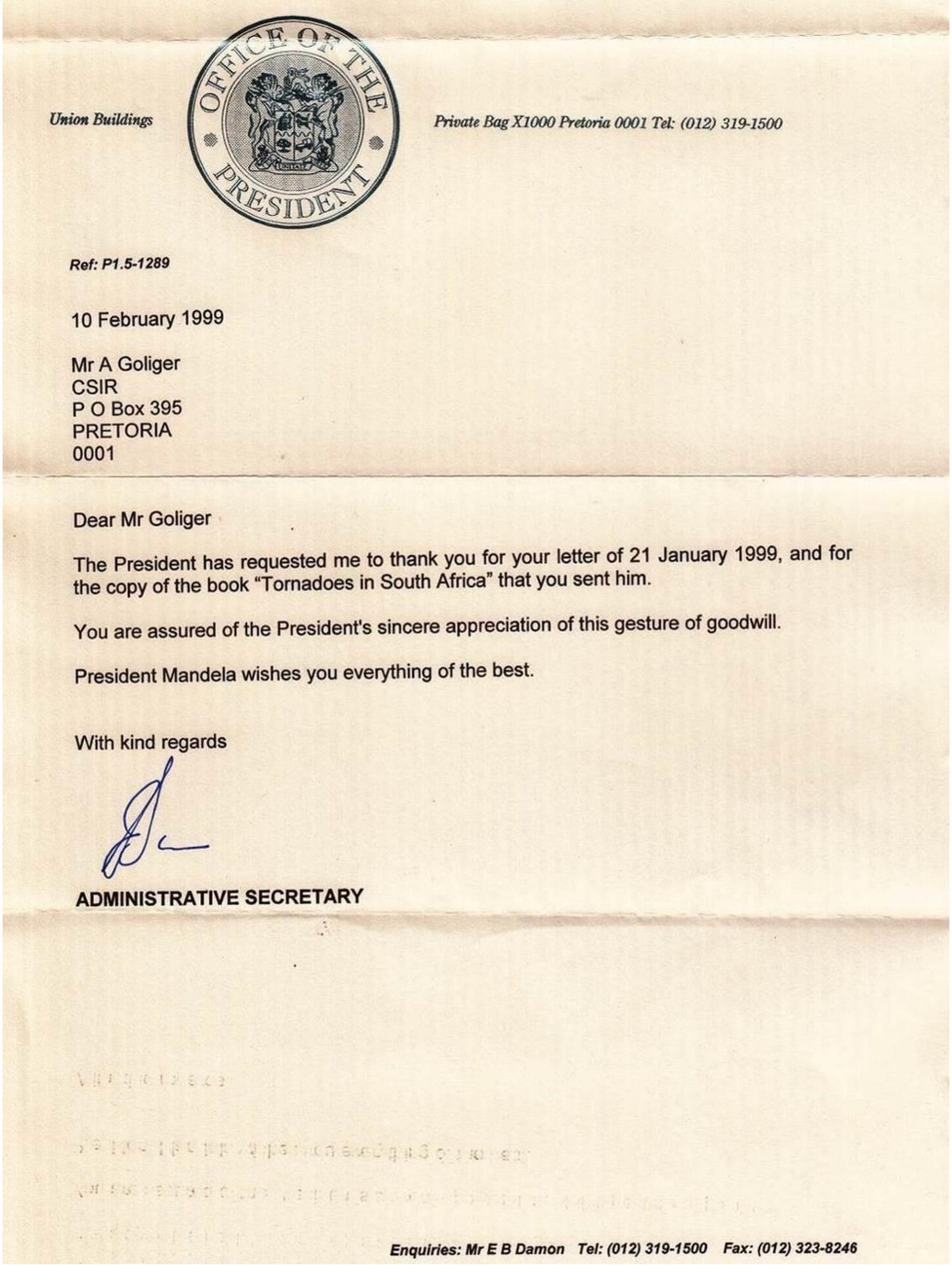
and outputs also demonstrate the vast benefits of a diverse (multi-faceted) scientific research process.

- Section 6 presents involvements in the development of standards;
- Section 7 describes contributions to the analysis of wind climatic data;
- Section 8 describes projects involving supervision of postgraduate research; and
- Section 9 – conclusions.


Union Buildings

OFFICE OF THE PRESIDENT

Private Bag X1000 Pretoria 0001 Tel: (012) 319-1500

Ref: P1.5-1289

10 February 1999

Mr A Goliger
CSIR
P O Box 395
PRETORIA
0001

Dear Mr Goliger

The President has requested me to thank you for your letter of 21 January 1999, and for the copy of the book "Tornadoes in South Africa" that you sent him.

You are assured of the President's sincere appreciation of this gesture of goodwill.

President Mandela wishes you everything of the best.

With kind regards

ADMINISTRATIVE SECRETARY

Enquiries: Mr E B Damon Tel: (012) 319-1500 Fax: (012) 323-8246

Figure 2.3: A letter from the SA Presidency

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Of interest to note is the apparent disparity in the levels of cohesion between some of the research activities. Studies presented in Sections 3 and 4 represent a wide spectrum of shorter-term topics and projects which reflect the diversity of author's involvements and interests. In many cases these were dictated by specific needs as well as the lack of related expert recourses at a national level. Section 5 summarises a long-term consistent involvement in several articulated research studies which formed a coherent area of research with a comprehensive set of outputs.

It is important to stress that the current dissertation attempts to summarise more than 30 years of highly diverse research activities of an individual employed by a corporate organisation focused on industrial research, development and implementation. Over those years the CSIR underwent significant changes (a re-focusing) of strategic objectives and these also affected the activities and outputs of the author. Furthermore, as a result of that, some activities, being regarded as of marginal relevance at the time, were not recorded as meticulously as might be justified from an academic perspective.

It is also relevant to note that several of the activities carried out by the author constituted a team effort involving inputs of other participants (in particular Drs RV Milford and JL Waldeck as well as Mr T van Wyk) whose contributions are gratefully acknowledged.

Finally, at some stages of his professional career, the author also had a chance to pursue and experience other civil engineering activities – e.g. as a young engineer in design and construction.

Comprehensive research into the loading and structural performance of low-rise housing (Goliger 1992b; Kasperski *et al* 1999; Mahachi *et al* 2004; Goliger and Mahachi 2006a; Mahachi and Goliger 2006; Mahachi *et al* 2007) developed a close relationship with the South African National Home Builders Registration Council (NHBRC). Between 2006 and 2012 (for two terms of office) the author, on appointment by the Minister of Housing, became a member of the NHBRC Council (as a non-executive director) and was also elected as the chair of its technical committee.

2. 2 Lectures and review of peer contributions

The author actively participated in various local and international conferences, workshops and symposia. Apart from conference appearances related to paper submissions, it also involved a fair amount of lectures, presentations and training courses. These were typically at the specific requests of various local and overseas

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professional and academic institutions as well as the industry. Unfortunately no diligent records in this regard have been kept.

Throughout his career the author has been actively involved in reviewing contributions by other researchers submitted to various local and international journals, conferences, workshops or institutions. These also provided an excellent platform for self-development opportunities by gaining the understanding of wind engineering research problems, processes, topics, techniques and trends. They also formed a useful background to author's involvement in the development of loading standards (described in Section 6). The review activities can roughly be grouped into the following:

2.2.1 International journals

These refer mainly to two technical journals specifically related to wind action and its effects, namely:

- *Journal of Wind Engineering and Industrial Aerodynamics*, and
- *Journal of Wind and Structures.* Since its inception in 1997 the author has been a member of its International Editorial Board.

Other reviews typically refer to wind-related papers which appeared in other scientific journals, and were made at the request of the respective editors, i.e.:

- *Journal of Natural Hazard*,
- *Journal of Computers and Structures*,
- *Journal of International Association for Bridge and Structural Engineering*, and
- *International Journal of Building and Environment*.

2.2.2 National journals

South Africa:

- *South African Journal of Science*, and
- *Journal of South African Institution of Civil Engineers*.

Poland:

- *Technical Transactions,* of Lublin University.

2.2.3 International conferences

On numerous occasions the author has been requested to contribute to various conference-related activities. These involved memberships of conference panels, scientific advisory committees, panels responsible for review and journal selections, and/or chairmanship of conference sessions, etc. These can broadly be considered in terms of the conference series or individual events, as listed below.

- *Asia Pacific Conference on Wind Engineering* (conference series, event Nos 3, 4 and 6),
- *International Conference on Wind Engineering* (conference series, all events from No 8 to 14),
- *International Symposium on Environmental Effects on Building and People* (4 to 7),
- *European & African Conference on Wind Engineering* (conference series, all events from 2 to 6),
- *International Conference on Structural Engineering, Mechanics and Computation* (SEMC) (conference series, events 2010 and 2013),
- *Lightweight Structures in Civil Engineering*, International Seminar of the IASS Polish Chapter (conference series, events 15 and 18),
- *Second International Symposium on Advances in Wind & Structures*, Busan, August 2002.
- *3rd International Conference on Problems of Technical Meteorology*, Ukraine, 2006.
- *Alan Davenport Engineering Symposium,* Canada 2002.
- *13th International Housing Warranty Conference 2010* (Chair of Technical Panel and Editor of the proceedings).
- *2014 Congress on Advances in Civil, Environmental and Materials Research*, (Busan).

2.2.4 Other reviews

No dedicated record of these activities was kept but a few which were identified in the process of developing the current report, are listed below.

- Review Panel of the SA Weather Bureau’s publication series on Climate of South Africa (2000) – external reviewer,
- Trans-critical flow around cylindrical towers: the stabilising role of vertical ribs. MSc thesis of Ms Lisa Alberti, Stellenbosch University (awarded in 2006) - external examiner.
- UK–Canada Joint Project on Wind Damage due to High Intensity Winds – external referee (2004).
- Design of Structural Steelwork in Southern Africa to SABS 10162 (Mahachi, 1999) – technical co-editor.

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3. Wind-tunnel structural testing

Figure 3.1 presents the CSIR's Boundary-Layer Wind-Tunnel laboratory. This is (i) a unique research facility on the African continent which, (ii) with the distinction of classical mechanical engineering facilities, (iii) enables the full-scale simulation of the atmospheric boundary layer under strong wind conditions.

Figure 3.1: The CSIR Boundary-Layer Wind-Tunnel laboratory

> *It was set-up in late 1970s at more or less the same time (and in collaboration with) the British Building Research Establishment wind tunnel. (At that stage fewer than 20 boundary-layer facilities were operational across the world.)*

Historically, the applications of wind-tunnel boundary-layer technology were related to the structural loading requirements for determination of forces and distribution of pressures. With time, the importance and relevance of quantifying the wind flow regimes in multifaceted situations became apparent and the technology evolved into the studies of environmental wind distribution in complex terrain (i.e. as affected by topography and built-up terrain.)

In large and/or developed economies, boundary-layer modelling turned into a vast specialist arena of wind engineering research. It branched into diverse fields of loadings (e.g. pressure measurements, force measurements, stadia vs. tall buildings, dynamic behaviour of chimneys or stability of long span bridges etc.), as well as numerous applications to environmental engineering (e.g. topographical influences, dispersion of pollution, erosion and transportation of loose material or pedestrian level studies). Each of these fields, embracing specific physical

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principles, modelling techniques and the related know-how, attracted and maintained an exclusively dedicated expertise.

The South African economy, due to its limited size and lesser demand for specialist design inputs, was not able to support a large pool of related experts. As an implication of this situation, over the years, it became necessary for the author to become involved and develop an understanding of all types of wind-tunnel measurements, which will be summarised in the dissertation. Due to the volume of information, these activities are considered in terms of the structural (Section 3) and environmental domains (Section 4).

3.1 Calibrations and sensitivity studies

3.1.1 Modelling of the boundary layer

The initial wind-tunnel research work at the CSIR carried out by the author concentrated on the calibration of tunnel and boundary-layer modelling of standard terrain types. For two reasons this work remained unpublished, namely:

- The information developed was unique in relation to the type of the wind tunnel, its geometry and the characteristics of the thyristor-controlled motor.
- Secondly, it remained unpublished for confidentiality purposes (protection of intellectual property). At that stage, following the increasing demand for building-aerodynamic inputs to the rapid development of tall buildings across the world, substandard wind-tunnel facilities (often as conversions of traditional mechanical wind-tunnels) started to appear in various countries.

The work involved a large number of measurements (of a parametric nature) in order to establish trends in regard to:

- mean and peak longitudinal velocity profiles,
- longitudinal, vertical and lateral turbulence profiles,
- length of longitudinal turbulence,
- power spectra of longitudinal turbulence,
- cross-correlation functions of turbulence, and
- Reynolds shear stresses.

The aim of these measurements was to evaluate and optimise scale modelling of these flow parameters/quantities. These were assessed against the principal textbook data, based on semi-empirical formulations originating in meteorological sciences.

> *The challenge of the project was related to complex relationships between various parameters (governed by fluid dynamics). This often resulted in situations in which improvements achieved in relation to some of them (or within specific areas of the wind tunnel) were detrimental to others. The unique experience gained from the parametric calibrations became a vital component of*

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the body of knowledge in order to optimise the selection of measurements for specific applications.

Figure 3.2 presents a typical comparison of (smoothed out) longitudinal velocity spectra obtained for a specific approach-floor roughness as a function of elevation, in the presence of *spires* and *tripping* walls of various heights. (An adequate wind-tunnel modelling of the spectral distribution of energy, in relation to its frequency, is critical. This constitutes an important characteristic of flow, which determines the magnitude of wind loading.) *The graphs in Figure 3.2 below provide a good indication of the amount of effort committed to the project – the development of each of the curves required measurements corresponding to a specific set of flow-modelling devices.*

3.1.2 Comparative studies

As a next step and following the calibration process, the CSIR joined two international comparative projects involving two specific structures:

- a tall building (about 180m high), specified by the Commonwealth Advisory Aeronautical Research Council (CAARC) in 1969, and
- a low-rise UK building (about 5m high) located in Aylesbury, specified by the BRE in 1972,

that were modelled and re-tested by several leading wind tunnels across the world.

Comparative results were communicated across the network of participating wind tunnels and provided the CSIR facility with international recognition and acclaimed status. A sample of the results is given in Figure 3.3. It presents a comparison of the mean and root-mean-square (*rms*) of along-wind dynamic responses at the top of the CAARC building (the crosses refer to the data measured by other wind-tunnels, and the circles to the NBRI/CSIR data).

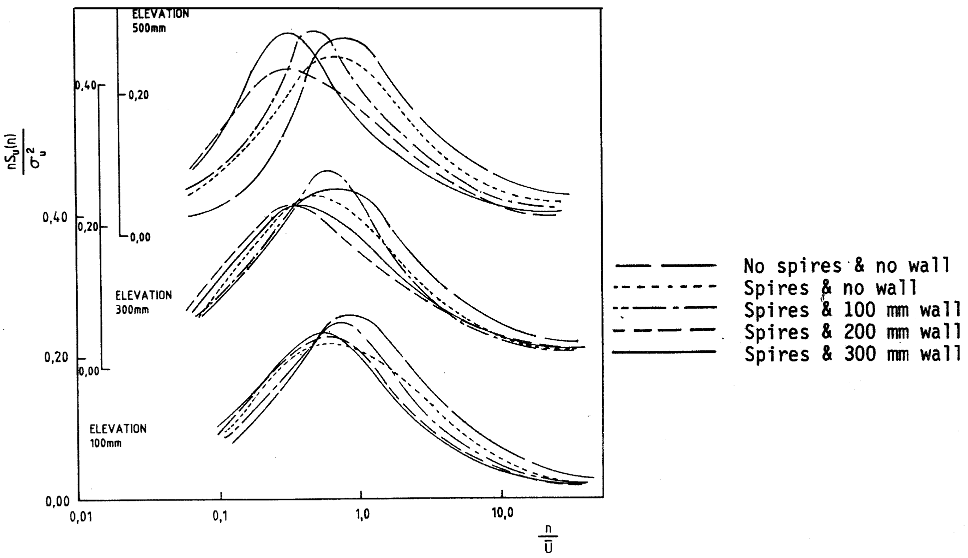

Figure 3.2: A comparison of longitudinal velocity spectra

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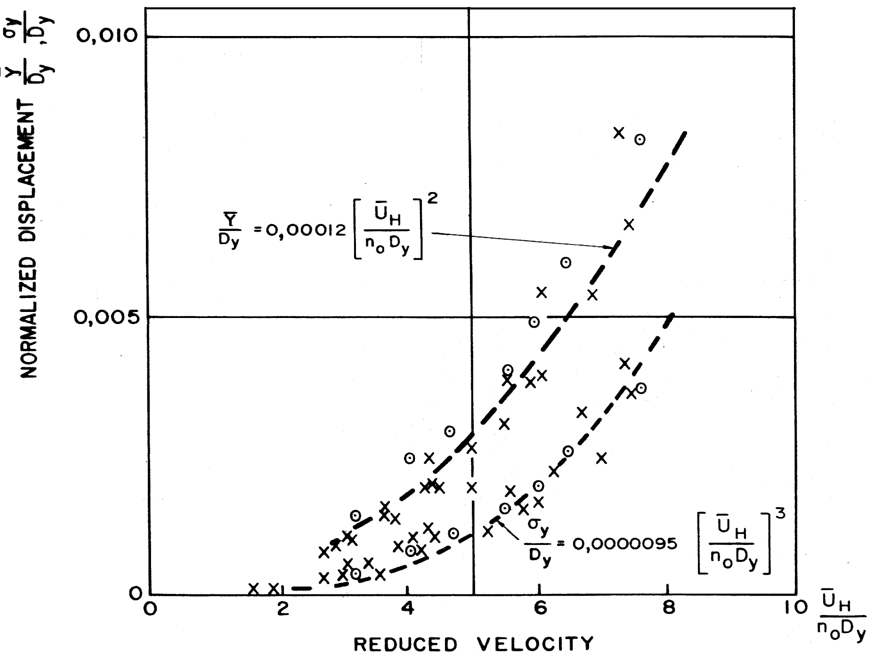

Figure 3.3: A comparison of the mean and rms along-wind displacement

A summary paper on comparisons of pressure measurement results related to both the CAARC and Aylesbury experiments was reported in Milford and Goliger (1989). In conclusion, it was demonstrated that a fair level of consistency can be obtained by different wind-tunnel laboratories, provided that the boundary-layer profile characteristics are correctly modelled and satisfactory measurement techniques are employed. Furthermore, a comparison with the full-scale data (from the Aylesbury experiment) also offered confidence in wind-tunnel modelling technology.

3.1.3 Sensitivity measurements

In the early days of boundary-layer testing a common modelling problem originated in the limited sizes of wind tunnels. This was a consequence of cost and instrumentation limitations, regarding:

- insufficient boundary-layer development length (often as a consequence of modifying and adopting mechanical engineering wind tunnels), which typically resulted in inadequate simulations of the intensity of longitudinal turbulence and spectral contents of the flow, while
- insufficient cross-sections led to less than optimal geometrical scales of the models.

An investigation into the effects of these distortions was undertaken as a follow-up of the comparative CAARC study (Goliger and Milford, 1988). It was found that distortions in the geometrical scale of up to 50% produce negligible errors, while

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similar changes in the magnitude of intensity of longitudinal turbulence introduced small but noticeable variations in the response of tall buildings.

3.2 Basic research

In the late 1980s a paper by Milford *et al* (1988) was published in *The Civil Engineer in South Africa*. This paper demonstrated the background, methodology, applicability and effectiveness of wind-tunnel modelling technology to investigate the pressure distribution over complex surfaces as well as overall loads – i.e. the forces and moments generated by various types of structures or their elements. The ability to qualify and quantify flow regimes in complex environments was also indicated.

This publication offered the NBRI/CSIR a fair recognition and exposure to the local engineering-design industry, and was followed by gradually increasing the demand for wind-tunnel and consulting inputs to various commercial developments. Despite the above involvement, several research activities and studies were still carried out, as highlighted in the following subsections.

3.2.1 Pressure distribution over a jumbo-jet hangar

Of particular prominence was the long-term project of full-scale pressure measurements over the roof of a jumbo-jet aircraft hangar at the then Jan Smuts (currently OR Tambo) airport.

This project was carried out by Dr Louis Waldeck between 1980 and 1988 (Milford *et al*, 1991/1992a). Upon its completion, a wind-tunnel research study was undertaken in which the above hangar and its surroundings were modelled and tested for a range of selected wind directions measured full-scale. The outputs of the full-scale and wind-tunnel experiments were then compared (Milford *et al*, 1991/1992b).

The comparison between mean and *rms* pressure coefficients was generally satisfactory. Trends – in terms of changes in pressures as a function of location and direction – were surprisingly similar, although for certain wind directions a shift between full-scale and wind-tunnel data was evident (Figure 3.4). Fair similarity of pressure spectra was observed.

Comparison of peaks was less satisfactory – several very high peak-pressure coefficients were measured full-scale, but not reproduced in the wind tunnel. This finding supported the outcomes of full-scale measurements of other structures undertaken elsewhere in the world. It also fuelled vibrant discussion and argumentation at the *8^th^ International Conference on Wind Engineering* in London, Ontario in 1991 (Davenport, 1992), regarding the design relevance and applicability

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of highly localised (with contributory areas lesser than 1m^2) extreme peaks observed full-scale.

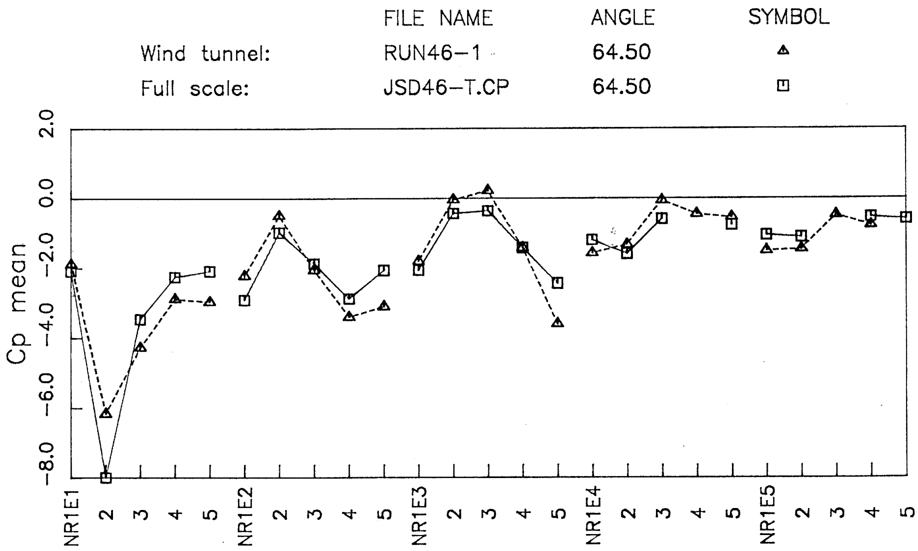


Figure 3.4: A comparison of the full-scale and wind-tunnel data

3.2.2 Microwave tower

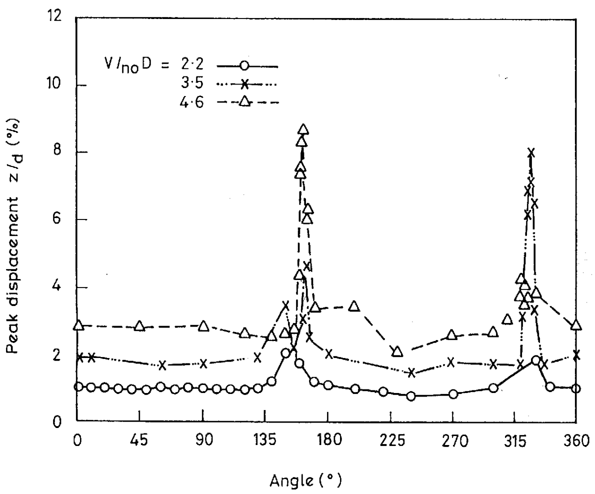
Some of the research studies at the CSIR were triggered by initial requests regarding full-scale problems experienced (or identified) by the engineering profession and/or construction industry.

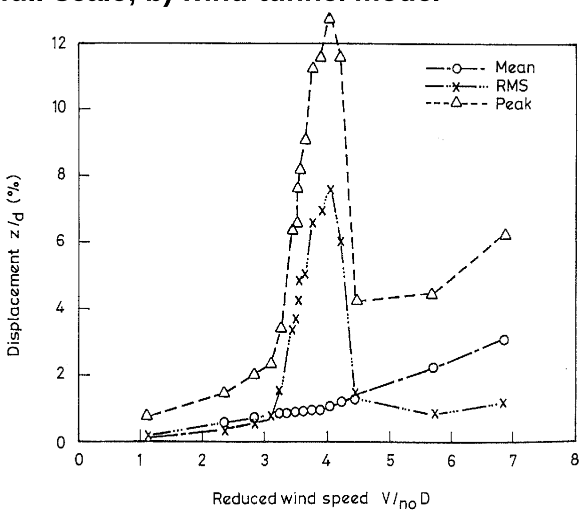
Of particular research interest was a comprehensive investigation of a 52m-high tower (Figure 3.5a) fitted with large microwave-tower reflectors and domes. Under a specific narrow band of wind directions and range of wind speeds, the tower experienced excessive oscillations which were detrimental in terms of the fatigue of structural members as well as a loss of signal. The investigation of the problem comprised full-scale measurements (amplitude, frequency structural and aerodynamic damping) and, subsequently, wind-tunnel and water-tunnel modelling. The outcomes were published by the British Journal of the Institution of Structural Engineers (Milford and Goliger, 1990).

