1 INTRODUCTION

1.1 THESIS OBJECTIVES

The overall objective of this thesis was to improve design procedures for large-scale structures constructed on or in rock.

The first objective of this thesis was the development of a comprehensive database and analysis of concrete and masonry dam incidents world-wide, with a view to developing methods of assessing the risk of failure of existing dam structures and as a consequence of this, identifying possibilities for improvement in design. The results from this work showed that a large proportion of dams had incidents associated with the strength of their foundations, which indicated a need for a better understanding of the strength of rock masses.

The second and major objective of this thesis was to provide a detailed assessment of the applicability of the Hoek-Brown criterion to estimating the shear strength of jointed rock masses and to improve upon any deficiencies found in the criterion. A particular focus was placed on low stress situations (e.g. dams and slopes) in weak materials. This work also included the development of methods for assessing the strength of intact rock and rockfill and new methods for estimating the stability of rock slopes using rock mass rating systems.

To achieve the first objective the author collated and analysed the largest and most comprehensive database of world-wide concrete and masonry dam incidents using both published literature and unpublished records personally obtained from the dam industry. Results were presented on what factors have led to a higher chance of a dam incident occurring. These results were then used to develop an approximate method of assessing probabilities of failure.

The process for assessing the Hoek-Brown criterion had several components. Firstly, large databases of triaxial tests on intact rock and rockfill were statistically analysed to assess the applicability of the Hoek-Brown criterion at the limits of intact rock and very poor rock mass. Secondly, analyses of the failures of large scale rock masses were

carried out to assess how well the Hoek-Brown criterion predicted the insitu rock mass strength. Finally, high quality triaxial tests on rock mass were obtained from the literature and used together with the results of the previous steps and plausibility checks to create new equations for estimating the parameters in the Hoek-Brown criterion.

1.2 THE BACKGROUND TO THIS THESIS

This thesis is divided into two sections: the risk assessment of concrete and masonry dam failures and accidents and their causes, and the shear strength of rock masses as shown in Figure 1.1.

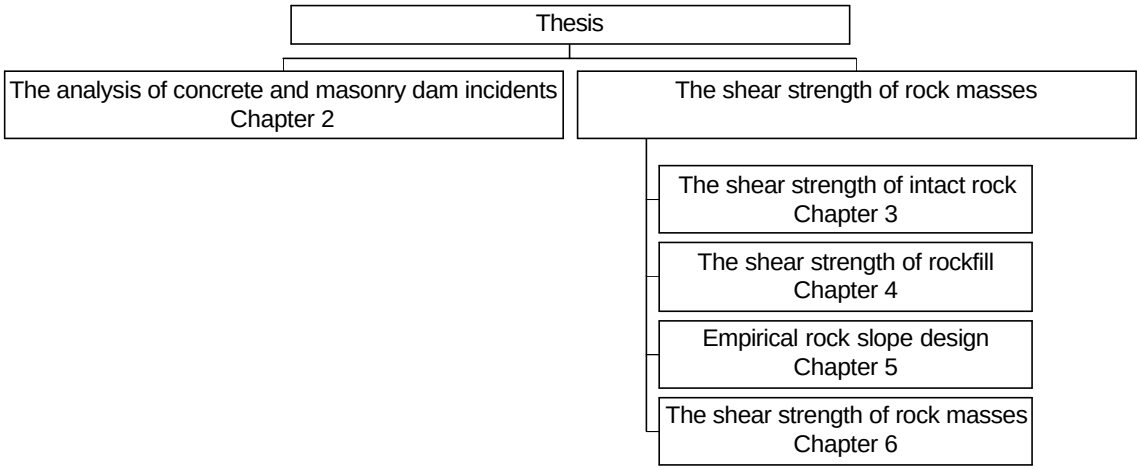

Figure 1.1. Thesis structure

The dams community as part of the Dams Risk Project (together with the ARC and The Faculty of Engineering at the University of New South Wales) provided initial funding for this research. Details of the specific contributors are provided in the acknowledgement section. The first section of the thesis (Chapter 2) was carried out in response to the specific needs of the research project and its sponsors. The aim of the project was to provide a guide as to which types of dams were more likely to experience incidents (failures and accidents) based on a statistical analysis of the historical performance of dams. The author's role on the project was to study concrete and masonry gravity dams.

