Geotechnical and Pavement Engineering
Selected Papers of Professor I. K. Lee

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FO REWORD

BY MAJOR GENERAL PETER J. DAY, AO
Commandant of the Australian Defence Force Academy 1986-1990

Amongst the undergraduates studying Civil Engineering at the University of Melbourne with Ian Lee in 1954 were a few Army officers. It was through one of these, Brigadier John McDonagh, that I first met Professor Lee. Using his earlier Army links he arranged for a continuing education workshop on pavement design to be held at the Army School of Military Engineering in the late 1970s. Much was gained from the exchange of information between the researchers from the Department of Civil Engineering Materials at the University of New South Wales (UNSW) and the ‘builders’ – the Army and Air Force engineers responsible for the repair and rapid construction of roads and airfields. This initiative of Professor Lee complemented the links already established with the UNSW through the Faculty of Military Studies at the Royal Military College (RMC). It was a link especially valued by me, then the Director of Engineers-Army, because it gave Army engineers a window into current work on geotextiles in Australia. At that time all our discussions on pavement expedients was with engineers in the defence force of the United States or Britain.

Professor Lee’s interest in helping military engineers solve pavement problems continued for the rest of his career. My next involvement with one of his workshops was in July 1985 when I was invited to open two held in Canberra. At this time he was Head of the Department of Civil Engineering at the embryo Australian Defence Force Academy (ADFA). The conduct of these workshops – on pavement design and welding – demonstrated the unquenchable energy of a man who was simultaneously organizing the transition of civil engineering students from the RMC to the new ADFA in 1986 as well as planning and supervising the fit-out of new facilities for his Department. At that time neither of us knew we would be working more closely together very soon when I became Commandant of the Defence Academy in December 1986.

Challenges and difficulties abounded in the early years of the Defence Academy. Construction of the accommodation and some laboratories was not completed until 1988 and it took even longer than this for academic and military components to forge teams from groups of people; many of whom had not worked together before. During this time the energy and organizing ability of Professor Lee was a great benefit to his Department as well as an example to others. He recruited new staff; improved the laboratory facilities; introduced a new undergraduate course in Maritime Engineering; initiated programs for Project Management at undergraduate and postgraduate levels; and developed courses for a Masters Degree in Engineering and a Graduate Diploma in Technology Management. A noteworthy feature of these programs was the flexibility given to graduate level students to choose subjects offered by other Departments of the University College. It seems that whenever the topic of academic innovation arose Professor preferred to ask ‘Why not?’ rather than ‘Why?’

Geotechnical Engineering is a field in which a practitioner faces the threat of being buried by his mistakes. At first glance it seems to offer little scope to proclaim: ‘If you want to know my achievements look around you!’ However, I believe the
quotation fits the work of Professor Lee with greater success than in the case of Ozymandias: his students and colleagues are the best monuments to his life’s work. The best example of my contention can be found in this collection of Professor Lee’s papers edited by two of his students and colleagues; Professor K. S. Li and Associate Professor S. R. Lo. The high esteem in which they hold Professor Lee is made manifest by the efforts they made to bring their project to completion.

I feel privileged to be associated with this tribute to a gifted engineer, an inspired mentor of undergraduate and postgraduate students, and a valued friend. His contribution to the education of military engineers was recognized when, on his retirement in 1993, he was appointed an Honorary Member of the Royal Australian Engineers.

Canberra
2003
Preface

Professor Lee has made significant contributions as an educator, a researcher, and a professional engineer. As remarked by a reviewer of his application for the degree of Doctor of Engineering, Professor Lee’s papers are characterized by their high quality and their being pioneering work at the time of their publication. He saw the need for and started research programs in many important areas long before they become mainstream research topics in geotechnical and pavement engineering. The impressive list of topics included geotechnical instrumentation, fundamental laboratory studies of soils and rocks, soil-structural interaction theory, rational approach to design and management of pavement system, geosynthetics, probabilistic methods and quantitative risk assessment, and modelling of soils using the particulate medium. Many of Professor Lee’s publications have become classics in their respective fields.

Professor Lee had never lost sight of the need to relate research work to practical issues and interacted regularly with practising engineers. His practical approaches to problem solving are reflected in many of his applied research papers.

