PHYSICAL MODELLING OF THE MOBILITY OF DRY GRANULAR LANDSLIDES

by

Sarah Kristen Bryant

A thesis submitted to the Department of Civil Engineering
In conformity with the requirements for
the degree of Master of Applied Science

Queen’s University
Kingston, Ontario, Canada
(September, 2013)

Copyright ©Sarah Kristen Bryant, 2013
Abstract

In geotechnical engineering, granular flows are often studied as a means to further the understanding of the mechanisms that drive landslide motion. High quality experimental data is essential in providing evidence for the development and verification of new theoretical methods that link complex grain interactions to the extended mobility of some landslide events. At present, limited experimental data is available that captures the full range of landslide mobility. In an attempt to add to the present data sources, high quality experimental data was obtained through the use of high speed cameras and physical modelling using a geotechnical centrifuge and a large scale landslide flume. These modelling techniques allow for landslide motion, representative of field scale events, to be observed in a well-defined and controlled setting. A series of nine tests were performed in a geotechnical centrifuge under varying slope inclinations and Coriolis conditions. The effects of Coriolis on landslide mobility were evident when comparing final deposit shapes and total runout. The effects of Coriolis were more pronounced for higher velocity situations and when material was travelling on the horizontal base section opposed to the sloped section of the physical model. A series of thirty tests were performed using a large scale flume under varying source volumes and basal friction conditions, capturing the grain scale interactions and overall runout behaviour. The grain interactions and ultimately the flow behavioural regimes developed were a function of material source volume and boundary roughness. The dimensionless inertial number was used to classify flows into behavioural regimes, but was found to break down when describing transitions to the granular gas behavioural regime. The runout-time results and final deposit shapes showed significant variation between test configurations, indicating the effects of volume and basal friction on overall mobility. Using the depth averaged numerical model, DAN, it was found that a single set of empirically derived frictional parameters (i.e. specific to internal and basal friction conditions) was appropriate for matching the overall mobility of the experimental flows over a range of flow volumes and slope inclinations.
Acknowledgements

This research program was performed under the supervision of Dr. Andy Take. I would like to extend sincerest thanks to Andy for this opportunity and the guidance and encouragement provided. His ever present enthusiasm towards this research program kept me motivated and excited throughout its duration. I would like to acknowledge Dr. Elisabeth Bowman at the University of Sheffield for offering her time, enthusiasm, and invaluable insights to furthering the progression of this work. It was very much appreciated. A special thank you to Ryley Beddoo for her invaluable mentorship.

This research was financially supported by the Canadian Foundation of Innovation, the Natural Science and Engineering Research Council of Canada (NSERC), and the Ontario Ministry of Research and Innovation. Thank you to the technicians at the Queen’s Coastal and Geo-Engineering Labs. Willy and Graeme, your smiling faces made my time at West Campus truly enjoyable. Thank you also to Lloyd, Paul, and Stan for getting the flume up and running. Without your efforts, there would have been no landslides to observe (and no thesis for me).

I would like to gratefully thank all who assisted in the testing process, particularly loading of the material, and I apologize to all those who may not have realized what they were getting into. To the graduate students of Ellis Hall, I may not have always shown it, but I did sincerely enjoy my time at Queen’s and that was in large part due to your friendship. Thank you. A special thank you to Emily, Josh, and Chris who have been with me from start to finish, we made it together. Thank you to my Ringette team and friends for the support and for always welcoming me home. Finally, thank you to my family: Bob, Sue, Matt, Kelly, Elise, Michelle, and Ryan. You were a constant source of love and encouragement. I whole heartedly thank you and promise not to put us through any more degrees.
# Table of Contents

Abstract ............................................................................................................................................. ii
Acknowledgements ........................................................................................................................ iii
List of Figures .................................................................................................................................. vi
List of Symbols ................................................................................................................................. ix

## Chapter 1 Introduction .................................................................................................................. 1

1.1 Granular Flows ....................................................................................................................... 1
1.2 Landslide Mobility ................................................................................................................. 2
1.3 Physical Modelling Techniques ............................................................................................. 3
1.4 Research Objectives ............................................................................................................... 4
1.5 Organization of Thesis ........................................................................................................... 5
1.6 References .............................................................................................................................. 7

## Chapter 2 Physical Modelling of the Mobility of Dry Granular Landslides Using a Geotechnical Centrifuge ........................................................................................................................................ 9

2.1 Introduction ............................................................................................................................ 9
2.2 Methodology ........................................................................................................................ 12
   2.2.1 Centrifuge Scaling Principles ........................................................................................ 12
   2.2.2 Experimental Apparatus ................................................................................................ 13
   2.2.3 Materials and Test Procedure ......................................................................................... 14
2.3 Results and Discussion .................................................................................................... .... 17
   2.3.1 Macro Runout Results ................................................................................................... 19
   2.3.2 Final Deposit Shapes ..................................................................................................... 20
   2.3.3 Effect of Slope Angle .................................................................................................... 21
   2.3.4 Depth Averaged Numerical Models ............................................................................. 23
2.4 Summary and Conclusions .................................................................................................. 27
2.5 References ............................................................................................................................ 30

## Chapter 3 Physical Modelling of the Mobility of Dry Granular Landslides Using a Large Scale Flume ........................................................................................................................................... 47

3.1 Introduction .......................................................................................................................... 47
3.2 Background .......................................................................................................................... 51
   3.2.1 Landslide Mobility ........................................................................................................ 51
   3.2.2 Dimensional Analysis .................................................................................................. 52
   3.2.3 Depth Averaged Numerical Models ............................................................................. 53
List of Figures

Figure 2.1 a) Description of a physical model to investigate landslide mobility and b) definition of terminology describing final landslide deposit ................................................................. 33
Figure 2.2 Definition of Coriolis effect in the centrifuge ........................................................... 34
Figure 2.3 Experimental test setup and soil release box ............................................................. 35
Figure 2.4 Geometry of centrifuge test setup for a) 70 degree slope and b) 45 degree slope .... 36
Figure 2.5 Sequence of granular flow down the 70 degree slope for a test performed at 1g ....... 37
Figure 2.6 Runout over time results of tests performed under varying centrifugal accelerations, on the 70 degree slope with Coriolis applied into the slope ......................................................... 38
Figure 2.7 Runout over normalized time of tests performed under varying centrifugal accelerations, on the 70 degree slope with Coriolis applied into the slope .............................................. 39
Figure 2.8 a) final runout and b) location of flow parallel co-ordinate of centre of gravity for tests performed on the 70 degree slope. c) final runout and b) location of flow parallel co-ordinate of centre of gravity for tests performed on the 45 degree slope ............................................................ 40
Figure 2.9 Final deposit profiles of tests performed on the 70 degree slope ................................. 41
Figure 2.10 Final deposit profiles of tests performed on the 45 degree slope ............................... 41
Figure 2.11 Displacement vectors generated through PIV analysis ............................................. 42
Figure 2.12 a) Runout over time and b) final deposit profiles of 1g test and DAN analysis on the 70 degree slope configuration ......................................................................................... 43
Figure 2.13 Runout over normalized time for experimental and DAN analysis results of tests on the 70 degree slope configuration ...................................................................................... 44
Figure 2.14 a) Runout over time and b) final deposit profiles of 1g test and DAN analysis on the 45 degree slope configuration ......................................................................................... 45
Figure 2.15 Runout over normalized time for experimental and DAN analysis results of tests on the 45 degree slope configuration ..................................................................................... 46
Figure 3.1 Illustration of a) three flow regimes used to classify flows at the micro grain scale and b) forces acting on a typical slice of landslide mass in a macro scale depth averaged model .... 84
Figure 3.2 a) Description of a physical model to investigate landslide mobility and b) definition of terminology describing final landslide deposit .................................................................... 85
Figure 3.3 Diagram of the Queen’s University Landslide Flume .................................................. 86
Figure 3.4 Photo of the rough surface and ceramic beads ............................................................. 87
Figure 3.5 Example of a) static mesh used in PIV analysis of granular flow, b) resulting quiver plot and c) velocity profiles generated from displacement vectors.................................................. 88
Figure 3.6 Time evolution of the downstream velocity profiles for the 0.34 m³ volume test on the rough surface................................................................. 89
Figure 3.7 Surface velocity profiles for 0.34 m³ volume test on the smooth surface .......... 90
Figure 3.8 Digitally generated “multiple exposure” image .................................................. 91
Figure 3.9 Digitally generated “multiple exposure” images for tests on the smooth surface...... 92
Figure 3.10 Digitally generated “multiple exposure” images for tests on the rough surface....... 93
Figure 3.11 Time evolution of flow heights for all test configurations .................................. 94
Figure 3.12 Evolution of flow heights over timescale t/T_total for all test configurations .......... 94
Figure 3.13 Time evolution of the downstream velocity profiles for the 0.06 m³ and 0.34 m³ tests on the rough surface and the 0.34 m³ test on the smooth surface. ............................... 95
Figure 3.14 a) Shear rate profiles and b) inertial number profiles with depth for flows on the smooth surface, within the CAM2 field of view .................................................. 96
Figure 3.15 a) Shear rate profiles and b) inertial number profiles with depth for flows on the rough surface, within the CAM2 field of view ............................................... 97
Figure 3.16 Evolution of depth averaged shear rate over time .............................................. 98
Figure 3.17 Evolution of depth averaged inertial number over time .................................... 99
Figure 3.18 Total distance travelled over time for all test configurations .......................... 100
Figure 3.19 Final deposit profiles for all test configurations .............................................. 101
Figure 3.20 a) Runout over time and b) final deposit profiles of 0.34 m³ test and DAN Analysis on the smooth surface. ............................................................ 102
Figure 3.21 a) Flow height over time and b) depth averaged velocity over time of 0.34 m³ test and DAN Analysis on the smooth surface at the CAM2 field of view. 103
Figure 3.22 a) Runout over time and b) final deposit profiles of 0.06 m³ test and DAN analysis performed on the smooth surface. c) Runout over time and d) final deposit profiles of 0.17 m³ test and DAN analysis performed on the smooth surface ........................................ 104
Figure 3.23 a) Runout over time and b) final deposit profiles of 0.34 m³ test and DAN analysis performed on the rough surface. ........................................................... 105
Figure 3.24 a) Flow height over time and b) depth averaged velocity over time of 0.06 m³ test and DAN Analysis performed on the rough surface at the CAM2 field of view. 106
Figure A.1 Images of ceramic beads used in the Digital Grain Size Analysis ....................... 116
Figure A.2 Images of ceramic beads used in the sphericity analysis .................................. 116
Figure A.3 Binary image with sphericity scores ................................................................. 116
List of Tables

Table 2.1 Centrifuge scaling laws used in geotechnical centrifuge testing. ........................................ 13
Table 2.2 Test Arrangements ............................................................................................................ 17
List of Symbols

\( \alpha \) Fahrböschung angle
\( \alpha_{Gi} \) Travel angle
\( N \) Centrifugal acceleration
\( N_g \) Effective gravitational acceleration
\( a_c \) Coriolis force
\( \omega \) Centrifuge angular velocity
\( g \) Gravitational acceleration
\( r \) Radius of centrifuge
\( R \) Runout, measured from the corner where slope meets base
\( d \) Mean particle diameter
\( \mu \) Basal friction
\( \theta \) Slope inclination
\( \rho_p \) Material density
\( h \) Height of flow, measured from base of flume
\( y \) Depth, measured from surface of flow
\( P \) Total stress
\( \dot{\gamma} \) Shear rate
\( < \dot{\gamma} > \) Depth averaged shear rate
\( I \) Inertial number
\( < I > \) Depth averaged inertial number
Chapter 1

Introduction

1.1 Granular Flows

A granular material consists of a large number of discrete particles, typically larger than 100μm in diameter, which interact through frictional and collisional contacts (Forterre and Pouliquen, 2009). Frictional contacts involve a sustained transfer of forces between adjacent particles, whereas collisional contacts are instantaneous interactions, often between loose particles. Granular flows occur when the continuous, adjoining body of the granular medium undergoes permanent deformation in situations such as travelling down inclined slopes (Iverson and Vallance, 2001).

Granular flows are encountered across a wide range of disciplines from industrial and commercial applications (e.g. pharmaceutical, cement, coal, grain) to geotechnical domains (e.g. debris flows and avalanche events). Predicting the behaviour of granular materials has therefore become an area of focus for a multitude of research communities. In geotechnical engineering, one of the primary motivations for studying granular flows is to better understand landslide behaviour and more accurately predict the overall mobility of these hazards. To that end, a considerable number of studies have been conducted in an attempt to further the understanding of the mechanisms that drive landslides. Numerical simulations (e.g. Campbell et. al. 1995; Hungr, 1995; Lo et. al. 2010; Savage and Hutter, 1989; Straub 1997), empirical relationships (e.g. Legros, 2002; Staron and Lajeunesse, 2009), characterization of natural events (e.g. Evans ET. al., 2009), and physical modelling (e.g. Iverson et.al. 2010; Major, 1997; Schaefer et. al., 2010) have been comprehensively explored.
1.2 Landslide Mobility

High velocity landslides are unpredictable events that pose a significant hazard to those living in mountainous regions. In some instances, these shallow flows can exhibit extreme mobility. Despite the ongoing research effort, no consensus has been reached as to the mechanisms responsible for the extended distal reach and heightened velocity of some landslides (Legros, 2002). For the ease of decision making, geoscientists and engineers often look to depth averaged models as a means of practical assessment of the potential mobility of landslide hazards. These models typically assume simplified and constant rheological continuaums, which generally do not account for the complex grain scale interactions of a granular flow (Zhou et. al., 2013). In order to develop a better understanding of the mechanisms behind landslide mobility, granular flows are often investigated from both micro grain scale (defined here as the scale of individual grains) and macro (defined here as the scale of the full landslide mass) runout perspectives.

Micro grain scale behaviour can be examined using a variety of experimental configurations (e.g. plane and annular shear, heap flows, inclined planes, vertical chutes, rotating drums). These studies typically involve the formation of steady, continuous flows where simple, constant shearing is achieved (GDR Midi, 2004). While high quality experimental data can be obtained in a well-defined and controlled setting, the experimental method of studying continuous flows may not be appropriate in capturing the full range of complex and variable flow behaviour observed in landslide events. As well, this method has generally not been applied to define macro runout behaviour, such as runout over time results and final deposit shapes.