Figure 3.5a presents a section of the tower and Figure 3.5b the wind-tunnel model (including the proposed remedial measure). In Figures 3.5c and 3.5d the variations of mean, root-mean-square and peak reduced displacements, as functions of wind directions (Figure 3.5c) and reduced wind speeds (Figure 3.5d), are presented. The excessive displacements corresponding to two wind orientations, and a specific range of the reduced wind speed, are evident. An introduction of perforated elements (Figure 3.5b), located between the domes of the reflectors, was recommended. This was in order to modify (disrupt) the flow regimes developing over the upwind dome, which generated buffeting effects on the downwind dome.

a) **b)**

Figure 3.5: Microwave tower: a) full-scale; b) wind-tunnel model





c) **d)**

Figure 3.5: Mean, rms and peak displacement as a function of: c) wind direction; d) reduced wind speed

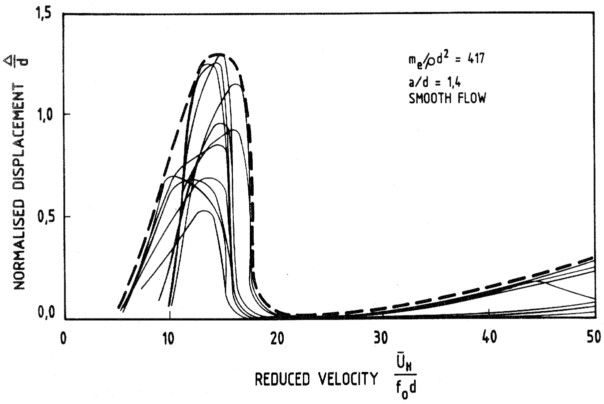
3.2.3 Chimneys in groups

The issue of excessive deflections/vibrations can be critical for the design of tall (or long) and slim structures like chimneys or decks of long-span bridges, as well as the design of large-scale industrial elements/facilities. Although several theoretical and semi-empirical predictive models are available, these have limited application and accuracy. In one of the joint projects involving the CSIR and Aachen Technical

University (with Prof Hans Ruscheweyh, the recipient of the Everite Visiting Scientist Award), a series of wind-tunnel aero-elastic simulations of chimneys, positioned in groups, was carried out. The simulations considered a range of geometrical distributions (spacing between individual flutes) and mass ratio distributions.

Figure 3.6a demonstrates the crosswind response of one of the configurations of the chimneys, and Figure 3.6b the corresponding envelope of the variation of peak normalised displacement with reduced velocity. It can be noted that for a certain relatively low range of wind velocities a tremendous displacement of chimneys takes place. Figure 3.6c is the visualisation of flow between chimneys derived from water-tunnel modelling. It was established that the rate of displacement was governed by the flow pattern developing between the chimneys as a function of distance between flutes and the direction of the flow.

The outputs of the research contributed to the development of the calculation procedure for crosswind vibration amplitudes of chimneys included in Annex E of Eurocode EN 1991-1-4:2005.



a) b)

Figure 3.6: Crosswind displacement of a group of chimneys: a) visualisation; b) as a function of reduced velocity

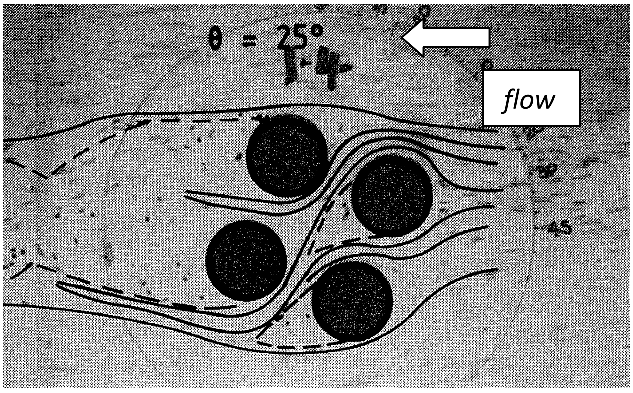


Figure 3.6: c) flow pattern between chimneys

3.2.4 Conveyer belt housings

Another example of an industry-related problem which triggered a comprehensive wind-tunnel research programme relates to aerodynamic forces generated over the housings of overland conveyer belts. No textbook and design-standard information on this topic was available, and largely irrational (and inconsistent) design requirements were stipulated and implemented by various role-players within the related industry.

The outcomes of the study demonstrated that, in some instances, the above practice resulted in the adoption of unsafe design parameters. In other cases, the introduction of small geometrical modifications would have resulted in substantial reduction of wind loading and subsequent cost savings. Figure 3.7a presents the central (instrumented) sections of two models used for pressure and force measurements respectively, and Figure 3.7b the variation of the drag coefficient with geometry. (The results of the study were published in Goliger and Waldeck, 1994 and 1995b).

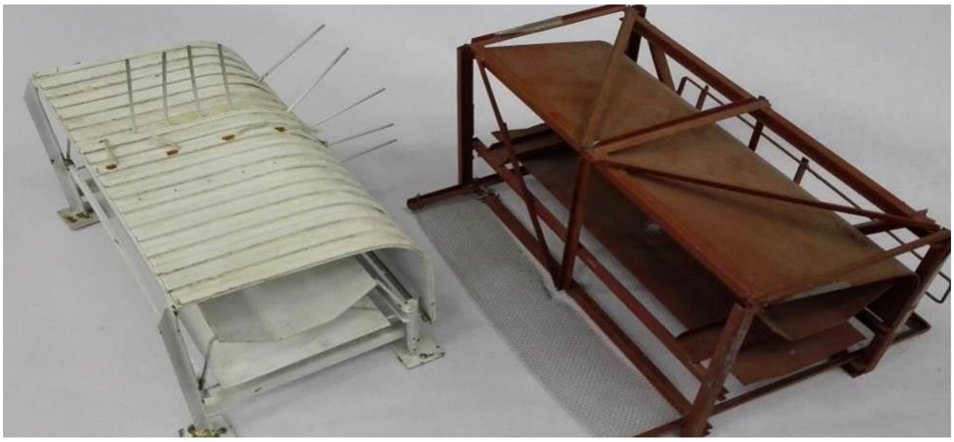


Figure 3.7: a) Pressure and force measurements models of a conveyer belt

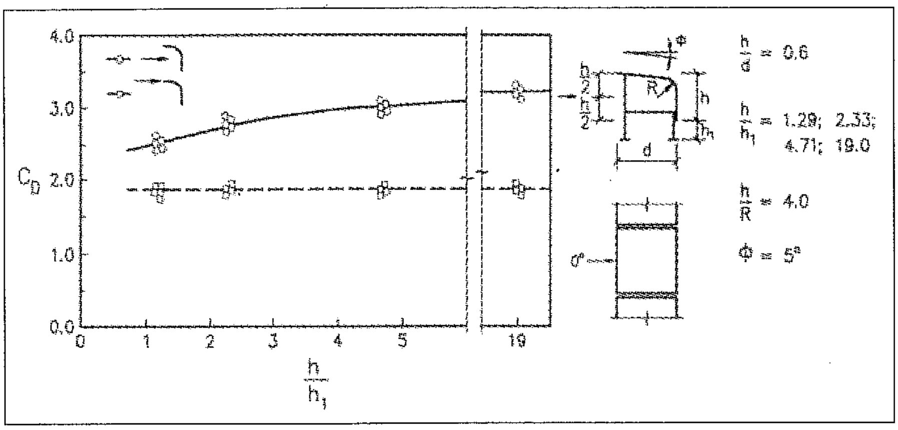


Figure 3.7: b) Drag coefficient as a function of aspect ratio

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3.3 Loads on buildings

Following the calibration studies and in addition to the research investigations highlighted above, the wind-tunnel facility progressively became recognised as a useful design tool and utilised by the South African design and construction industry.

A multitude of studies have been undertaken over the years, which can broadly be grouped into the measurement/quantification of:

- pressures,
- forces/moments, and
- environmental wind impacts.

It is stressed that, despite the commercial context and applications, several wind-tunnel investigations had a robust research component in which their aims were not only to evaluate the implications of wind action, but rather to identify the reasons for adverse action and to optimise the situation – i.e. to reduce the magnitude of negative impacts. These activities also enabled the development in South Africa of the author's unique expertise in building aerodynamics.

It is important to note that studies of building developments typically refer to built-up city terrains in which the influences of the neighbouring buildings can be substantial and, in some cases, overriding. Such influences, depending on wind directions, can either reduce the wind loadings (due to the protection of upwind buildings) but also magnify them due to wind-speed acceleration, vortex-shedding and -buffeting.

It is therefore of critical importance that in all such studies the surrounding environment of the site concerned, within a distance of few hundred metres in the full scale, is also included. Similar requirements also apply to significant structures (large or tall) positioned further away. A typical wind-tunnel model of a city terrain is presented in Figure 3.8. Of relevance to note are the boundary-layer flow-processing devices seen in the background of the model. Their specific form and distribution, corresponding to various approach-terrain conditions, were developed on the basis of comprehensive and cumbersome modelling efforts, summarised in Section 3.1.1, and furthermore the wind-tunnel topographical studies which will be highlighted further in the report, in Section 4.1.

Most of the studies examined building developments and referred to:

- either buildings of unusual form (radically different from the simplified geometry stipulated in loading standards), or
- buildings located in unusual environments (e.g. close by other large or tall structures).

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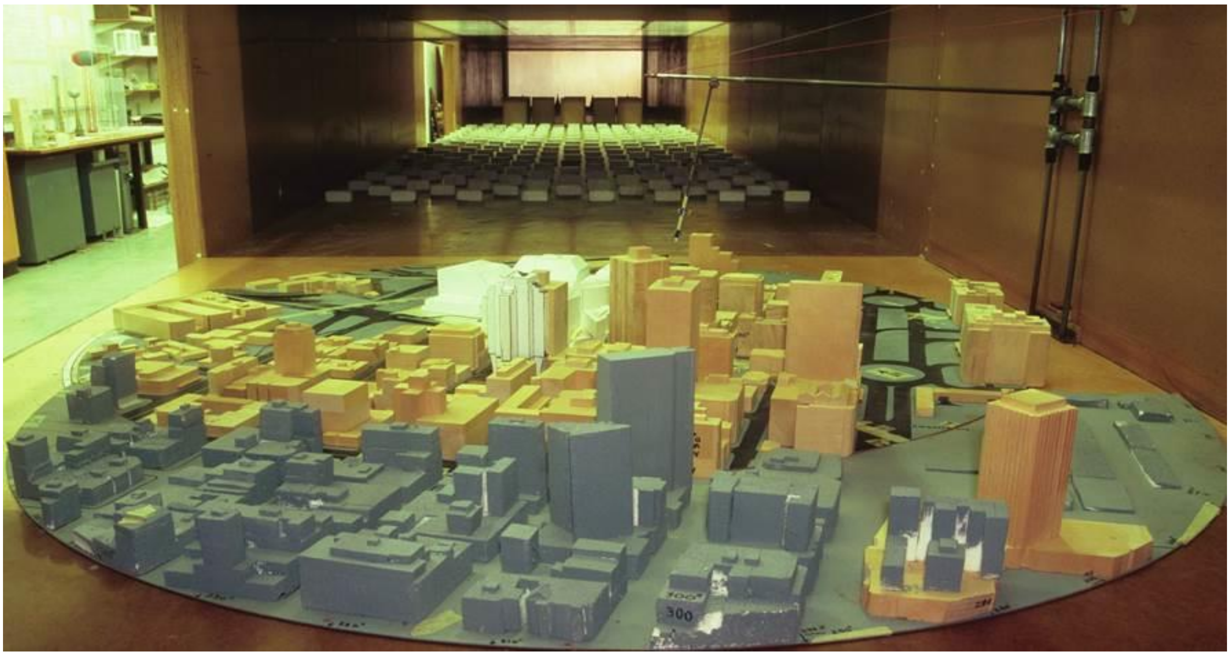

Figure 3.8: Wind-tunnel model of a city environment

Examples of such buildings are given below. The building presented in Figure 3.9 comprised an assembly of various geometrical forms, all envisaged to be entirely glazed. Due to the presence of rounded-off surfaces, this study also required research and modelling of the relationships between the Reynolds number (which determines the flow separation from the building surface) and the magnitude of pressures. These investigations involved artificial surface-roughening of the model.

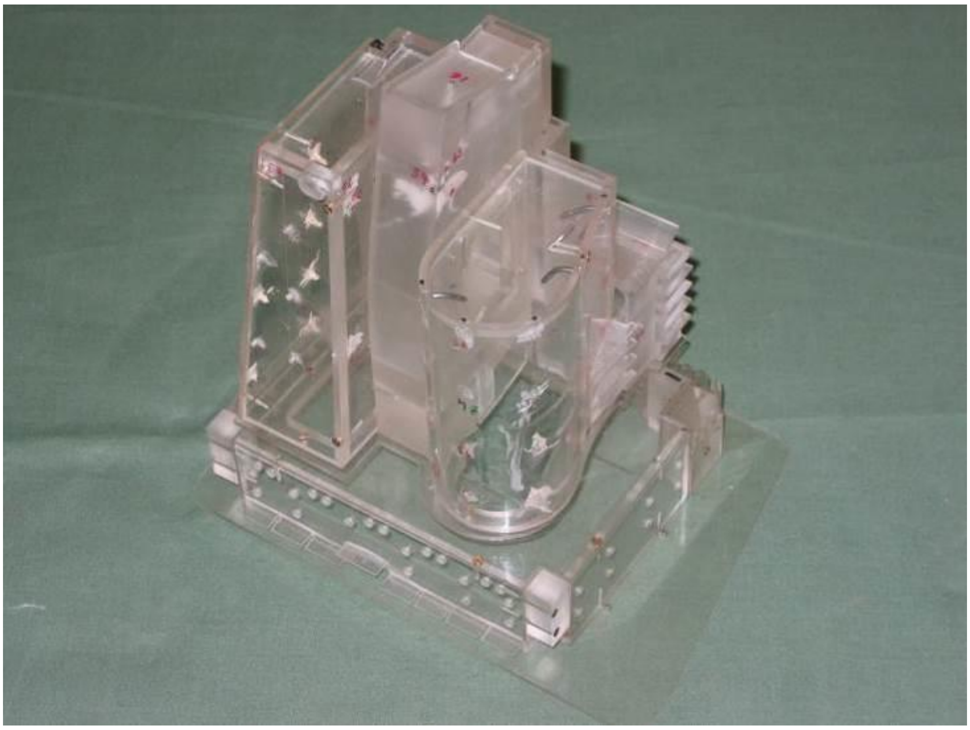

Figure 3.9: Complex building geometry

Figure 3.10a presents the wind-tunnel pressure measurements model of a low-rise pavilion located next to the prominent Civic Centre building in Cape Town (Figure 3.10b). Figure 3.10a also includes the Scanivalve pressure-transducer instrumentation used in wind-tunnel measurements.

These measurements revealed that, in some areas of the roof, design-pressure coefficients greatly surpass those which could be determined on the basis of the South African wind loading standard SABS 1060-1989 (applicable at the time). This was caused by a combination of several influences, namely:

- the flow characteristics generated by the prominent surrounding topography,
- blockage effects of the building 'slab' of the Civic Centre,
- flow deficit behind the 'slab', and
- shedding of the vortices along the upwind edge of the tall building.

Another example of a building structure which, due to its uncommon form, generated wind loads in excess of those which could be derived from the loading standards, as is presented in Figure 3.11. This building was facing the open sea – i.e. well-correlated wind-flow conditions. Its façade was divided into several semi-enclosed terraces (cubicles), each containing a dominant opening facing the open sea. The overturning moments, which were measured in the wind tunnel, exceeded by more than 20% those which could be derived from loading standards and textbook information.

a) b)

Figure 3.10: a) City Council Pavilion in Cape Town; b) wind-tunnel model

This was due to the flow entrapment phenomena developing over the terraces, which effectively increased the positive pressure coefficients to:

- $C_p \approx +1{,}0$ (stagnant flow) across the entire façade, as opposed to

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- $C_p = +0{,}8$, stipulated for windward façades in most of the loading standards (taking into account 3-dimensionality of the flow resulting in a reduction in positive pressure coefficients closer to the building edges).

Figure 3.11: Building model located on force balance

3.4 Other types of structures

Several studies referred to a variety of industrial-type structures and applications, e.g. cranes, antennas, elements of machinery, conveyer belts, ships, deflectors/ barriers – some of them of a confidential nature. A few technically interesting and scientifically challenging projects are selected as highlighted below.

3.4.1 Cape Town Harbour

A prominent project to mention is the comprehensive research project carried over nearly a decade that was aimed at the optimisation of the operations of Cape Town Harbour. Under strong south-easterly winds the operations of the harbour were severely affected, including wind-induced accidents to containers, cranes, ships and even a drilling platform.

The research included, among other things, full-scale measurements, quantification of the wind field affected by topography, optimisation of the port's stacking areas, optimisation of building layouts and container cranes (in order to reduce wind loads) as well as the introduction of wind deflectors with various geometrical forms and layouts (Goliger *et al*, 2015).

Figure 3.12 presents contour lines of the reduction in aerodynamic force along the Container Terminal achieved by one of the proposed, and tested, layouts and forms of large-scale shell deflectors. These demonstrate that a substantial reduction of aerodynamic force can be achieved along a substantial portion of the terminal (accommodating four berths).

Figure 3.13a demonstrates (schematically) the complexity of flow regimes which develop over a fully loaded container ship and affect a container crane. Figure 3.13b presents a wind-tunnel model of one of the Container Terminal cranes (utilised at the time in the Cate Town harbour). Based on the results of wind-tunnel testing, the design of the next generation of cranes (currently in use) has been optimised. (The optimisation process was carried out in collaboration with the German manufacturer Krupp).

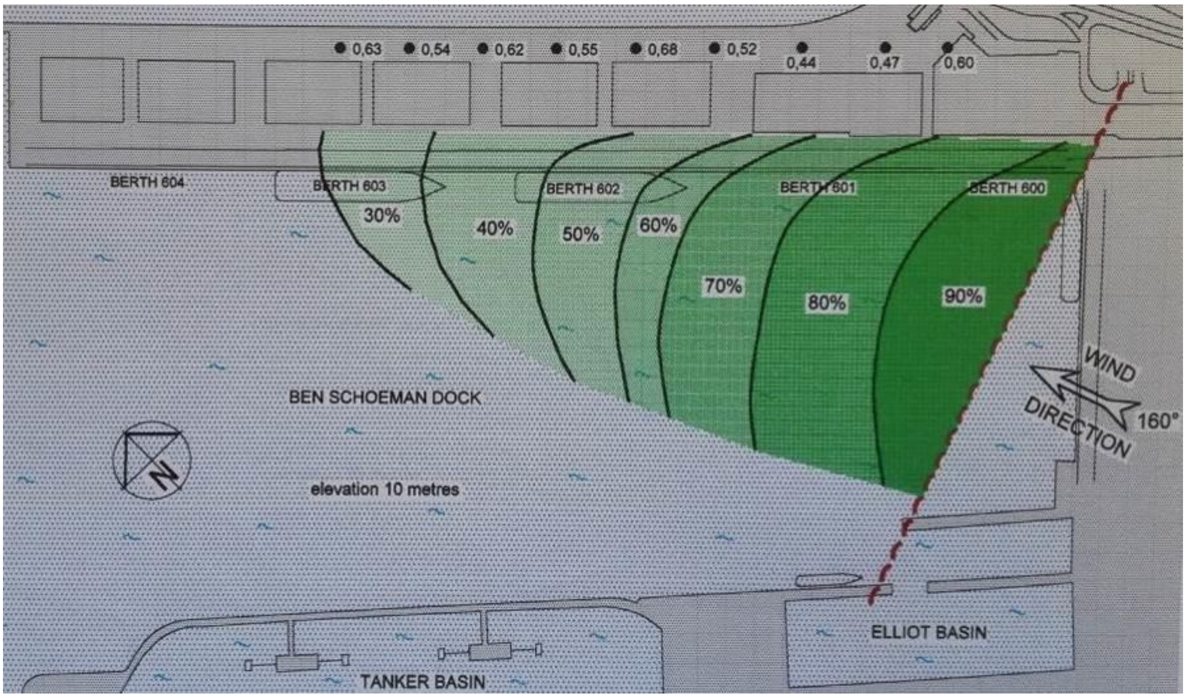
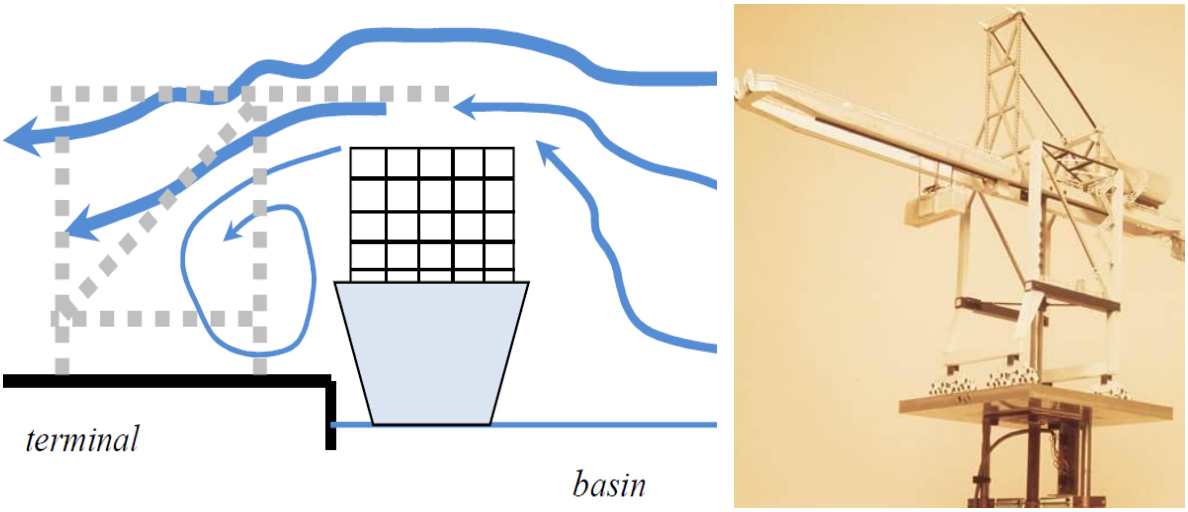


Figure 3.12: Contour lines of the reduction in aerodynamic force



a) **b)**

Figure 3.13: a) flow over a container ship; b) wind-tunnel model of crane

3.4.2 SANAE base

Another interesting and challenging study referred to an optimisation of the form and distribution of a new (at the time) SANAE base in Antarctica (Figure 3.14a) in 1991. The previous South African base had to be abandoned due to the excessive build-up of snow, which had taken place over the years - resulting in the base being buried several metres under the snow.

The new station was envisaged to be placed on top of an elevated ridge, and wind-tunnel investigations concentrated on two aspects, namely:

- the distribution of the design loads over various surfaces subjected to wind speed of 210 km/hr (nearly 60 m/s), and
- the optimal geometry (the aspect ratio and cross-section) and distribution of (height and distance between) the units, in order to maximise the wind speeds underneath and within the close vicinity of the units, i.e. to reduce snow deposition.

Figure 3.14b presents a section of the pressure measurements model. In view of the shape of the SANAE base modules, the models also necessitated comprehensive comparative measurements of the effects of surface roughening in order to model the Reynolds number dependence of flow separation.

Figure 3.14c presents contour lines of the normalised wind speeds behind the base, corresponding to a specific distribution of units, the elevation above ground level and wind direction.

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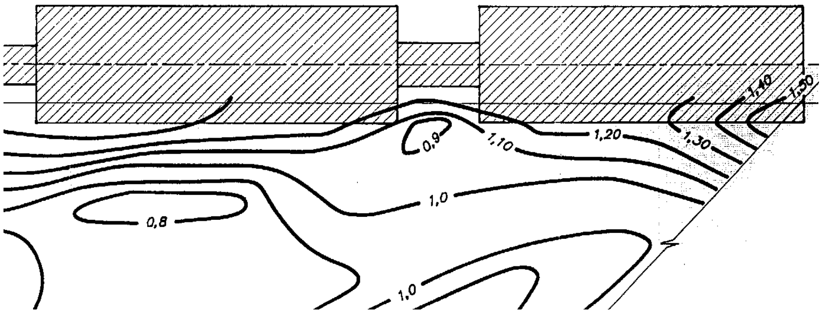
a)

b)



c)

Figure 3.14: SANAE base: a) full-scale; b) wind-tunnel pressure model; c) contour lines of normalised wind speed

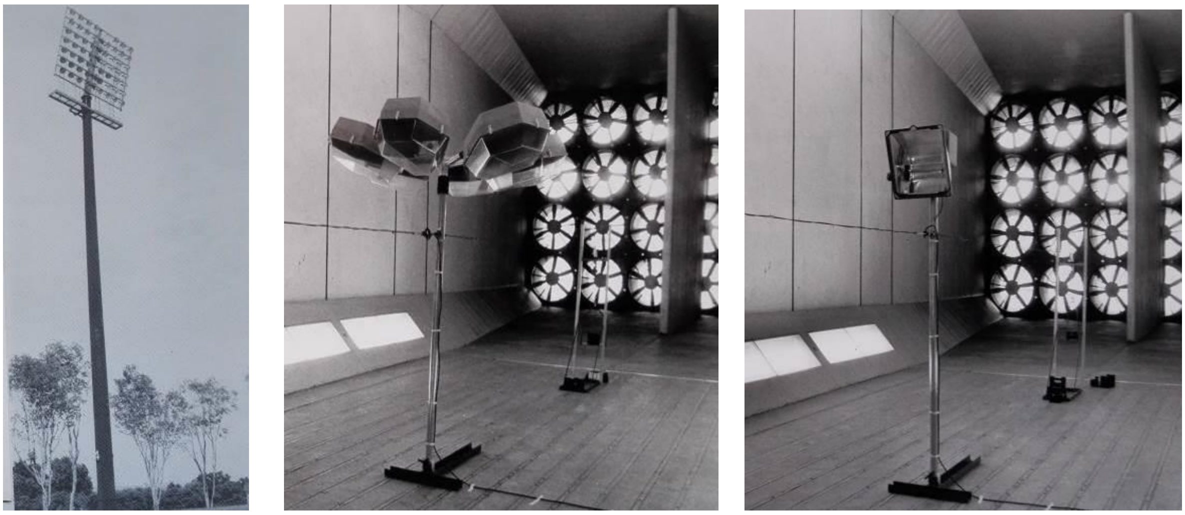
3.4.3 Loading of lighting masts

The outputs of one of the wind-tunnel research projects found direct implementation in the relevant SABS standard. A comprehensive set of measurements was undertaken in collaboration with the South African Institute of Steel Construction (SAISC) in order to quantify the wind loadings of various types of industrial light fittings and their assemblies. The set of force coefficients derived was then included in SABS 0225, Edition 1 (1991).