In 1985, Professor Lee made an important career decision to set up and head the Department of Civil Engineering at the Australian Defence Force Academy (ADFA) campus of the University of New South Wales (UNSW). We are very fortunate to have been PhD students and / or colleagues of Professor Lee at UNSW-ADFA. He has no doubt influenced us deeply as we see him practise the principles he has always upheld. He has instilled in us the importance of honesty and rigour in academic research and the need to carefully scrutinize errors in computational or experimental results that can influence interpretation.

This book is published as a tribute to Professor Ian K. Lee as an outstanding researcher and to thank him as our remarkable teacher and mentor. It also marks the 20th anniversary of the setting up of the ADFA campus of UNSW at which Professor Lee had set up a world-class geotechnical research facility. The book contains selected papers of Professor Ian Lee. We have asked Professor Lee to write a prologue to give readers some information about his research activities over the past few decades.

Acknowledgements are gratefully made to a number of publishers and organizations for granting their permissions to reproduce Professor I.K. Lee’s papers published in this book. They include A A Balkema, American Society of Civil Engineers, ARRB Transport Research Ltd, Australian Geomechanics Society, and Thomas Telford Ltd.

K.S. Li, S. R. Lo and J. Chu

2006
Professor Ian Kenneth Lee
BIOGRAPHY

Professor Ian Lee graduated from the University of Melbourne in 1954 with a Bachelor in Civil Engineering with Honours. He had previously completed a Diploma in Mechanical Engineering and had entered the University of Melbourne with advanced standing. After completing his undergraduate studies, Ian Lee pursued full-time research studies at the Melbourne University, leading to the award of Master of Engineering Science with First Class Honours in 1956. He then completed part-time PhD studies in the same university in 1961.

The PhD program involved analytical and experimental studies of load settlement and moment-rotation relationships of footings. These pioneering analyses were building blocks facilitating the prediction of the soil-structure interaction of a multi-storey framed structure supported by either isolated footings, piles, raft foundations, or a raft-pile system.

During the period 1960-1965, Ian Lee was appointed a Lecturer, then Senior Lecturer in Civil Engineering at the University of Melbourne. He spent a sabbatical leave at the University of Manchester in 1961 where he completed experimental studies with Professor P.W. Rowe who had recently published his outstanding and controversial stress-dilatancy theory for granular soils. Returning to Melbourne, Ian Lee supplemented his teaching and research studies by consulting experience in site investigations, slope stability, foundation engineering as applied to soft soils, stiff clays and expansive soils.

Following a brief career as a Senior Geotechnical Engineer with H.G. Acres, Canada, Ian Lee accepted an appointment in 1967 as a Senior Lecturer offered by the University of Sydney. He was promoted to Associate Professor in 1969. This was a very stimulating and productive period for him as it provided the opportunity to discuss, debate, and work with a group of outstanding academics with similar attitudes and research interests, namely, Professors E.H. Davis, H.G. Poulos, J.R. Booker, and a structural specialist, Associate Professor H. Harrison, together with talented graduate students undertaking Masters or PhD studies.

One principal area of the research undertaken by Ian Lee at the University of Sydney was the application of the plasticity theory as developed by Professors Davis and Booker, to predict the progressive change in active/passive pressure regimes for a 0 to 360 degree range of direction of wall movement. The analyses, which had led to subsequent publications of the classic papers by Lee and Herington, considered both the associated and non-associated flow rules and suggested rational explanations for displacement profiles of backfill as observed in the Cambridge experimental studies.

Soil-structure interaction studies were resumed at the University of Sydney by Ian Lee with particular emphasis on the analysis of raft foundations. Numerical analyses of the rate of settlement of layered soil deposits were completed and the results compared with formal solutions published by Professor Rowe. Ian Lee also started experimental measurements of the deformation behaviour of rocks in collaboration with O.G. Ingles and W. White, both of whom later joined the School of Civil Engineering, the University of New South Wales.
In 1971, Ian Lee accepted the appointment as Professor of Civil Engineering and Head of the Department of Civil Engineering Materials at the University of New South Wales (UNSW). It was a difficult decision for him to leave the University of Sydney, but the offer by UNSW provided the opportunity to create and head a new Department responsible for the integrated teaching, including design, of materials commonly used in civil engineering. The Department subsequently included strong geotechnical and concrete technology groups, and a small but very talented metals group with particular responsibilities in the areas such as fatigue, welding and corrosion. The geotechnical group included Professor I.K. Lee, Associate Professor O.G. Ingles, W. White, and a computational specialist, Professor S. Valliappan.