The second section of this thesis (Chapters 3-6) had its origins in the results of Chapter 2 and the general interests of the author and the project sponsors. It was found that failure through the foundation was common in the list of dams analysed. Furthermore, it was

found that information on how to assess the strength of the foundations of dams on rock masses was limited. For example, the ANCOLD (1991) guidelines on design criteria for concrete gravity dams suggest using references such as McMahon (1985) and Hoek (1983) to assess the strength of the foundation. The guidelines also state that "in the absence of more reliable data, preliminary analysis of foundations on sound jointed hard rock where sub-horizontal joints are not continuous, the following peak effective shear strength parameters are suggested:"

c_{peak} = $0.14\sigma_c$ or 1.4MPa whichever is the lesser, where σ_c is the unconfined compressive strength of the rock substance.

ϕ_{peak} = 45°

This approach is very misleading and in many cases would over-estimate the strength.

The authors aim for this section was to assess how good the methods for estimating rock mass strength were and to suggest possible changes to existing methods or new methods if required

The work on rock mass strength was extended from looking at the foundations of dams to looking at the strength of rock masses in slopes and other works. This was mainly in an attempt to find better case studies to analyse, to cover a wider stress range and to provide a work on rock mass strength that had applicability wherever an assessment of rock mass strength was required.

The different sections of the thesis given in Figure 1.1 are described in more detail below.

1.3 THE CHAPTERS IN THIS THESIS

1.3.1 The Analysis of Concrete and Masonry Dam Incidents

Many attempts have been made at compiling and assessing statistics of dam failures. The main attempts at assessing dam incidents on a world-wide scale have been by ICOLD (1974, 1983 and 1995). ICOLD (1974) analysed previous dam failures and accidents based on questionnaires provided by the National Committees on Large Dams. ICOLD

(1983) attempted to improve the completeness of the information with further questionnaires. An existing dam population was also developed by ICOLD for comparison with failures. The population comprised a sample of dams from the ICOLD World Register of Dams (ICOLD 1973, 1976 and 1979). ICOLD (1995) was an attempt to update the statistics on failures of dams with particular emphasis on comparisons with dam types, heights and years commissioned of existing dams. Although an extensive analysis, the ICOLD attempt lacks depth in some key areas. Most notably in information on the foundation conditions and the geometry of the dams where failures have occurred. The accuracy and consistency of the ICOLD data has also come into question during this current research.

Various other attempts have been made to compile data on failures and accidents, all of which either suffer from a lack of detail or from a limited data set. Most of the statistical analyses of failures and accidents and attempts to determine probabilities of failure (Von Thun (1985), da Silveira (1984, 1990), Fell (1996), Blind (1983), and Schnitter (1993)) tend not to go into much detail, generally assessing only height, year commissioned and type of dam structure. Most of the emphasis in the analysis of dam incidents has been on embankment dams.

This section of the thesis (Chapter 2) describes the creation and analysis of a database on concrete and masonry dam incidents known as *CONGDATA*. The aim was to carry out as complete a study of concrete and masonry dam incidents as was practicable, with a greater emphasis than in other studies on the geology, mode of failure, and the warning signs that were observed. The study assessed the characteristics of the population of dams, and compared these with the characteristics of those dams that had experienced incidents. This helped to provide a guide as to which dams were more likely to experience incidents.

This analysis was used to develop an approximate method of assessing probabilities of failure. This can be used in initial risk assessments of large concrete and masonry dams along with analyses of stability for various annual exceedance probability floods.

1.3.2 The shear strength of rock masses

Methods used for assessing the shear strength of jointed rock masses are based on empirical criteria (Hoek and Brown, 1980, Yudhbir et al, 1983, Ramamurthy et al, 1994 and Sheorey, 1997). As a general rule such criteria are based on laboratory scale specimens with very little, and often no, field validation.

The most commonly used strength criterion, having received widespread interest and use over the last two decades, is the Hoek-Brown empirical rock mass failure criterion, the most general form of which is given in Equation 1.1. Hoek and Brown (1980) developed this rock mass criterion as they "found that there were really no suitable criteria for the purpose of underground excavation design" (Hoek, 2001). The equation, which has subsequently been updated by Hoek and Brown (1988), Hoek et al. (1992), Hoek et al. (1995) and Hoek et al (2002), was based on their criterion for intact rock. The only 'rock mass' tested and used in the original development of the Hoek-Brown criterion was 152mm core samples of Panguna Andesite from Bougainville in Papua New Guinea (Hoek and Brown, 1980). Hoek and Brown (1988) later noted that it was likely this material was in fact 'disturbed'. The validation of the updates of the Hoek-Brown criterion have been based on experience gained whilst using this criterion. To the author's knowledge the only data published supporting this experience has been two mine slopes cited in Hoek et al (2002).

$$\sigma'_1 = \sigma'_3 + \sigma_c \left(m_b \frac{\sigma'_3}{\sigma_c} + s \right)^a \qquad (1.1)$$

This thesis assesses the Hoek-Brown criterion in detail and modifies it into a more generalised form to account for various inconsistencies in the current version. The assessment of the criterion is carried out by looking at several of its bounds including intact rock (Chapter 3) and rockfill (Chapter 4). Case studies of various failures and highly stressed rock masses are used, together with published laboratory test results on rock mass samples, to assess the Hoek-Brown criterion and to develop new equations that can be used to estimate the parameters of the Hoek-Brown equation (Chapter 6).