Full-scale prototypes and scale-model elements were developed, instrumented and tested in two different wind tunnels at the CSIR. Figure 3.15a presents an image of a full-scale mast supporting a floodlight array, Figures 3.15b and 3.15c represent two of the lighting configurations placed in a large (mechanical engineering) wind tunnel, and Figures 3.15d and 3.15e the small-scale wind-tunnel models.

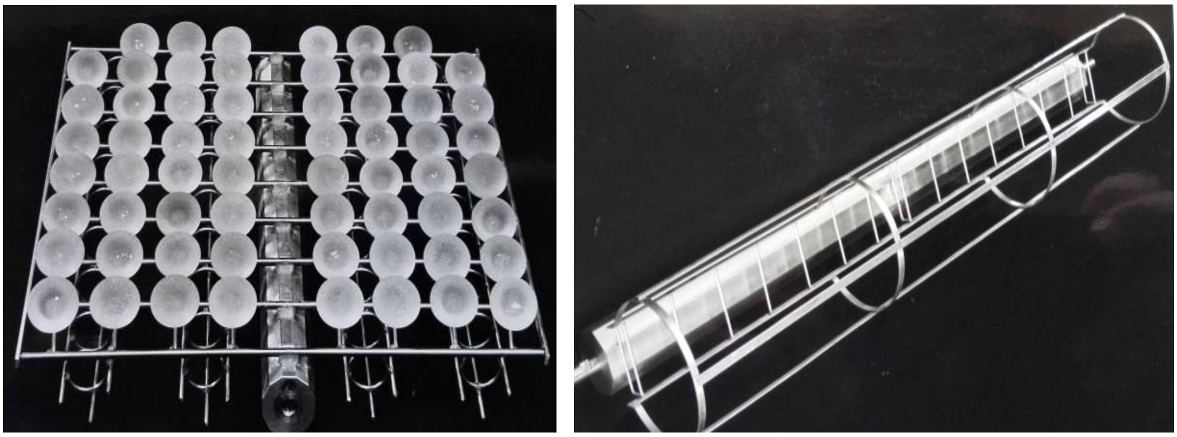
Figure 3.15f presents an extract from one of the tables of SABS 0225, in which the wind loading drag-force information governing the design, derived from wind-tunnel testing, has been implemented. This information was widely welcomed by the related steel manufacturing and design industry as it provided a common reference base to be adopted by various role-players.

Historically, wind loading parameters used by the design and steel manufacturing industry for lighting masts, were largely inconsistent - often adopted as guesstimates. Apart from huge safety concerns and implications (e.g. the collapse of floodlights during sports events (see Figure 3.15g)), these encouraged uncompetitive cost-cutting practices.



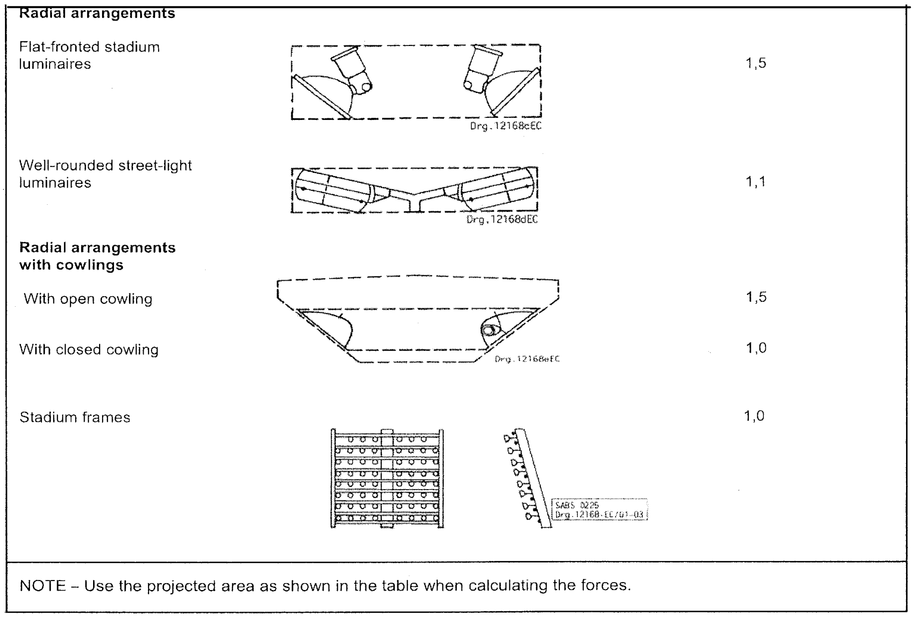
a) b) c)

Figure 3.15: a) a floodlight; b) an array of lights; c) a single light fitting



d) e)

Figure 3.15: d) model of a floodlight; e) a section of a pole with a ladder



Radial arrangements		
Flat-fronted stadium luminaires		1,5
Well-rounded street-light luminaires		1,1
Radial arrangements with cowlings		
With open cowling		1,5
With closed cowling		1,0
Stadium frames		1,0
NOTE – Use the projected area as shown in the table when calculating the forces.		

Figure 3.15: f) Information on drag-force coefficients (SABS 0225)

Figure 3.15: g) Collapse of a floodlight at a stadium in Mpumalanga

3.5 Sports stadia

The roofs of sports stadia can generate substantial wind loadings due to their size and nearly horizontal orientation. These loads are a function of several unique geometrical features (e.g. size, layout or slope), spatial relationships (e.g. form of the grandstands in relation to the roof layout) and their mutual interferences, which cannot be predicted theoretically or replicated in the design of other spatial/ geometrical situations. Over the years, several sport stadia have been modelled and tested at the CSIR laboratory, some of them in preparation of the 2010 Fifa World Cup.

Figures 3.16a to 3.16d present images of some of the stadia, which were tested at the CSIR wind tunnel under the supervision of the author – namely Mbombela, Athlone, Bloemfontein and Turfhall (Cape Town).

a)

b)

c)

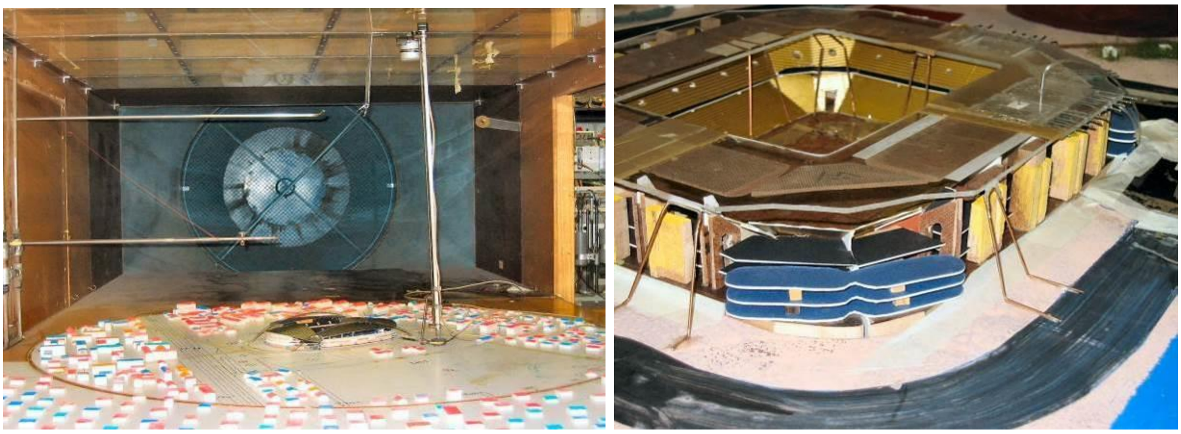
d)

Figure 3.16: a) Mbombela Soccer Stadium; b) Athlone Stadium; c) Free State Stadium in Bloemfontein; d) Turfhall Softball Olympic Stadium

Structural load testing of the Green Point Stadium in Cape Town was carried out in an overseas wind tunnel in close collaboration with its architect. However, structural designers realised the importance of topographical influences on the wind flow regimes developing over the stadium. They requested a wind environment study of the area, as influenced by the prominent Cape topography (see Section 4.1 and Figure 3.17), to be performed at the CSIR. The issue of the importance and relevance of topographical wind-flow modelling will be discussed in Section 4.1, in relation to the environmental engineering studies.

Figure 3.18a presents the wind-tunnel test section, which includes the model of Athlone Stadium and its surroundings. Figure 3.18b is a close-up of the Mbombela Stadium model.

Figure 3.17: Green Point (now Cape Town) Stadium in relation to local topography



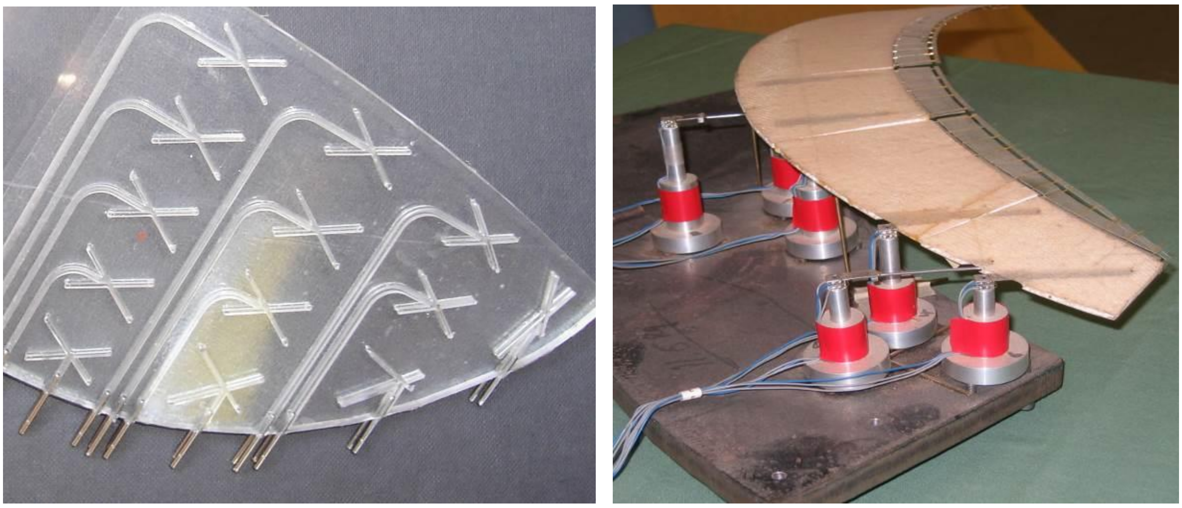
a) b)

Figure 3.18: Wind-tunnel models of a) Athlone stadiu; b) Mbombela Soccer Stadium

Various investigations carried out into the structural loadings included measurements of pressure distributions and the resultant forces. Importantly, the flow regimes affecting fairness of the game (i.e. over the pitch) and comfort, as well as the safety of spectators (over the grandstands), were also required.

Of interest is the issue of modelling technology. Traditional technologies for the testing of stadia were based on the resultant pressure distributions determined from independent measurements of pressures over the top and bottom roof surfaces, and their subsequent integration. This methodology typically resulted in unduly conservative design parameters. In the modern approach, also developed and implemented in the CSIR laboratory (with the significant contribution of Dr Louis Waldeck), instantaneous measurements of pressures over both surfaces were carried out.

This practise requires an intricate detailing of the models. An example of a section of such a model roof is presented in Figure 3.19a. (It should be noted that the 'cross-arrangement' of pressure taps enables an area average integration of pressures. Both pressure ducts and crosses, seen in Figure 3.19a, were machined on both sides of the Perspex sheeting.) Figure 3.19b presents a model component of a section of the roof used for measurements of the resultant forces generated over the entire roof.



a) b)

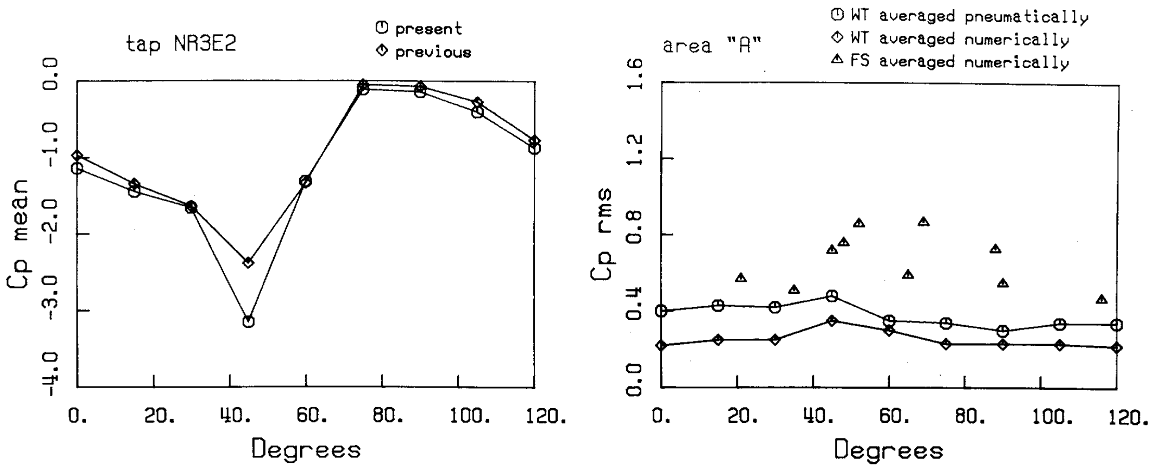
Figure 3.19: a) Close-up of pressure ducting; b) force balance model

An adoption of this technology required an investigation into the physics of surface-pressure averaging, in order to eliminate undesirable volumetric response distortions without affecting the measured peak values. Extensive comparisons were made between the pneumatic (i.e. air volume) vs numerical (i.e. signal) averaging. It also necessitated the introduction and calibration of dedicated flow restrictors in order to ensure the required frequency response of the signal. (Their characteristics differed in comparison with standard flow restrictors related to a single point signal.)

This investigation established that numerical averaging of pressures disregards the spatial correlation of pressures, and typically results in lower values of the root-mean-square pressure coefficients (as compared to the pneumatic averaging). However, there is a good degree of consistency between the pneumatically and numerically averaged mean results.

These trends are depicted in Figures 3.20a and 3.20b. Figure 3.20a refers to the mean pressure coefficients and the *'present'* data refers to pneumatic averaging. In Figure 3.20b the corresponding full-scale (FS) data are also included, which indicates a fairly poor comparison with wind-tunnel (WT) data. This issue was raised in Section 3.2.1.

Of particular technical interest, and a challenge, was the study of the Mbombela Stadium in north-eastern part of the country. The roof of this stadium was designed to be fitted with double 'skin' – i.e. top and bottom sheeting. This was in order to prevent bird nesting under the roof (and the consequent untidiness of the venue), frequently observed in many structures of this nature.



a) b)

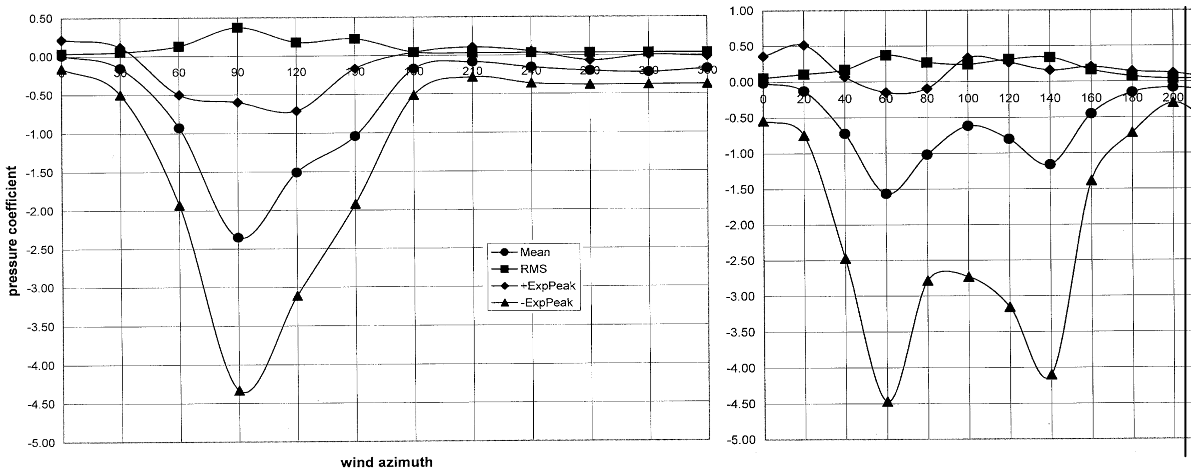
Figure 3.20: Comparisons of pressure coefficients: a) mean; b) root-mean square

The wind loading effects of so-called 'double skin' elements is complex, as it results from a combination of pressures acting on both surfaces of both layers. Further to that, depending on the 'aerodynamic porosity' of the connections between sheeting, a volumetric dynamic response of the air volumes within the void can develop. This issue requires evaluation of energy spectra of the internal pressures developing in the inner air volumes as a function of relative aerodynamic porosity of the system. Figure 3.21 presents a model of a roof corner section.

Figure 3.21: A double-layer roof corner

In Figure 3.22a a sample of wind-tunnel output data, presenting the variation of the resultant pressure coefficients with wind direction over one of the panels of the roof, is presented. It can be seen that, for the wind azimuth of about 90°, resultant mean and peak pressure coefficients are substantially higher than those which would have been derived from any wind loading manuals. This finding demonstrates the critical importance of wind-tunnel testing of such types of structures.

It is important to note that in Figure 3.22a the extreme resultant peak pressure, $\hat{C}p_R \approx -4{,}5$, coincided with a relatively high magnitude of mean pressure of about $\bar{C}p_R \approx -2{,}5$. In some cases this relationship is less pronounced e.g. $\hat{C}p_R \approx -4{,}5$ and $\bar{C}p_R \approx -1{,}5$, as presented in Figure 3.22b. This situation is introduced by specific spatial relationships and typically indicates generation of irregular (in the time domain) flow separation, vortices and high localised pressures. Engineers and architects are often unaware of or ignore this issue, despite it posing huge risks to localised failures of the sheeting (especially concealed sheeting systems). All large-span sheeting failures are triggered by initial localised detachment, followed by removal of the entire sheets, as presented in Figure 3.23.



a) b)

Figure 3.22: Variations of pressure coefficients with wind azimuth (10 sec averaging time): a) high peak and mean coefficients; b) high peak coefficient

Figure 3.23: Failures of large-span concealed roof-sheeting systems

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An important aspect of the wind loading of large-span roofs relates to modelling the intermediate construction stages of roof sections. In such circumstances the distribution of pressure coefficients may be radically different from the final status and this should also be taken into consideration. Although the corresponding mean return period (i.e. the magnitude of wind speed) is much shorter, this situation may constitute the overriding loading situation for internal sections of the roofs.

Some of the aspects and outputs of the work discussed above have been reported in Goliger (2005a; 2005c and 2010), Gizejowski and Goliger (2009) and Goliger *et al* (2010). No details of the wind-tunnel techniques summarised above were published owing to very limited applicability to the broader engineering profession and also for confidentiality (know-how) purposes.

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4. Environmental engineering studies

Wind action (e.g. loading) affecting the entire environment – including the human body – originates in flow regimes determined by spatial relationships between all elements and open spaces. The important role of boundary-layer wind-flow modelling is, therefore, to investigate and gain the understanding of wind regimes which develop in specific situations.

Over the years the author has been involved in numerous wind-environmental research studies. Often such studies are closely interconnected with others, but can broadly be grouped into the assessment of wind flow as follows:

- wind flow as influenced by complex topography,
- wind-flow regimes over large-scale terrain/developments
- wind-flow distribution over building structures
- wind flow affecting the distribution of pollution, erosion and deposition of small particles, and
- wind flow within a densely built environment (closely related to pedestrian-level wind-tunnel studies).

The related research and various types of studies undertaken in the past are summarised in the following sub-sections.

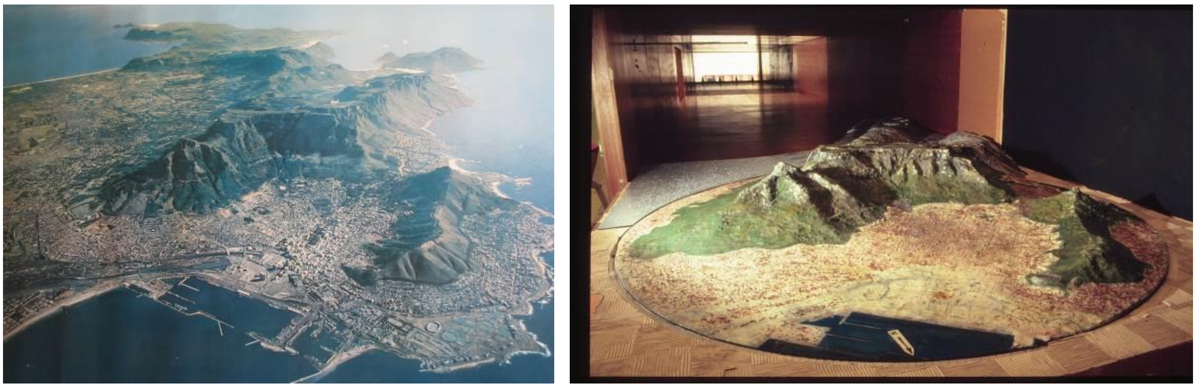
4.1 Topographical modelling

Initial wind modelling (Goliger and Milford, 1989/1991) concentrated on a fairly gentle topography characterising the approach to the Pretoria Central Business District (CBD). The city, like many others in South Africa, is located between two gentle mountain ridges running approximately east-west. The closest hill with a more than 150m elevation (classified as having a steep slope) is located within a distance of about 1,3km upwind of the city outskirts.

Various flow parameters were investigated. It was found that while the upwind hill had a noticeable effect on wind characteristics developing in an open terrain, it had a negligible influence on the wind at the lower elevations within the city. Therefore the development of the boundary layer over the city is dominated by the surface-friction effects produced by the buildings.

The author's interactions with local authorities and site surveys in Cape Town indicated a substantial impact from the dominant topography, affecting flow directionality, spatial correlation, strength and consistency. A survey of the related literature at the time revealed the presence of simplified mathematical formulations in the topographical two-dimensional influences; this is not applicable to the Cape Town situation.

Subsequent contacts with international experts and the literature review also revealed the pioneering work carried out by Prof Jacques Hertig and his team at EPFL (Switzerland). This work was directed at the modelling of wind-flow distribution affecting the safety of traffic within the Alps' valleys. Two study visits by the author to EPFL took place in 1988 and 1989 and were followed by the development of a Cape Town topographical model and comprehensive wind-tunnel testing of this model. (Some of the findings related to flow reorientation and the presence of updrafts were re-examined and confirmed in another wind-tunnel laboratory. This was due to the radical nature and implications of these phenomena.) Figures 4.1a and 4.1b present the Cape Town topography and its wind-tunnel model respectively.



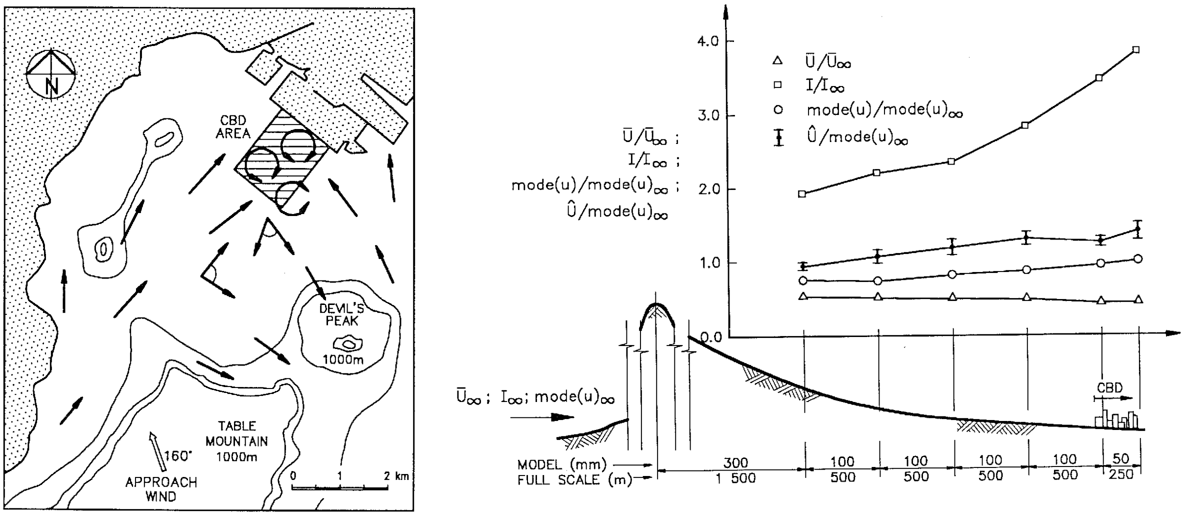
a) b)

Figure 4.1: Cape Town topography: a) full scale; b) model scale

The outcomes of the project were reported at the 8th *International Conference on Wind Engineering* in London, Ontario, Canada (Goliger *et al* 1991/1992; subsequently selected for the special issue of the *Journal of Wind Engineering and Industrial Aerodynamics*, Goliger *et al*). The uncommon topic and unexpected findings of the paper generated robust debate and large interest from the conference participants. In a sense, it also became a catalyst for other topographical wind-tunnel modelling programmes elsewhere in the world. Extensive modelling of topography is currently implemented in all studies of large-span modern bridges across mountainous terrains.

The outcomes of the study demonstrated that, for a specific range of wind directions, the influence of the topography on the flow approaching the CBD is significant, both in terms of its re-orientation and the substantial changes in statistical characteristics as a function of the elevation. Samples of the output data are demonstrated in Figures 4.2a and 4.2b.

Figure 4.2a presents the directional pattern behind the mountain for a wind azimuth of 160° (corresponding to the most significant direction of south-easterly prevailing winds). It can be seen that the directions of localised flow have large spatial variability, including over areas of flow recirculation). Figure 4.2b demonstrates the magnitude of changes in various flow parameters, as influenced by the mountain. A database of these quantities has been developed in order to provide boundary-layer modelling inputs to future studies within the Cape Town metropolitan area.



a) **b)**

Figure 4.2: Characteristics of wind as influenced by topography: a) directional; b) quantitative representation

Detailed analyses showed that the wind climate over the Cape Town CBD is determined by three major flow regimes merging over the Foreshore area, namely:

- the redirected and scooped flow over the eastern slopes of Devil's Peak and Table Mountain,
- the flow over the top of the mountain (at full scale this flow is affected/limited by the shallow/supressed vertical ceiling of trade winds), and
- most importantly, the south-easterly flow drawn in (due to the flow deficit) and re-oriented along the slope of the Twelve Apostles and further across the gap between Lion's Head and Table Mountain (Figure 4.3).