Professor Lee had brought new changes to the School of Civil Engineering since joining UNSW. Civil Engineering Materials subjects were included in the undergraduate program, including some electives in the final year. A formal coursework/research project Masters program was introduced for both full-time and part-time students. The range of subjects provided adequate choice and specialization, and complemented the existing and highly regarded course work graduate programs in the areas of Structural Engineering, Water Engineering, and Management. A series of workshops, short courses and conferences were also organized and presented, with the specific objective of giving professional civil engineers the opportunity to be exposed to developing technology and analytical techniques. The practice adopted for Short Courses was to invite highly regarded international and national experts to be keynote speakers or to completely present the course. Invited international geotechnical presenters included Professor C. Monismith, Professor M. Harr, Professor R. Hudson, Professor Peter Lumb, Professor J. Mitchell, Professor P.W. Rowe, Professor E. Schultze, Professor L. Endersbee, and Professor Per Ulidtz. Similarly, courses in other areas such as concrete technology, welding, corrosion were also organized.

The two classic books, namely Soil Mechanics-Selected Topics (Butterworths, 1968) and Soil Mechanics-New Horizons (Newnes Butterworths, 1974), which were both edited by Professor Lee, were partly based on courses he organized at the University of Melbourne, the University of Sydney and later at UNSW.

Professor Lee continued soil-structure interaction research with S.J. Hain at UNSW leading to numerical analysis techniques for raft and raft-pile foundation. Numerous other experimental and analytical geotechnical and other materials research projects were actively pursued by the staff and graduate students under the leadership of Professor Ian Lee. Selected geotechnical projects included:

- Development of effective boundary conditions by W. White to obtain reliable predictions of the response of dynamically loaded footings.
- Analytical solutions predicting the effectiveness of rock blasting.
- Techniques for calculating representative values of primary and secondary rate parameters of soft soil deposits were established based on analytical modeling and available field data.
- Laboratory based measurements of the deformations and pore pressures hence representative rate parameters were completed for the stress paths
imposed by construction of fill embankments.

- Experimental studies on the development of passive pressures were compared with predicted values for a range of directions of movement of a rigid wall.
- A detailed study was made of the properties of a deep weathered dolerite, facilitated by a programmed loading frame.
- A cell designed for applying precisely controlled multi-axial loading to a cubic soil sample had been progressively developed by Professor Lee. An improved system was developed by S. R. Lo which ensured an essentially uniform normal stress distribution over each boundary surface face of the soil cube.

In 1982, Professor Ian Lee initiated a long term co-operative research project with Tongji University, PRC. The primary objective was to further develop the soil-structure analyses published by Lee and Hain for a raft foundation (1974), and a raft-pile foundation (1978), to provide design procedures for several of the multi-storey buildings which were to be erected in the immediate future in China. The UNSW co-operation with the Tongji University team led by Professor X. Zhao, provided numerous contributions over the period 1982 to 1992. Professor Lee completed two major lecture tours in China during the same period. He also took time in writing a textbook entitled Geotechnical Engineering (1983) jointly with W. White and Associate Professor Ingles.

In 1985, Professor Ian Lee, W. White, and Dr. S. Yeomans transferred to the Australian Defence Force Academy (ADFA) campus of UNSW, based in Canberra, to effect the transition of the Civil Engineering Department from the mantle of the Royal Military College to a Department within the newly formed Australian Defence Force Academy (ADFA). The greatest factor invigorating the teaching and research next to the leadership of the Commandant, Admiral P. Sinclair, and the Rector, Professor J. Wilson, was the appropriate funding allocated to establish staffing, computing facilities, laboratory and field equipment.

Undergraduate teaching of Civil Engineering at ADFA campus was greatly enhanced by the appointment of new staff in the areas of project management, water engineering, and geotechnical engineering. The Department of Civil Engineering at ADFA saw rapid development, both in taught courses and research studies, under Professor Ian Lee’s leadership. A Masters program was instituted in 1986, available to both military and civilians. A very active program of short courses also rapidly developed. All courses were well attended and appreciated by the Service and Civilian attendees - particularly the computer based project management courses.