The individual chapters in this section of the thesis not only provide a basis for modifying the Hoek-Brown criterion (discussed in Chapter 6) but also have their own individual results including:

- Chapter 3 - A statistical analysis of a database of over 4500 triaxial tests on intact rock and the subsequent development of new shear strength criterion for intact rock.

- Chapter 4 - A review of current criteria for the shear strength of rockfill and the development of a new shear strength criterion for compacted rockfill based on a database of over 550 rockfill triaxial tests gathered from the literature and sponsors.

- Chapter 5 - An analysis of current empirical slope design methods and the development of new slope design curves based on the author's database of mine pit slopes.

1.4 PUBLISHED PAPERS/REPORTS

The following papers and reports were published during the period of this thesis.

Douglas, K.J. (1998) Case studies in the assessment of rock mass criteria. *3rd Young Geotechnical Professionals Conference*, Melbourne.

Douglas, K.J. and Mostyn, G. (1999) Strength of large rock masses – field verification. Rock Mechanics for Industry, Proceedings of the 37th U.S. Rock Mechanics Symposium, Vail, Colorado, USA. 1:271-276. Balkema, Rotterdam, ISBN 90 5809 099 X0.

Douglas, K., Spannagle, M. and Fell, R. (1998a) Estimating the probability of failure of concrete and masonry gravity dams. *1998 ANCOLD-NZSOLD Conference on Dams*, Sydney.

Douglas, K., Spannagle, M. and Fell, R. (1998b) *Report on Analysis of Concrete and Masonry Dam Incidents*. UNICIV, The School of Civil and Environmental Engineering, The University of New South Wales.

Douglas, K., Spannagle, M. and Fell, R. (1999a) Analysis of Concrete and Masonry Dam Incidents. *The International Journal on Hydropower & Dams*. 6(4):108-115. Aqua~Media, Surrey, ISSN 1352-2523.

Douglas, K., Spannagle, M. and Fell, R. (1999b) Estimating the probability of failure of concrete and masonry gravity dams. *ANCOLD Bulletin*. No. 112:53-63. Australian National Committee on Large Dams, ISSN 0045-0731.

Duran, A. and Douglas, K. (1999) "Do slopes designed with empirical rock mass strength criteria stand up*?" Proceedings ISRM 9th International Congress on Rock Mechanics*, Paris, France, 1, pp. 87-90. Balkema, Rotterdam, ISBN 90 5809 070 1.

Duran, A. & Douglas, K.J. (2000) Experience with empirical rock slope design. *GeoEng2000: An International Conference on Geotechnical & Geological Engineering*, 19-24 November, Melbourne, Australia, 2, pp. 41 and CD-Rom paper no. SNES1186, Technomic Publishing, Pennsylvania, ISBN 1-58716-068-4.

Glastonbury, J. & Douglas, K.J. (2000) Catastrophic rock slope failures. *GeoEng2000: An International Conference on Geotechnical & Geological Engineering*, 19-24 November, Melbourne, Australia, Vol. 2 pp. 21 and CD-Rom paper no. SNES0507, Technomic Publishing, Pennsylvania, ISBN 1-58716-068-4.

Helgstedt, M.D., Douglas, K.J. and Mostyn, G. (1997) A re-evaluation of in-situ direct shear tests at Aviemore Dam, New Zealand. *Australian Geomechanics*, 37 (June), pp. 56-65.

Mostyn, G. & Douglas, K.J. (2000) Issues Lecture: The shear strength of intact rock and rock masses. *GeoEng2000: An International Conference on Geotechnical & Geological Engineering*, 19-24 November, Melbourne, Australia, Vol. 1, pp. 1389-1421, Technomic Publishing, Pennsylvania, ISBN 1-58716-067-6.

Mostyn, G., M.D. Helgstedt and K.J. Douglas (1997) "Towards field bounds on rock mass failure criteria". *International Journal of Rock Mechanics and Mining Sciences*, Vol. 34 (3-4): Paper No. 208.