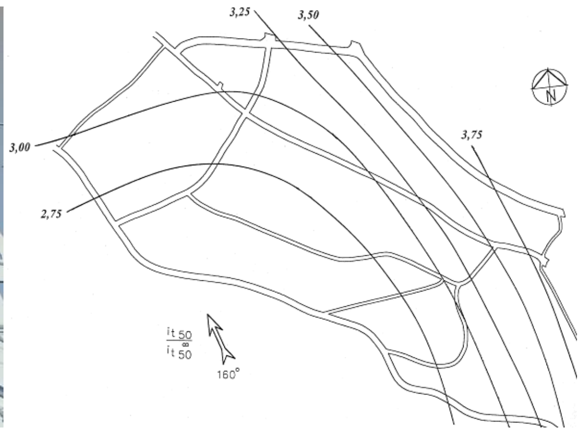
Figure 4.3: Wind flow in the gap between the mountains

Subject to the fluctuations of the approaching free-stream south-easterly flow (in the time domain), the mutual relationship between the above three components also varies over time. This results in highly complicated flow conditions developing over the CBD area which also include updrafts.

4.2 Large-scale and urban planning

The outcomes of topographical modelling created an awareness of its relevance among Cape Town city planners and other major role-players. Two macro-scale investigations were undertaken for the optimising and forward planning of large-scale land pockets in the Cape Town metropolitan area (the District Six and Culemborg precincts). Figure 4.4a presents the envisaged bulk distribution of buildings related to Cape Town's Vision 2050, and Figure 4.4b a typical data output regarding the distribution of relative turbulence intensity over District Six (for a specific wind azimuth).

Another prominent study was aimed at a comprehensive quantification of the wind environment over the Port of Cape Town, as well as the neighbouring Victoria & Alfred Waterfront. This information was developed for operational optimisation purposes and also for the Port's Forward Planning committee. (At that stage, large-scale radical changes in the layout of the port were considered, including migration of the Container Terminal, establishment of a large passenger terminal and a hotel precinct. The wind environment situation formed one of the contextual considerations of the project.)



a) **b)**

Figure 4.4: a) Mass distribution of buildings for CT Vision-2050; b) wind flow distribution over District Six

An example of the output data is given in Figure 4.5, which depicts contour lines of normalised wind speed corresponding to the most critical orientation of south-easterly prevailing wind. The results of the study were presented to all harbour stakeholders. It was comforting to find out that the presence of the localised zone of reduced wind speeds established over the central portion of the Ben Schoeman Basin was also confirmed by the port pilots as well as the operational processes regarding the movement of large vessels within this basin.

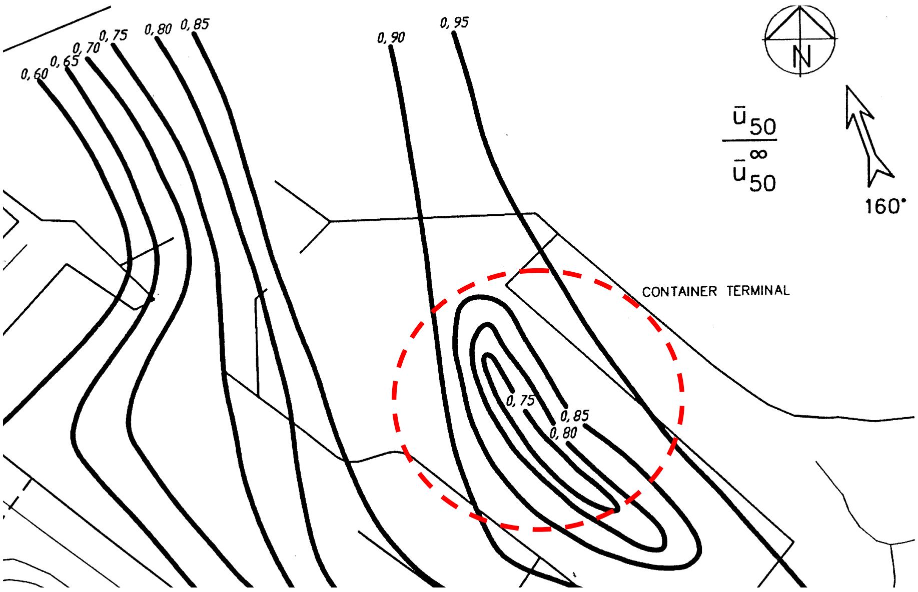


Figure 4.5: Contour lines of normalised wind speed (azimuth 160°)

4.3 Pedestrian-level wind environment

In many cities throughout the world unpleasant and sometimes dangerous wind conditions are experienced by pedestrians (Figure 4.6). In South Africa this is especially evident in coastal cities like Cape Town and Port Elizabeth. A prime example of such a situation is the Cape Town Foreshore, in which a combination of:

- the severe wind climate of south-easterly trade winds,
- the adverse effects of prominent topography, and
- the development of tall and large buildings, surrounded by large open spaces,

have created unacceptable wind conditions affecting the public.

In the mid-1980s the re-emergence of the 'public realm' (space between buildings) as a focus of safe city building layout received substantial international attention across the spectrum of all role-players. This was accompanied by a growing awareness of public and large social and private spending into highly pedestrianised open city spaces. (In several cities across the world it resulted in extensive pedestrianisation of street-level traffic closures, as well as redirecting/submerging main traffic routes in order to provide open public access to waterfronts.) These social trends also resulted in an emergence of wind-tunnel technology applications to investigate and improve wind-environment conditions.

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The initial topographical wind-tunnel modelling involving the author coincided and followed extensive collaboration with the Cape Town City Planning department, undertaken in the late 1980s focused at the pedestrian-level wind-tunnel modelling. Historically, some of the tall building structures developed in Cape Town were tested in mechanical engineering wind tunnel facilities at local universities, without due consideration of the boundary layer and ignoring the influence of the dominant topography.

Figure 4.6: Pedestrian wind conditions on the Cape Town Foreshore

Pedestrian-level wind studies involve qualitative and quantitative types of measurement. Traditionally absolute or relative methodologies and criteria have been used in wind-environment studies. The approach followed by the author adopted a probabilistic approach, based on principles postulated mainly by Prof Nick Isyumov and Professor Alan Davenport (1975 and 1981). In principle, it was founded on the mathematical relationships of the boundary-layer profiles (and their transitions) in combination with the directional probabilities of wind speed occurrence.

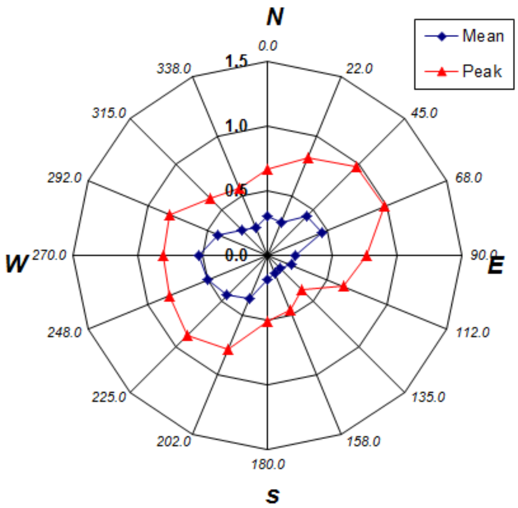
In the case of Cape Town an additional substantial complication and challenge was introduced by the presence of Table Mountain and its overriding impacts in terms of wind speed and directional characteristics. *(A complex integration process for the full-scale and wind-tunnel data was developed. As an outcome, a matrix of the conversion factors, applicable to the data derived from wind-tunnel testing, was developed. This process and the data were not published in order to protect the intellectual property.)*

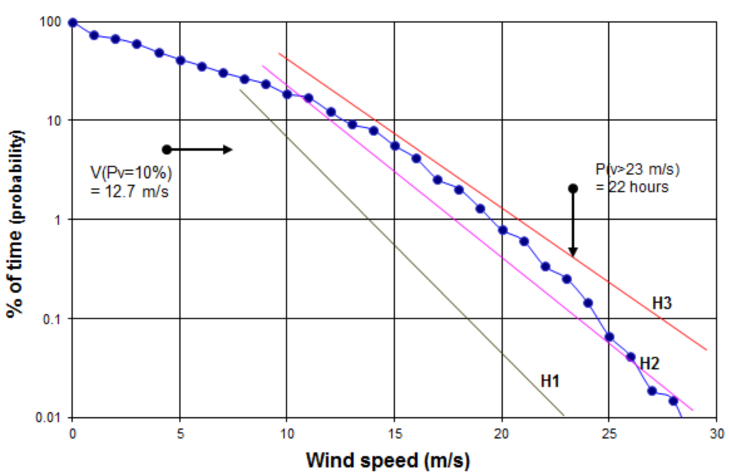
Numerous wind-tunnel projects have been carried out over the years, mainly (but not only) concerning the Cape Town area. These included most of its recent developments in the Foreshore and V&A areas (e.g. the Convention Centre, the

One&Only, the Clock Tower Precinct, Table Bay Hotel, Dolphin Beach and many others). The related research and developmental work was reported in several publications: Goliger and Birkby 1993; Richards and Goliger 1997; Goliger and Richards 1997; Kasperski *et al* 1999; Goliger 2001; Goliger *et al* 2004b; Goliger and Mahachi 2006b and 2008b. A few of the most notable and challenging projects are highlighted below.

Examples of typical output data are presented in Figures 4.7a and 4.7b. On the basis of such data optimal remedial measures are investigated in order to improve adverse wind conditions. Figure 4.7a is the wind-tunnel rose. Figure 4.7b presents the wind-speed probability of occurrence graph overlaid on the standard criteria of pedestrian-level comfort.

These criteria were developed in collaboration with the Cape Town City Council Planning Department, and reflect probabilities of wind-speed occurrence in terms of three types of human outdoor activities/exposure (H1 to H3) and the international threshold of danger corresponding to wind of 23 m/s.



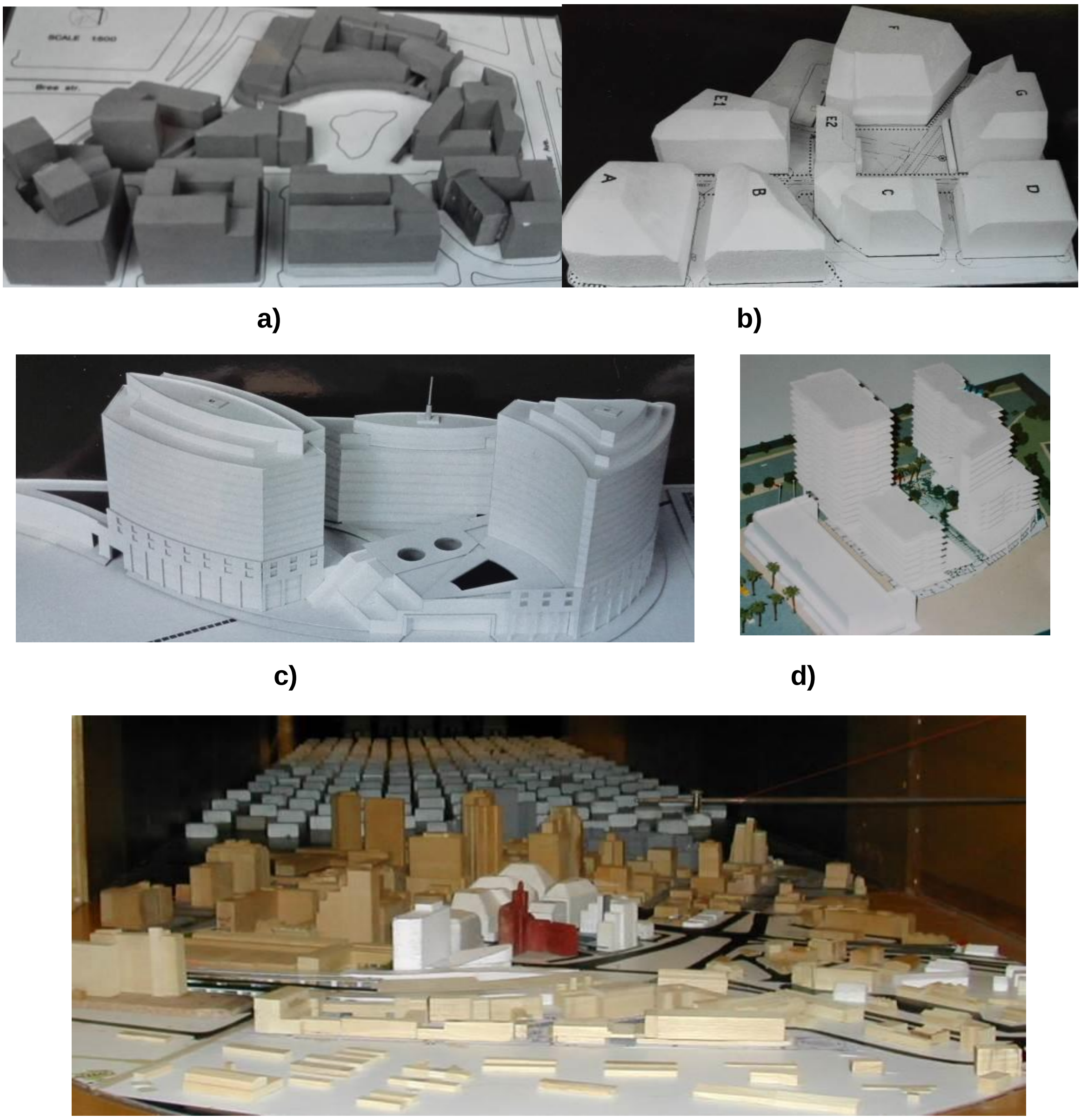


a) **b)**

Figure 4.7: a) Wind rose; b) wind speed probability of occurrence

One of the projects, the Waterfront Hotel Precinct, constitutes an excellent example of a comprehensive long-term proactive approach to the phased spatial development of a prime commercial area of Cape Town. Despite the extreme wind conditions observed over this area, the precinct was envisaged for extensive outdoor access and utilisation – due to its prime location opposite the main entrance to the V&A.

The aim of the study was to quantify the wind-environment impact of various bulk distribution scenarios so as to optimise conditions at specific areas of the development envisaged for extensive outdoor use. A set of images included in Figures 4.8a to 4.8e demonstrates various configurations and building structures which were considered and tested in the wind tunnel.



a) b)

c) d)

e)

Figures 4.8: a) Planning Ensemble I; b) Ensemble II; c) land portions B&C; d) portion F; e) testing of Ensemble II

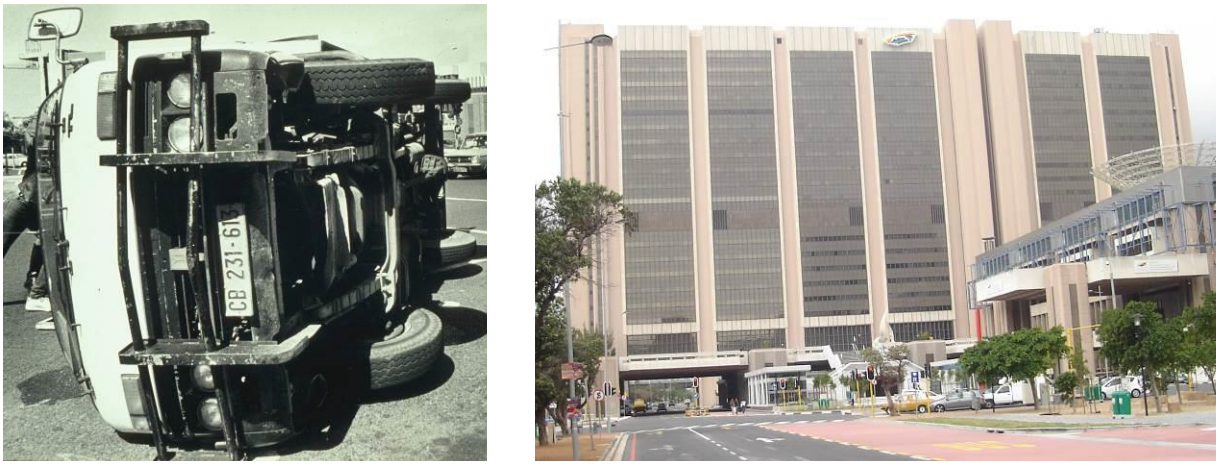
It is of relevance to mention that the wind-environment effects constituted one of the important, but not overriding, aspects of the town planning process. In fact, the bulk distribution corresponding to planning Ensemble I offered a superior wind-environment situation, but was overwritten by the commercial requirements of minimum available floor space. Further departures from height restrictions were also granted to some of the buildings (e.g. Holiday Inn and former Cullinan Hotel – Figures 4.9a and 4.9b).

a) **b)**

Figures 4.9: a) former Cullinan hotel; b) Holiday Inn Waterfront

One of the most challenging studies refers to the Cape Town City Council building, which is renowned for the extreme ground-level wind environment generated within its vicinity (Figure 4.6 and 4.10a) owing to its:

- positioning – relative to Table Mountain and with a large open space,
- orientation - facing prevailing winds,
- size – extensive façade in the order of 20 000 m^2 (Figure 4.10b), and
- form – large openings at ground level (Figure 4.10b).



a) **b)**

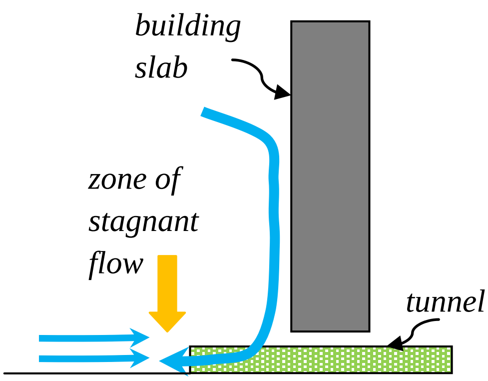
Figures 4.10: a) an overturned vehicle; b) the building slab raised on columns

Wind-tunnel measurements and the subsequent statistical process indicated that, on average, for more than 350 hrs per year, the threshold wind speed for human danger (23 m/s) is exceeded in the areas surrounding the building.

As an outcome of a comprehensive spatial transportation study of the Cape Town Metropole, the area of concern was identified as a unique focal point for the positioning of the central distribution station of the Cape Town Integrated Rapid Transport (IRT) system. A renowned overseas architectural expert was requested to investigate and propose an effective remedial measure to ameliorate the wind situation.

The architect's proposal was to introduce two large-scale roofs integrated with both façades of the building slab and extending to a distance of about 100 metres away from the slab. Due to its prohibitive cost, this idea was not followed and the author was approached and given a mandate to identify and test all possible remedial measures. The City Council was prepared to accept significant modifications to the Civic Centre buildings (e.g. 'punching'/venting ducts across the building, the introduction of 'wind gutters' attached to the façade, the introduction of large canopies to 'laminate' (in horizontal direction) the air volumes, and modifications to the façades.

Due to the enormous volumes of 'blocked' air (in the order of 30 million cubic metres per minute) all measures proved unable to provide the desired levels of reduction in wind-speed magnitude experienced in the vicinity of the building. An innovative solution, that of an independent *tunnel* (sleeve structure) housing the station, was proposed to the IRT development committee. The inlet to the *tunnel*, facing the south-easterly winds, was kept a considerable distance away from the building slab, in an area of relative calm, in which the downwash flow would meet and counteract the incoming free-stream flow (Figure 4.11a). This area was also confirmed by full-scale measurements. Figure 4.11b presents the southern entrance to the IRT Central station.



a) **b)**

Figures 4.11: a) Flow principle; b) southern entrance to IRT Central station

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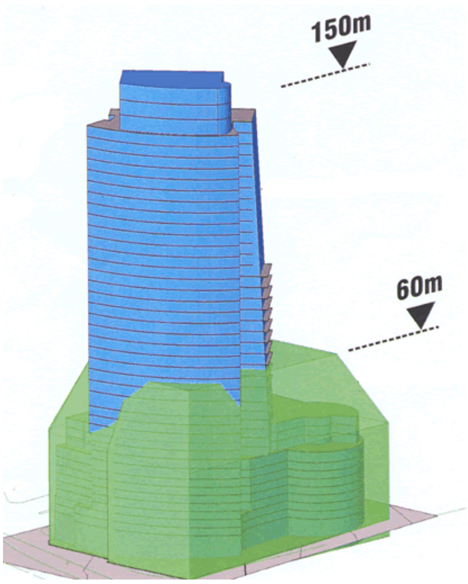
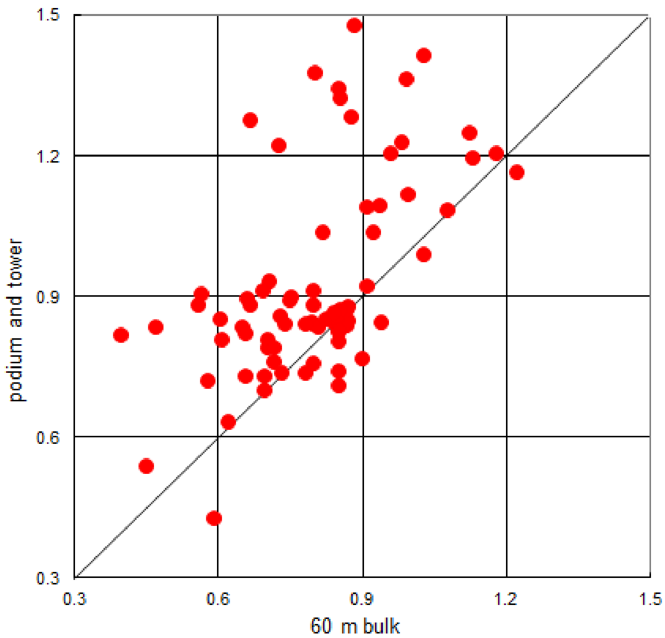
4.4 Impact of tall buildings

Tall and large buildings have a fundamentally detrimental impact on the wind conditions at low levels within their immediate vicinity. Unfortunately, economic/ commercial considerations, related to the demand for and cost of land within large cities, often override environmental factors – and each year more such buildings are introduced.

In one of the projects an intense argument ensued in this regard and a claim was made (by a renowned and commercially motivated architect) that a substantial departure from the height restriction of a specific building site will not have any effect on wind-environment conditions at its base. As a result of this discussion, it was agreed to undertake a set of comparative wind-tunnel measurements in which two versions of the proposed building were modelled – namely a 60m, low, bulk building and a 150m tall building, including a podium with a tower.

Figure 4.12a demonstrates the differences between alternative versions of the building, and Figure 4.12b a comparison of wind-speed parameters (normalised mean and root-mean-square wind speeds), measured at street level in the vicinity of the building. This is in a form similar to a regression analysis, from which it can be seen that substantially higher wind speeds are generated at the street level with the tall version of the building being in place.





a) **b)**

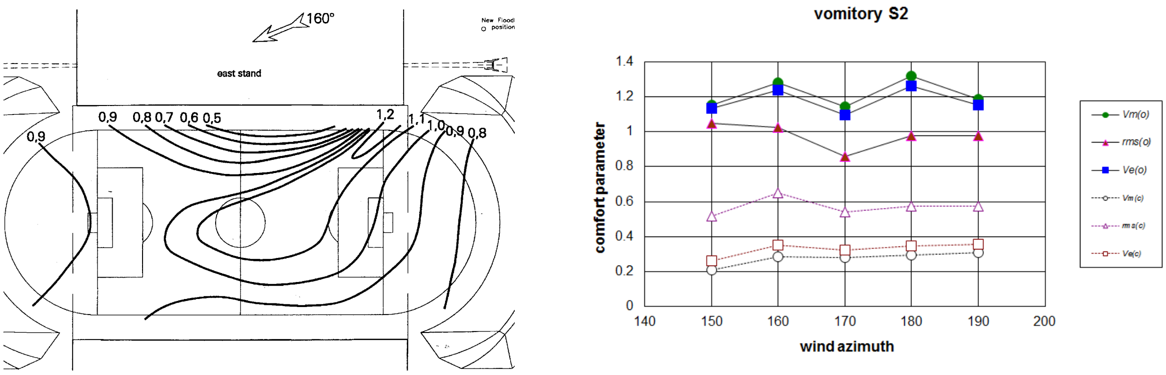
Figures 4.12: Comparisons of: a) building configurations; b) wind speeds

4.5 Sport facilities

Wind-environment conditions are important in the design of large sport facilities in order to ensure the fairness of the competition (acceptance of scores/records) and also spectator comfort. These were investigated in several of the wind-tunnel studies of South African stadia supervised by the author (Goliger 2010).

The contour lines of relative windiness over the pitch of one of the stadia, presented in Figure 4.13a, identified largely uneven wind-flow distribution under the prevailing winds. In combination with the localised wind-direction pattern (not included), this situation largely disadvantages one of the teams. (This finding supported the claims of the local soccer clubs and contributed to the disqualification of the specific stadium from major international tournament games.)

Figure 4.13b demonstrates the magnitude of improvement in wind conditions which could be achieved within one of the access tunnels (*vomitories*) to the grandstand, due to a partial closure of the neighbouring section of the concourse. (Open markers refer to the closed configuration of the concourse.)



a) **b)**

Figures 4.13: a) Wind distribution over the pitch; b) improvement of wind conditions

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5. Research on wind damage and tornadoes

The research on South African tornado events undertaken at the CSIR constitutes an excellent example of the benefits of a comprehensive, multi-faceted and long-term scientific programme carried out by a team of committed people. These activities enabled investigation and quantification of the occurrence and implications of vaguely known and understood (almost anecdotal) weather phenomena, which have devastating consequences at a regional scale, and impact the South African economy due to interruptions in power supply.

This research demonstrates several attributes, benefits, goals and outputs, as highlighted below:

- The critical importance of basic and consistent research supported and carried out by a research organisation *on behalf* of the national interest and benefit.

- An incremental approach to solving a research problem in which an initial, industry-specific request was broadened and extended to cover research of national relevance - also in relation to other industries (e.g. reinsurance).