Flume studies involving singular landslide events of finite volumes of source material can be used to investigate the mobility of granular landslides from initiation to deposition. This experimental
method allows for both the micro grain scale and macro runout behaviour of granular landslides to be observed. However, as the majority of these studies are completed in laboratory settings, the scale of the experimental apparatuses is often limited. Where reduced scale particles are used, it may be difficult to observe micro grain scale interactions. In contrast, scaling issues are commonly associated with the use of relatively large particles in reduced scale models, meaning that results may not accurately represent field-scale events.

Due to the inherent difficulties associated with the majority of flume studies, limited experimental data exists that captures both micro grain scale and macro runout behaviour of granular landslides. This data is essential in providing evidence for the development and verification of new theoretical methods that link together the complex grain scale interactions to the extended mobility of some landslide events.

1.3 Physical Modelling Techniques

One way to overcome the scaling difficulties associated with reduced scale models is to use a geotechnical centrifuge. Geotechnical centrifuges provide an opportunity to investigate landslide behaviour using small scale models in a well-defined setting with control over stress levels. While increased energy can be applied to the system, rapidly shearing materials within a rotating frame of reference will also experience an additional Coriolis force. The impact of the Coriolis force is a complex subject that can have a resounding effect on the outcomes of physical modelling, being significantly variable across different test configurations. An alternative method to investigating landslide behaviour at field-scale stresses is to use a large scale physical model. Field scale particles can be used without encountering scaling issues, although access to large scale facilities may be limited.
In both forms of modelling, high speed cameras can be incorporated to capture high quality images illustrating the micro grain scale shearing behaviour. Measurements of micro grain scale behaviour can be obtained through Particle Image Velocimetry (PIV); a form of digital image correlation where an image is divided into subsets and the texture within each subset is matched in successive images to determine displacements (e.g. White et. al., 2003). The macro runout behaviour can also be observed prior to, during, and after a simulation in a controlled environment. Through the use of a geotechnical centrifuge and a large scale flume, high quality data sets can be obtained for a variety of unique test configurations.

1.4 Research Objectives

The overall goal of this research program is to obtain unique, high quality data sets of the runout behaviour of granular landslides. Physical models and high speed image analysis will be used to capture this behaviour from both micro grain scale and macro runout perspectives. The specific objectives pertaining to this research include:

- Obtaining data on the macro mobility of landslide runout experiments conducted in a geotechnical centrifuge. Particular emphasis will be placed on evaluating the impact of Coriolis effects on physical models, which will be varied by modifying the slope geometry and direction of the slope in relation to the rotating frame of reference. As well, determining the suitability of depth averaged numerical models to match experimental results.

- Obtaining data on the micro grain scale shear behaviour and macro mobility behaviour of landslide runout tests performed on a large scale landslide flume. Varying material
volumes (0.06 m³, 0.17 m³, and 0.34 m³) and basal friction conditions (smooth and rough surfaces) in combination to conduct experiments using six unique test configurations.

- Investigating the micro grain scale behaviour of tests performed on a large scale landslide flume through PIV image analysis, including observations of velocity profiles, flow heights, shear rates, and dimensionless inertial numbers, with particular emphasis placed on observing the effects of varying volume and basal friction conditions.

- Investigating the macro runout behaviour of tests performed on a large scale landslide flume under varying volume and basal friction conditions and determining the suitability of depth averaged numerical models to capture that behaviour.

1.5 Organization of Thesis

This thesis has been prepared in manuscript format in accordance with the regulations outlined by the School of Graduate Studies at Queen’s University. Chapter 1 of this dissertation includes a general introduction, which is preceded by an abstract. Chapters 2 and 3 are original manuscripts, which have not been submitted to journals at present.

Chapter 2 presents the results of landslide runout experiments conducted in a geotechnical centrifuge at the Centre for Cold Ocean Resource Engineering in St. John’s, Newfoundland. The impact of Coriolis on macro runout behaviour and the suitability of depth averaged numerical models to match experimental results are highlighted.

In Chapter 3 of this thesis, experimental results of landslide runout experiments performed using high speed imaging and a newly developed large scale landslide flume at Queen’s University are presented. The effects of varying material volume and basal friction conditions are illustrated
from both micro grain scale and macro runout perspectives. The suitability of depth averaged numerical models to capture the experimental runout behaviour is presented.

The overall conclusions determined though this research program are discussed in Chapter 4.
1.6 References


Chapter 2
Physical Modelling of the Mobility of Dry Granular Landslides Using a Geotechnical Centrifuge

2.1 Introduction

High velocity landslides, such as debris flows and rock avalanches, pose a significant hazard, especially to those living in mountainous regions. In some cases landslides exhibit extreme mobility, resulting in high velocity situations and extensive distal reaches (Legros, 2002). Many hypotheses have been postulated on the mechanisms responsible for the extended mobility of some landslides. Despite the ongoing research effort, no general consensus has been attained.

Landslide mobility is often defined by the Fahrböschung term (Hsü 1975; Corominas 1996), proposed by Heim (1932). The Fahrböschung is the ratio of the fall height, $H$, measured vertically from the lowest point on the base to the crest of the source volume, to the total runout length, $L$, measured horizontally from the crest of the source volume to the farthest distal reach of the landslide, as shown in Figure 2.1. The Fahrböschung angle, $\alpha$, is $\tan^{-1} (H/L)$ and is often assumed to be synonymous with the effective coefficient of friction of the material (Straub, 1997). The travel angle, $\alpha_G$, which is the angle between the centre of gravity of the source volume and the centre of gravity of the final deposit ($\tan^{-1} (H_G/L_G)$) is also used to quantify landslide mobility. As Fahrböschung takes into consideration the total distal reach opposed to the centre of gravity of the deposit, it is often the preferred mobility term from a hazard assessment analysis perspective.

Physical experiments allow for the examination of landslide runout behaviour in a well-defined and controlled setting. An array of crucial information can be collected prior to, during, and after
a simulation, which serves to further the understanding of the mechanics and rheologies of granular flows. A considerable number of physical landslide experiments have been completed in recent years that examine the runout behaviour of gravity driven flows of a finite volume of source material (e.g. Gray et. al. 1999; Hutter et. al. 1995; Iverson et. al. 2010; Schaefer et. al. 2010). For physical modelling conducted in laboratory settings, the scale of the flume apparatuses is often limited by the experimental space available. As the behaviour of geomaterials is dependent on the stresses applied, these experiments may not accurately represent a field-scale event; particularly where partial saturation of material, entrainment or depositional processes, or fracture phenomenon is involved.

Centrifuge runout experiments offer a unique opportunity to investigate landslide behaviour using small scale flumes in a well-defined laboratory setting with control over stress level. Geotechnical centrifuges are particularly valuable for specific subsets of landslide models where field-scale stresses are required. Bowman et. al. (2010) used a geotechnical centrifuge to examine bed erosion and entrainment by debris flows, where increased stress levels were required to develop important flow mechanisms. A geotechnical centrifuge was also used for the investigation of dynamic fragmentation of rock avalanches, where enhanced acceleration was required to fracture coal particles (Bowman et. al. 2012). For some physical models, it may be desirable to modify the physics of a problem in order to test the robustness of a proposed rheological model in capturing that behaviour.

While geotechnical centrifuges provide the advantage of applying increased energy to a well-defined and controlled environment, this advantage comes with added complexity of Coriolis effects. The reader is referred to Bowman et. al. (2012) for a discussion of Coriolis effects pertaining to avalanche runout experiments performed in a geotechnical centrifuge, where a
variety of slope configurations are considered. The specific case where the plane of runout coincides with the plane of centrifugal rotation, as per the experimental setup, is addressed here.

Landslide mobility is often modeled using shallow flow approximations where the slide material is considered as a homogeneous equivalent fluid (e.g. Hungr, 1995; Savage and Hutter, 1989). The fluid is divided into a number of slices that are free to deform, but maintain contact with each other as motion progresses. The volume of each slice remains constant. Each slice will travel at a velocity unique to that slice with minimal shearing of the fluid with depth. The Coriolis phenomenon can be explained by considering an individual slice of the landslide mass as shown in Figure 2.2.

Rapidly moving particles within a rotating frame of reference (i.e. a geotechnical centrifuge) will experience an additional Coriolis acceleration force. The downslope motion of the material slice is driven by a normal force $N_g$ due to gravity and travels at tangential velocity $v$. This tangential velocity generates an additional Coriolis acceleration force $a_c$ of magnitude of $2m \omega v$ for each material slice, where $m$ is the mass of the slice and $\omega$ is the centrifuge angular velocity (Taylor, 1995). As seen in Figure 2.2, the Coriolis force can act either towards or away from the slope depending on whether the tangential velocity acts with the centrifuge angular velocity $\omega$ or is opposed to it. Where the landslide body moves in the same direction as the centrifuge angular velocity, the Coriolis force will act towards the centrifuge axis and into the slope, adding to the effective gravitational acceleration (Figure 2.2a). Where the landslide motion is opposed to the angular velocity, the Coriolis force will act away from the centrifuge axis and away from the slope, reducing the effective gravitational acceleration (Figure 2.2b). Thus the direction of Coriolis acceleration can be controlled by changing the direction of the testing apparatus in relation to the rotating frame of reference.
The continuously evolving nature of landslide events results in complex and variable Coriolis effects. Since the Coriolis force is velocity dependent, it follows that each slice in a flow will experience a unique magnitude of Coriolis force. For an accelerating flow, where velocities are continuously changing, a singular slice will experience a different Coriolis force at each point in time.

The objective of this paper is to investigate the impact of Coriolis on physical models of landslide runout by performing centrifuge runout experiments for cases where no Coriolis force is applied (tests performed at 1g), where the Coriolis force acts into the slope, and where the Coriolis force acts away from the slope, with particular emphasis on landslide runout-time results and final deposit characteristics. The suitability of depth averaged numerical models based on shallow flow approximations, to match the runout behaviour of experiments conducted in geotechnical centrifuge is examined.

2.2 Methodology

2.2.1 Centrifuge Scaling Principles

As the frictional behavior of geomaterials is stress-level dependent, geotechnical centrifuges are used to apply field-scale stresses to reduced-scale models. Scaling principles used in geotechnical centrifuges have been developed over time for dynamic processes. The principles employed in the context of debris flow, avalanche runout, and rock fall experiments (e.g. Bowman et. al., 2012; Chikatamarla et. al., 2006; Kailey et. al., 2011), may be applied to the motion of landslide runout experiments. Table 2.1 includes the scaling principles relevant to this paper (Taylor, 1995). In general, stresses in a physical model of scale $1/N$, can be increased to prototype scale by applying
centrifugal acceleration equivalent to $N$ times the earth’s gravity. Based on the developed scaling principles, the stresses and velocities generated in the model are equivalent to the prototype values with a unity scale factor.

**Table 2.1 Centrifuge scaling laws used in geotechnical centrifuge testing, based on $Ng = r\omega^2$ (where $r$ is the centrifuge radius and $\omega$ is the angular velocity).**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prototype (field)</th>
<th>Model (centrifuge)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity acceleration</td>
<td>$g$</td>
<td>$Ng$</td>
</tr>
<tr>
<td>Stress</td>
<td>$\sigma$</td>
<td>$\sigma$</td>
</tr>
<tr>
<td>Linear Dimension</td>
<td>$x$</td>
<td>$x/N$</td>
</tr>
<tr>
<td>Volume</td>
<td>$V$</td>
<td>$V/N^3$</td>
</tr>
<tr>
<td>Mass</td>
<td>$m$</td>
<td>$m/N^3$</td>
</tr>
<tr>
<td>Velocity</td>
<td>$v$</td>
<td>$v$</td>
</tr>
<tr>
<td>Acceleration</td>
<td>$a$</td>
<td>$aN$</td>
</tr>
<tr>
<td>Time (inertial)</td>
<td>$t_i$</td>
<td>$t_i/N$</td>
</tr>
<tr>
<td>Energy</td>
<td>$E$</td>
<td>$E/N^3$</td>
</tr>
</tbody>
</table>

**2.2.2 Experimental Apparatus**

Landslide runout experiments were carried out at the Centre for Cold Ocean Resources Engineering (C-CORE) in St. John’s, Newfoundland, Canada. The C-CORE Geotechnical Centrifuge has a maximum radius of 5.5 m and a maximum centrifugal acceleration of 200g. The experimental apparatus consisted of a metal release box (inside dimensions 255 mm × 96 mm × 45 mm) with a hinged door (Figure 2.3). The release box was secured to the top of a sloped section. Material was released through the hinged door to travel down the slope and runout onto a
flat base. The door of the release box was secured by a manual locking system and released by a pneumatic actuator.

The release box system, slope, and horizontal runout section were contained within a plane strain box of width 274 mm, depth 520 mm, and length 735 mm, with 76 mm thick transparent acrylic (Perspex) sidewalls. Glass sheets were secured to the inside of the acrylic sidewalls to reduce boundary friction to 13° as measured by Saiyar et. al. (2011). This box was secured within the centrifuge so that the plane of material runout and the plane of centrifugal rotation were concurrent. The plane strain box could be positioned with the slope facing either into or away from the direction of centrifugal rotation, dictating the direction of acceleration force due to Coriolis with respect to the slope.

A high speed Phantom v9.0 camera (1000 frames per second at a maximum resolution of 1632 × 1200 pixels) was used to record high resolution cross-sectional images of the landslide runout. The camera was positioned perpendicularly to the transparent sidewall, capturing a full view of both the slope and horizontal runout section. Control markers of known spatial location were secured to the inside of the glass within the field of view. These markers are used to relate image space co-ordinates to the global co-ordinate system of the plane strain box. Non-flicker illumination of the field of view was accomplished using two direct current 450-watt halogen, Sealed Beam Aircraft Lights positioned at very low angles off the sidewall to reduce glare.

2.2.3 Materials and Test Procedure

Tests were carried out at slope angles of 70° and 45° from the horizontal. The overall geometry of the centrifuge model was modified between the two slope inclinations to allow the setup to best
fit within the plane strain box. As shown in Figure 2.4a, the 70° slope setup resulted in a 410 mm long sloped section, a 397 mm long horizontal runout section, and an initial fall height of 438 mm, measured vertically from the base to the centre of gravity of the source volume. The 45° slope setup (Figure 2.4b) consisted of a 330 mm long runout section, a 310 mm long horizontal runout section, and an initial fall height of 283 mm. Due to the varying test geometries, tests performed on the 45° slope have less potential energy to drive the downward motion of the granular flow. Tests performed on the 70° slope, with all other conditions being consistent, will generate higher flow velocities than tests performed on the 45° slope. These slope inclinations were found to generate sufficiently varying velocity conditions in which to investigate the effect of Coriolis in different velocity situations.