There had been a similar boost in the recruitment of research students both at Masters and PhD level. From 1988, the computer controlled testing facilities in UNSW at ADFA were fully operational. Professor Lee and his geotechnical group were able to complete a series of projects establishing the behaviour of soil elements subjected to a range of stress and strain loading paths, leading to the discovery of a wide range of new behaviour of soils including pre-failure strain softening and instability (sometimes referred to as static liquefaction). The Department also saw a productive period of research in the development of
probabilistic methods in slope stability analysis and limit state design of foundations. With the full support by Professor Ian Lee, the International Conference on Probabilistic Methods in Geotechnical Engineering was organized in ADFA in 1992.

A graduate level program of appropriate Project Management topics was provided by the Department to contribute to a new training initiative proposed by the Army Material Corp. This course entitled Australian Technical Staff Officers Course (ATSOC) was presented in 1992, and illustrated a type of high level contribution ADFA could provide to the Services.

Professor Ian Lee also played a major role in introducing a Graduate Diploma in Technology Management at ADFA with the enlightening feature that graduate level students could compose their program from the subjects offered by the Departments of Civil Engineering, Computer Science, and Economics and Management. A Master's program was later proposed following the good response to the Graduate Diploma.

In recognition of contributions to the University of New South Wales, he was made an Emeritus Professor after his retirement in 1993. The University of Melbourne also awarded him a Doctor of Engineering in recognition of his significant contributions to academia, particularly his research in geotechnical engineering.

Following his retirement, Professor Lee was engaged as a consultant for a range of geotechnical projects and technical litigations. He had been deeply involved for some years in the Institution of Engineers Australia's (IEAust) Standing Committee on Accreditation of Engineering Degree Courses, and became Chair of the Sub-Committee responsible for Civil and Environmental Engineering. He is also one of the group of members of IEAust who conduct formal reviews of applications for admission to the status of Chartered Professional Engineer.

Professor Lee is a Fellow and a Chartered Professional Engineer (Civil) of The Institution of Engineers, Australia and a Fellow and Life Member of the American Society of Civil Engineers. He was appointed as an Advisory Professor of Tongji University, Shanghai, PRC, in 1985. He has been a Visiting Professor at several Universities, and has contributed to the organization of, and has participated in, the presentation of geotechnical topics at International Conferences and Courses in Australia, Japan, PRC, Indonesia, Singapore, USA, Mexico, UK and Thailand. He initiated, as Chair of the Piling Code Committee, the introduction of Limit State Design format into what became the Australian Piling Code issued by the Standards Association of Australia, AS2159.

Professor Lee has a distinguished academic career. He served on the prestigious Australian Research Grants Committee (now the Australian Grants Committee). He has pioneered and made significant contributions in several research areas. Ian Lee strives for quality and not quantity in his publications. A case in point is his research in pavement engineering, which traditionally is characterized by empirical design rules with little reference to geotechnical engineering. Professor Lee pioneered the introduction of geotechnical concepts in pavement engineering as early as the late 1960s. He kick-started a major research project at the ADFA campus in the early 1990s, just before his retirement, on the influence of loading path on the
response of sub-base subject to cyclic loading. The findings of this project had led to a rational explanation of why the high stiffness inferred from pavement performance might not be measured by a standard cyclic triaxial test. He had supervised and worked with many graduate students in his research, including J.R. Herrington, S.J. Hain, P. Boonlualohr, M.R. Hausmann, A. Cipullo, S.C R. Lo, K. Matsuzaki, J. Yeaman, K.S. Li, J. Chu, G.M. Zhuang, M.M. Zhao, K. Chen, and others.

K.S. Li, S. R. Lo and J. Chu
2006
PROLOGUE

My research contributions can be grouped in the following areas:

CONSTITUTIVE RELATIONSHIPS OF GEO-MATERIALS

The major thrust of fundamental material research was on the constitutive relationships of soils and rocks, with particular reference to the influence of stress and strain loading paths.

A major contribution to the understanding of the components of shear strength of granular soils followed from my involvement with Professor P.W. Rowe. Also, precise triaxial tests on feldspar established data consistent with the predictions of the stress-dilatancy for this high $\phi$ granular material. Related basic studies were completed for brittle soils using a computer controlled testing frame developed by CSIRO. Subsequent measurements of the deformations of a sandstone subjected to repeated loading revealed the progressive development of negative values of Poisson’s ratio on reloading. Further experimental studies, made possible by the programmed testing facility, were completed on samples extracted from a deeply weathered rock ranging in state from extremely weathered to fresh. Detailed deformation and strength profiles were recorded, and revealed features related to the degree of weathering. Experimental techniques, including precise measurement of volumetric strains, were developed.