- Cross-organisational initiative and cooperation involving the CSIR, Eskom and the SA Weather Service.

- A multi-disciplinary approach in which a statistical methodology developed for mining exploration purposes (lognormal frequency distribution to predict the spatial concentration of gold) was implemented in order to derive the risk of occurrence of meteorological phenomena (with variable characteristics and strength) over diverse geographical regions.

- Public visibility, in which the research outputs culminated in a publication on South African tornadoes, developed jointly by the CSIR and SA Weather Bureau.

  Interestingly, the book's release coincided with the release of the Hollywood film 'The Twister' and generated considerable public interest and exposure for the CSIR. A copy of the book also reached the SA President at that time, Mr Nelson Mandela, who had personally experienced one of the tornadic events in KwaZulu-Natal.

- The development of scientifically based information and solutions at a local level which, due to their relevance, generated international visibility, interest and application to other climatic situations.

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- Finally the experience and expertise obtained in the application of statistical methodology to the meteorological domain was successfully applied in geotechnical research, for mapping of the soil variability of heaving clays (Keyter *et al* 1996).

In the following subsections, the most relevant and stimulating aspects and stages of the research are summarised.

5.1 Investigations of wind damage events

The inception of structural engineering activities at the former National Building Research Institute of the CSIR took place in 1950s. Since then, apart from basic laboratory/testing research, a fair amount of effort was committed to the full-scale monitoring of structural performance of the built environment. These activities were funded from research grants across various types of structures (e.g. housing, multi-storey buildings, water reticulation and industrial structures, slender structures/chimneys), and involving (in alphabetical order), *Messrs Evert Banniga and Graham Beattie, Dr Adam Goliger, Mr Clarry Hodgkinson, Drs John Laurie, Brian Lunt and Rodney Milford, Messrs Martin Smit and Tersius Van Wyk and Dr Louis Waldeck.*

In the early days the relevance and severity of aspects of wind action were identified. It was realised that, because of

- the absence of snow and icing,
- the southern exposure of the land mass to *trade winds*, and
- the potential for severe *convective activities*,

wind action constitutes the least known and most critical environmental loading of structures in South Africa. Similarities were drawn with the extreme-wind climates of southern Australia and mid-USA.

As an outcome of this realisation, two types of activities were supported and carried out, namely:

- the monitoring of newspapers and collecting reports related to wind damage carried out by the CSIR's regional officers represented in various provinces; a similar activity, focused on all weather-related events was also carried out by the librarian at the SA Weather Bureau, and
- the identification, inspecting, documenting and analysing of large-scale wind-damage events.

These activities resulted in capturing some historical records of tornado activity (Figures 5.1a and 5.1b), and wind-induced disasters – e.g. the annihilation of Albertynsville in 1952 (Figure 5.2a), the footprint of a microburst in Prieska (Figure 5.2b) or damage caused by the Bronkhorstpruit tornado (Figure 5.2c).

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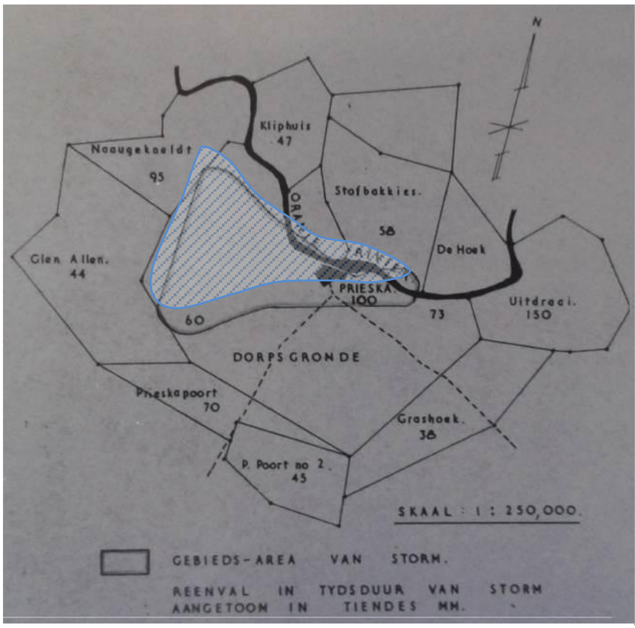
(Unfortunately some of these historical reports/records went missing during various relocations and restructuring processes at the CSIR over the years.) Large numbers of events which took place between the late 1980s and mid-2000 were investigated and documented in CSIR internal reports. Reports on two significant tornadoes, both taking place in 1999 (Manenberg - 29 August, and Heidelberg - 21 October) were published (Goliger and De Coning, 1999; De Coning *et al*, 1999). It is of interest to note that the historical data on the occurrence of strong events and wind damage were distorted by a few factors, namely:

- substantially lower population and developmental density,
- poor media coverage and accessibility, and
- a tendency in which most excessive wind events were referred to as tornadoes or hurricanes.

a) b)

Figure 5.1: a) Tornadic funnel over Dalton (New Hanover), 23 April 1948; b) Tornado in Sabie, 18 December 1948

Figure 5.2: a) Devastation of Albertynsville (outside Soweto), 30 November 1952



b) **c)**

Figure 5.2: b) Footprint of a microburst in Prieska, 3 December 1959;
c) Damage to a reinforced concrete frame in Bronkhorstspruit, 10 May 1949

5.2 Wind action on transmission lines

In the late 1980s the CSIR was approached by the Power Transmission division of Eskom with a request to undertake a comprehensive research study into:

- the wind loading structural design models of transmission lines (towers and conductors), as well as
- the failures of transmission lines due to extreme wind events.

This research involved:

- review of the state of the art regarding international practice and the existing wind loading models,
- investigation into the wind climatic characteristics of South Africa applicable to transmission lines,
- site investigations of specific power-line failures identified by Eskom (Goliger, 1993), and
- analyses of failures and determination of relevant statistics and prediction models.

It is of interest to note that during the initial phase of the project (in March 1990) a significant tornado event devastated the economic hub (at the time) of Welkom. The widespread damage (including 4 000 houses and 17 major Eskom power lines – see Figures 5.3a and 5.3b) paralysed the local economy. This event abruptly indicated the relevance and validity of tornado research.

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a) b)

Figure 5.3: a) and b) Damage to power lines in Welkom, 20 March 1990

The related research work was carried out between 1989 and 1994 and reported in several internal reports. Some of the work was protracted and also published, with Eskom's permission (Goliger, 1993; Milford and Goliger 1994).

5.3 Database on severe wind events

The work on the project undertaken for Eskom identified a need for the setting up of a comprehensive database of all strong and extreme wind events which took place in South Africa over a selected (fairly recent) time period. The development and maintenance of such a database took place between 1990 and 2000. This activity was eventually discontinued due to a lack of interest and support from the relevant role-players (e.g. SA National Disaster Centre, SA Weather Service and Dept. of Local Government).

The development of the database included surveys of the archives of the CSIR, the State Library, the SA Weather Bureau's climatic reference system and various related publications. A similar approach to setting up national databases was adopted internationally – e.g. in the USA and UK. Each damage incident was interrogated and indexed in terms of:

- type of event,
- related weather conditions,
- date, time, duration,
- extent/affected area,
- description,
- references,
- human loss (death, injuries, homeless people involved),

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- damage to infrastructure, and
- financial/economic impact.

As a result, nearly 1 000 events were classified, quantified and indexed (Milford and Goliger, 1993).

5.4 Wind-damage and disaster-risk model

The author's involvement in the South African National Disaster Committee was initiated by Professor Alan Davenport, who at the time was the United Nations Disaster Committee envoy to South Africa.

In combination with several wind-damage and disaster investigations (Section 5.1) as well as the development of the database (see Section 5.3), this led to a recognition of the significance/magnitude of wind-induced damage in South Arica. Furthermore, a need for development of a common, scientifically based platform, in which the risks, related statistics and their implications could be quantified, became apparent.

This problem was identified as a suitable topic for a PhD dissertation, undertaken at Stellenbosch University between 2000 and 2002, titled 'Development of a wind damage and disaster risk model for South Africa'. This research was reported in a number of joint publications: Goliger and Retief (2001a, 2001b, 2005, 2006, 2007); Goliger *et al* (2002, 2003a, 2003b, 2004a and 2013); Goliger and Mahachi (2008a, 2008b) and Hoffer *et al* (2001/2002).

It is of specific interest that, in view of the poor geographical coverage of wind climatic observations, a spatial approach was adopted. In this approach the probabilities of damage and disaster were expressed as a function of several parameters – e.g. types of wind events and their zones, spatial extent and frequency of occurrence, as well as developmental distribution. This followed the principles postulated by McDonald (1983) (Goliger and Retief 2001a and 2003a) for quantification of tornadic events.

5.5 Tornado activity

The database of strong or destructive wind events (Section 5.3) was subjected to a comprehensive scrutiny process in order to identify and separate the events of tornadic origin. In order to achieve the required levels of certainty, the data which was collected was examined and classified in terms of several criteria, which were developed on the basis of tornadic expert literature generated mainly in the USA. In view of the unique aerodynamic characteristics of tornadic events, several positive descriptors were identified and utilised in the evaluation process, namely:

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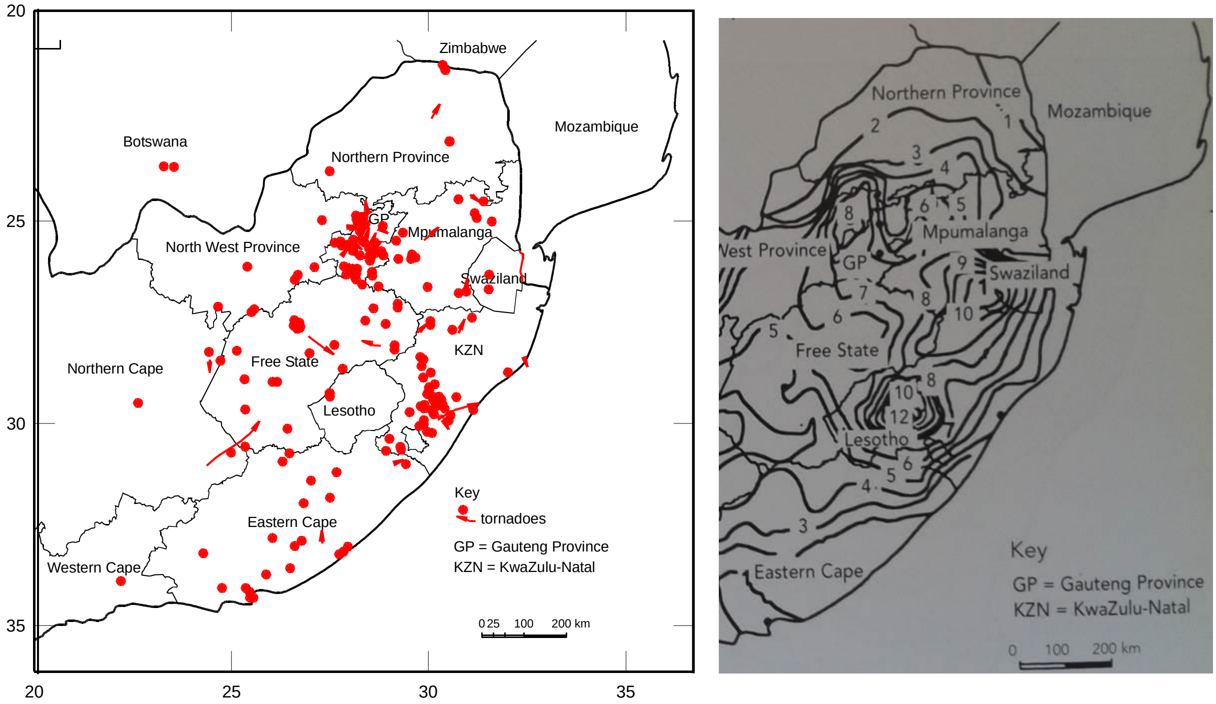
- the occurrence in relation to severe convective activity,
- limited spatial extent, i.e. the footprint/path of damage,
- limited duration,
- the magnitude of wind (based on damage evaluation),
- witness accounts (noise, movement, presence of the funnel),
- characteristics of action (e.g. twisting motion, presence of outwards pressures), and
- uplift and air transportation of relatively small but heavy objects – e.g. machinery, cars (also people or animals) over large distances.

An exceptional characteristic of tornadic events, in clear distinction from all other severe wind phenomena, is their *selectiveness* of damage – i.e. areas with no evidence of damage in the immediate proximity of places of total destruction. An excellent example of such a situation is presented in Figure 5.4. This figure demonstrates the devastation of a section of a large warehouse outside Nigel (east of Johannesburg), while other sections, as well as the surrounding structures remained unscathed. This is a consequence of a very limited width and also a discontinuous path of a tornado containing places with uplifts and touchdowns of the funnel.

Figure 5.4: Spatial extent of damage (Duduza tornado, 3 October 2011)

The process and outcomes of the tornado database have been included in several reports to Eskom and summarised in Goliger (1992a, 1992b and 1993), Milford and Goliger (1994) and Goliger *et al* (1997). About 200 tornadic events have been identified in the period between 1905 and 1991. The vast majority of events took place over the eastern part of the country and their geographical distribution is presented in Figure 5.5a.

Correlation between the tornado occurrences and other weather phenomena was also examined. A fair similarity was observed between thunderstorm, hail and lightning activities. Figure 5.5b presents the geographical distribution of the average number of lightning flashes per square kilometre per year (Geldenhuys, year unknown).



a) b)

Figure 5.5: a) Tornado activity in the east of South Africa (1905 – 1997); b) average number of lightning flashes per square kilometre per year

The confirmed events were subsequently categorised in terms of their size and severity by using an internationally accepted Fujita/Pearson classification. More than 60% were classified as F1 and F0 (moderate) events and nearly 40% as F2 and F3 (considerable to severe) events. (It should be noted that the Fujita/Pearson scale was developed on the basis of North American construction practice, which largely reflects lightweight frame housing, and this may indicate higher vulnerability to windstorms than traditional brickwork construction.

5.6 Tornado statistics

Several characteristics of tornado events were identified (Goliger *et al,* 1997/1998) and analysed in terms of:

- the probability distribution of their intensity (i.e. size),

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- path length and width,
- yearly distribution,
- seasonal distribution,
- time of the day, as well as
- human and material losses.

A yearly distribution of the confirmed tornadoes is presented in Figure 5.6. It can be seen that, on average, few events occur per year in South Africa.

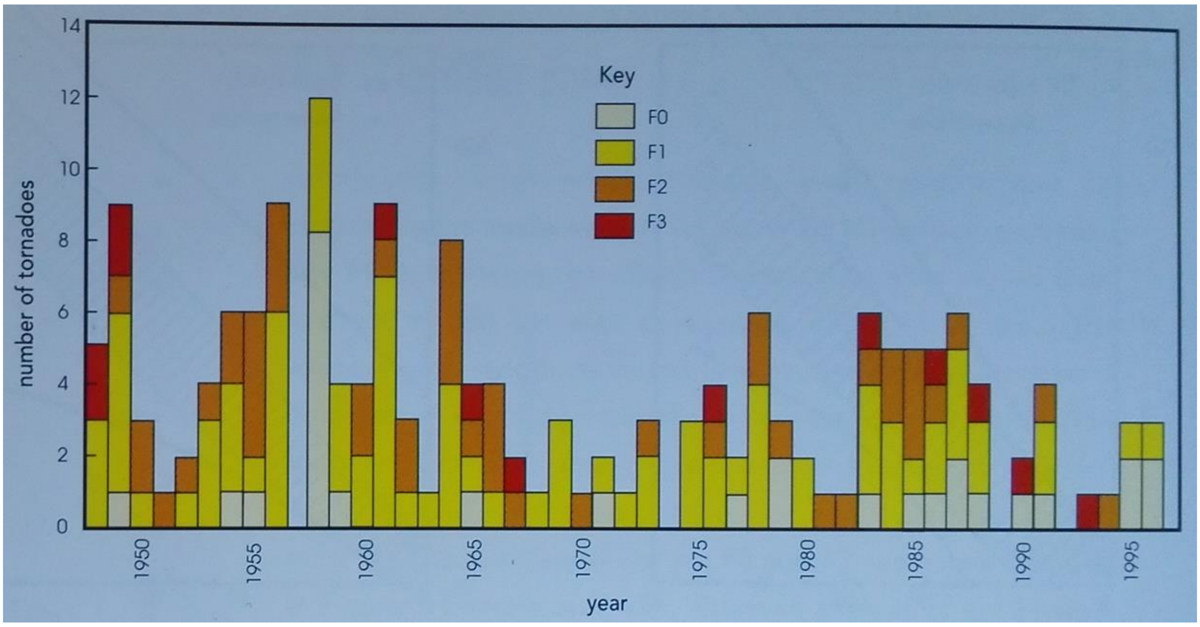

Figure 5.6: Yearly occurrence of tornadoes in South Africa

The geographical distribution of historical tornadic occurrences across the country, formed a useful base for the identification of regions of the country most susceptible to tornadic events. In terms of the entire country, tornado occurrences are rare and, once they take place, they affect only a very limited area (up to a few square kilometres). The likelihood of a tornado striking a specific region can be expressed in terms of the number of tornadoes over a given period of time (e.g. a year) which took place over a specified unit of area (e.g. a degree of latitude/longitude or kilometres square).

Based on the distribution of historical events, the development of a contour map of mean rate of occurrence per unit area was undertaken. Similar maps have been developed for several countries – e.g. USA or Canada. It should be stressed that these do not indicate the probability of a tornado striking a particular point, but rather a strike per unit area.

A few relevant issues can be noted in regard to the analysis:

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- Only the relatively recent (i.e. more reliable) period between 1948 and 1991 was considered.
- Only the eastern part of the country was included in the spatial analysis.
- In order to obtain a point estimate of probabilities, it was necessary to assume that the occurrence of tornadoes is time-independent; which suggests that the probability of two or more tornadoes striking the same place in the same year is virtually non-existent. *(Well, to prove the feebleness of this statistical assumption, as a result of an unprecedented heat wave over northern KwaZulu-Natal and southern Mpumalanga in December 1986/January 1987, two tornadoes struck Piet Retief within 10 days, with parallel tracks a distance of 500 metres away from each other!)*
- No corrections have been applied to account for unreported tornadoes, while some of the international statistical models widely propagate the underrating of the risks – in the absence of such corrections. The initial modelling for arbitrarily selected geographical areas indicated that, in statistical terms, the influence of unreported tornadoes, on a probability of a threshold wind speed being exceeded, is small.

The initial investigation into an appropriate statistical methodology revealed the suitability of spatial statistical modelling Kriging which had been developed for use by South African gold mines (Journel and Huijbregts, 1978). In essence, this methodology considers the outputs (i.e. the variables) of sample evaluation (i.e. ore content) and the distance between the places where samples were taken. The related procedure considers all permutations of pairs of observations in terms of the variable window sizes.

The development process of the model was reported in Milford and Goliger (1993) and Goliger *et al* (1997). In summary it was based on a 25km geographical grid and several window sizes. As a result a semi-variogram of South African tornadoes (Figure 5.7) was developed, which indicated that a window size (radius) of up to 160km in geographical scale (65mm in model scale) provides statistically similar results in terms of the spatial correlation of tornadoes.

Based on the outcomes of the semi-variogram analyses a window size (radius) of nearly 90km in geographical scale was selected, which provided a fair distribution of contour lines, reflecting the prevalence of tornadic occurrences over the specific areas of KwaZulu-Natal and Gauteng (Figure 5.8).

It is of interest to note that the highest occurrence rate can be observed, from Figure 5.8, to be $1x10^{-4}$ *per square kilometre per year*, while the Midwest of the USA is characterised by an occurrence rate of $5x10^{-4}$ *per square mile per year* (which translates to about $2x10^{-4}$ *per square kilometre per year*). Such occurrence rates can be treated as statistically similar. This constitutes a significant finding of the analysis, as it equates the risks of SA tornadic events to that over the legendary 'tornadic alley'. (The highest occurrence rate observed in the USA (around Dallas and Kansas City) is $6x10^{-4}$ *per square kilometre per year*. In contrast, the occurrence of tornadoes in South Africa has been regarded as anecdotal (even by the relevant disaster authorities) and, the main reason for that has been the huge difference in the extent of the affected areas (e.g. more than 10 times between Kansas and Gauteng), i.e. implying the rate of occurrence of tornadic events in Gauteng to be 20 times less per year.

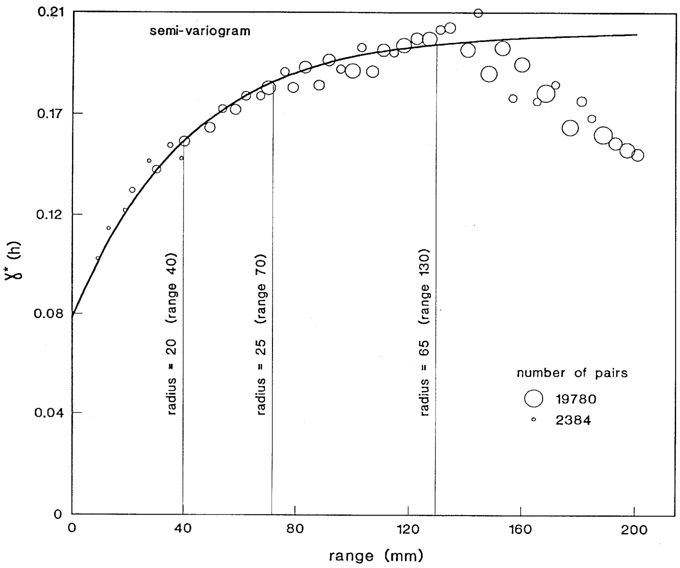

Figure 5.7: Semi-variogram of South African tornadoes

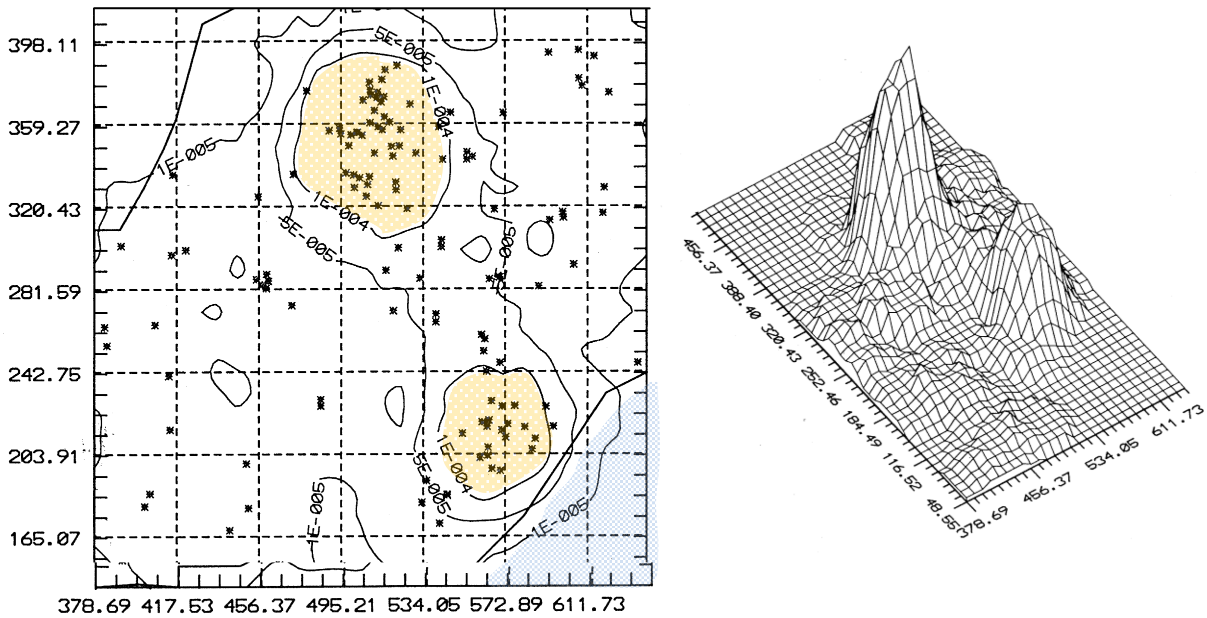

Figure 5.8: Contour lines of the annual occurrence rate per square km of tornadoes (2-d and 3-d interpretations)

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5.7 Insurance industry

The vast majority (if not all) major wind-related disasters in South Africa have resulted from tornadoes and microbursts generated by intense thunderstorms. Depending on the density, distribution and type of human development, the economic scale and impacts of such events can be substantial. In contrast with small-scale damage to individual structures, such events typically involve extensive damage underwritten by the reinsurance industry. The research on tornadic activities in South Africa provided the CSIR with international exposure and attracted the attention of the insurance industry.

Outcomes of the work were included in the Munich Reinsurance Hazard Profile of South Africa (MunichRe, 1998). This document is widely accepted as the global reference for the determination of natural hazards for all geographical regions from which national hazards are then derived. The author was given an opportunity to deliver a lecture at the International Disaster Reduction meeting and also a presentation at the head office of MunichRe. Relevant inputs were also requested from another major reinsurer Alexander Howden Limited which, at the time, considered entering the South African market for underwriting large governmental housing schemes.

5.8 Risk model for transmission line design

From a statistical perspective, the rate of occurrence of tornadic events in SA, which has been determined, is low. It implies that any square kilometre located within Gauteng or KwaZulu-Natal (Figure 5.8), which are the most prone to tornadic events, has a chance of 1 in 10 000 years to be struck by a tornado. (Most of the structures have a substantially smaller extent than a square kilometre and only large industrial complexes (e.g. Sasol) may have a footprint of a few square kilometres.) That said, such risks are relevant to the design of high-risk structures (e.g. those containing nuclear or biological material).

For elongated or line-like structures (e.g. pipelines or transmission lines) covering large distances, the probability increases with their length. The outcomes of the process of developing a tornado-risk model for transmission-line design in South Africa had a substantial impact on the related design approach and are, therefore, highlighted below.