Non-cohesive sand with a nominal diameter between 1.40 mm and 2.36 mm, as determined through a sieve analysis (i.e. 100% of the sand passed the No. 8 (2.36 mm opening) sieve, while 100% of the sand was retained on the No. 14 (1.40 mm opening) sieve), was used for all tests. The slope and horizontal runout sections were covered with a roughened surface equivalent to sandpaper. The critical internal friction angle of the sand and the interface friction angle between the sand and the roughened base were determined through experimental procedures described in Zhou et. al. (2013). The internal friction angle and the interface friction angle were both found to be 38°

Prior to each test, dry material was loosely packed into the soil release box until it was completely filled. This resulted in approximately 1.52 – 1.60 kilograms of sand being used in each test. The mass was determined by weighing the remaining material and subtracting from a known initial mass. Once filled, the manual latch for the hinged door of the release box was secured and the release box attached to the top of the slope.
The Phantom v9.0 camera was then positioned and manually focused. Due to low light conditions, the depth of focus when using a large aperture was very limited. The camera was carefully focused on the window or a view slightly behind where the soil would be viewed in order to achieve sufficiently bright images. The high speed camera was triggered to begin recording images the instant the trapdoor of the soil release box was released.

Upon initiation of a test, the centrifuge was spun up to the desired g-level and the halogen lights were turned on. The pneumatic actuator was remotely triggered to open the hinged door of the soil release box, initiating image recording and releasing the material down the slope. When the material came to a rest on the horizontal runout section, the image recording was terminated, the lights were turned off, and the centrifuge was spun down. Images from the Phantom camera were downloaded from the camera during the spin down process. When the centrifuge came to a rest, additional photographs of the final deposit profiles were taken with a digital camera. Measurements of the final deposit shape were taken using a Laser Distance Sensor by Baumer Electric with an accuracy of ± 0.2 mm. The sensor was set at a fixed height above the base, and depth readings were taken in a grid pattern at five evenly spaced positions across the width of the horizontal runout section and in 50 mm increments along the profile starting from the end wall. The deposit profiles across the width of the flume were very consistent with an average standard deviation in deposit height of 1.2 mm at each profile location. Depths across the five width positions were averaged at each profile location. The sand within the plane strain box was then collected using a vacuum trap and weighed to ensure that no sand was lost during testing. It is important to note that under increased stresses and high velocity situations, the individual sand grains tended to experience very minor fragmentation upon impact with the horizontal runout section. New material was substituted for the crushed particles as required.
Two tests, one on each the 45° and 70° slope inclinations, were conducted without the use of a geotechnical centrifuge (i.e. performed at 1g). The test procedure was similar to that described above with the omission of the centrifuge spin up and spin down processes. As these tests were conducted outside of a rotating frame of reference, no additional Coriolis force was generated.

2.3 Results and Discussion

Six tests were performed on the 70º slope and three on the 45º slope with a roughened base. Table 2.2 contains the details of the test arrangements.

Table 2.2 Test Arrangements

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Slope (º)</th>
<th>Slope Length (mm)</th>
<th>Base Length (mm)</th>
<th>Mass of Sand (grams)</th>
<th>Centrifugal Acceleration, N</th>
<th>Direction of Coriolis Force*</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>70</td>
<td>410</td>
<td>397</td>
<td>1555</td>
<td>1</td>
<td>No Coriolis</td>
</tr>
<tr>
<td>35</td>
<td>70</td>
<td>410</td>
<td>397</td>
<td>1546</td>
<td>30</td>
<td>AS</td>
</tr>
<tr>
<td>36</td>
<td>70</td>
<td>410</td>
<td>397</td>
<td>1547</td>
<td>50</td>
<td>AS</td>
</tr>
<tr>
<td>58</td>
<td>70</td>
<td>410</td>
<td>397</td>
<td>1569</td>
<td>10</td>
<td>IS</td>
</tr>
<tr>
<td>60</td>
<td>70</td>
<td>410</td>
<td>397</td>
<td>1551</td>
<td>30</td>
<td>IS</td>
</tr>
<tr>
<td>62</td>
<td>70</td>
<td>410</td>
<td>397</td>
<td>1546</td>
<td>50</td>
<td>IS</td>
</tr>
<tr>
<td>26</td>
<td>45</td>
<td>330</td>
<td>310</td>
<td>1541</td>
<td>1</td>
<td>No Coriolis</td>
</tr>
<tr>
<td>45</td>
<td>45</td>
<td>330</td>
<td>310</td>
<td>1604</td>
<td>30</td>
<td>AS</td>
</tr>
<tr>
<td>48</td>
<td>45</td>
<td>330</td>
<td>310</td>
<td>1519</td>
<td>30</td>
<td>IS</td>
</tr>
</tbody>
</table>

*AS = Coriolis applied away from the slope; IS = Coriolis applied into the slope
Figure 2.5 shows a typical sequence of the sand leaving the soil release box and travelling down the 70° sloped section to runout along the horizontal base. The initial material release point is shown in the upper right corner of the field of view (Figure 2.5a), at the leading edge of the source volume. As the material is released and travels down the slope, the flow elongates and thins. There is noticeable agitation of particles as the material reaches the corner and hits the horizontal base. The material then runs out along the horizontal section to settle in a final deposit shape.

Runout, R, is measured in terms of travel distance along the sloped and horizontal sections, with the corner between them being designated (0, 0). For the 70° slope, this corresponds to a runout value of -0.410 m at the initial material release point. As the material travels down the slope, the runout value approaches zero before becoming a positive value as it turns the corner to run out on the horizontal base. The maximum runout distance that can be achieved for the 70° slope is 0.397 m, where the material will reach the limits of the plane strain box. Material on the 45° inclination will have an initial runout value of -0.330 m at the instant of material release and a final runout limit of 0.310 m from the corner.

Cross sectional images of the granular flows were recorded for the purpose of determining the frontal position over time of the landslides as they propagated down the sloped section to run out onto the horizontal base. The frontal positions were determined by manually extracting the image co-ordinates of the leading edge of the flow and relating those values to the global co-ordinate system of the plane strain box.

Figure 2.6 shows the frontal runout-time results for three tests performed at varying centrifugal accelerations, on the 70° slope with Coriolis directed into the slope. It was observed that while the
total runout was equivalent, the time required for the material to reach the slope was significantly varied between tests. Where larger centrifugal accelerations were applied (i.e. 50g as opposed to 10g), the overall energy in the system was increased and higher velocity situations developed. Scaling principles are required to relate outcomes between tests performed at different centrifugal accelerations.

In order to compare frontal runout-time results between different test arrangements, the model runout-time was normalized using a modified version of the method described by Lo et. al. (2010). The normalized time is calculated by dividing the model time by \((d/ Ng)^{0.5}\), where \(d\) is the mean particle diameter (1.88 mm for all tests), \(g\) is the gravitational acceleration (9.81 m/s\(^2\)), and \(N\) is the centrifugal acceleration specific to each test arrangement. Figure 2.7 shows the frontal runout–normalized time result for the three tests conducted at varying centrifugal accelerations with the same Coriolis and slope conditions. By normalizing the time, the individual results fall on a single curve. This result is to be expected with a purely frictional rheology, where a high degree of repeatability and internal consistency exists between tests performed at varying centrifugal accelerations, with all other factors remaining constant.

### 2.3.1 Macro Runout Results

To investigate the effect of the Coriolis force, characteristics of the final deposit position are compared between tests conducted on the same test geometries. Figures 2.8a and 2.8c show the total model runout of the tests performed on 70º and 45º slopes, respectively. For both slope inclinations, when the direction of the Coriolis force was set to act away from the slope, the total runout was significantly larger than in the 1g, no Coriolis test. The total runout of the 1g test was in turn much larger than those tests where the Coriolis force was set to act into the slope.
Figures 2.8b and 2.8d show the runout location of the flow-parallel co-ordinate of the centre of gravity of the final deposit shape for tests performed on the 70° and 45° slope inclinations, respectively. For both slope inclinations, it was observed that material experiencing a Coriolis force away from the slope had a centre of gravity location further along the runout section from the corner than the tests performed at 1g. Material experiencing a Coriolis force into the slope had a centre of gravity location much closer to the corner than tests performed at 1g.

It is important to note that for the 70° slope tests where Coriolis acted away from the slope, the material ran out to hit the end wall. The runout was constrained by the dimensions of the plane strain box, which ultimately had an effect on the total model runout as well as the location of the centre of gravity.

2.3.2 Final Deposit Shapes

The final deposit shapes of the tests performed on the 70° and 45° slopes are shown in Figures 2.9 and 2.10, respectively. It was observed that Coriolis effects had a significant influence on the final deposit shape.

Where Coriolis force acted into the slope, the total runout was greatly decreased and a significant amount of material remained on the inclined section compared to tests performed at 1g. This was found to be true for both 70° and 45° test geometries. When the landslide mass moves in the same direction as the centrifuge angular velocity, the additional Coriolis force adds to the effective gravitational acceleration. On the sloped section, this additional force increases the effective basal friction resistive force, while the driving force of the downslope motion remains unchanged. As
the material reaches the horizontal runout section, the additional gravity force from Coriolis acts equivalent to an increased effective basal friction force, diminishing the velocity at a magnified rate compared to tests performed at 1g. These factors combined ultimately led to a reduced total runout with a substantial amount of material piled up on the inclined section.

It was observed that where Coriolis was applied away from the slope, the total runout was greater and the final deposit thinner, than the 1g tests for both slope geometries. While material still remained on the inclined section upon coming to a rest, the effect was much less pronounced than for the 1g and Coriolis into the slope cases. Where the runout motion of the landslide opposes the direction of centrifuge angular velocity, the additional Coriolis force subtracts from the effective gravitational acceleration. On the sloped section, this force acts to decrease the effective basal friction resistive force, while the driving force of the downslope motion remains unchanged. On the horizontal runout section, the Coriolis force acts to reduce the effective basal friction force. Here the flow experiences a diminished rate of velocity decline, resulting in a greater total runout and a thinner, elongated final deposit shape.

2.3.3 Effect of Slope Angle

As Coriolis is velocity dependent, runout experiments were performed on two different slope inclinations in order to evaluate Coriolis effects for significantly varying velocity conditions. The Particle Image Velocimetry (PIV) code, geoPIV (White et. al., 2003) was used to generate displacement vectors corresponding to landslide motion as the leading edge of the granular flow approached the horizontal runout section. PIV is a form of digital image correlation where grain texture is matched in successive images to determine displacements. In the tagging version of this technique, a select number of grains are manually tagged and a square subset is generated at each
tagged grain with the centroid of the subset coinciding with the centroid of the chosen grain. The texture within each subset is searched for in consecutive images within a specified search zone. The displacement between the matching patches is equivalent to the displacement experienced by the individual grains. The patches for these analyses were 64 pixels by 64 pixels and a search zone of 30 pixels was specified.

Figure 2.11 shows displacement vectors generated for motion across two consecutive images (0.001 seconds), superimposed on images of the granular flows for four test configurations as they reach the corner. The relative size of the vectors within each image is proportional to the magnitude of displacement. While each image is at the same overall scale, the vectors in Figure 2.11a and Figure 2.11c were scaled up by a factor of eight in order to better illustrate the movement of the grains. No scaling factor was used in generating Figures 2.11b and 2.11d. Therefore, the relative size of the displacement vectors in Figure 2.11 can only be directly compared between test configurations conducted under equivalent centrifugal accelerations. For tests performed on the 70º slope, higher velocities are achieved as the flow approaches the corner, compared to tests performed on the 45º slope. This is shown by the larger displacement vectors in Figure 2.11a compared to Figure 2.11c for the 1g tests performed on the 70º and 45º slopes, respectively.

Figure 2.11b shows a test performed on the 70º slope at 30g centrifugal acceleration with the Coriolis force acting away from the slope. It is observed that due to the decreased effective gravitational acceleration, the material leaves the surface of the sloped section as seen by the open space developed between the landslide mass and the slope. Displacement vectors indicate the majority of the material follows a similar path as that observed for the 1g test (Figure 2.11a), with some material moving opposite to the main flow direction to fill in the corner area. In this case,
the runout behaviour of the landslide has been altered by the Coriolis to more reflect that of a free fall event with air being entrapped as the material leaves the sloped section.

Figure 2.11d shows a test conducted on the 45º slope at 30g centrifugal acceleration with the Coriolis force acting away from the slope. In contrast to the result of the 70º slope test with similar centrifugal acceleration and Coriolis conditions, the material remains on the sloped section and the runout behaviour looks similar to the 1g result (Figure 2.11c). The result of the material leaving the slope on the 70º slope, but remaining on the 45º slope is directly related to the slope geometry and ultimately the higher velocity situation formed. It can be concluded that the effect of Coriolis is more pronounced where higher velocity situations can develop, for example, due to steeper slope geometries, such that an unrealistic situation may occur in comparison to the field behaviour in extreme cases.

2.3.4 Depth Averaged Numerical Models

Runout behaviour can be predicted using depth averaged models, typically based on shallow flow equations. These models are particularly effective for practical assessment of geotechnical hazards and efficient decision making. The numerical shallow flow model, Dynamic Analysis of Landslides DAN (Hungr, 1995; Hungr and McDougall, 2007; Hungr, 2008), can be used to simulate the runout behaviour of rapidly moving granular flows. This program invokes an equivalent fluid approach, with governing equations and model assumptions described in Hungr (1995). The landslide mass is regarded as a fluid with a purely frictional internal rheology. The basal flow resistance can be modeled using a variety of flow rheologies or constitutive behaviours. The rheological model parameters used in depth averaged numerical models are typically obtained through back-analysis of field or experimental results. McKinnon (2010)
developed a standard back-analysis approach for the calibration of rheological parameters for a number of natural landslide events. This method involves an iterative process where rheological parameters are varied within a typical range and model performance is evaluated in terms of the ability of the model to match runout characteristics such as runout distance, final deposit shape (length and thickness), flow duration, and flow velocities.