The availability at a later stage of new advanced computer controlled systems combined with the successful development of a three dimensional loading system applied to a 100mm cubic sample provided the opportunity to complete a range of significant studies. For example, a method for applying controlled strain increments was developed, thus providing the opportunity for collecting a mass of basic data on pre and post failure stability, and the behaviour at large strains. These studies were seen to be of particular importance in liquefaction analyses. Strain softening under stress and strain increments was studied during the application of three different principal stresses. Such studies were considered to greatly contribute to the understanding of constitutive relationships.

ANALYSES OF GEOTECHNICAL STRUCTURES, FOUNDATION-STRUCTURE INTERACTION

Modelling and the development of analytical techniques for a range of structures and foundation systems were commenced at my early stage of studies, and continued over a period of some 40 years. Early papers developed the analyses providing the load-settlement and moment-rotation of strip footings, and examined the influence of roughness of the soil-footing interface. An elegant mechanical loading system provided a facility to independently control settlement and rotation of a model footing. This system provided the means to
trace the settlement and rotation paths to failure for any selected combination of increasing applied force and moment.

Analytical solutions to multi-bay framed structures on strip footings were developed. This soil-structure analysis was then extended to a multi-bay, multi-storey structure supported on a raft foundation, and revealed the effect of the flexibility of the raft (modelled as a thin plate), and resolved the differences in settlement profile predicted by the use of a linear elastic soil model (semi-infinite and finite layers) and the earlier Winkler (spring) model. The analysis was improved and further generalized by the use of the sub-structure analysis, thus providing detailed predictions of the effects of the major variables on raft settlements and rotations. Further analyses were completed using the non-homogeneous (Gibson) model. Several papers compared predicted settlements and forces developed in the raft, and included the unusual case of the predicted / recorded performance of a 15,000 tonne semi-submersible oil rig during construction.

A subsequent major contribution was the development of the interaction analysis to the raft-pile foundation system. As well as providing an analysis tool, it was possible to undertake sensitivity studies, and to compare predicted and published data for several multi-storey buildings, including, for example, a 12 storey building in Shanghai. The analysis for this structure incorporated non-linear and elasto-plastic soil models. A further major advance was made by the use of three dimensional finite elements for the structure, raft, and pile system. Extensive sensitivity studies were completed on a 8 bay by 2 bay structure, and performance data of a 30 storey building in Frankfurt were compared with the corresponding values predicted by the three dimensional analysis. Several other multi-storey structures were analysed, and included a study of the effects of various soil models (linear elastic, Lade, Duncan, Chang) for both raft and raft-pile systems. The studies reflected the importance of improving the constitutive model for the supporting soil, thus confirming the need to continue the basic studies undertaken by our research group (including use of statistical and probabilistic tools), to take advantage of the data provided by multi-dimensional loading of 100mm cubic samples under controlled stress and / or strain paths.

Measurement of the non-linear, stiffness behaviour of the soft soil deposit at the site of a major oil tank complex, made it possible to predict settlement profiles by successive corrections of the stiffness of each finite element. Stress path tests established that the (logarithm) of the representative stiffness – axial stress for a given stress increment ratio was closely linear.

Similarly, analyses were completed to predict the progressive build-up of pore pressures, horizontal and vertical movements, and rotations of an off-shore gravity structure. Particular use was made of the mechano – lattice developed by a member of the research group, Associate Professor W. Yandell.
PILE FOUNDATIONS

Several unresolved pile situations were identified during the development of the raft-pile analysis and several were encountered during consultations, such as the need to model soil anisotropy and layering. Solutions were developed.

The Randolph-Wroth analysis was extended to predict the effect of stiffening (compaction) or softening (due to remoulding) of the surrounding soil.

Studies considering the uncertainties in the estimation of the shaft bearing capacity of a pile were initiated by Dr. Li. It is considered that this was a very significant contribution to a problem which had not been properly appreciated nor addressed. Furthermore, studies on limit state design were of particular significance to the review of the first (1980's) Australian Piling Code (AS2159) initiated by Australian Standards and myself. A significant feature shown by the limit state studies was that the sensitivity of the reliability index to the proportions of shaft and base loading was smaller when the load reduction factor was based on the total capacity of the pile. This work is also of relevance to the raft-pile design when “failure” occurs in the outer piles.