From first principles, and assuming that all tornadic tracks cross transmission lines, the tornado risk for a transmission line with a length L can be transformed to a form in which the probability of tornadic wind speed v_j is given by:

$$P(v \geq v_j) = L \cdot \mu \cdot R(F_j)$$

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where μ is the mean annual occurrence rate for a given area (as demonstrated in Figure 5.8) and $R(F_j)$ is the tornado intensity damage function. Analysis of spatial characteristics of SA tornadoes has shown that this function can be reasonably approximated by the Fujita variation function, as extended by McDonald (1983). Where the transmission line extends across more than one zone, the probability of exceeding a threshold wind speed can be taken as the sum of probabilities within individual zones.

Transmission lines, however, are subject not only to tornadic winds but also to thunderstorms and other types of synoptic wind storms. The probability of a threshold wind speed v_j being exceeded due to all types of winds can be approximated as:

$$P(v \geq v_j) = P_0(v \geq v_j) + P_t(v \geq v_j)$$

where $P_0(v \geq v_j)$ reflects that for thunderstorms and other large-scale storms, while $P_t(v \geq v_j)$ the probability of tornadic wind speeds being exceeded.

Based on results obtained by Milford (1987) and implemented in SABS 10160-1989, the probability distribution of $P_0(v \geq v_j)$, for a 3-second gust can be approximated by:

$$P_o(v \geq v_j) = \exp\left[\frac{0{,}528 - (v_j/40)^2}{0{,}118}\right]$$

Note that there are several climatic approximations for this equation to be roughly valid for transmission-line sections of about 100km long within greater South Africa (e.g. the use of a 3-second gust or typical extent of the thunderstorm footprint.) The resulting combined probability distribution is given in Figure 5.9 (Milford and Goliger, 1995; Goliger *et al* 1997).

The graph refers to three generic geographic zones (A to C – not defined in the current document) with different annual occurrence rates and for transmission lines 1, 10 and 100 km in length. It can be seen that for low wind speeds, the probability of exceedance is dominated by conventional storms, while for high wind speeds by tornadoes.

It is of interest that the model described above is based on a geometrical assumption in which footprints of tornadic events do not overlay but cross over the transmission lines (i.e. are perpendicular). In defiance of this approximation, a major tornado event struck Midrand in April 1994, with its footprint being parallel and less than two kilometres away from a set of several major Eskom supply lines in Gauteng.

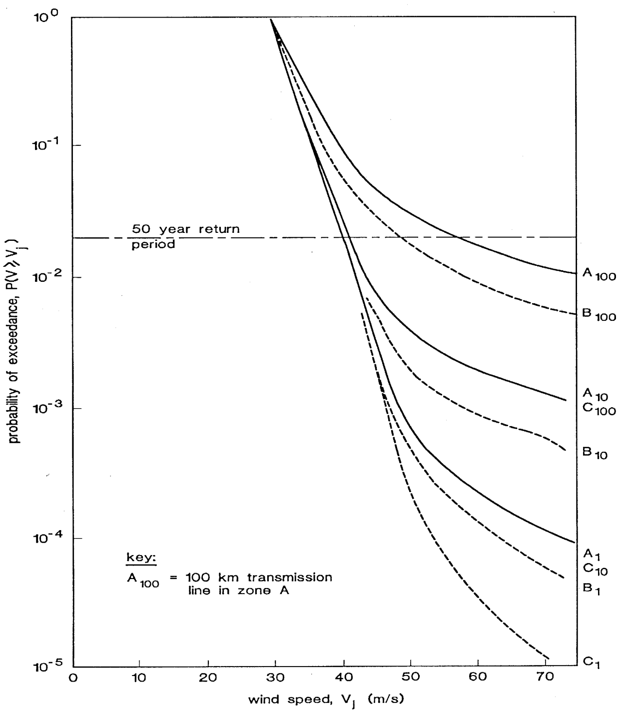


Figure 5.9: Wind-speed probability distributions

5.9 International involvement and impact

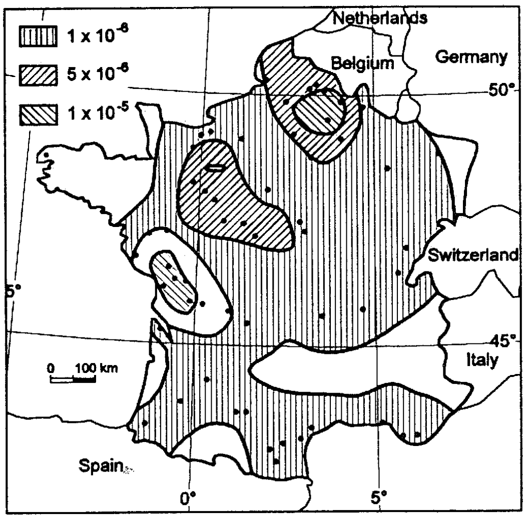
The findings discussed above became noteworthy to the related industry. It had implications for the design of transmission lines crossing areas prone to tornadic events, and constituted a radical input to the local and international transmission-line design paradigm (Milford and Goliger, 1995). Historically, design practice was dominated by the North American expertise and approach, in which most critical were the loads (and dynamic excitations) generated in harsh winter conditions, due to icing of the conductors. Several failures of the transmission lines which took place in late 1980 in Argentina, Australia and South Africa supported the CSIR's research philosophy and findings.

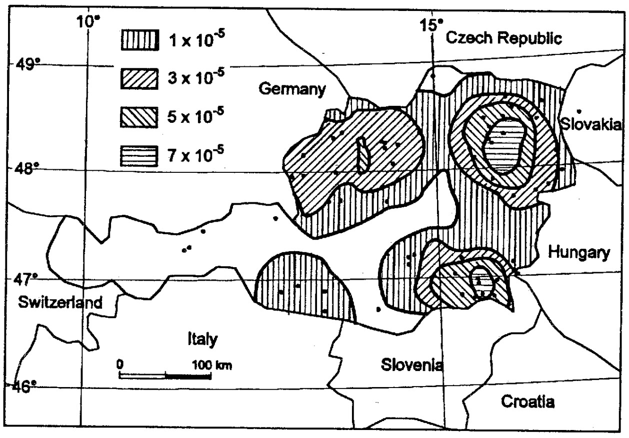
This research was communicated by Eskom to the international transmission-line operator's forum. A High Intensity Wind International Task Force was formed, facilitated by Professor Alan Davenport and Brian White (from Canada); with Australia (Henry Hawes), South Africa (Dr Rodney Milford) and Argentina (Professor Maria Schwartzkopf) as the founding countries. The activity was supported by energy-utility organisations in the respective countries, several universities as well the international journal of *Engineering Structures*. The aim of this activity was to re-align the modified wind loading principles with the structural engineering design standards dealing with power lines (under the title of *Transmission Line Design and High Intensity Narrow Winds, abbreviated to HIW.*)

A series of international workshops took place. (Interestingly, one of these also attracted the interest of the aviation industry. This was triggered by a few aviation accidents (and near-accidents) which occurred at the time and had been caused by microbursts.) The author was requested to facilitate inputs on downbursts/ microbursts and straight-line winds - dirrecoco's (Goliger, 1995; Goliger and Waldeck 1995a).

In terms of our involvement with and inputs to the HIW Task Force, the author was tasked to undertake a comprehensive research project into tornado occurrences across the world. This constituted the second significant international attempt of such a nature, after the initial survey conducted by Professor Ted Fujita (1973). This work involved contacts with a large number of national weather organisations and researchers across the world, as well as the collection and review of existing data form various countries. *(Interestingly, all these efforts took place before the rise of Internet communication.*)

Apart from the information which was derived, for a few countries (e.g. Australia, France, Austria) Kriging methodology had been successfully applied. The output information of the research was published in Goliger and Milford (1997/1998). Figures 5.10a and 5.10b present the maps of the mean rate of tornado occurrences developed for France and Austria. It can be seen that the highest mean occurrence rates are $1x10^{-5}$, which are an order of magnitude lower than that in South Africa. These frequencies are, however, considered to be of relevance to the nuclear energy programmes in Europe.





a) b)

Figure 5.10: Maps of mean rate of tornado occurrences in: a) France; b) Austria

5.10 Application to Geotechnical Engineering

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Following the rapid advances in geotechnical research which took place after the Second World War, it became widely acknowledged that the difficulties associated with foundation engineering on expansive soils did not result from an absence of adequate engineering solutions. These were rather related to a lack of suitable land within metropolitan areas, as well as deficiencies in recognising the spatial extent and depth of adverse soil conditions. The backdrop to that was also related to the prohibitive economic consequences of the indiscriminate application of raft foundations to individual housing units.

> *At that stage, the Soil Mechanics and Foundation Engineering Division at NBRI, CSIR (established by Professor JE Jennings and subsequently headed by Drs George Donaldson and AAB (Tony) Williams) constituted a unique centre of expertise for geotechnical engineering on a national and international scale. At the time, with the significant population growth which took place in South Africa in the 1950s, this centre had a critical impact and made significant contributions to the rapid development programmes in housing across the country.*

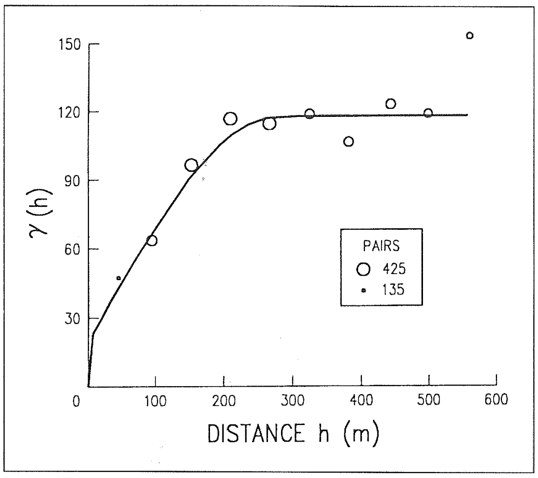
One of the research projects undertaken in the early 1990s was aimed at the development of a reliable statistical methodology for quantifying the risks of damage on expansive soils within urban areas. Two previous studies on the distribution of heaving clays had been carried out beforehand (Collins, 1957; Jennings and Kerrich, 1962). However the limited amount of soil samples prevented the development of meaningful spatial models.

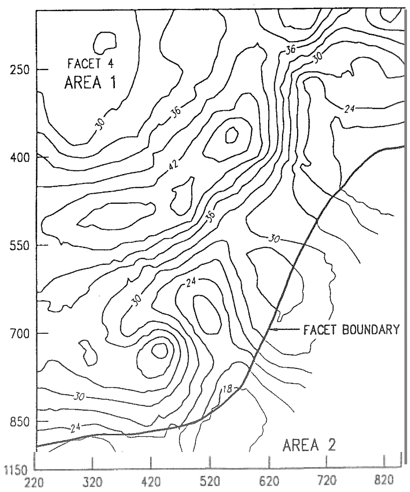
A northern suburb of Pretoria, Theresa Park, located on the notorious ‘swart turf’, (very active soil residue from *norites* of the Bushveld Complex) was selected for the study. The suburb is situated at the base of the Magaliesberg mountain range, with the general drainage directed into a broad, flat gully to its north. A large number of housing units distributed within the area had been reported to be cracking. This also included a few structural collapses.

The project involved measurements and predictions of variation in soil properties within the study area and, in view of his previous experience with Kriging methodology, the author was invited to join the geotechnical research team headed by Dr Tony Williams.

The initial analysis of land systems, supported by aerial photography, permitted the team to demarcate various facets and soil boundaries. Subsequent sampling of soil parameters was carried out to a depth of 2m at more than a hundred locations; of these, only 98 were used in the subsequent analysis. The samples were then subjected to *heave indicator* tests (Van der Merwe’s method of heave prediction). The results, in combination with the spatial distribution of sampling locations, formed the inputs to Kriging analysis.

In Figure 5.11a a semi-variogram obtained for one of the areas of Theresa Park is presented and in Figure 5.11b the corresponding plot of contour lines of plasticity index prediction. The contour lines which were derived constituted a critical outcome of the research regarding the large variability of soil properties which could be present within a land facet. The variation in the representative plasticity index in Figure 5.11b ranges between 24 and 48.





a) b)

Figure 5.11: a) A semi-variogram; b) contour lines of plasticity index prediction

Such a range of values questioned (interrogated) the validity of one of the basic assumptions of geotechnical research regarding heaving clays. All previous studies carried out at the CSIR were based on a premise of insignificant variance of soil properties within a land facet. Importantly this philosophy was also implemented in the predictions of heaving clays for large housing developments across South Africa – e.g. in Port Elizabeth, Bloemfontein and Welkom. *(Our research established that a stable variance can only be obtained at a sampling spatial interval of less than 50m, i.e. much less than that of the few hundred metres commonly implemented at the time within the house construction industry.)*

A joint paper by Keyter *et al* (1996) was awarded the SAICE Jennings Geotechnical Award for 1996.

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6. Contributions to development of standards

During his career the author has been involved in several local and international standardisation committees. These activities can be considered mainly in terms of the inputs to:

- the initial formulation stages of wind actions in Eurocode and ISO standards,
- the SANS 10160 Loading Committee (in particular Part 3), and
- involvement in other South African standards.

These are summarised in the following subsections.

6.1 International wind loading standardisation

The author provided modest contributions and improvements to the development of two international standards, namely:

- In response to an international call for inputs from the wind engineering profession, the author prepared a submission regarding the proposed scope and format of the ISO 4354 (1990/1991). This information was then collated by Dr John Chen (Australia).
- A review has been conducted and submitted, regarding the initial version of ISO 4354, which was then piloted by Professor Melbourne (Australia).
- Following a personal request, the initial version of Eurocode (ENV 1991-2-4) was reviewed and the related submission forwarded to its secretary (at the time), Dr Michael Hortmans, and chair Professor Hans Ruscheweych (both from Germany).

At one of the international meetings the author formulated and presented a critique regarding the unwarranted accuracy of processes included in most wind loading standards. This viewpoint originated from his contacts and exposure to the full-scale measurements programme of the boundary layer undertaken by the German Institute Für Meteorologie (Dr N Beyer and Professor Gerd Tetzlaff), research work at Ruhr-Universität Bochum, as well as the initial loading comparisons conducted in terms of the submission for the SA Loading Conference (Goliger *et al* 1998; Goliger 1999).

Figure 6.1 demonstrates the large range of scatter obtained from long-term measurements of roughness length (u_*). The measurements were carried out throughout the year at a specific (undeveloped) site outside Hanover. This parameter constitutes one of the basic inputs for defining the standard boundary-layer logarithmic profiles.

This critique received fervent support and endorsement at the international meeting of Wind Engineering Association. At that meeting, jointly with Dr M Kasperski (Germany), the author was elected as a co-coordinator of Working Group B, tasked with investigating and reporting on the levels of reliability of wind loading stipulations (IAWE, 2002). The report of Group B was presented in the International Codification Forum in Lubbock, Texas (Kasperski *et al* 2003).

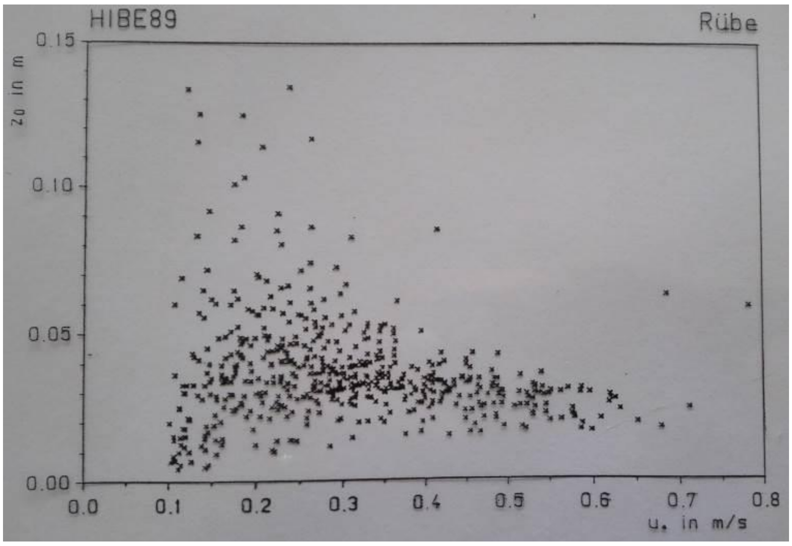

Figure 6.1: Range of roughness length measured at a specific site (courtesy Professor G Tetzlaff)

The involvement in international activities summarised above provided useful exposure and background to the development of the SA wind loading stipulations described in the following sub-section.

6.2 Revision of SA wind loading standard

6.2.1 Background

Historically, international design wind-loading standards had been based on research conducted in late 1940s. The South African loading code (SABS 0160-1989) was based on the old British Code (CP3 1952), including inputs by Dr Rodney Milford.

> *CP3 1952, like many other national codes, was based on an old Swiss code. Most external pressure coefficients quoted in the long-standing standards were based on wind-tunnel measurements that had been carried out without due consideration to boundary-layer modelling.*

Since then, most international wind standards have undergone a substantial updating process which has incorporated modern research findings and processes. These modifications have resulted in a more realistic and accurate description of wind action. Towards the late 1990s a broad consensus was reached by most South African stakeholders in engineering design that the status of the 1989 version

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needed to be assessed and its future revision needed to be considered and investigated.

6.2.2 Initial assessment

In 1998 the *South African National Conference on Loading* was convened by the South African Institution of Civil Engineers (SAICE), in which all types of loadings stipulated in SABS 0160 were assessed. The author's involvement in the review and development of international wind loading specifications, summarised in Section 6.1, provided a useful background to this activity. An extensive review of wind loading stipulations was reported in Milford and Goliger (1991), Goliger *et al* (1998), Goliger (1999), Mahachi and Goliger (1999) and Goliger *et al* (2001).

Due to the volume and complexity of information involved, it is not practical (or feasible) to highlight all related aspects of wind loadings and their design implications which were considered in the developmental process and implemented in SANS 10160-3: 2010. These were documented in various publications referred to in the current section and also presented to the engineering profession in three series of full-day seminars organised by Stellenbosch University (2008, 2012 and 2014.)

However, a useful insight into the essence of loading modernisation is demonstrated in Figures 6.2a and 6.2b, in which a comparison is made between the external area-pressure distributions derived from SABS0160-1989 and AS 1170.2 for a typical small building structure with wind facing its gable wall. It can be seen that the Australian standard stipulates a more elaborate set of loading zones and a diverse magnitude of pressures.

In terms of the aerodynamic principles (supported by wind-tunnel evidence) the distribution in Figure 6.2b constitutes a considerably more accurate reflection of the pressure distribution (and magnitude of overall loads) observed in the full scale. An application of such a distribution enhances design economy and safety. For most of the elements it implies a reduction in stresses; but, on the other hand, it also recognises the larger magnitude of pressures close to the zones (leading edge) where separation of loading takes place. For large-scale commercial structures (e.g. warehouses) these differences may imply substantial differences in the sizing of structural elements (i.e. also costs).

As an outcome of the 1998 loading conference a SAICE Loading Committee chaired by the late Professor A Kemp, and subsequently by Professor P Dunaiski, was established with the task of reviewing all types of loadings and preparing a new version of the South African loading standard. The author became a *member* of the committee and also its *champion* of wind loading stipulations.

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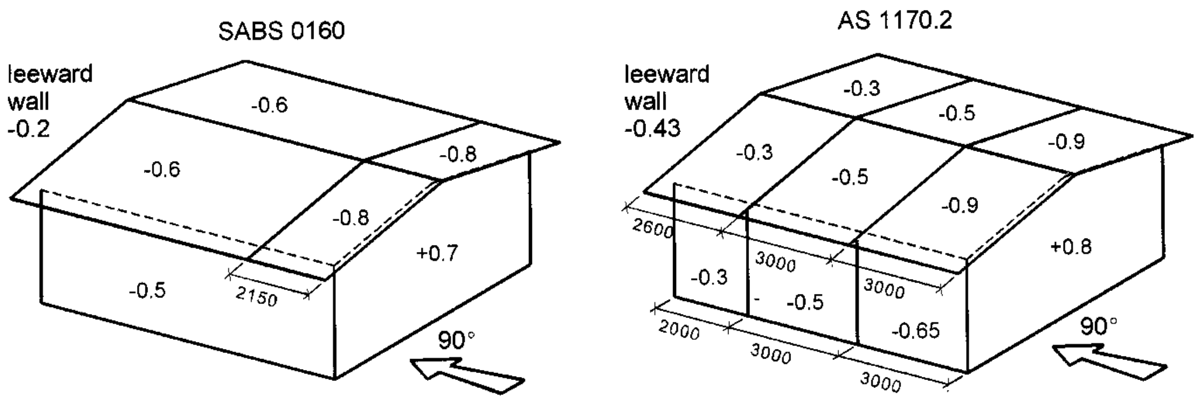

a) b)

Figure 6.2: Comparison of pressure zones: a) SABS 0160-1989; b) AS 1170.2

6.2.3 Survey of standards

On behalf of the Loading Committee, a detailed survey of international wind loading procedures was undertaken in order to capture recent advances and modernisation of the design (Goliger *et al* 2001). The aim of this survey was to identify a possible model standard which could be followed or adopted. The foremost options which were considered were the relevant versions of Eurocode (ENV1991-2-4), ANSI/ASCE 7-95 (USA) and AS 1170.2 (Australia). A proposed draft South African Standard was developed on the basis of *Section 3 Detailed procedures: Static analysis* of AS 1170.2-1989. However, upon its completion, it was indicated that a radical revision of the Australian Standard compromised the use of a potentially obsolete reference.

Following the above setback, a decision was made to reconsider Eurocode EN 1991-1-4, *Actions on structures: General actions – Wind actions,* as a possible reference document. Importantly, at that stage the voluntary version ENV 1991-2-4 was converted into the normative Eurocode, and a substantial amount of international efforts went into the 'cleaning-up' and streamlining process of the document. Furthermore, alignment with European construction-industry practices and the market became recognised as potential opportunities for the South African designers.

The outcomes of the Eurocode analysis showed that it had captured the recent advances in design practice across an extensive range of structures and situations. A thorough assessment proved the merit of its adoption as a reference document for the development of wind actions in the future SANS 10160 (Goliger 2005b and 2007), as well as Goliger *et al* (2013), and this was endorsed by the Loading Committee.

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6.2.4 SANS 10160-3 and its scope

The work of the Loading Committee took several years, as various sources of information and the implications of changes had to be considered. During this process the author served as the *champion* of wind loading stipulations.

The new version of the code had far-reaching implications on the design paradigm. It severed the historical links with CP3 (1952) and substantially increased the amount of design effort. Some changes were necessary in order to implement outputs of modern research. Initial comparative calculations indicated in most, but not all, design situations a fair increase in the design loads. This reflected contemporary research findings and, following several large-scale disastrous wind events, also international trends and sentiments towards increasing the structural reliability of the built environment.

In view of the volume of information and wind loading aspects which are considered in SANS 10160-3, only the most important issues and departures from the Eurocode reference document are highlighted. These are unique to the South African situation and the respective rationales are highlighted below in a bulleted form. *In many instances the author's wind engineering and building aerodynamics background, as well as exposure and involvement in international codification, enabled him to identify the problematic areas and the sources of divergences from European experts and countries. Subsequently it enabled him to optimise and formulate the relevant proposals submitted to the SA Loading Committee.*

- The code excludes dynamically sensitive structures and buildings higher than 100m (e.g. dynamically sensitive elements of structures or tall buildings and most chimneys and masts). This was in order to accommodate calls from the industry to reduce and simplify the contents of the standard. Designs of such structures in South Africa are uncommon and typically performed by specialised and experienced consultants (often involving international consortia), with the use of specialised design procedures, overseas manuals, software and wind-tunnel modelling.

- Similar considerations apply to the design of offshore structures which are subjected to severe loading resulting from the *combined* action of wind and waves. This exclusion in the code had resulted from interactions with the SA consulting industry, and indicated some offshore structures in SA have been designed without due consideration of this phenomenon.

- The design processes for bridges are governed by the requirements of the relevant national authorities (e.g. TMH7 (1981) required by Sanral), and were excluded from the standard.

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- Similar views refer to transmission-line design, which has to follow the design manuals and standards of the International Electrotechnical Commission (e.g. ASCE, 1984 or IEC, 1988) prescribed by Eskom.

- SANS 10160-3 excludes structures or their elements which accommodate movement (e.g. telescope dishes, revolving antennas and movable roofs). Such structures may be subject to additional load components generated owing to their movement.

- Finally, in line with several international design manuals, SANS 10160-3 does not cover the design of high-risk structures (e.g. those containing biological or nuclear material), and wind action due to high-intensity winds (e.g. tornadoes or microbursts). The Code also comments on the design of buildings and structures of unusual form or shape and refers to expert advice and literature, or wind-tunnel testing.

- A revised map of the fundamental value of a 10-min basic wind speed was developed as an extension of the map included in SABS 0160, in combination with inputs by weather service climatologists. These took into account topographical characteristics of the southern and south-western Karoo and the directional prevalence of winter storms. Depending on the geographical regions, *actual* or *effective fundamental basic wind speeds* were adopted. *The nature of this estimative process of application identified a critical need for a comprehensive statistical re-analysis of South African wind speed data, which was subsequently followed, as described in Section 7.4.*

- SANS 10160-3 did not adopt the logarithmic wind-speed profile stipulated in the Eurocode, as the level of differences (in comparison with the power-law profile) does not warrant the introduction of the related complexity. International research indicates the logarithmic profile to be marginally more representative at low elevations than the power law profile. However, in most design cases this issue is of little relevance due to the overriding influence of the surrounding environment, which is site-specific. Importantly, the use of a logarithmic profile became unnecessary, in view of the exclusion of the dynamic procedures in SANS 10160-3.

- The proposed set of profile parameters resulted in a set of uniformly spaced profiles and thus eliminated unwarranted interpretations (and unsafe practices) in adopting Terrain Category 3 vs 2, as per SABS 0160-1989.

- In line with the Eurocode, SANS 10160-3 adopted a fairly conservative set of stipulations regarding changes in terrain category. Industry practices indicate

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this issue to be often misinterpreted or ignored, and this could lead to a underrating of the magnitude of wind speeds. Generic procedures accounting for the impact of the immediate surrounding environment are also included.

- SANS 10160-3 does not consider directional design – i.e. to account for the directional prevalence of strong winds in relation to the orientation of the structure. This possibility is attractive in view of its cost-saving implications, but was not contemplated in view of the poor geographical coverage and record length of full-scale Weather Service observations.