The back-analysis approach described in McKinnon (2010) was used to evaluate the suitability of the depth averaged numerical model to match the mobility of the centrifuge experiments by visually comparing the outcomes of each method in terms of total runout distance, the runout-time results, and the final deposit shapes. It is important to note that DAN does not include a feature to account for additional Coriolis acceleration forces. Rheological parameters used to match the runout behaviour of tests performed at 1g (i.e. no Coriolis force generated) may not be applicable for cases where Coriolis forces are applied.

A frictional soil rheology with a Modified Savage-Hutter approach to inter-slice pressures, described in Hungr (2008), were adopted for both the 70° and 45° slope geometries. For the frictional rheology, the soil unit weight, and the interface and internal friction angles must be specified. The unit weight of the sand was determined to be 15.1 kN/m³, which was used in the modelling of both test cases. Internal and interface friction values of 38°, were experimentally determined. For the purposes of the back analysis, the internal friction angle was held constant at 38° and the interface friction angle was derived through an iterative process. For both slope inclinations, an interface friction angle of 38° was used in the initial trial. The interface friction angle was typically varied by ±0.5° per iteration until the best match was visually determined.
For tests conducted on the 70° slope, it was determined that the best match of the macro runout behaviour was achieved using an interface friction angle of 36°. It is important to note that a minor smoothed transition from the sloped section to the horizontal runout section was implemented in the numerical model in the interest of numerical stability. Without this transition, the model was not able to successfully converge. The experimental and best match DAN results for the front runout and final deposit shapes are shown in Figure 2.12 for the 1g test conducted on the 70° slope inclination. The model and experimental results match remarkably well using the best match back-analyzed rheological parameters.

The frontal runout-normalized time results for six test arrangements conducted on the 70° slope and the depth averaged numerical model results are shown in Figure 2.13. It is observed that there is almost negligible difference between the Coriolis cases when examining the runout-time behaviour on the sloped section. This outcome is a result of the relative magnitude of the Coriolis acceleration force. As seen in Figure 2.2, when material is travelling down the sloped section, the Coriolis force either reduces or adds to the effective gravitational acceleration, decreasing or increasing the force resisting the downslope motion of the material, respectively. However, the magnitude of the driving force of the downslope motion remains unchanged by the Coriolis force. The magnitude of the Coriolis force in dictating motion on the sloped section is relatively minimal compared to the driving force, which remains consistent for all Coriolis cases. As a result, there is negligible difference between the Coriolis cases when considering the runout-time result on the sloped section.

As the material runs out on the horizontal runout section, the effects of Coriolis become most apparent. As shown in Figure 2.2, when the material is travelling on the horizontal base section, the additional Coriolis force will continue to add to or reduce the effective gravitational
acceleration as the material decelerates. However, as there is no longer a driving force, the magnitude of the Coriolis force relative to all other forces acting on the material will be much more significant. As the Coriolis force generated is unique to each test arrangement, striking differences between the Coriolis cases for runout behaviour on the horizontal base section are observed.

On the horizontal base section, where Coriolis acts to increase the effective gravitational acceleration (Coriolis into the slope), the rate of velocity decline is much greater. The leading edge of the material ultimately requires more time (normalized) to come to a rest on the horizontal runout section, with a smaller total runout when compared to the 1g, no Coriolis test. Where Coriolis subtracts from the effective gravitational acceleration (Coriolis away from the slope), the rate of velocity decline is reduced. The leading edge requires less time to come to rest (or in this case reach the end wall), with a greater total runout compared to the 1g case. The depth averaged numerical model developed for the 1g case is not able to match the runout behaviour on the base when Coriolis is applied. This is also evident when examining the final deposit shapes.

For the 45° slope depth averaged numerical model, the internal friction angle was once again held constant at 38° and the interface friction angle varied, with an initial trial value of 38°. An interface friction angle of 36° was found to produce a good result comparing the front runout and final deposit shape results to the 1g test (Figure 2.14). A smooth transition between the slope and horizontal base was not required for this model to converge.

The frontal runout-normalized time results for three test arrangements conducted on the 45° slope and the depth averaged numerical model results are shown in Figure 2.15. The results are analogous with those described for the 70° slope with almost negligible runout-time differences
between the Coriolis cases observed on the sloped section and significant differences observed on the horizontal runout section.

The DAN depth averaged numerical model was able to accurately match total runout, runout-time results, and the final deposit shape of tests performed at 1g using a single set of best match back derived rheological parameters. The best match parameters being equivalent for both the 70° and 45° slope geometries illustrates the robustness of the model to account for varying slope geometries, where consistent frictional and boundary conditions are applied. DAN currently does not have a feature to account for Coriolis and is therefore not able to match the macro runout behaviour where Coriolis forces are applied. A depth averaged model capable of accounting for Coriolis force is required to model the runout behaviour of all test arrangements. The development of such a model is outside the scope of this current work, but is recommended for future studies.

### 2.4 Summary and Conclusions

Physical experiments were conducted in a geotechnical centrifuge to investigate the effects of Coriolis on landslide runout behaviour. A series of nine tests were performed on 70° and 45° slope inclinations under varying Coriolis conditions. Through these physical models experimental data sets have been produced which captures the impact of Coriolis.

It was observed that where Coriolis is applied into the slope, this additional force acts to increase the effective gravitational force, reducing the total runout of the granular flow compared to tests performed on the same geometry at 1g. Final deposits were shorter and thicker with a substantial amount of material remaining on the sloped section. Conversely where the additional Coriolis
force acts away from the slope, the material has a reduced effective gravitational force and greater total runout is observed. Final material deposits were thinner and more elongated, with less material remaining on the sloped section.

The effect of Coriolis is magnified for high velocity situations such as steeper inclination angles. This was experimentally observed through the examination of runout behaviour and corresponding displacement vectors of tests performed at 45° and 70° as they approached the horizontal runout section.

Through the frontal runout–normalized time results, it was observed that the impact of Coriolis is significantly more pronounced on the horizontal runout section compared to the sloped section. This was a result of the magnitude of the Coriolis force being more significant, relative to the magnitudes of the resisting and driving forces, when the material was on the horizontal base section versus the sloped section.

The suitability of a depth averaged numerical model, DAN, to match the runout behaviour of the centrifuge experiments was evaluated. It was determined that DAN was able to reasonably model the centrifuge experiments where no Coriolis force was applied (i.e. tests performed at 1g), using best match back derived rheological parameters. A single set of empirically derived parameters was found to be appropriate for both the 70° and 45° slope inclinations, illustrating the robustness of the model. Where Coriolis forces are applied, DAN is unable to match the overall experimental runout behaviour using the best match, back-derived parameters. The addition of a feature in the DAN modelling approach to account for Coriolis forces would be required in order to describe the mobility of all experimental results using a single set of empirically derived parameters.
In this paper it has been experimentally shown that Coriolis creates more complex acceleration conditions, which greatly influences the runout behaviour of physical models and hinders the ability of depth averaged models to capture that behaviour.
2.5 References


Figure 2.1 a) Description of a physical model to investigate landslide mobility and b) definition of terminology describing final landslide deposit including total horizontal length \( L \), vertical drop \( H \), Fahrböschung angle \( \alpha \), and runout from the corner \( R \). \( \alpha_G \), \( L_G \), and \( H_G \) are measured with respect to the centre of gravity of the landslide mass.)
Figure 2.2 Definition of Coriolis effect in the centrifuge for a) acceleration due to Coriolis \( (a_c) \) acting into the slope and horizontal base and b) acceleration due to Coriolis acting away from the slope and horizontal base. Gravitational acceleration \( (N_g) \) and velocity of the landslide \( (v) \) are defined with respect to the centre of gravity of a slice of the landslide mass. Diagram provides a top down view of experimental setup when centrifuge is in motion.
Figure 2.3 Experimental test setup and soil release box
Figure 2.4 Geometry of centrifuge test setup for a) 70 degree slope and b) 45 degree slope
Figure 2.5 Sequence of granular flow down the 70 degree slope for a test performed at 1g (Test 25), with the runout reference point, R = 0, located at the corner.
Figure 2.6 Runout over time of tests performed under varying centrifugal accelerations, on the 70 degree slope with Coriolis applied into the slope
Figure 2.7 Runout over normalized time of tests performed under varying centrifugal accelerations, on the 70 degree slope with Coriolis applied into the slope
Figure 2.8 a) final runout and b) location of flow parallel co-ordinate of centre of gravity for tests performed on the 70 degree slope. c) final runout and b) location of flow parallel co-ordinate of centre of gravity for tests performed on the 45 degree slope. Asterisk (*) indicates the centre of gravity location was influenced by material hitting the end wall.
Figure 2.9 Final deposit profiles of tests performed on the 70 degree slope

Figure 2.10 Final deposit profiles of tests performed on the 45 degree slope
Figure 2.11 Displacement vectors generated through PIV analysis showing landslide motion for tests completed on a) 70 degree slope at 1g, b) 70 degree slope at 30g with Coriolis acting away from the slope, c) 45 degree slope at 1g, and d) 45 degree slope at 30g with Coriolis acting away from the slope. Displacement vectors in a) and c) have been scaled to 8 times their actual size for better visual of grain movements.
Figure 2.12 a) Runout over time and b) final deposit profiles of 1g test and DAN analysis on the 70 degree slope configuration. For DAN Analysis, an internal friction angle of 38° and an interface friction angle of 36° were used to achieve the results shown.
Figure 2.13 Runout over normalized time for experimental and DAN analysis results of tests on the 70 degree slope configuration. For DAN Analysis, an internal friction angle of 38° and an interface friction angle of 36° were used to achieve the results shown.
Figure 2.14 a) Runout over time and b) final deposit profiles of 1g test and DAN analysis on the 45 degree slope configuration. For DAN Analysis, an internal friction angle of 38° and an interface friction angle of 36° were used to achieve the results shown.
Figure 2.15 Runout over normalized time for experimental and DAN analysis results of tests on the 45 degree slope configuration. For DAN Analysis, an internal friction angle of 38° and an interface friction angle of 36° were used to achieve the results shown.
Chapter 3

Physical Modelling of the Mobility of Dry Granular Landslides Using a Large Scale Flume

3.1 Introduction

Predicting the flow behaviour of granular materials has been a major preoccupation of a number of multidisciplinary research communities. Granular flows are often encountered in pharmaceutical, cement, coal, chemical, and grain industries or wherever bulk handling of granular solids is required. Dry granular flow in these applications has been comprehensively studied through a variety of experimental configurations including plane and annular shear flow (e.g. Bagnold, 1954), high shear granulators (e.g. Reynolds et. al. 2008), vertical chute flows (e.g. Chevoir et. al. 2001), inclined chute flows (e.g. Ancey 2001; Hanes and Walton, 2000; Holyoake and McElwaine, 2012; Louge and Keast, 2001; Savage, 1979), heap flows (e.g. Taberlet et. al. 2003; Zhou et. al. 2002), and rotating drums (e.g. Felix et. al. 2007). This type of work typically involves the formation of steady, continuous flows of granular materials under varying test geometries, where simple, constant shearing is achieved (GDR Midi, 2004).

Granular flows have also received considerable attention from the geosciences and engineering communities in predicting the behaviour of debris flows and avalanches. These investigations typically involve a singular landside event of a finite volume of source material. Material volumes may increase or decrease during the runout process if erodible boundary conditions exist or deposition occurs. Landslide behaviour has been investigated through numerical simulations using discrete element models (e.g. Campbell et. al. 1995; Lo et. al. 2010; Straub 1997) and depth averaged models (e.g. Hungr, 1995; Hungr and McDougall, 2007; Savage and Hutter, 1989).
Empirical relationships have been explored based on the runout behaviour of both physical experiments and naturally occurring events (e.g. Legros, 2002; Staron and Lajeunesse, 2009). Physical experiments of landslides down inclined chutes have been conducted to study specific aspects of landslide behaviour including depositional processes of debris flows (e.g. Major 1997), entrainment of bed material (e.g. Iverson et. al. 2010a), and the effects of varying boundary and material conditions on the final runout behaviour (e.g. Davies and McSaveney 1999; Schaefer et. al. 2010).

Recent advances in physical and numerical modelling techniques have allowed for granular flows to be evaluated at the micro grain scale (defined here at the scale of individual grains or a collection of grains), furthering the understanding of the mechanics of landslides. Forterre and Pouliquen (2009) classified granular flows into three main flow regimes, quasi-static, liquid, and granular gas, based largely on flow velocity and particle interactions (Figure 3.1a). In the quasi-static regime, particles are densely packed and interact through frictional contacts. Displacement rates in this regime tend be very small. In the liquid or frictional regime, both frictional and collisional contacts exist between the particles and the material behaves similar to a flowing liquid. Displacement rates are typically higher in this regime and the particles densely packed. Finally, in the granular gas regime, particles interact solely through collisions and the high velocity flows tend to be very dilute with low volume fractions (GDR Midi, 2004).

In the granular physics community, dimensional analyses are often used to classify granular flows into the three flow regimes. Recent studies of granular flows at the micro scale have led to the development of new constitutive laws from dimensional analysis that can be used to represent the rheologies of granular flows (e.g. Da Cruz et. al., 2005; Daniel et. al., 2007; Depken et. al., 2006; Jop et. al. 2006; Louge and Keast, 2001). These new theoretical methods consider basal friction,
μ, to be dependent on the normal stress and shear rate (and ultimately the inertial number), which vary temporarily across a granular flow. While these methods have been used to describe micro grain scale behaviour of continuous, steady flows, they generally have not been applied to define the macro (defined here as the scale of the full landslide mass) runout behaviour of granular landslides of a finite source volume.

The micro behaviour of granular flows is very complex, made more unpredictable by the development of different flow rheologies and basal friction conditions within a single event. When confronted with such complexity, engineers often resort to more simplified methods for efficient decision making. The macro scale analysis of runout behaviour, particularly for the practical assessment of landslide hazards, can be carried out using depth averaged models (e.g. Hungr, 1995; Hungr and McDougall, 2007; Hutter et. al, 1995). These models are commonly based on shallow flow equations where the granular material is represented as a homogeneous mass, divided into a number of slices that remain in contact as the mass deforms (Figure 3.1b). In contrast to micro scale analyses, macro scale depth averaged models typically assume a constant basal friction throughout the duration of the flow.

As described above, micro grain scale studies typically focus on local rheologies of continuous, steady flows and macro mobility investigations often adopt constitutive simplifications in the face of complex micro grain scale interactions. Limited studies exist with the primary objective of connecting micro grain scale mechanisms to macro runout behaviour of landslide mobility. Zhou et. al. (2013) offers one example of a recently developed theoretical method that extends the Savage-Hutter equation (Savage and Hutter, 1989), commonly used in depth averaged models, to account for the dependence of basal friction on shear rate and normal stress. With any newly proposed numerical or theoretical model, high quality experimental data sets are required to
provide physical evidence to support the proposed theoretical framework and to verify modelling outcomes.