Further studies showed that the “experience based” strength reduction factors adopted in the revised (1995) Australian Piling Code were in reasonable agreement with a rigorous statistically based study of a large amount of pile test data, completed by Dr. Li and Dr. Lo in the 1990’s.

SLOPES, EMBANKMENTS AND RETAINING STRUCTURES

Early studies in the 1960’s included the development of small boundary earth pressure cells, and the use of these cells in laboratory and field embankments and a model dam.

Extensive theoretical studies were completed to predict the development of active and passive pressures on the face of a rigid retaining structure as a consequence of movements into or away from the retained soil. Plasticity analyses were completed for all possible directions of wall movement, and both associated and non-associated flow rule models were used. A critical examination of the theoretical predictions with the Cambridge experimental data demonstrated the applicability of the non-associated flow rule model. Generalized passive pressure solutions for a $c, \phi, \gamma$ soil and variable wall and surcharge slopes were established. From the stress, hence velocity fields, the admissibility of the velocity field for wall translation and rotation were investigated. Comparisons were made of predicted and experimental data. Further studies were made to establish the effect of the roughness of the wall-soil interface, hence the degree of mobilization.

Further theoretical studies on the progressive development of the pressures at the wall-soil interface were completed – extending the Clough and Duncan approach, and including both the non-linear elastic and the elastic – plastic models. Numerous cases of a translating and rotating rigid wall were completed,
and comparisons with the elegant experimental data obtained by Rowe and Peaker at Manchester were encouraging.

**SOFT CLAY ENGINEERING**

Studies included the extension of the non-linear consolidation analysis to the axi-symmetric situation appropriate for the analysis of settlement rate of a surcharged soft soil deposit penetrated by sand or PVC drains. Settlement analyses to include the effects of rate of surcharging and layering were applied to several major projects to establish representative values of the coefficients of primary and secondary consolidation.

A number of analytical solutions were established based on the Biot multi-dimensional model were completed for several types of foundation systems, soil models and geometry.

**PAVEMENT ENGINEERING**

Early (1960) studies were an attempt to establish the effectiveness of the theoretical predictions of stresses and deformations in a flexible pavement based on the rebound modulus. It was evident that a major effort was needed, as later illustrated by the data obtained at Sydney University by Davis and Sparks, who built a realistic test track subjecting the pavement to a rolling wheel loading.

A very detailed study of the design of proposed pavements of the “new” International Airport Sydney was undertaken with the particular objective of accurately predicting long term settlements of a complex array of soft soil layers beneath the runways. Subsequent recorded settlements were consistent with predictions.

A major contribution to pavement studies was the undertaking of formal research studies in pavement management maintenance, following contact with several of the US, Canadian, UK, and European academics who pioneered techniques and continued outstanding research contributions, notably, Professors Monismith, Professor Hudson and Professor Per Ullidtz. Studies also included field measurements of the progressive development of corrugations, and analysis based on a dynamic half car loading model. A detailed study of the membrane encapsulation system, MESL, was completed as one of a series of studies on mobility of heavy vehicles traversing soft grounds.

Ian K. Lee  
Sydney, 2006
List of Publications of Professor I. K. Lee

1957


1960

1961

1962


1963


1964

1965

1966

1968


1969


1970

1971


1972


1973


1974


1975
1976


1977

1978


1979


1980

1981

1982


1983


1984


1985


1986

1988


1989


1990


1991


1992


1993


1994


1995

1996

1997

2002


# TABLE OF CONTENTS

**FOREWORD**

**PREFACE**

**BIOGRAPHY**

**PROLOGUE - I. K. LEE**

**LIST OF PUBLICATIONS OF PROFESSOR I.K. LEE**

## Part I - Behaviour of Geo-materials

Energy Components During the Triaxial Cell and Direct Shear Tests  
P.W. Rowe, L. Barden and I.K. Lee (1964) ................................................................. 1

Stress-Dilatancy Performance of Feldspar  
I.K. Lee (1966) .............................................................................................................. 17

The Influence of Initial Grain Shape and Pore Anisotropy on Strength of Brittle Soils  
O.G. Ingles and I.K. Lee (1971) ...................................................................................... 43