During the development process of the revised wind loading standard an acute need for updated climatic wind information for South Africa became apparent. The related follow-up initiative, leading to a comprehensive research project, is summarised in Section 7.4.

6.2.5 Documenting

The developmental process of SANS 10160 was presented in a commentary publication due to Retief and Dunaiski (2009). Two of the papers included refer specifically to wind loading stipulations (Part 3), as follows:

- Goliger *et al* 2009a summarises the comparisons of wind design procedures, international models (with emphasis on the Eurocode), the South African strong wind climate, site exposure, characterisation of terrain categories and profiles and pressure coefficients.
- Goliger *et al* 2009b presents an overview of the new wind loading procedures included in SANS 10160-3.

6.3 Other standards

Apart from the Loading Standard, the author was also involved and made inputs to various South African standardisation committees, but mainly the following:

- SABS 0225, Edition 1 (1991). The design and construction of lightning masts (discussed in Section 4.4.3).
- Technical Committee on Overhead Lines TC11 (South African Chapter of the International Electrotechnical Commission.
- SANS 10237:2008. Steel and aluminium roof and side cladding (currently under revision, SC 81B, co-chair, jointly with Johan vd Westhuizen of GRS).
- SANS 10400-L:201X, Edition 3.1, The application of National Building Regulations Part L: Roofs.

Of particular engineering interest, industry relevance and impact, is the author's involvement in the development of SANS 10237. This emerged from extensive experience in wind-damage investigations and analysis (Section 5.1), in

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combination with the long-term testing of various roof sheeting systems carried out at the CSIR.

Several investigations of wind-induced failures indicated them taking place at wind speeds clearly lower than the minima stipulated in the design standards of the built environment – i.e. the wind loading code. In most instances these affected large modern industrial facilities covered with concealed roof-sheeting systems (see Figure 6.3). These events were consistently and, totally unjustly, blamed on *freak or hurricane-strength* winds, or alternatively on *climate change* and the relevant parties (e.g. the owners, designers or contractors) often sought confirmation thereof from the Weather Service or the author.

Figure 6.3: Uplift of a concealed roof-sheeting system

The technology of concealed sheeting originates from Australia and was aimed at roofs with low slopes (less than 5), for which wind-uplift loading becomes critical. Despite its appeal, the technology is complex and contains several conceivable pitfalls. Such systems are attractive to the construction industry, developers and architects in view of the ease and speed of erection and no requirement for punching of the membranes. However, the lack of positive fixing requires the uplift loads to be resisted by an exceptional grip of the sheeting, which in turn requires excellent and consistent profiling of the membrane in, combination with installation brackets of adequate deformation strength.

This situation was unacceptable and, at several professional forums, the author raised serious concerns on the matter of the increasing (and uncontrolled) usage of substandard sheeting systems. The author’s inputs and activities involved:

- investigating the product’s suitability and manufacturing deficiencies,

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- advocating and promoting the idea of setting up an industry standards and forum, (in collaboration mainly with Messrs Eben Nel (Safintra), Dennis White (MacSteel) and Dr Hennie de Clerq (Steel Institute), and
- participation in the development of relevant standards.

These activities created industry awareness, and led to the setting up of the Southern African Metal Cladding and Roofing Association (SAMCRA) and a gradual improvement of manufacturing and construction standards.

Regarding the first bulleted point above – it is important to note that the full-scale action of wind has an intense fluctuating (i.e. dynamic) nature, which is difficult and prohibitively costly to reproduce in the laboratory testing environment. Because of this grossly simplified loading procedures are applied by means of uniformly distributed static loading. Figure 6.4a presents the roof-sheeting testing rig developed at the Division of Built Environment (CSIR). The uplift of the sheeting is simulated by an array of airbags placed between a rigid base and the sheeting (Figure 6.4b).

a)

b)

Figure 6.4: a) and b) CSIR testing rig for sheeting systems

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7. Analysis of wind climatic data

7.1 Importance of wind-speed magnitude

In principle, wind action on a specific structure can be represented in a simplified form in which the load effect, L_W, combines wind action $\hat{W}_A$ (determined by the dynamic pressure affecting the specific structure) and loading response characteristics, $\overline{R}_W$. For historical and principal reasons peak wind action is typically combined with mean response characteristics.

$$L_W = f(\hat{W}_A; \overline{R}_W)$$

In accordance with Bernoulli's law of physics, dynamic pressure is proportional to the mass of the fluid (i.e. the air) and also, in a quadratic relationship, to the speed of the fluid, i.e.:

$$\hat{W}_A = f(\rho; \hat{v}^2)$$

Strictly speaking, Bernoulli's equation does not hold well for turbulent flow conditions, as experienced within the built environment. It is nevertheless the best physical approximation which can be utilised. This relationship clearly demonstrates the principal importance of the accurate determination of wind speed in order to ensure the required levels of reliability of the design chain.

Since early 1990s the advent of modern instrumentation technology, in combination with IT processing abilities, has triggered unprecedented development of wind-tunnel modelling capabilities. As a result a large number of boundary-layer wind-tunnel facilities were developed across the world. Subsequently, a substantial amount of testing of loading parameters for various types of structures, geometries, spatial configurations and surroundings, etc., was carried out. A huge amount of universally applicable knowledge was generated and the wind-loading response for a variety of structures became well understood and quantified. This information made it possible to identify a more accurate description of loading zones, as discussed in Section 6.2.

Unfortunately, the wind-action component of loading ($\hat{W}_A$) is site-specific and, primarily, it requires a thorough statistical description of wind-speed occurrence. In many instances and countries of the world the exponential growth in universal wind-tunnel research knowledge has not been accompanied by spatially representative and comprehensive measurements of full-scale wind fields. (Such full-scale measurements are typically the responsibility of the respective national weather service authorities.)

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In a sense this resulted in an *anomalous* situation, in which a component of loading effect, which has a linear influence on the resultant loading, has been researched and quantified to a much larger extent than the component which has a quadratic influence on the resultant loading. This issue was challenged by the author internationally (see Section 6.1).

7.2 South African Weather Service and wind climate

In South Africa, the Weather Service (SAWS), formerly the Weather Bureau, is the official custodian of capturing and storing climatic data related to all weather phenomena, including wind speed and direction. Historically, the distribution of weather stations across the country was poor. The map of regional wind speed, which appeared in SABS 1060-1989, was developed by Dr Rodney Milford (1987) as no related expertise was present at the time at the SAWS. The map was based on statistical analysis of 15 available and reliable weather stations. *(In comparison, the UK map, contemporary at the time, was based on the records of nearly 60 recorders distributed over nearly one-fifth the geographical area!)*

That said, the wind-speed recorders used for the analysis were typically located at airports (i.e. within an open terrain category) and complied with international exposure requirements, as well as diligent maintenance standards.

In 1990, following developments in remote sensing and internet data transfers, the SAWS embarked on a rapid process in which large numbers of automatic weather stations (AWS) have been deployed across the country, resulting in more than 170 operational recorders by 2007. In the early days of AWS deployment, the CSIR (Drs Waldeck, Milford and the author) came across the new installations and identified the exposure shortcomings in some of them. This issue was raised on several occasions with the SAWS management, including an offer of collaboration in the siting of new AWSs. Unfortunately, these appeals did not receive the required attention and follow-up. Furthermore, despite the CSIR's requests, no dedicated wind-climate expert within the SAWS was identified or trained.

The improper positioning of the wind recorders refers to ignoring the topographical influences, as well as the impact of the immediate surroundings. Such situations can be demonstrated on the basis of the AWS at Beaufort West. The wind meter is located:

- within the close proximity of a series of large water tanks (Figure 7.1a),
- on top of a prominent hill (with an elevation of a few hundred metres), and
- with significant topography in the background (Figure 7.1b).

Further to that, during its operation, this installation has been moved from another location, resulting in a totally different exposure of the installation. This change has not been documented. (Ironically, a large open plain with excellent wind exposure is

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present on the eastern side of Beaufort West, but has not been considered by the SAWS.)

a) b)

Figure 7.1 a) and b): Positioning of the SAWS AWS at Beaufort West

Figure 7.1c presents the location (indicated by the white arrow) of another AWS outside Wepener. The anemometer is positioned at the base of dominant topography, blocking the approach of the prevailing north-westerly winds.

Figure 7.1: c) Topography to the north-west of Wepener AWS

Local influences can either accelerate or decelerate wind flow and also modify wind orientation. Regrettably, despite these obvious shortcomings, the SAWS has consistently maintained this issue to be of secondary importance due to its overriding mandate being the prediction and observation of all climatic parameters at a macro scale (which are determined at substantially higher elevations). Further to that, the principle of serving not only the built environment but also various other industries (e.g. transportation, agriculture, fishing) was raised. (Such argumentation is immaterial as, apart from the aviation industry, all climatic effects related to and affecting human activities take place close to the ground surface.)

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Over many years of interaction with the Weather Service, the author managed to establish that, *de facto*, the overriding priority for siting SAWS AWSs are the availability of power supply and protection against theft or vandalism. This situation become preposterous when a technical division of a large parastatal organisation questioned the validity of wind-speed data captured by the Weather Service and requested the author to re-confirm its legitimacy.

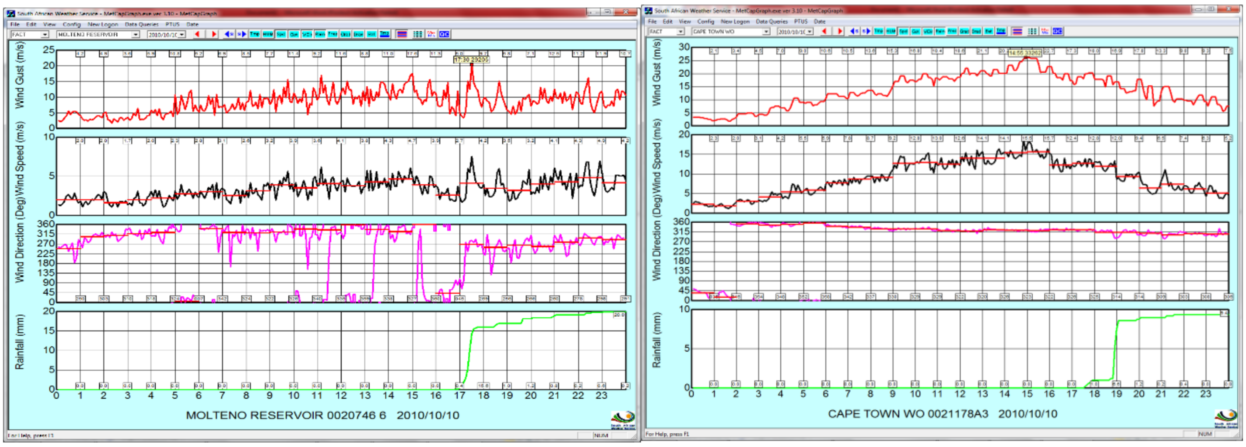
7.3 Complexity of the South African wind climate

The climate of South Africa is complex, ranging from sub-tropical (KwaZulu-Natal) and Mediterranean (Western Cape) zones to desert (Kalahari), and this finds its reflection in the wind climate (Kruger 2002). Furthermore, in distinction with most small and medium-sized countries, it is dominated by several types of strong wind events with different origins and characteristics.

The wind climate relevant to the built environment is critically influenced by complex topography – i.e. the presence of large mountain ranges. This issue is demonstrated most effectively within the greater metropolitan area of Cape Town. In this area several wind-speed anemometers, including a few Weather Service installations, are present. Figures 7.2a and 7.2b compare wind speed and direction recorded by SAWS, on the same day, at the Molteno reservoir (located at the upper portion of the city bowl) and Cape Town International Airport.

The overall character of time traces in time domain differs substantially. This can be considered by comparing the time traces of mean wind speed (2nd from the top). The mean wind speed at Molteno hovered below 5 m/s, with few exceptions, while the wind speeds at the CT International Airport were between 10 m/s and 15 m/s for most of the day. These differences are due to topographical influences and also an inadequate exposure of Molteno. *(On the day of concern a wind-induced failure of an advertising structure, resulting in loss of life, took place on the Cape Town Foreshore and large discrepancies between the SAWS weather recorders were exploited by various parties involved in the subsequent legal process.)*

The diversity of South Africa's wind climate can critically impact the development and operation of the built environment, as demonstrated on the basis of the recently developed Ngqura (Coega) Harbour. For the last few years, since commencing its operations, the harbour has frequently experienced adverse environmental wind conditions, leading to stoppages and delays in the movement of container vessels and loading/unloading the cargo. A few accidents involving ships and containers have taken place and the author has been approached to investigate the nature and characteristics of the wind climate and its port's operational implications.



a) b)

Figure 7.2: Wind records: a) Molteno Reservoir; b) CT International Airport

The environmental planning of the facility was carried out under an assumption that the wind climate characteristics observed at Port Elizabeth airport are also applicable to Coega. Two SAWS AWSs were subsequently introduced in the bay area, one in close vicinity to the harbour and also one on Bird Island. The spatial distribution of all three recorders is indicated in Figure 7.3. Another AWS installation, positioned within the port, in close proximity to the Coega SAWS recorder, was also implemented by the CSIR Stellenbosch.

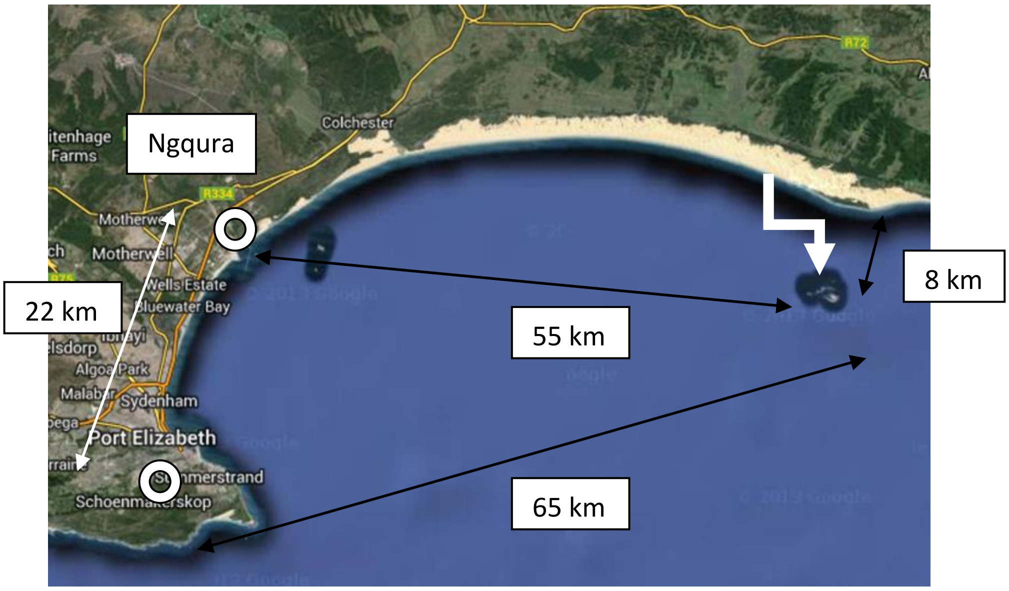


Figure 7.3: Geographical distribution of AWSs

From a general climatic perspective (articulated by the SAWS), all three wind recorders are treated as being located within a homogenous climatic zone - *south-east coastal grassland*, dominated by large-scale frontal events. These should reflect a consistent wind situation (apart from the difference in the open sea

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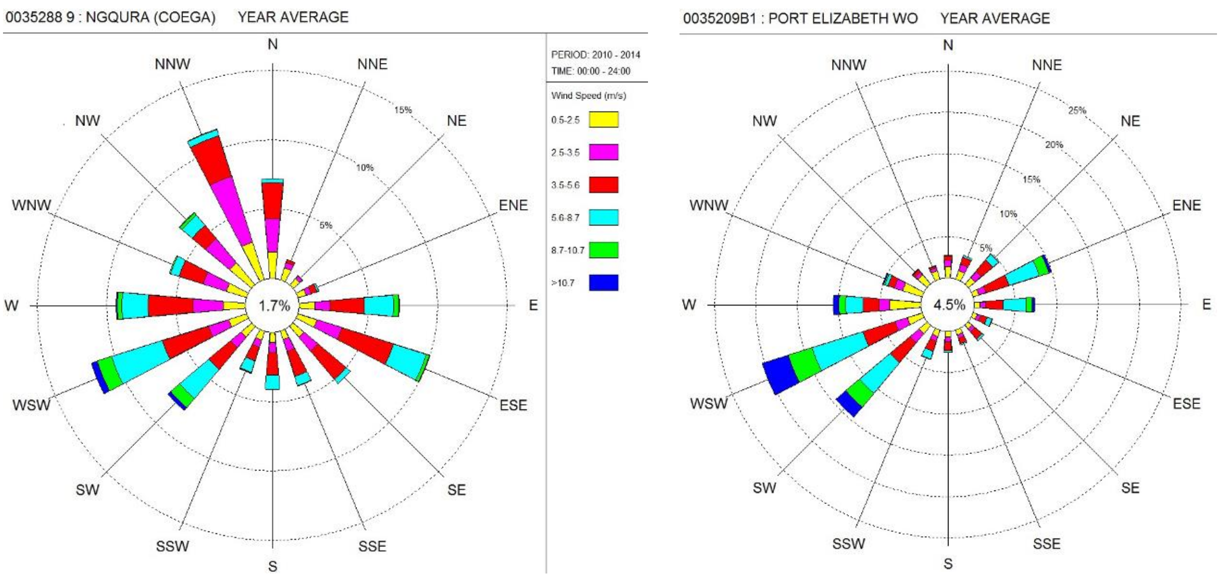
exposure of Bird Island.) In fact, on a geographical scale the separation distance of 22km is negligible and substantially smaller than those between most of the AWS installations across the country, on the basis of which regional wind predictions are made.

Figure 7.4 compares the wind roses derived from the data obtained from two of the recorders, namely:

- Coega (between 2010 and 2014) - Figure 7.4a, and
- Port Elizabeth (PE) data (between 2000 and 2014) - Figure 7.4b.

(Note: for historical reasons data is typically analysed and presented in terms of 22,5° directional intervals. Furthermore, the colour coding reflects wind-speed ranges in distinctive intervals originating from the conversion between the imperial and SI units.)



a) **b)**

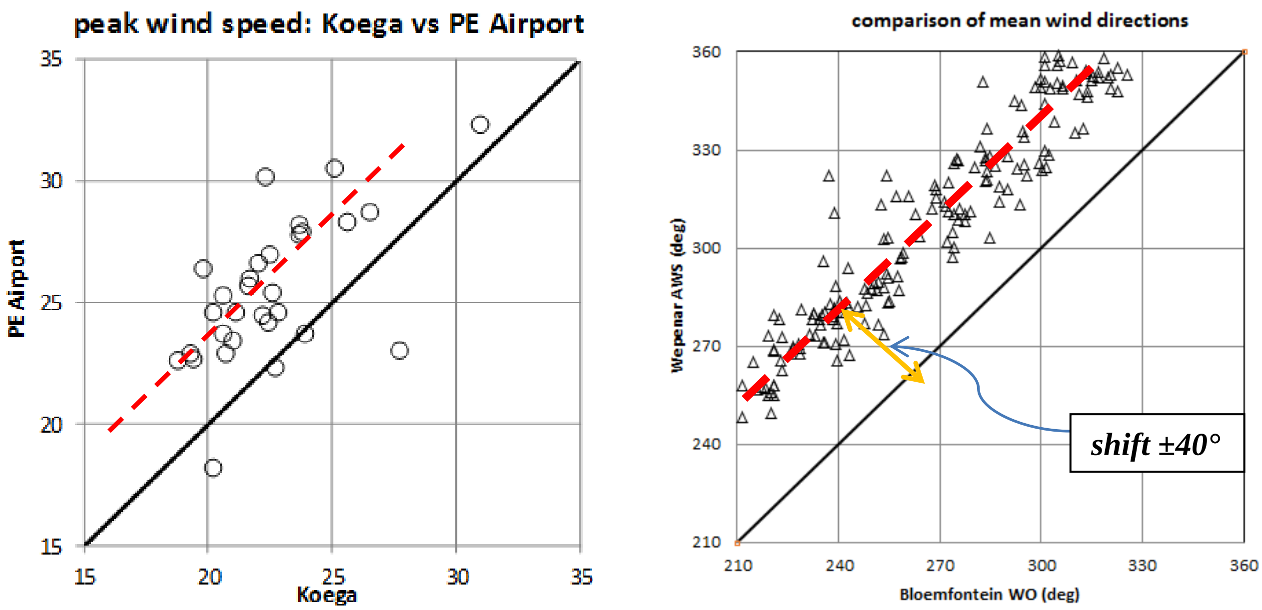
Figure 7.4: Wind roses: a) Coega; b) Port Elizabeth Airport

Substantial differences can be noted between both wind roses in terms of the directional prevalence of wind, although for both weather stations the strongest winds (>10,7 m/s) have been recorded for the WSW and SW directions. This issue has been investigated further by filtering and analysing data sets from both recorders, corresponding to the same time period. As a result of this analysis 30 independent (i.e. separated by at least a 24 hour time period) strongest wind events were identified. The magnitude of the instantaneous wind speed was about 25m/s or higher and, in all but two cases, these had a strong westerly component.

These peak wind speeds are compared in Figure 7.5a in a form similar to that of the regression analysis, in which values corresponding to the Coega wind recorder are plotted against the x-axis and the equivalent Port Elizabeth data on the y-axis. It can be seen that notably larger values were recorded at the Port Elizabeth Airport. Both wind meters have a reasonably good positioning and unobstructed surroundings for the westerly range of winds (and these were inspected by the author). The only explanation for the differences relates to the presence of:

- the open-sea approach over St Francis Bay (about 10km to the south-west of the PE Airport),
- a prominent mountain range about 20km to the west of Coega (hosting Groendal Nature Reserve), and
- the mountain range 40km to the north (between the Klein Karoo and Addo Park).

Figure 7.5b presents a similar situation related to the directional distortions in wind data owing to the presence of dominant topography. It can be seen that about a 40° difference in the measured flow directions is observed between Bloemfontein and Wepener (see discussion related to Figure 7.1c).



a) b)

Figure 7.5: Comparisons of wind: a) speeds; b) directions

The differences, which were highlighted above, indicate the complexity of SA's wind climate as well as the critical importance of consistent and rationally based siting of wind-speed recording facilities. This is in order to ensure the reliability and spatial representation of the records of wind speed and direction which can be utilised by the built-environment profession and industry.

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7.4 South African strong-wind climatology

The problems raised in Sections 7.2 and 7.3 constitute a formidable impediment for the structural design industry, which is continuously faced with optimising and balancing the two conflicting objectives of:

- leaner or more accurate design, in order to better reflect the actual loading and reduce the amount and sizes – and effectively the costs – of structural elements and, conversely,
- to ensure robust structures in order to reduce the risk of failure – i.e. human loss and economic impact.

The above aspects have a direct impact on the competitiveness of the design industry and are important on a national scale. In view of these considerations the need for a more accurate description of the magnitude and geographical distribution of extreme winds became apparent to the Loading Committee (Section 6.2). In order to improve the situation described in Section 7.2 and also to develop the relevant expertise and a champion within the SAWS, a proposal was made in 2007 by Stellenbosch University (SU), in which an opportunity for a PhD research on wind climate was created for an SAWS scientist. The challenge was undertaken by Mr Andries Kruger, who obtained his PhD degree in 2010.

The research was carried out under co-supervision from Professor Johan Retief (SU) and the author. The expertise provided by both supervisors was complementary: that from Professor Retief in terms of reliability, and from the author in terms of wind engineering perspectives.

Apart of the PhD dissertation (Kruger, 2010), the research has been reported in several co-authored publications – namely Kruger *et al* (2008; 2010; 2011a; 2011b; 2012; 2013a; and 2013b).

The above publications document extensively the research premise, the process and outcomes, and these aspects will not be duplicated in the current report. As mentioned above, the author's contribution and influence centred on the wind engineering aspects and design implications of the study. Some of these inputs were linked to experiences and interactions with overseas experts on full-scale data capturing accuracy and processing as well as the development of wind loading standards.

A few of these considerations and principles, which served as useful guidelines in the research process, are highlighted below.

Data filtering and corrections: Based on the author's experience and exposure to full-scale measurements conducted at the CSIR (Dr Louis Waldeck), wind-tunnel

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capturing of time-variable data, as well as the accessing of data archives and interactions with the respective SAWS staff, the author stressed the importance of, and insisted on, a diligent review and filtering of the full-scale data files in order to eliminate records containing electronic interferences (intermittent lack of signal, spikes, shifts in amplitude or background noise) and also to identify discontinuities in the data.

Independence of extreme events: The analysis of full-scale data on extreme winds is based on a principle of independence of the highest peak wind speeds which were recorded over a specific period of time – e.g. a year. Over the years, the general weather patterns of geographical areas are not consistent. It is often the case that one specific large-scale wind event, which was generated by a temporal and spatial combination of a few coinciding factors, may produce several extreme peaks over a period of a few hours or days. Therefore, the independence of such extreme records needs to be thoroughly examined. (On the other hand, in some years, characterised by a mild climate, maxima recorded peaks might be far lower.)

Validation of exposure: As discussed in Section 7.2, the CSIR's investigations of wind damage and disasters (carried out over a few decades) have indicated that a substantial number of SAWS (formerly SA Weather Bureau) wind-speed recorders were improperly positioned. At the initial stage of the research by Dr Kruger, the positioning of each of the SAWS AWS was evaluated and categorised in terms of the following classes:

- reasonable positioning,
- improper approach-surface roughness,
- influence of nearby obstructions, and
- influence of topography.

As a result of this elaborate process, involving a combination of site inspections, analysis of SAWS photographic documentation and Google maps, only about 50% of the stations were found to be adequately positioned. The likely effects of incorrect positioning were also assessed in terms of under- or over-estimation of wind speeds for the ranges of wind directions. A set of correction factors was then derived to transform the observations to that of the standard for reference-surface roughness (z_0). *Unfortunately it was not possible to quantify and correct for topographical and local influences, as this would require undertaking a comprehensive and costly wind-tunnel modelling programme.*

Handling of isolated extreme values: This issue follows the author's exposure to international submissions and debates on wind-capturing and -processing practices, and various interactions with the relevant researchers. In several such statistical reviews and analyses the presence of exceedingly sporadic and abnormally high peak wind-speed values were reported. Among other things, this issue has led to serious discrepancies in the process of integrating European basic wind-speed maps (especially between the UK and France, Poland and Germany). Following several deliberations and argumentation, the international wind-engineering community reached consensus that there is no rational reason for disregarding such abnormal values.