The majority of experimental micro grain scale data is obtained using inclined chutes where material is continuously re-circulated and constant, steady flows are developed. While high quality data can be obtained in a well-defined and controlled setting, the full range of flow regimes developed in a singular landslide event may not be observed using this experimental method. A number of flume studies exist that observe macro landslide behaviour from initiation to the formation of steady-state flows through to depositional processes (e.g. Iverson et. al., 2010a; Iverson et. al., 2010b; Hutter et. al., 1995). However, very few of these studies concurrently capture micro grain scale interactions. For both described testing methods, the scale of the experimental apparatus is often limited. Micro grain scale behaviour is not easily captured where reduced scaled particles are used in conjunction with reduced scale models. Conversely, scaling problems are commonly associated with the use of larger particles in reduced scale models, meaning data obtained may not accurately represent field scale behaviour. It can be seen that high quality data that captures the full range of landslide mobility from both micro grain scale and macro runout perspectives can be difficult to obtain. As a result, the number of studies that provide high quality physical data for theoretical and numerical model verification is very limited.

In this paper, high speed imaging and a large-scale landslide flume are used to obtain unique, high quality data that captures the full range of flow behaviour of finite granular flows. The objective of this research is to produce physical data that can be later used to link micro grain scale observations to macro scale landslide mobility behaviour. Particular emphasis is placed on observing the effects of varying material volume and basal friction conditions. These unique data
sets can provide physical evidence to support proposed theoretical methods and verify numerical modelling outcomes. The suitability of depth averaged numerical models to capture the runout behaviour is assessed.

3.2 Background

3.2.1 Landslide Mobility

In geotechnical engineering, one of the primary motivations in studying granular flows is to better predict the overall mobility associated with landslide hazards including the predicted distal reach and maximum velocity. The mobility of landslides is typically quantified using the Fahrböschung term (Corominas, 1996; Hsü 1975), by Heim (1932), which is the ratio of the vertical fall height, $H$, to the total horizontal runout length, $L$, as defined in Figure 3.2. The Fahrböschung angle, $\alpha$, follows as $\tan^{-1}(H/L)$ and is sometimes referred to as the apparent coefficient of friction (Straub, 1997). Mobility can also be classified by the travel angle, $\alpha_G$, defined as the angle formed by the centre of gravity of the source volume and the final deposit. Fahrböschung is used more frequently than travel angle as, from an overall hazard assessment perspective, it is often the furthest distal reach, as opposed to the centre of mass of a landslide that is of primary concern. In some instances landslides demonstrate extreme mobility, resulting in extensive distal reaches and very low Fahrböschung angles (Legros, 2002). A number of hypotheses have been proposed as to the mechanisms that may lead to this extended runout (e.g. basal fluidization, grain segregation, entrapped air, depositional and erosional processes, etc.), but currently there is no general consensus among the research community (Legros, 2002; Straub, 1997).
3.2.2 Dimensional Analysis

Dimensional analyses are commonly used to quantitatively classify granular flows into one of three flow regimes: quasi-static, liquid, and granular gas. One approach to defining the flow regime is by means of the Savage number, which considers the ratio of the collisional normal stress to the total normal stress (Savage and Hutter, 1989). In recent years, the inertial number, equivalent to the square root of the Savage number, has been frequently used in granular physics to classify flows in large systems of rigid particles (Forterre and Pouliquen 2009). The inertial number is defined as:

$$ I = \frac{\dot{\gamma} d}{\sqrt{P/\rho_p}} \quad (3.1) $$

where $\dot{\gamma}$ is the shear strain rate, $d$ is the mean particle diameter, $P$ is the total stress, and $\rho_p$ is the density of the material. The physical meaning of the inertial number is best described by considering two layers of grains, with the upper layer travelling over the lower. A macroscopic time $t_{\text{macro}}$ is required for a grain to travel over a grain below it. A microscopic time $t_{\text{micro}}$ then exists where the grains are rearranged and the top grain settles into a lower position. The inertial number is the ratio between the microscopic and macroscopic timescales $t_{\text{micro}} / t_{\text{macro}}$ (GDR Midi, 2004).

As discussed in Forterre and Pouliquen (2009), in the quasi-static regime, the time required for macroscopic deformations is relatively large compared to time required for microscopic rearrangements. Therefore, small inertial values ($I < 10^{-3}$) correspond to flow behaviour typical of
the quasi-static behavioural regime. As flows become more rapid, macroscopic deformations require less time leading to larger inertial numbers. Large inertial numbers ($I>10^{-2}$) typically correspond to the dense liquid behavioural regime (GDR Midi, 2004). It is important to note that the described limits provide for a transition zone between the quasi-static and liquid behavioural regimes. Limits are not typically described for the transition to the granular gas behavioural regime, although Da Cruz et. al. (2005) provided evidence to suggest that the upper limit of the liquid regime is around $I \cong 10^{-1}$, at which point the inertial number begins to decrease as the kinetic regime is reached (Zhou et. al., 2013). Forrerre and Pouliquen (2009) postulated that the local rheology observed in the granular gas behavioural regime cannot be described by the inertial number, but rather is better expressed by kinetic theory.

3.2.3 Depth Averaged Numerical Models

Depth averaged models can be used to predict macro scale landslide runout behaviour. These types of models are often used by the geosciences and engineering communities for practical assessment of landslide hazards. One such model used to simulate the runout behaviour of rapid landslides is Dynamic Analysis of Landslides DAN (Hungr, 1995; Hungr and McDougall, 2007; Hungr, 2008). This numerical modelling approach is based on depth-averaged, one-dimensional shallow flow equations. In this analysis an equivalent fluid approach, described by Hungr (1995), is used where a discrete volume of material representing a landslide is treated as a homogeneous flowing fluid. The internal behaviour of the flow is always considered frictional, while the approach to inter-slice pressures can be modeled using a number of alternative flow rheologies. The governing equations and model assumptions used in the development of the original version of DAN are described in detail in Hungr (1995). In depth averaged numerical models the rheological model parameters are often obtained through extensive back-analysis of an actual
landslide event. Therefore, a model is typically calibrated for a specific site based on previous events occurring at or near that site.

3.2.4 Large-Scale Physical Models

Experiments on landslide mobility (with notable exceptions e.g. Iverson et. al. 2010a; Iverson et. al., 2010b; Major, 1997; Okura et. al., 2002) are generally limited in size by the experimental setting available. Scaling limitations are often associated with laboratory experiments (Iverson et. al., 2010a). In order to properly scale geomaterials in reduced-scale models, reduced-scale particles would be required. However, as inertial number is dependent on the mean particle size as shown in Equation (3.1), smaller particle sizes may not accurately represent field-scale events. This implies that in order to investigate both micro grain scale and macro runout behaviour, a large-scale physical model with relatively large particle sizes is preferable.

Large-scale physical experiments allow for the use of high speed cameras to examine the micro scale shearing behaviour of field-scale particles. Measurements of the flow behaviour at the grain scale can be obtained through Particle Image Velocimetry (PIV). PIV is a form of digital image correlation where an image is divided into a grid of subsets and the texture of each patch is matched in successive images to determine displacements (e.g. White et. al., 2003). Recent experimental work by Dijkhuizen et. al. (2007), Jesuthasan et. al. (2006), and Schaefer et. al. (2010) has demonstrated that this image analysis data stream enables the investigation of the internal structure and behaviour of granular flows to an extent previously unattainable.
3.3 Experimental Setup and Methodology

3.3.1 Experimental Apparatus

The Queen’s University landslide flume is a 2.09 m wide channel with an 8.23 m long sloped section and a 36 m long horizontal runout section. The sloped section is fixed at 30° to the horizontal. The base of the flume is aluminum and the 1.21 m high side walls are made of 19 mm thick, tempered glass. The extent of the glass side walls and aluminum base is limited to a length of 3.68 m for the horizontal runout section, as shown in Figure 3.3.

A soil release box with a hinged door is secured at the top of the sloped section to hold the source material prior to release. The position of the hinged door is controlled by a pneumatic air system and actuators. The soil release box has a footprint of 1.50 m length by 1.75 m width and a height of 0.75 m perpendicular to the slope, for a maximum capacity of 1.68 m³ of material.

Five camera fields of view, referenced as CAM1 through CAM5, have been selected to capture the flow. Their position in relation to the initial material release point is indicated in Figure 3.3. Control markers of known spatial location are secured to the inside of the glass walls within each field of view and are used to relate local image space co-ordinates to the global coordinate system of the flume.

A fully synchronized camera system of five Prosilica GX 1050 cameras (100 frames per second (fps) at a maximum resolution of 1024 pixels x 1024 pixels) is used for all test configurations to determine the exact position over time of the granular flow. Each camera is fitted with a 24 mm Nikkor lens and positioned at a distance of approximately 1.5 m perpendicularly to the glass
sidewall. Illumination is achieved using two - 500 watt, T3 halogen bulbs for each field of view location.

High resolution, cross sectional images of the flow can be recorded using a Phantom v9.0 camera (1000 fps at a maximum resolution of 1600 pixels x 1200 pixels). A 50 mm Nikkor lens is used with the camera positioned at 1.0 m to the glass sidewall. The fields of view are illuminated by a PALLITE VIII ring-shaped high speed (i.e. flicker free) light source, which includes eight – 300 watt projection lamps.

3.3.2 Materials and Preparation

Landslide runout tests were conducted at the Queen’s Landslide Facility using dry, granular material of 0.06 m³, 0.17 m³, and 0.34 m³ source volumes. The granular material is rounded, ceramic beads (Denstone Ceramic Bed Support Media), supplied at a nominal diameter size of 3 mm. The reported grain size was verified using the Digital Grain Size (DGS) program, developed by the US Geological Survey, which approximates the grain size of non-cohesive sediment from digital photographs (Buscombe et. al., 2010). From this approach, the average grain size was found to be 3.02 mm with a standard deviation of 0.66 mm. The sphericity of the granular material was also evaluated through the examination of digital images. The granular material was found to be 94.5 percent spherical with a standard deviation of 2.6 percent. Further details of the ceramic bead characterization completed for this study are included in Appendix A.

The basal surface of the slope and horizontal runout section is smooth aluminum plate, lined with a frictional bumpy (rough) surface for some test configurations. The rough surface consisted of 1.65 mm thick, steel sheets perforated with 3.97 mm diameter holes in a hexagonal pattern at 4.76
mm on center spacing. A close-up view of the rough surface and granular material used in the runout tests is shown in Figure 3.4. The rough surface closely resembles the frictional surface adopted in the discrete element model by Lo et. al. (2010) and encourages the development of more collisional flows. Landslide runout tests were completed on the original aluminum (smooth) and the rough surface for each of the three volumes, resulting in six unique test configurations. The purpose of the six configurations was to evaluate the effect of both volume and basal friction on the micro grain scale and macro runout behaviour.

Prior to each test, the granular material was initially packed in the soil release box as a uniform rectangular prism with horizontal top, as shown to scale in the Figure 3.3 inset. The initial release point of the material for all tests series is 6.73 m from the corner along the sloped section, at an initial drop height of 3.78 m. Upon testing, the door of the soil release box was opened at 0.4 m/s (under 550 kPa of pressure), which was sufficient to clear the releasing material.

For each test configuration, the Prosilica high speed cameras were used to determine the position over time of the front of the material as it propagated down the sloped section. Cameras were secured at each of the five camera fields of view (CAM1 through CAM5) and triggered simultaneously prior to material release. Images were recorded at 100 fps. For tests completed on the smooth surface, cameras were also set up in profile along the horizontal runout section to capture the front of the flow as it came to a rest.

High resolution images of the cross sectional view of the flow were recorded using the Phantom v9.0 camera. For each test configuration, these cross sectional images were recorded at camera views CAM1 through CAM4. The Phantom was manually triggered prior to the release of the material. In order to maintain both the resolution required for PIV image analysis and the
recording time required to capture the entirety of the flow, images were recorded at 700 fps to 1200 fps.

Measurements of grain displacements were obtained through Particle Image Velocimetry (PIV) using geoPIV (White et. al, 2003). In the static mesh version of this technique, a rectangular mesh of subsets is fixed at a co-ordinate location within a field of view. Each subset within the image captured at an instantaneous position in the granular flow, has a unique texture which is matched in successive images to determine particle displacements. For these analyses, the base of the static mesh was aligned with the base of the flume. Each mesh was 192 pixels in width, with each individual patch being 64 pixels by 64 pixels, resulting in five columns of patches. The number of rows is dependent on the maximum flow height of the landslide and therefore varied between tests. The limits of an example static mesh with the relative size of an individual patch are shown in Figure 3.5a. The patches were spaced every 32 pixels on center in the flow direction and every 8 pixels on center in the flow-normal direction, which amounts to significant overlap. The maximum grain movement between successive frames was typically between 20 to 25 pixels.

Figure 3.5b shows the patch displacement vectors across five consecutive images using the static mesh shown in Figure 3.5a. The five columns of arrows correspond to the five columns of patches. For this example, there are fifteen arrows per column corresponding to fifteen rows of patches. The position of the tail of the displacement arrow is fixed at the centre of the patch. The relative size of the arrows is proportional to the magnitude of the displacement. Erroneous vectors due to poorly correlated subsets were manually removed from the results.

Velocity profiles are generated by averaging the displacements across the columns for a pair of consecutive images. Velocity profiles can be produced for the flow-normal, W direction (Fig. 3.3)
and the flow-parallel, U direction, with displacements in the flow-parallel direction being significantly larger. Figure 3.5c shows the cross sectional velocity profiles in the flow direction, U, for the four consecutive image pairs. This process can be completed for every image of the flow as it passes the camera field of view. With high resolution images recorded at 700 fps to 1200 fps, it is possible to obtain velocity profiles of the flow every 1.4 to 0.8 milliseconds.

The Phantom high speed camera was also used to record images from a top down view for the purpose of evaluating the effect of sidewall friction in one selected test configuration. Images of the 0.34 m³ volume test on the smooth surface were recorded at 1000 fps. The camera was fitted with a 24 mm Nikkor lens and positioned perpendicularly to the base of the slope, at 5.08 m down the slope from the initial material release point (coincident with the CAM2 field of view). In order to maintain sufficient image resolution, the field of view was limited from the proximate glass sidewall to the centre line of the flume.