Response of Granular Soil Along Constant Stress Increment Ratio Path  
S-C.R. Lo and I.K. Lee (1990) .......................................................................................... 57

Strain-Softening Behaviour of Granular Soil in Strain-Path Testing  
J. Chu, S-C.R. Lo and I.K. Lee (1992) ........................................................................... 79

Particulate Modelling of the Asymptotic Behaviour of Granular Soils  
B.L. Liu, I.K. Lee and J. Chu (1992) ............................................................................ 97

Response of a Granular Soil During Strain Path Testing  
J. Chu, S-C.R. Lo and I.K. Lee (1993) .......................................................................... 105

Instability of Granular Soils Under Strain Path Testing  
J. Chu, S-C.R. Lo and I.K. Lee (1993) ............................................................................ 147
Strain Softening and Shear Band Formation of Sand in Multi-Axial Testing
J. Chu, S-C.R. Lo and I.K. Lee (1996) ................................................................. 165

Part II - Foundation Engineering and Analysis of Foundation-Structure Interaction

Elastic Settlements of Footings with Rough Interface
I.K. Lee (1963) ........................................................................................................ 185

Foundations Subject to Moment
I.K. Lee (1965) ........................................................................................................ 193

Field Measurements at a Soil Structure Interface
I.K. Lee (1968) ........................................................................................................ 199

Stresses Beneath Granular Embankments
I.K. Lee and J.R. Herington (1971) .................................................................... 221

Discussion of Experimental and Theoretical Investigations of a Passive Earth Problem
I.K. Lee (1971) ........................................................................................................ 229

Structure-Foundation Interaction Analysis
I.K. Lee and P.T. Brown (1972) ........................................................................... 233

A Theoretical Study of the Pressures Acting on a Rigid Wall by a Sloping Earth or Rock Fill
I.K. Lee and J.R. Herington (1972) .................................................................... 253

Effect of Wall Movement on Active and Passive Pressures
I.K. Lee and J.R. Herington (1972) .................................................................... 279

Rational Analysis of Raft Foundation
S.J. Hain and I.K. Lee (1974) .............................................................................. 297

The Analysis of Flexible-Raft Systems
S.J. Hain and I.K. Lee (1978) ............................................................................... 315

Soil-structure Interaction Analysis and its Application to Foundation Design in Shanghai
X. Zhao, M. Chao I.K. Lee and S. Valliappan (1985) ........................................... 335
Part III – Soft Clay Engineering

One-dimensional Consolidation of Layered Soils
E.H. Davis and I.K. Lee (1969) ................................................................. 359

A Study of the Settlement Characteristics of the Soil Deposits at Kingsford-Smith Airport, Sydney-

Non-Linear Consolidation Analysis of Clay Layers

Prediction of Settlements of Large Oil Storage Tanks

Pore Pressure Dissipation Measurements in a Deep Soft Clay Deposit
W. White and I.K. Lee (1986) ................................................................. 399

The Response of Shanghai Clay in Multi-Axial Tests
I.K. Lee, X. Zhao, S-C.R. Lo, Y. Yang, X. Wei and X. Wu (1988) ........... 403

Part IV – Pavement Engineering

Stresses and Deformation in Two Layer Pavement Structures under Slow Repeated Loading

Stress and Deflection Measurement in Subgrade Materials
I.K. Lee and J.R. Morgan (1966) ............................................................. 437

Development and Instrumentation of the Model Road Test Track at Sydney University
G.H. Sparks, H. Taylor and I.K. Lee (1968) ............................................. 447

Applications of the Mechano-Lattice Analysis in Materials Engineering
A Preliminary Field Study of the Influence of Membrane Stiffness in a Granular MESL Pavement


A Systems Approach to Infrastructure Maintenance with Particular Reference to Pavement Management

I. K. Lee (1994) ................................................................................................................529

**Part V - Reliability Methods and Slope Stability**

The Assessment of Geotechnical Safety

K.S. Li and I.K. Lee (1992) ..................................................................................................549

Limit State Design in Geotechnics

K.S. Li, I.K. Lee and S.C.R. Lo (1993) ..............................................................................585

Towards Limit State Geotechnical Codes in Australia


The RTA Guide to Slope Risk Analysis Version 3.1


A Study of the Accuracy and Precision of Some Landslide Risk Analyses