This approach became even more relevant, and was adopted in Kruger's study, in view of the short data sets available from some of the weather stations. Such short observation periods (in the order of 10 to 15 years) may not detect long-term climatic trends. This situation is demonstrated in Figure 7.6 for the 11-year record measured in Struisbaai. It can be seen that, while most of the yearly maxima wind speeds were about 30 m/s and less, one of the records was in excess of 40 m/s.

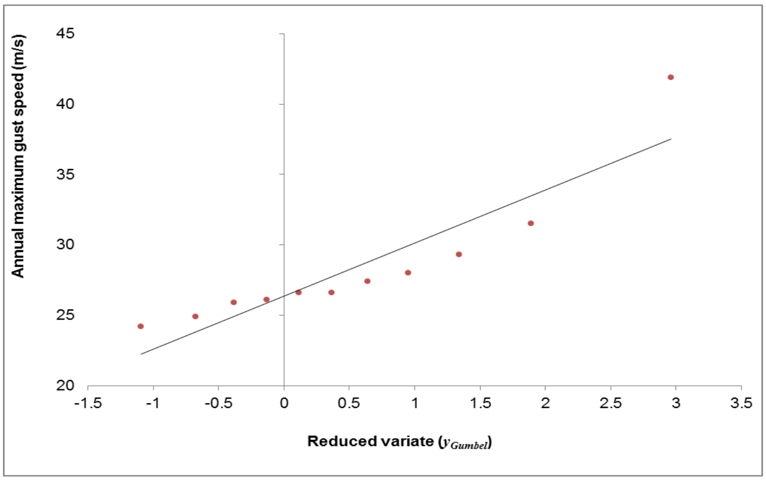

Figure 7.6: Gumbel extreme value distribution for Struisbaai (1997-2008)

Rationally based accuracy levels: This issue relates to the author's long-term experience in wind-tunnel modelling and his understanding of the associated practical levels of accuracy that can be achieved and transferred into the design process. This type of background provided useful guidance (a reference level) in some of the aspects of data processing undertaken in the study.

Length of observation in the integration of data sets: As mentioned earlier in the current report, at the beginning of the 1990s a national process of introducing AWS instrumentation was initiated by the SAWS. In this process all old Dines (pressure tube) anemographs were also replaced with RM Young sensors and this also enabled full automation of data capturing and transferal.

This resulted in a situation in which, at the time of the analysis undertaken by Dr Kruger, more than 10 weather stations contained *old* and *new* data sets. Because of the limited length of the *new* time series (typically less than 15 years) an integration of both such data sets would have provided an excellent opportunity for obtaining a few long-term records of 30 to 50 years of continuous observation, which could be used for possible sensitivity and reliability analyses.

An investigation into the feasibility of such integration was carried out. It was established that the time series before and after the changeover exhibit noticeably different characteristics. This situation is demonstrated in Figure 7.7, which presents mean monthly wind speeds at the Durban Weather Office for the period 1956 to 2008. The changeover to new instrumentation took place in September 1992, and was followed by a noticeable change in the average level of windiness.

This could be due to a change in the positioning of the old vs new anemometers as, for various reasons, such changes have been introduced in the past by the SAWS (without documenting them). Other reasons could be the accuracy of calibrations, or the human factor or error in the digitising process. (In the old system all 'hourly means' less than 1,5 m/s were entered into the database as being 0 m/s.)

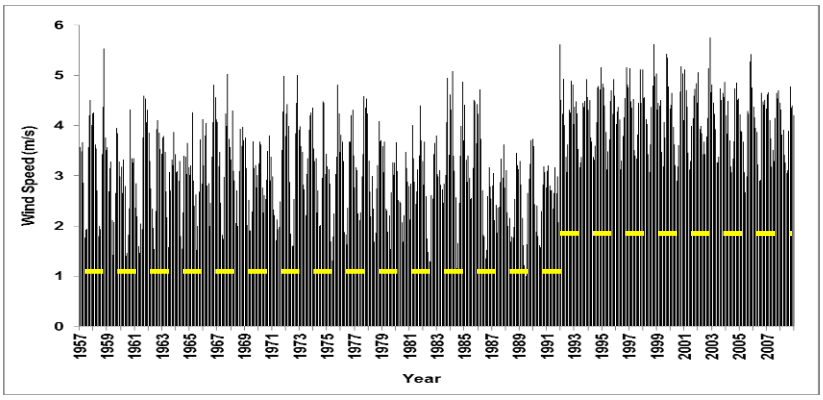

Figure 7.7: Monthly mean wind speed (m/s) for Durban Weather Office (1956 – 2008)

Because of the above findings, the idea of integrating *old* and *new* records was not pursued any further. Later on it was established that a similar process had been attempted by the Australian Weather Service, but not finalised due to discrepancies.

The investigation by Dr Kruger considered all pertinent factors – i.e. wind climatology, the origin and types of strong wind events, measuring systems, statistical methodologies for assessing random process and rare events, the SAWS network of wind recorders and their exposure, as well as the spatial mapping and clustering of quantiles as affected by the topography. At the time of preparing the current report, the outcome maps of the *fundamental-value basic wind speeds* were submitted for implementation in SANS 10160-3. This represents the culmination of a

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process of advancing the proper treatment of the most important component of designing for wind loads (Section 7.1), as promoted by the author (Sections 6.1).

The project resulted in a comprehensive and prominent update of the statistical description of wind climate of South Africa. It also facilitated the development of a champion within SAWS – i.e. specific wind-related expertise and an appreciation of the critical importance of reliable capturing, recording and assessing wind data, and its impact on the design of built environment.

The study preceded completion of Phase I of the Wind Atlas for South Africa developed by the National Energy Development Institute for the assessment of power-generation wind resource. Although this activity is aimed at quantification of sustained winds, it complements the efforts of the project carried out by Dr Kruger. One of the future work packages of the atlas will also consider extreme winds.

It is envisaged that a similar analysis to that carried out by Dr Kruger, would need to be followed in about 15 to 20 years, once the observation period of most of the recorders will increase to about 30 years and more. In addition an extensive array of AWS records should improve the resolution of strong wind records. This will enable the development of a new set of statistics with substantially enhanced levels of confidence in wind climate of the country. Opportunities still remain for improving the standardisation of the exposure of newly deployed AWS.

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8. Supervision of postgraduate research

At this point it is relevant to raise the issue of the CSIR's underlying mandate as the Council for Scientific and Industrial Research, which differs substantially from that of universities. Over the years, the CSIR's activities were focused on applied research and development, and related educational considerations were very limited. Only in recent years has this focus been broadened to also facilitate academic activities – e.g. lectures or inputs to research studies.

Despite employment circumstances and constraints, the author was involved in several research projects and wind-tunnel investigations involving students from various local (e.g. Stellenbosch, Witwatersrand, Pretoria) and overseas universities (e.g. Aachen, Ruhr, Warsaw). All these contributions followed specific needs and requests from the respective academic staff. A few of these projects involving endorsement by the author as a study co-leader are highlighted below. (The involvement in Dr Kuger's PhD research was highlighted in Section 7.4.)

8.1 Wind loading of cross-vault buildings

The author was requested by Witwatersrand University (Prof Mitch Gohnert) to co-supervise MSc research by a Mr Bradley on wind loadings of buildings with cross-vault geometries. The related experimental work was carried out at the CSIR's boundary-layer wind tunnel. The study concentrated on measurements of the distribution of external pressure coefficients as a function of geometrical differences, wind orientation, turbulence characteristics of the flow, and surface roughness. Three roof geometries – namely *flat, convex and concave* – were considered, as compared in Figure 8.1a.

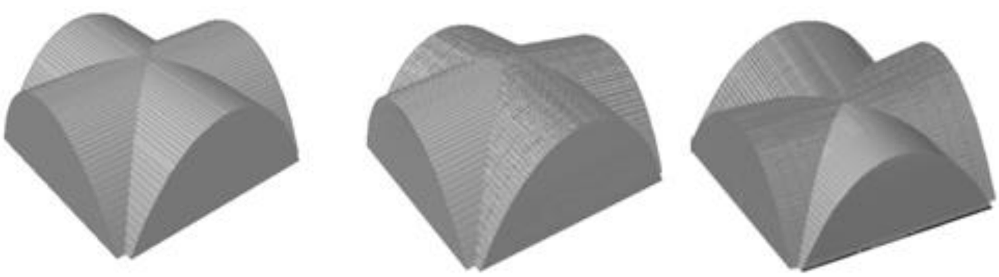

Figure 8.1: a) Comparisons of geometries

Of particular interest was the investigation into the effects of surface roughness which, in view of the shape of the roofs (i.e. round surfaces), play a significant role in establishing the confidence levels of loading parameters as affected by separation points of the flow (i.e. Reynold's number). This investigation also included a comparison of numerical and pneumatic pressure averaging and,

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furthermore, the development of a computer algorithm based on the ESDU 80025 (1988).

Despite of the apparent visual similarity of the models, involving small geometrical changes in the apex, several interesting trends regarding the distribution of mean, root-mean-square and peak pressures were established at certain wind directions and areas of the roofs. Figure 8.1b presents a typical output data of contour lines of the mean and root-mean-square pressure coefficients, related to specific boundary layer characteristics, geometry, surface roughness and wind orientation.

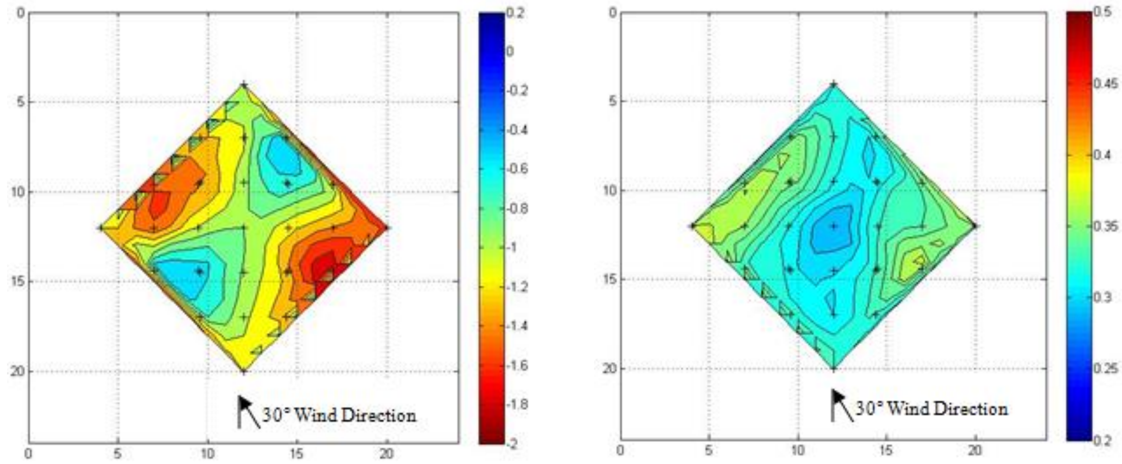

Figure 8.1: b) Distribution of mean and c) root-mean-square pressure coefficients

The outcomes of the research are included in Bradley (2011) and were also presented at the *13th International Conference on Wind Engineering* in Amsterdam (Bradley *et al*, 2011).

At the time of preparing the current report, research by Mr Bradley into the wind loading of vaulted roofs was continued in terms of his PhD studies. Two joint papers, Bradley *et al* (2015a and 2015b), have been submitted to the SAICE Journal and SEMC Conference respectively.

8.2 Monitoring the response of a tall building

Professor Marian Gizejowski, an overseas partner, and the author became joint recipients of the first South Africa–Poland Research Cooperation Programme Award, granted by the Polish Ministry of Higher Education in collaboration with the SA National Research Foundation (NRF).

The aims of the award were to encourage and support engineering research collaboration and joint academic studies. The related funding permitted the identification and support of a suitable student interested in Wind Engineering

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science and a relevant research topic (Cwik, 2013). The study considered a 208m-tall building with complex geometry, located in Warsaw (Poland). The objective of the project was to investigate the feasibility of assessing the structural integrity of tall buildings (popularly referred as a *building's health*) by monitoring their loading response to a quantified wind action component. The study comprised full-scale and wind-tunnel measurements, as well as computational fluid dynamic (CFD) modelling.

Figure 8.2a presents the building and its geometry, and Figure 8.2b a wind-tunnel model of the building and its surroundings. A sample of the output results, which compare wind-tunnel and CFD modelling data, is presented in Figure 8.2c.

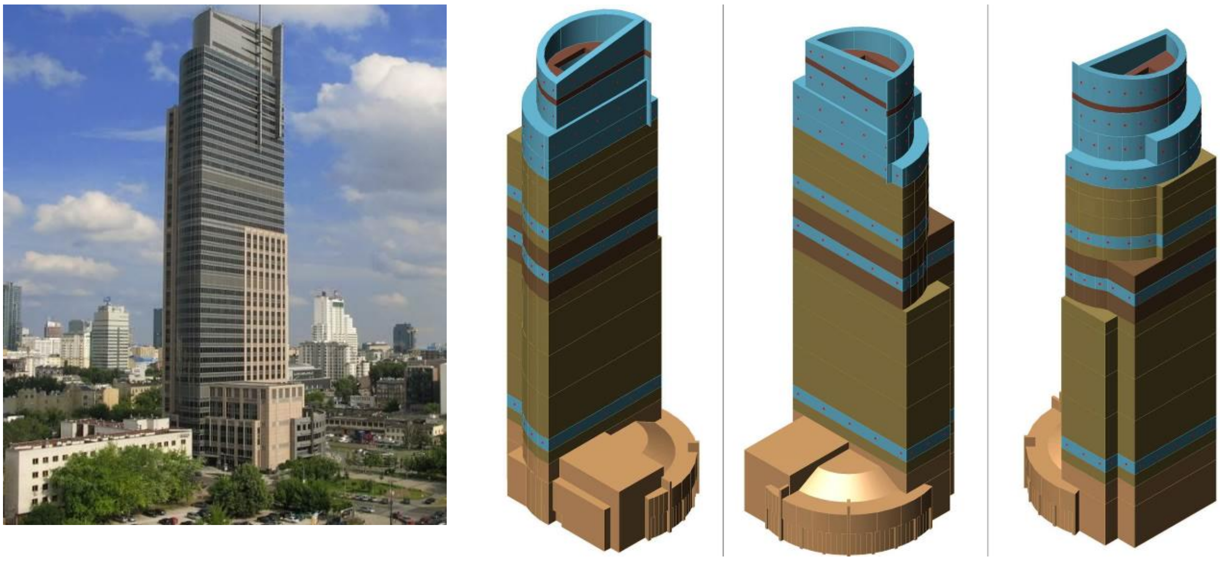

Figure 8.2: a) The WTT building in Warsaw

Figure 8.2: b) Wind-tunnel model

It is relevant to note that the comparison of the CFD and wind tunnel observations looks good, and surprisingly so in terms of the magnitude of pressure coefficients. It is stressed, however, that the CFD modelling was carried out after completion of wind-tunnel measurements and the numerical input parameters were adjusted. A

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process such as this, in which the results of physical modelling serve as a reference base for numerical modelling, is commonly implemented in research. This confirms that current CFD modelling capabilities are able to provide an efficient way of predicting trends in the data.

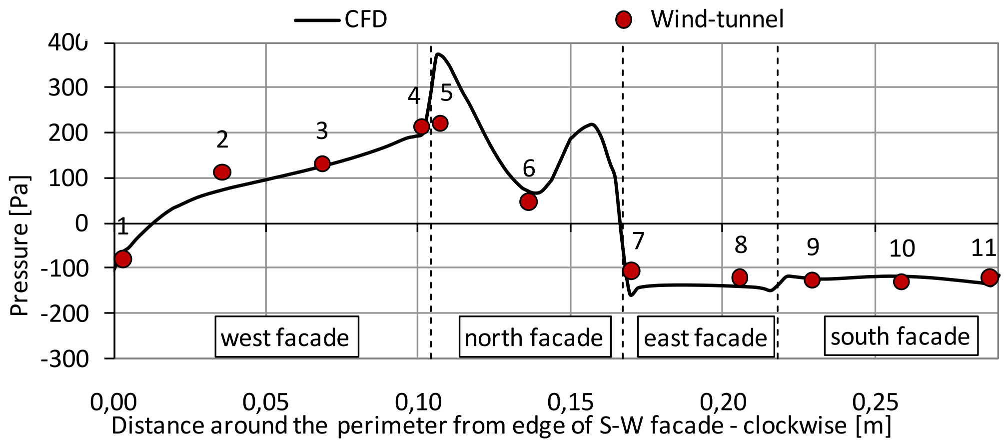

Figure 8.2: c) Comparison of wind-tunnel CFD results

The research by Dr Cwik confirmed the feasibility of the proposed methodology in which building response subjected to a known (i.e. quantifiable) force is measured and assessed against its predicted behaviour. The implementation of such a methodology may offer substantial cost and time savings on a national scale. *(Current Polish building regulations follow the European protocols, which enforce regular structural inspections of tall buildings. These involve the exposing and testing of structural elements, which can sometimes be prohibitively costly.)*

Several problems were identified in relation to full-scale measurements. These relate to installations, the identification of a suitable wind situation, the accuracy of measurements, optimal location of reference points and the presence of electronic and weather-related interferences.

The research and its outcomes were presented at two EU scientific forums/ workshops and are also included in a series of publications (some in Polish): Cwik *et al*: 2009, 2012a, 2012b, 2013; Cwik 2013 and Sitek *et al* 2013.

8.3 Crest-fastened metal cladding

This involvement follows several years of the author's association and numerous investigations related to the roof-sheeting industry (see Section 6.3). The initial discussions with Mr Stephan were in support of formulating the scope and methodology of his Masters research. Following the author's recommendation, the preliminary consideration of researching *concealed sheeting systems* was discarded and the study was redirected to *positively fixed sheeting* only.

In the author's opinion, based on extensive full-scale investigations of damage and laboratory testing experience, the structural performance of concealed sheeting is governed by a variety of largely unpredictable and erratic factors related to the materials, rolling and installation processes. In view of the level of inconsistencies, it would be hardly feasible (especially within a relatively short period of time) to establish any clear and scientifically based trends or dependencies.

The research project was then initiated under the supervision of late Professor Peter Dunaiski and, upon his departure, taken over by Mr Etienne van der Klashorst, who requested co-supervision inputs from the author (Stephan, 2013).

The study was based on specific 0,47 and 0,50 mm thick-steel IBR products provided by a well-established Cape Town sheeting manufacturer. It comprised physical and numerical modelling. Physical modelling involved material (sheet and fasteners) and assembly testing. Figure 8.3a presents the testing rig (based on the principle of inflatable airbags, Figure 8.3b a close-up of a ridge deformation, and Figure 8.3c a typical graph of output data.

a) b)

Figure 8.3: a) testing rig; b) localised deformation

Several conclusions and recommendations were made regarding the progressive deformations, load resistance and modes of failure. Some of the findings are applicable to the specific system and material only, while others are largely relevant to all types of positively fixed cladding. The related South African performance and design specifications of the industry are vague and unreliable, and the uplift resistance of various systems cannot be verified.

The airbag method constitutes an effective tool for testing the uplift resistance in relation to forces acting on the attachments, as well as the bending moments. This methodology does not, however, facilitate the representation of the spatial and temporal wind-action variabilities. Furthermore, measurements of the reaction forces indicate that the distribution of loading may not necessarily be uniformly distributed over the entire sample.

It was established that the configurations of the IBR sheeting are governed by two initial modes of failure – i.e. localised around the crests (for low-spans) versus mid-span buckling (above a specific span length for each configuration).

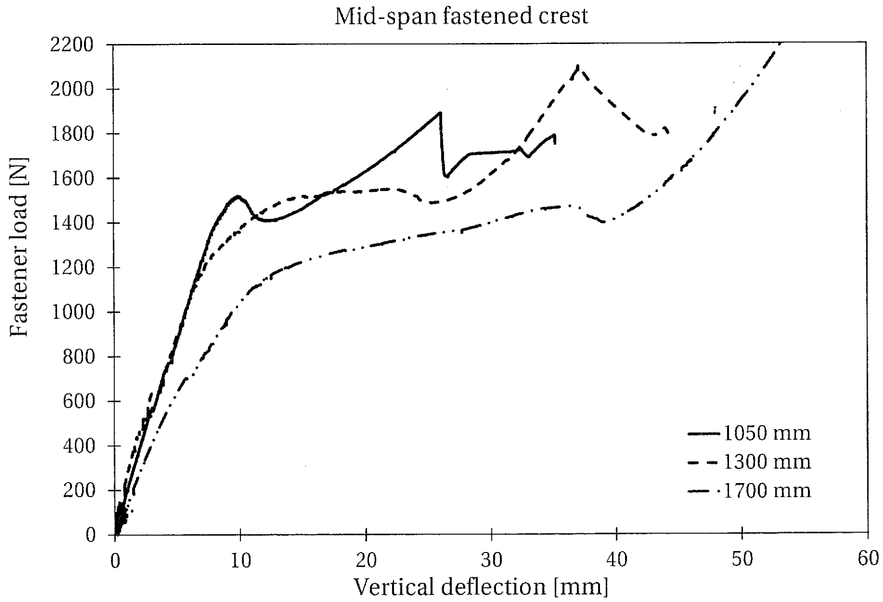

Figure 8.3: c) comparison of fastener load-deflection curves

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9. Conclusions

This dissertation constitutes a brief overview of a professional career and the personal development of the author, which spanned over more than 30 years. The author's professional activities concentrated largely on the fairly specialised discipline of *wind engineering and building aerodynamics*. In terms of the South African situation, given a relatively small economy and a shortage of specialised engineers, such a career can be regarded as unique.

The limited availability of expertise within the related domain exposed the author to a diverse spectrum of research topics and interactions with a number of leading international experts.

Early engagement in wind-tunnel activities facilitated the author's involvement in international calibration efforts of a fairly contemporary technology for the time: boundary-layer modelling. This was in contrast to traditional wind-tunnel testing carried out in mechanical engineering facilities. It also provided a useful platform to gain understanding of principles, benefits, shortcomings and reliability of the physical modelling of wind and structure interactions.

The author's initial involvement in the modelling of loading effects on structures formed the basis, which progressed into exploring the impacts of the surroundings on wind structure, i.e. environmental investigations involving topographical effects, large scale flow regimes, as well as the complexity of flow in built-up terrain. The outputs of topographical wind-tunnel modelling generated international interest and peer recognition. Numerous pedestrian-level investigations of built environment enabled the environmental and architectural optimisation of several large-scale developments in South Africa (mainly in Cape Town).

Modelling experience provided a useful context to the full-scale observation of extreme wind action and its consequences. These were directed into the climatic aspects of wind action (i.e. types and zones of strong wind occurrence), which culminated in the co-supervision of PhD research on wind statistics. Furthermore, substantial effort was committed towards observing and quantifying adverse wind impacts on the built environment - analyses and documentation of damage and its spatial distribution. This enabled the development of statistical information and related risk modelling. As a further extension, an analysis of South African tornadoes provided statistical perspective into these extreme but rare wind events, and provided substantial international exposure and recognition. The expertise, which was gained, also enabled to participate and provide research inputs to a totally unrelated discipline of foundation engineering.

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Full-scale investigations have highlighted the importance of the reliable capturing of full-scale wind data and identified a series of shortcomings in the SA Weather Service's observation and recording systems.

Finally, the integration of the author's experience in model- and full-scale investigations enabled the development of unique, to South Africa, knowledge and expertise in the wind loading design chain. This knowledge has been, and continues to be, disseminated extensively in support of the design profession and academia and has also been used in the development of the relevant SABS loading standard (SANS 10160-3).

The considerations included in the dissertation demonstrate the complexity of wind-action aspects which are influenced by several site- and structure-specific parameters.

Over the last fifty years or so, substantial progress has been achieved in expanding the volume of knowledge and developing predictive models in relation to some of these parameters, especially those describing the distribution of external pressures. Furthermore, straightforward universal rules have been developed in respect of the presence and impact of dominant openings (intentional and accidental).

However, relatively little research has been conducted into the mechanisms of generating and distributing the internal pressures as a function of the general aerodynamic porosity of the external shell, as well as the internal divisions, into separate air volumes.

The biggest source of uncertainty in predictive models relates to an adequate description of the free-stream dynamic pressure applicable to a specific design. This is in terms of the climatic information regarding the *fundamental value of the basic wind speed* and also the modifications of flow regime due to the surrounding environment (terrain roughness, topography and neighbouring structures). By implication, the above statement indicates the critical importance of:

i) adequate and consistent capturing and analysis of the representative full-scale wind-climate data, which remains the responsibility of national weather monitoring authorities, and

ii) quantification of the impact of site-specific surrounding influences, which can only be predicted reliably on the basis of wind-tunnel modelling (or extensive experience in that domain).

Most of the current international wind-loading standards are based on a conservative principle of omni-directional design, in which the directional prevalence of strong and extreme winds is ignored. Furthermore, the application of loads in two principal, *x* and *y,* geometrical axes of structures is typically considered. It can be

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contemplated that the implementation of directional design which, without a doubt, will take place in future international design practice, will bring reductions in predicted wind loadings and, therefore, costs.

Finally, on a personal note, the professional activities carried out by the author have provided the platform for a fulfilling research career and pragmatic outputs in support of the local engineering and architectural design industries. Furthermore, they have facilitated the development of rational cross-disciplinary expertise and understanding of the mutual relationships between the various elements of wind action.

In the future, the development of similar research outputs and diverse expertise will be difficult in view of the trends towards specialisation and cost-cutting, as well as the ever-increasing pace of the design and construction industries. The growing perception of the acceptability (and even superiority) of computer-generated analysis, derived by computational fluid dynamics (CFD) software, is distressing. Such software packages, often used by unqualified individuals, provide visually impressive outputs. However, these results are often based on substandard inputs and unfounded assumptions, far removed from actual physical relationships and phenomena governing wind action.

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