After the material came to a rest on the horizontal runout section, photographs of the final deposit shapes were taken with a digital camera. Manual depth readings of the final deposit were taken every 0.25 m along the flume profile, at five evenly spaced locations across the width of the flume. Measurements were averaged across the width of the flume to obtain a final averaged profile. The repeatability of the tests was verified by comparing the final averaged deposit shapes within each test configuration to the mean profile shape for that configuration. The thickness varied by less than 3.1 mm on average (or one particle diameter) at each profile position, with a maximum variation of 10.6 mm.
3.4 Results and Discussion

Testing was conducted at three volumes of material (0.06 m³, 0.17 m³, and 0.34 m³) on two surfaces (smooth and rough), resulting in six unique testing configurations and a total of thirty tests (five tests per configuration). All tests were undertaken at a slope inclination of 30º.

3.4.1 Observations of Micro Grain Scale Behaviour

Velocity profiles obtained through PIV analyses provide valuable information on the internal structure of granular flows and are the foundation for a variety of granular physics relationships. Typical results of the local flow at CAM4 to CAM1 locations are shown in Figure 3.6 for the 0.34 m³ (largest) volume tests on the rough surface. Images for these tests were recorded at 700 fps and velocity profiles plotted every 0.1 seconds. The velocity profiles have been averaged within a range of ± 0.01 seconds about the incremented profile.

With the exception of the camera located at the transition from the slope to the horizontal base (CAM1), the local behaviour observed at each camera view was consistent among the remaining camera positions. For the entirety of the flow, considerable slip velocities at the base were observed and higher velocities were recorded at the surface of the flow, compared to those measured along the base of the flume. Higher depth-averaged velocities and lower shear rates were observed at the leading edge of the flow compared to the main body. As the landslide progressed, the velocity profiles were more linear, indicating that a near constant shear rate was achieved. As a dense, steady flow was attained, the mean velocity of the granular flow deceased and the mean shear rate increased. At the trailing edge of the flow, velocity profiles were more curved, indicating a transition away from the near constant shear rate. Depth averaged shear rates
were typically lower at the trailing edge of the flow compared to the main body. The local result at the CAM1 location was influenced by the granular flow approaching the corner where the slope meets the horizontal runout section. In contrast to the generic behaviour described above, velocity profiles nearing the trailing edge of the flow in CAM1 indicated considerably less shearing with depth, compared to behaviour observed in the other camera views, as the material came to a rest with a significant amount of material remaining on the inclined section.

The micro grain scale flow behaviour is evaluated by considering the different camera positions along the flume. As the flow progressed from CAM4 to CAM1 locations, the flow accelerated as indicated by the increasing mean velocities observed. Examination of the velocity profiles within the steady, main body of the flow at each progressive camera location revealed increasing shear rates with distance down the flume. The flow height of the main body remained relatively constant across camera positions. The flow height at the leading and trailing edges was typically greater than the main body flow height.

The effect of sidewall friction was evaluated by recording images of the free surface flow from a top down view at the CAM2 location. Figure 3.7 shows velocity profiles generated for the 0.34 m³ volume test on the smooth surface, plotted every 0.1 seconds. The leading edge velocity profile revealed that the surface velocities at the sidewall were very similar to those at the centre of the flume, indicating minimal effect due to friction. However, as the flow progressed, the effect of sidewall friction became more pronounced with the flow velocities declining near the sidewalls. This region of decline was limited to about 50 mm (approximately 17 particle diameters) off the glass, past which sidewall effects were diminished. Within the main body of the flow, the sidewall caused a decline in velocity of approximately 0.5 m/s compared to the velocity at the profile centre. While it is ideal to completely mitigate the effects of sidewall
friction, this issue is largely unavoidable. The velocity decline effects observed in these experiments was similar to those observed in other physical models (e.g. Jop et. al. 2005; Schaefer et. al. 2010).

The CAM2 field of view was chosen to compare the results of the different test configurations, as the maximum velocity and shear rate have been achieved and the flow remains unaffected by the transition to the horizontal runout section. In the following sections, all results presented for the different test configurations were generated at the CAM2 field of view, at a distance of 5.08 m down the sloped section from the initial point of material release.

3.4.1.1 Qualitative Analysis of Flow Behavioural Regimes

Figure 3.8 shows a digitally generated “multiple exposure” image showing an example of the position of individual grain particles over 0.004 seconds of flow. Different flow behavioural regimes can be qualitatively identified through visual inspection of the paths of discrete particles.

Figure 3.9 shows these “multiple exposure” images for the 0.34 m$^3$, 0.17 m$^3$, and 0.06 m$^3$ volume tests conducted on the smooth surface at the leading edge, middle, and trailing edge of the flow. Granular flows consisting primarily of dilute, saltating particles with a low volume fraction were observed at both the leading and trailing edges of the flows, and dense, steady flows with a high volume fraction were observed at the middle, for every volume on the smooth surface. Based on the behavioural regime definitions by Forterre and Pouliquen (2009), the dilute, saltating flows are characteristic of the gas behavioural regime and the dense, steady flows are typical of the liquid behavioural regime. It is evident that the structure of the flows was not constant, but rather had different behavioural regimes within a single event. Figure 3.10 shows the “multiple
exposure” images for the 0.34 m³, 0.17 m³, and 0.06 m³ volume tests conducted on the rough surface. Similar results as those of the smooth surface were observed, granular gas behavioural regimes existed at the leading and trailing edges of the flows and the middle regions of the flows were characteristic of the liquid behavioural regime. The smallest volume test was an exception to this general behaviour, where the entirety of the flow consisted of dilute, saltating particles, characteristic of the granular gas behavioural regime.

The experimental results indicate that flow regime was a function of landslide volume. Comparing the three volume tests performed on the smooth surface, it was observed that for smaller volumes the flows tended towards the granular gas behavioural regime throughout the entirety of the flow. This effect was more pronounced on the roughened surface, with the entirety of the 0.06 m³ volume flow on the rough surface consisting of dilute, saltating particles. For larger volumes on both surfaces, a distinctly dense, steady regime developed within the main body of the flows. The results of Figures 3.9 and 3.10 highlight the contrast between experiments where continuous, steady flows are developed and those that examine singular landslide events of a finite volume of source material.

3.4.1.2 Numerical and Dimensional Analysis of Flow Behavioural Regimes

The flow heights over time for the six test configurations (Figure 3.11) were manually determined from the high resolution cross-sectional images, at 0.1 second intervals. The flow height was defined as the perpendicular distance between the flume base and the highest point above the base where a substantial volume of material was observed (i.e. excluding discontinuous, loose beads above the surface of the main flow body). The time required for the entirety of the granular flow to pass the observation point was unique for each test. As expected, larger volume landslides,
took longer to pass the observation point than smaller volume flows for similar boundary conditions. Granular flows on the smooth surface required less time to pass the observation point than flows travelling on the rough surface.

In order to compare between configurations, instantaneous runout-times, $t$, for a given test were divided by the total time, $T_{\text{total}}$, required for the flow to pass the observation point (Figure 3.12). The flow heights were remarkably similar in the main body of the flow (from approximately 0.1 to 0.7 on the time scale of $t/T_{\text{total}}$) for all test configurations, with the exception of the 0.06 m$^3$ flow on the rough surface. In this case, the considerably higher flow height was a direct result of the flow being in the dilute, low volume fraction granular gas regime throughout its entirety. In general, the saltating leading and trailing edges of the flow had greater flow heights than the dense, steady main body, with the leading edge producing the maximum flow height.

For the purpose of further evaluating volume and boundary roughness effects, the velocity profiles of the 0.06 m$^3$ test on the rough surface and the 0.34 m$^3$ tests on both the smooth and the rough surface were compared at the CAM2 field of view (Figure 3.13). Considerable slip velocities were observed for all test configurations. For the 0.34 m$^3$ tests, in the leading edge granular gas behavioural regime, higher mean velocities, lower shear strain rates, and greater flow heights were observed. As the flows transitioned to the dense, liquid behavioural regime, velocities decreased and a remarkably steady shear strain rate and flow height were achieved. The velocity profiles revealed a slight increase in mean velocity and flow height, and a decrease in shear strain rate as the flow transitioned back to the granular gas behavioural regime at the trailing edge. In general, the test performed on the smooth surface produced higher mean velocities and lower shear strain rates, compared to the rough surface. For the 0.06 m$^3$ test on the rough surface, the whole of the flow was in the granular gas behavioural regime. As a result, the
velocity profiles remained largely unchanged throughout, indicating relatively high velocities, low shear strain rates, and a substantially greater flow height compared to the large volume test on the rough surface.

At an instantaneous point in time, the velocity-depth data can be used to calculate shear strain rate, $\dot{\gamma}$, with depth by dividing the velocity differential by the elevation differential. Using Equation (3.1) and the shear strain rate-depth results, the inertial number with depth can then be calculated at an instantaneous time. In open channel flow, the total stress term, $P$, increases with depth, $y$, and is defined by GDR Midi (2004) as:

$$P = \rho_p g (h - y) \cos \theta$$  \hfill (3.2)

where $\rho_p$ is the bulk material density, $g$ is gravitational acceleration, $h$ is the height of flow, and $\theta$ is the angle of slope inclination.

The shear rate and inertial number profiles with depth, corresponding to the leading edge, middle, and trailing edge regions of the 0.06 m$^3$, 0.17 m$^3$, and 0.34 m$^3$ volume tests on the smooth surface, are shown in Figure 3.14. At the leading and trailing edges of the flows, where the flows consisted of dilute, saltating particles, the mean shear rates and inertial numbers were relatively low. At the leading edge of the flow, volume effects were observed where the shear rate and inertial number profiles indicated lower mean values with decreasing volume. This is a result of the smaller volume tests having a more pronounced tendency towards behaviour in the granular gas behavioural regime. Within the main body (middle region), both the shear rates and inertial numbers were increased for all volumes as the flow becomes more dense and steady. Volume effects were less obvious in the middle and trailing edge regions of the flows.
The shear rate and inertial number profiles with depth for the three volume tests on the rough surface are shown in Figure 3.15. Similar results to the tests conducted on the smooth surface were observed with the leading and trailing edge flows producing reduced mean shear rate and inertial numbers compared to the middle flow regions. As described previously, for the smallest volume test on the rough surface, the entirety of the flow consisted of dilute, saltating particles, characteristic of the granular gas behavioural regime, whereas the larger volume tests transitioned to dense, steady flows in the middle region. This result can be seen quantitatively when comparing the shear and inertial profiles of the different volume tests on the rough surface. At the leading and trailing edges of the flows, the shear rate and inertial number profiles were relatively consistent between the three volumes. In the middle region of the flow, the mean shear rate and inertial numbers corresponding to the small volume test were significantly lower than the results of the other volume tests.

An effective way to compare these quantitative results between different test volumes and basal surface conditions of interest is to average the shear rate and inertial number profiles with depth. A depth-averaged shear strain rate, \( \langle \dot{\gamma} \rangle \), can be determined by averaging the shear strain rate-depth result. Depth averaged shear strain rates were determined at 0.1 second intervals for the 0.06 m\(^3\) volume test on the rough surface and the 0.34 m\(^3\) volume tests on the smooth and rough surfaces. Depth-averaged results are plotted against \( t/T_{\text{total}} \) in Figure 3.16.

The depth averaged shear rate of the granular flows was observed to be a function of basal friction, flow volume, and ultimately of the flow behavioural regime produced by these conditions. Where granular gas behavioural regimes existed, at the leading and trailing edges of the 0.34 m\(^3\) flow and the entirety of the 0.06 m\(^3\) flow, shear strain rates were relatively low. Flows
within these regions were extremely dilute and particles interacted primarily through collisional contacts, resulting in infrequent shearing motion.

For the 0.34 m³ flows, when the leading edge had passed (at approximately 0.1 on the normalized time scale) an increase in the shear strain rates was observed. Within the main body, larger shear rates were the result of dense, steady flows, with particles interacting through frictional-collisional contacts. These shear rates remained relatively constant as the main body passed the observation point, up to a about 0.7 on the normalized time scale, at which point the flow transitioned to the gas behavioural regime and a significant decrease in shear rates was observed. While the same overall behaviour was observed on both surface types, the granular flow travelling on the smooth surface generally had lower shear rates than the flow on the rough surface. This indicates that where similar behavioural regimes exist, boundary roughness has an effect on flow behaviour.

The depth averaged inertial number, \( < I > \), is determined by averaging the inertial number-depth results at 0.1 second time intervals. Figure 3.17 shows the depth-averaged inertial numbers over time. As the depth averaged inertial number is dependent on the shear strain rate, similar patterns to those described above for evaluation of the shear rate over time are observed. Where the granular flows were dilute and collisional, relatively low inertial numbers were observed and when the flows were dense and frictional-collisional, relatively high, constant inertial numbers were observed. The results shown in Figures 3.14 through 3.17 highlight the connection between the flow behavioural regimes observed from the “multiple exposure” images and numerical and dimensional analysis.
Based on the regime limits described by GDR Midi (2004), the depth averaged inertial numbers for all test configurations are greater than the lower limit of the liquid behavioural regime ($I > 10^{-2}$). It was observed that dilute, saltating flows have low shear rates and higher flow heights compared to dense, steady flows that have higher shear rates and lower flow heights. As the inertial number is shear rate and flow height dependent, the highest inertial numbers observed were for dense, steady flows. The inertial numbers were decreased in the dilute, saltating regions of the flows. This result is consistent with the findings of Zhou et. al. (2013) and Da Cruz et. al. (2005). Both studies illustrated that the effective friction coefficient is a function of the inertial number and increases with increasing inertial values. The inertial number and effective friction was very low in the quasi-static regime and reached maximum values in the liquid behavioural regime before decreasing as the granular gas behavioural regime was reached.

Holyoake and McElwaine (2012) observed that the friction-inertial rheology was developed and validated primarily for steady flows with low inertia, and found that the inertial number was not appropriate for classifying flows across all behavioural regimes. Through dimensional analysis, it was determined that all flows were quantitatively classified into the liquid behavioural regime. However, examination of the “multiple exposure” images clearly reveals flow regions that are characteristic of the granular gas behavioural regime (i.e. at the leading of trailing edges of a typical flow, and the entirety of the 0.06 m³ flow on the rough surface). Therefore, it can be concluded that the inertial number may not be appropriate for describing flows characteristic of the granular gas behavioural regime. Fortherre and Pouliquen (2009) postulated that a volume fraction parameter may need to be incorporated in the equation for inertial number or kinetic theory used to describe the full range of possible flow behaviour.
3.4.2 Observations of Macro Scale Runout Behaviour

3.4.2.1 Front Runout and Final Deposit Shapes

Figure 3.18 shows the results of the frontal runout timing tests. The front of the landslide was defined as the first appearance of a substantial volume of material (i.e. excluding discontinuous, loose beads that headed the main body of the flow in the granular gas regime). All flows accelerated from rest from the same initial point of release and have similar runout behaviour up to about 1.2 m of runout. Past this point, the tests completed on the smooth surface continue to accelerate at a higher rate and reach the corner of the flume in less time than their volume equivalents on the rough surface. A volume effect is evident, where the leading edge of the flow for smaller volume tests requires more time to reach the corner than larger volume tests completed on the same surface. This was found to occur on both the smooth and rough surfaces, although the effect of volume is more pronounced on the rough surface. These results are consistent with findings in Staron and Lajeunesse (2009) that suggests the apparent friction coefficient (i.e. Fahrböschung angle) typically decreases with an increase in the volume of a landslide.

Final runout was measured to the front of the main body of the landslide mass (i.e. excluding loose beads that preceded the main body). For each volume pair, the tests completed on the smooth surface travelled 1.25 m to 1.50 m further than the tests completed on the rough surface. A cross sectional view of the final deposit shapes, determined through manual depth readings, is shown in Figure 3.19 for all test configurations. Volume effects include an increased deposit height at all profile locations when volume is increased.
3.4.2.2 Calibration of Depth Averaged Numerical Model and Results

Depth averaged numerical models, such as DAN (Hungr, 1995; Hungr and McDougall, 2007; Hungr, 2008), are often used to predict macro scale landslide runout behaviour for efficient decision making. Rheological parameters used in these models are often determined through back analysis. A method of standardized back analysis for DAN modelling was developed and used extensively by McKinnon (2010) for the calibration of a large number of natural landslide events. This method involved an iterative process of varying rheological parameters and comparing the bulk external results of the model in terms of runout distance, final deposit shape (length and thickness), flow duration, and the flow velocities, to experimental or field results where available.

The method of back analysis developed by McKinnon (2010) was used to determine the suitability of the DAN depth averaged numerical model in matching the runout behaviour of the large-scale flume experiments. The experimental results of front runout, final deposit shapes, and flow height and velocity distributions obtained from the high-speed image analysis, were considered when determining the rheological parameters of the model. As these parameters account for boundary and material conditions, once derived from a calibration test, they may be applied to similar landslide events where material and boundary conditions remain constant. In the case of these experimental results, two sets of parameters were derived, one for tests performed on the smooth surface and one for tests performed on the rough surface.

A frictional material rheology and a Modified Savage-Hutter lateral pressure assumption, described in Hungr (2008), were assumed for these analyses. The frictional material rheology requires the unit weight of the material and the internal and interface friction angles to be specified. Raymond (2000) reported the unit weight of the ceramic beads to be 14.8 kN/m³. A critical internal friction angle of 33.7º, at low confining pressures, was determined previously
through triaxial testing performed by Raymond et. al. (2002). The interface friction angles between the ceramic beads and both the smooth and roughened surfaces were determined through the experimental procedure described in Zhou et.al. (2013) and Hutter et. al. (1995). The interface friction angles of smooth and roughened surfaces were found to be 23º and 34º, respectively.

It is important to note that the experimental procedures described in Zhou et. al. (2013), Hutter et. al. (1995) and Raymond et. al. (2002) to determine the interface and internal friction angles, involve nearly constant, very low strain rate shearing of the material. Therefore, the interface and internal friction angles observed in the laboratory are representative of pseudo-static conditions. Hungr and McDougall (2007) postulated that due to the complex and varying particle interactions during landslide events, laboratory derived parameters may only be valid within a very limited domain of space and time. In DAN modelling, the complex material is represented as an equivalent fluid and the constitutive parameters of that fluid are not be measured in the laboratory, but rather are back-derived from real landslide cases or results of flume experiments (Hungr, 1995). The back-derived parameters are considered to be apparent, rather than actual values, and describe the dynamic, bulk behaviour of the prototype over the entirety of the flow (Hungr and McDougall, 2007).

For the purposes of the back analysis, a unit weight of 14.8 kN/m³ and internal friction angle of 33.7º were held constant for all test configurations. An iterative process of varying the interface friction angle and comparing the model performance with the experimental results of front runout-time and final deposit shape was conducted. The iterative process is a practical way of determining the interface friction angle, as this parameter is variable across a granular flow, being dependent on a number of factors including volume fraction, shear rate, and normal stress (Louge and Keast, 2001; Jop et. al., 2005; Zhou et. al., 2013).
A Voellmy material rheology was also considered, which incorporates dynamic shear resistance in the form of a turbulence term. Trials were conducted using rheological parameters within the range considered by McKinnon (2010). However, the Voellmy rheology was found to produce poor results compared to the frictional rheology and model outcomes for those trials were not included in the results.

Using the 0.34 m³ volume test as the calibration test for the smooth surface, it was determined that the model and experimental macro runout results were remarkably consistent using an interface friction angle of 22º. It is important to note, that in order to achieve the front runout result, the saltating or gas behavioural regime at the leading edge of the flow was ignored and the front of flow re-defined as the first instance of the dense, main body of the landslide. This ultimately shifted the runout-time curve, increasing the time required for the material to reach the corner. The experimental and best match DAN results for the front runout and final deposit shapes are shown in Figure 3.20.

The model outcomes can also evaluated at local observation points coinciding with the CAM1 through CAM4 fields of view. Figure 3.21 shows the depth averaged velocity and flow height results for the 0.34 m³ granular flow on the smooth surface at the CAM2 location. The flow behavioural regimes developed over time are indicated in Figure 3.21a. The overall time required for the flow to pass the field of view in the DAN analysis was similar to that observed in the experimental results. In general, the experimental flow heights were greater than those produced by the depth averaged numerical model, with the most notable differences occurring where flows were dilute and saltating (granular gas regime), at the leading and trailing edges of the flow. The experimental depth averaged velocities were typically lower than those produced by the depth
averaged numerical model. The effect of sidewall friction may have been a factor in this result. Overall, the depth averaged numerical model was able to reasonably match the runout timing, from global macro and local perspectives, as well as the final deposit shape of the granular flow. To an extent, the model was able to match the local depth averaged velocity and flow height results, with the exception of the flow heights at the leading and trailing edges of the landslide, where flows were characteristic of the granular gas behavioural regime.

With these rheological parameters held constant, models were developed for the 0.06 m³ and 0.17 m³ volume tests on the smooth surface. It was observed that the depth-averaged model was able to reasonably match the global macro and local runout-time results, the total runout, and the final deposit shapes (Figure 3.22). The model was less suitable at matching the local depth averaged velocity and flow height results, particularly in regions where flow behaviour was characteristic of the granular gas regime.

For tests conducted on the rough surface, the 0.34 m³ volume test was used to determine a best match interface friction angle of 25.5°. As shown in Figure 3.23, a reasonably good match was achieved when considering both the global macro runout results and the final deposit shape. The depth averaged numerical model was less suitable at matching the flow height, depth averaged velocity distribution, and timing result at the local CAM2 field of view. This interface friction value was held constant and models developed for the 0.06 m³ and 0.17 m³ volume tests on the rough surface. Reasonable results were once again achieved when evaluating the global macro runout-time, total runout, and final deposit shapes. The model was not able to match the local flow height and timing results and was less suitable at matching local velocity results, with the poorest model performance coming from the smallest volume test on the rough surface (Figure 3.24). As the entirety of the 0.06 m³ flow on the rough surface was characteristic of the granular
gas behavioural regime, this result highlights the previous outcome that DAN is less suitable at matching local behaviour where flows are dilute and saltating. This result is not unexpected as DAN is based on a depth-averaged shallow water (i.e. fluid) approximations.

It is notable that the model apparent interface friction values determined through the iterative process, were found to be lower than those determined using a geotechnical laboratory method. Laboratory geotechnical methods are typically based on the soil acting in a pseudo-static condition which is the norm for most geotechnical problems, but is not the case here. Research on steady uniform flows (Louge and Keast, 2001) has shown how collisions that occur within a flowing granular medium reduces friction below pseudo-static values. As the flume experiments and depth averaged numerical models are based on unsteady, rapidly shearing flows where considerable slip velocities at the base of the flume are observed, it is reasonable that lower coefficients of apparent basal friction were determined through the back-analysis process compared to those found in the laboratory.

In turn, it is notable that a single set of empirically derived frictional parameters for DAN (i.e. one value each for the two different basal conditions and one internal value) are obtained for the tests presented here that are applicable over the full range of volumes. The practice of using small-scale case studies (e.g. in the field) to calibrate parameters for DAN for similar classes of flow may indeed be sufficient because this method inherently provides the frictional-collisional mechanism that is needed for calibration. Hence, it would appear that full a priori physical calibration of friction for this class of problem would require a method that considers the mobility of the grains as part of the calibration process itself.
3.5 Summary and Conclusions

Large-scale physical experiments were conducted to obtain high quality data sets capturing the full range of unsteady flow behaviour observed in discrete granular flows and to evaluate the suitability of depth averaged numerical models in capturing that behaviour. High speed image analyses were used to capture both the micro grain scale and macro mobility behaviour of the landslide events, greatly adding to the limited experimental data currently available. A series of thirty tests were performed (six unique test configurations) at material volumes of 0.06 m³, 0.17 m³, and 0.34 m³, on smooth and rough surfaces.

It was observed that granular flows are not constant in terms of rheology, rather distinct and varying flow behavioural regimes can exist within a singular landslide event. The leading and trailing edges of the flow are typically dilute and saltating, dominated by collisional particle interactions (granular gas behavioural regime), whereas the middle flow region is typically dense and steady with frictional-collisional contacts (liquid behavioural regime). The flow regime developed was found to be a function of flow volume and boundary roughness. At small flow volumes, the experimental data indicates that the flow behaviour tends towards the granular gas behavioural regime throughout the entirety of the flow. This effect was more pronounced as the roughness of the basal surface increased.

PIV image analysis was used to develop velocity profiles for individual tests as the granular flows travelled past observation points. The profiles revealed that the saltating regions of the flow (leading and trailing edges) exhibited lower shear strain rates, higher flow heights, and higher velocities than the dense, steady flow regions. Past the initial saltating region, the flow transitioned into a dense, steady flow, characterized by a remarkably steady shear strain rate and height of flow, maintained throughout the entirety of main body region.
It was observed that flow height and depth averaged shear rate are a function of volume and basal friction, and ultimately the flow behavioural regimes developed by these conditions. Where dilute, saltating flows occurred (typically at leading and trailing edges) flow heights were higher and shear rates lower. Where dense, steady flows existed, (main flow body), it was observed that the flow heights were lower and depth averaged shear rates higher. The flow heights in the main body of the flow were similar for all test configurations, with the exception of the 0.06 m³ flow on the rough surface. The depth averaged shear rates were typically higher for equivalent volume tests conducted on the rough surface compared to those on the smooth surface.

Dimensional analyses, using the inertial number, were completed to quantitatively classify the flow behavioural regimes observed. For all test configurations, the depth averaged inertial numbers classified the bulk flow behaviour as being characteristic of the liquid behavioural regime. Experimental findings indicate that the inertial number, which is directly derived from the shear rate and flow height, may not apply for describing transitions from the liquid to gas behavioural regime. A volume fraction term or kinetic theory may be required.

The macro mobility, including runout-time and final deposit shape, was observed for all test configurations. Tests performed on the smooth surface required less time to reach the horizontal base section and had a greater total runout than their volume equivalents on the rough surface. Larger volume tests required less time to reach the horizontal base and had increased deposit heights at all profile locations compared smaller volume tests conducted on the same rough surface.
The suitability of depth averaged numerical models, specifically DAN, to match the runout behaviour of the experimental tests was evaluated. Model parameters were calibrated through back-analyses of previous events with equivalent boundary conditions. Despite the complexity of the multiple flow behavioural regimes observed in each discrete event, the depth averaged numerical model, DAN, was observed to reasonably match the macro runout behaviour, including total runout, macro runout-time results, and the final deposit shape, however, suitable matches of the macro runout-time result were only achieved when the initial saltating region of the flow was ignored. The model was less suitable at matching local observation point data, particularly where flows were dominated by dilute, saltating particles (granular gas behavioural regime). This result was not surprising as DAN is based on a depth-averaged shallow water (i.e. fluid) approximation of the flow.

The calibrated basal friction values were found to be lower than those determined using laboratory geotechnical methods. This result was not unexpected as the laboratory results are based on pseudo-static conditions, whereas the experimental results involve unsteady, rapidly shearing flows. A single set of empirically derived frictional parameters for DAN were obtained for each basal friction case and were applicable for matching the overall mobility of the experimental flows over the full range of volumes.

In general, depth averaged models remain a practical tool in assessing landslide hazards from an overall mobility perspective and for effective decision making. There is scope for further refinement – namely, the ability to vary friction and other parameters according to granular-liquid behavior would be an advantage. However, it must be borne in mind that the flows conducted here were dry and that DAN fundamentally considers flows as a single phase material. Where
pore pressures ratios within field scale situations vary significantly, the effective frictional characteristics will be different resulting in different velocity and runout behavior.
3.6 References


Figure 3.1 Illustration of a) three flow regimes used to classify flows at the micro grain scale and b) forces acting on a typical slice of landslide mass in a macro scale depth averaged model. (Figure modified from Armanini, 2013 and Hungr, 2008)
Figure 3.2  a) Description of a physical model to investigate landslide mobility and b) definition of terminology describing final landslide deposit including total horizontal length (L), vertical drop (H), Fahrböschung angle (α), and runout from the corner (R). (α_G, L_G and H_G are measured with respect to the centre of gravity of the landslide mass)
Figure 3.3 Diagram of the Queen’s University Landslide Flume. The U, V, W axis system is defined with respect to the sloped section and the X, Y, Z axis system is defined with respect to the horizontal runout section.
Figure 3.4 Photo of the perforated metal sheet used to create the bumpy (rough) surface and the ceramic beads used in the landslide runout experiments
Figure 3.5 Example of a) static mesh used in PIV analysis of granular flow, b) resulting quiver plot showing displacement during 0.005 seconds of motion, and c) velocity profiles generated from displacement vectors
Figure 3.6 Time evolution of the downstream velocity profiles for the 0.34 m³ volume test on the rough surface within the CAM4 through CAM1 fields of view. Time step between velocity profiles is 0.1 seconds. The average time required for the entirety of the flow to pass a field of view was approximately 5.2 seconds.
Figure 3.7 Surface velocity profiles for 0.34 m³ volume test on the smooth surface. Time step between velocity profiles is 0.1 seconds.
Figure 3.8 Digitally generated “multiple exposure” image showing grain positions over 0.004 seconds of flow (three consecutive images) for close up view of the 0.06 m³ flow on the rough surface at the CAM2 field of view.
Figure 3.9 Digitally generated “multiple exposure” images showing position of grains over three consecutive images at (i) leading edge, (ii) middle, and (iii) trailing edge of flow, past CAM 2 field of view, for 0.34 m³, 0.17 m³, and 0.06 m³ tests on the smooth surface. Flows are travelling from right to left.
Figure 3.10 Digitally generated “multiple exposure” images showing position of grains over three consecutive images at (i) leading edge, (ii) middle, and (iii) trailing edge of flow, past CAM 2 field of view, for 0.34 m³, 0.17 m³, and 0.06 m³ tests on the rough surface. Flows are travelling from right to left.
Figure 3.11 Time evolution of flow heights for all test configurations within CAM2 field of view. Time step between markers is 0.1 seconds.

Figure 3.12 Evolution of flow heights over timescale $t/T_{Total}$ for all test configurations within the CAM2 field of view. Time scale obtained by dividing each instantaneous time by the total time required for the material to pass the CAM2 field of view.
Figure 3.13 Time evolution of the downstream velocity profiles for the 0.06 m³ and 0.34 m³ tests on the rough surface and the 0.34 m³ test on the smooth surface within the CAM2 field of view. Time step between velocity profiles is 0.1 seconds.
Figure 3.14 a) Shear rate profiles and b) inertial number profiles with depth at the (i) leading edge, (ii) middle, and (iii) trailing edge of the 0.06 m³, 0.17 m³, and 0.34 m³ granular flows on the smooth surface, within the CAM2 field of view.
Figure 3.15 a) Shear rate profiles and b) inertial number profiles with depth at the (i) leading edge, (ii) middle, and (iii) trailing edge of the 0.06 m³, 0.17 m³, and 0.34 m³ granular flows on the rough surface, within the CAM2 field of view.
Figure 3.16 Evolution of depth averaged shear rate over time for 0.06 m³ and 0.34 m³ volumes on rough surface and 0.34 m³ volume on smooth surface, within the CAM2 field of view. Time scale obtained by dividing the instantaneous times by the total time required for material to pass the field of view.
Figure 3.17 Evolution of depth averaged inertial number over time for 0.06 m$^3$ and 0.34 m$^3$ volumes on rough surface and 0.34 m$^3$ volume on smooth surface, within the CAM2 field of view. Time scale obtained by dividing the instantaneous times by the total time required for material to pass the field of view.
Figure 3.18  Total distance travelled over time for all test configurations. Runout-time results shown define the front of the material to be the first instance of a substantial volume of material, excluding discontinuous loose beads that headed the main flow body.
Figure 3.19 Final deposit profiles for all test configurations. (0,0) is the point where the slope meets the horizontal base. A typical result is shown for each test configuration.
Figure 3.20 a) Runout over time and b) final deposit profiles of 0.34 m³ test and DAN Analysis on the smooth surface. For DAN analysis, an internal friction angle of 33.7° and an interface friction angle of 22° were used to achieve the results shown.
Figure 3.21 a) Flow height over time and b) depth averaged velocity over time of 0.34 m³ test and DAN Analysis on the smooth surface at the CAM2 field of view. For DAN analysis, an internal friction angle of 33.7° and an interface friction angle of 22° were used to achieve the results shown.
Figure 3.22 a) Runout over time and b) final deposit profiles of 0.06 m³ test and DAN analysis performed on the smooth surface. c) Runout over time and d) final deposit profiles of 0.17 m³ test and DAN analysis performed on the smooth surface. For DAN analysis, an internal friction angle of 33.7° and an interface friction angle of 22° were used to achieve the results shown.
Figure 3.23 a) Runout over time and b) final deposit profiles of 0.34 m³ test and DAN analysis performed on the rough surface. For DAN analysis, an internal friction angle of 33.7° and an interface friction angle of 25.5° were used to achieve the results shown.
Figure 3.24 a) Flow height over time and b) depth averaged velocity over time of 0.06 m³ test and DAN Analysis performed on the rough surface at the CAM2 field of view. For DAN analysis, an internal friction angle of 33.7° and an interface friction angle of 25.5° were used to achieve the results shown.
Chapter 4

Conclusions

Unique, high quality data sets capturing the runout behaviour of granular landslides have been successfully obtained. High speed cameras were used to capture the mobility of singular landslide simulations conducted using both a geotechnical centrifuge and a large scale flume.

A series of nine physical landslide experiments were performed in a geotechnical centrifuge under varying slope inclinations (70° and 45°) and Coriolis conditions (Coriolis applied into the slope, Coriolis applied away from the slope, and no Coriolis). The effect of Coriolis on macro scale mobility outcomes was evaluated. General conclusions with regard to physical modelling conducted in geotechnical centrifuge include:

- The total runout of the granular flow was reduced and the final deposits were shorter and thicker where the Coriolis force acted to increase the effective gravitational acceleration (Coriolis applied into the slope), compared to tests performed using the same test geometry at 1g.
- The total runout was greater and the final deposit thinner and more elongated where the Coriolis force acted to decrease the effective gravitational acceleration (Coriolis applied away from the slope), compared to tests performed at 1g using the same test geometry.
- The effect of Coriolis was more pronounced for higher velocity situations, for example, where steeper inclinations were used. In extreme cases, unrealistic model situations may occur in comparison to the prototype.
• The impact of Coriolis was more pronounced on the horizontal runout section compared to the sloped section, due to the magnitude of the resultant forces acting on the landslide mass in each situation.

• Using the best match back derived rheological parameters, the depth averaged numerical model, DAN was able to reasonably model the experimental outcomes of tests performed at 1g. Equivalent back-derived parameters were independently found for both test configurations, illustrating the robustness of this modelling approach where consistent material and boundary conditions exist.

• The addition of a feature in the DAN modelling approach to account for Coriolis forces would be advantageous in order to describe the mobility of all experimental results using a single set of empirically derived friction parameters.

A series of thirty tests (six unique test configurations) were performed using a large scale flume under varying source volumes (0.06 m³, 0.17 m³, and 0.34 m³) and basal friction conditions (smooth and rough surfaces). The full range of flow behaviour observed in these granular landslides was captured from both micro grain scale and macro mobility perspectives. General conclusions with regard to physical modelling conducted using a large scale flume include:

• The leading and trailing edges of singular landslide events were typically dilute and saltating, dominated by collisional particle interactions, characteristic of the granular gas behavioural regime. The middle flow region was typically dense and steady with frictional-collisional contacts, characteristic of the liquid behavioural regime.

• The behavioural regime developed was a function of flow volume and boundary roughness. At small flow volumes, the flow behaviour tends towards the granular gas
behavioural regime throughout the entirety of the flow. This effect was more pronounced as the roughness of the basal surface increased.

- Flow heights and depth averaged shear rates were a function of the flow behavioural regimes developed. Velocity profiles and the analysis of “multiple exposure images” typically revealed lower shear strain rates, higher flow heights, and lower volume fractions in the saltating regions of the flow (typically leading and trailing edges) compared to the regions of dense, steady flows (main body regions). The flow heights in the main body of the flows were similar for all test configurations, with the exception of the 0.06 m³ flow on the rough surface where collisional interactions were dominate throughout. The depth averaged shear rates were typically higher for equivalent volume tests conducted on the rough surface compared to the smooth surface.

- Dimensionless inertial numbers were used to classify flows into behavioural regimes. In general, inertial numbers were near constant across the main flow body, with lower depth averaged inertial numbers calculated for the dilute, saltating flow regions. While flows in all test configurations were classified in the liquid behavioural regime, experimental results indicated that the inertial number may not apply when describing transitions to the granular gas behavioural regime.

- The macro runout behaviour of tests performed under the varying volume and basal friction conditions was observed. Tests performed on the smooth surface required less time to reach the horizontal base section and had a greater total runout than their volume equivalents on the rough surface. Larger volume tests required less time to reach the horizontal base and had increased deposit heights at all profile locations compared smaller volume tests conducted on the same rough surface.

- The depth averaged numerical model, DAN was able to reasonably match the macro runout behaviour (final deposit and runout-time results) of the physical models. Suitable
matches of the runout-time results were only achieved when the initial saltating region of the flow was ignored. These models were not able to consistently match local runout behaviour (velocity, flow height, local timing) observed at specific observation points. A single set of empirically derived frictional parameters for each basal friction condition, was appropriate for matching the overall mobility of the experimental flows over the full range of flow volumes.

- There is scope for further refinement of depth averaged models with regard to the ability to vary friction and other rheological parameters according to the flow regime developed.

The high quality data sets obtained through this research program add to the presently limited experimental data sources that capture both micro grain scale and macro runout behaviour of granular landslides. This data is offered to provide others with experimental evidence for the development and verification of new theoretical models and to assess the capabilities of existing models in predicting landslide mobility. Overall, these results are believed to aid in furthering the understanding of the mechanisms that drive landslide motion, which is essential for the accurate prediction of the mobility of these hazards.
Appendix A

Characterization of Granular Material used in Large Scale Flume Experiments

A.1 Introduction

Dry, granular material was utilized in the large scale flume experiments at the Queen’s University Landslide Facility. The rounded particles, referred to as ceramic beads, are Denstone Ceramic Bed Support Media (Saint-Gobain NorPro, 2005) manufactured by Saint-Gobain NorPro in Akron, Ohio. This Appendix provides information on the characteristic properties of the ceramic beads obtained through literature review, laboratory testing, and digital image analysis.

A.2 Average Particle Size Verification

The ceramic beads were supplied from Saint-Gobain NorPro at a reported nominal diameter size of 3 mm. In a previous study by Raymond in 2000, the same material was sieved through a US No. 4 (4.76 mm) sieve and retained on a US No.8 (2.13 mm) sieve.

A Matlab program entitled Digital Grain Size (DGS), developed by the US Geological Survey, was used to verify the average particle size of the ceramic beads reported in the literature. This program approximates the grain size of non-cohesive sediment from digital photographs (Buscombe et. al., 2010). The latest version of this program for Matlab was downloaded in a package from the USGS website (US Geological Survey, 2012).
This program utilizes a spatial autocorrelation algorithm and is based on the theory that the autocorrelation of an image will fluctuate with grain size (Rubin, 2004). Unlike similar programs, Digital Grain Size does not identify and measure individual grains, rather it completes statistical analysis on the image as a whole. This method therefore avoids potential errors caused by grains overlapping (causing grains to appear smaller) and grains of similar texture touching (causing grains to appear larger). Where the material is uniform, as is the case for this study, no calibration is required prior to running the program (Rubin, 2004).

Images were obtained from a Canon EOS 5D 12.8 megapixel digital camera with a 50 mm lens. The camera was held at a constant position using a tripod with the camera lens pointed vertically downward, perpendicular to the surface of the grains. All images were taken at close range with the lens positioned 440 mm above the granular material. A ruler was placed in the field of view of the first photograph in order to convert measurements in pixels to millimeters. The pixel resolution was found to be 0.068889 mm/pixel for this test setup. The measuring tape was removed in subsequent photographs with the tripod and camera remaining in the same position, maintaining this resolution.

Illumination was achieved using two – 500 watt, T3 halogen bulbs, carefully positioned to reduce the occurrence of shadows behind grains. Figure A.1 shows the images that were used with the program. The first image includes the ruler and the second image shows the same camera view, with the ruler removed.

Using the Digital Grain Size code, the average grain size of the ceramic beads for the image above was found to be 3.02 mm with a standard deviation of 0.66 mm. This value was confirmed using a second image with the configuration of ceramic beads rearranged. This value for average
particle size, taking the standard deviation into account, fits within the sieve range determined by Raymond (2000) and is consistent with the nominal particle size reported by the manufacturer.

A.3 Sphericity of Ceramic Beads

In order to determine the sphericity of the ceramic beads, image analysis was completed using the Matlab code “Separating objects in an image”. This code was obtained online from the Matlab Central website and was modified to better suit the needs of this study (Matlab Central, 2011). The code converts an image of the ceramic beads to a binary image. Once in binary form, the *regionprops* function is used to determine the major and minor axis lengths, area, perimeter, and centroid of each connected object (i.e. the ceramic beads). Objects with a minor axis length smaller than a specified threshold are omitted from the analysis eliminating erroneous results. The code gives a score representing the sphericity of the connected objects by comparing: a. the largest and smallest axis; b. the area of the object with that of a perfectly round object and; c. the perimeter of the object with that of a perfectly round object. The average of the three scores is the value representing the sphericity of that individual object. A score of one indicates that the object is perfectly circular and the score decreases with decreasing sphericity.

For this study, images were obtained from a Canon EOS 5D 12.8 megapixel digital camera with a 50 mm lens. Illumination was achieved using two – 500 watt, T3 halogen bulbs, carefully positioned to reduce the occurrence of shadows behind grains. The image was cropped and the contrast and brightness adjusted prior to the analysis.

Figure A.2 shows the image of ceramic beads that was used in the analysis. Unlike the Digital Grain Size code, this code identifies individual objects in the image and determines properties for
each one. To avoid erroneous results associated with grains overlapping and grains with similar
textures touching, the ceramic beads were spread out in a single layer. The binary image with the
sphericity scores labeled over the individual beads is shown in Figure A.3. The average sphericity
of all ceramic beads used in the analysis was 0.945 (94.5%) with a standard deviation of 0.026
(2.6%).
A.4 References


Saint-Gobain NorPro. (2005). "Denstone Support Media." *Denstone Ceramic Bed Support Media*, obtained online on August 20, 2012 from Saint-Gobain NorPro website:


Figure A.1 Images of ceramic beads used in the Digital Grain Size Analysis

Figure A.2 Images of ceramic beads used in the sphericity analysis
Figure A.3 Binary image with sphericity scores