# Chapter 1

# Introduction

Avalanches, debris flows, and landslides are geophysical hazards which involve rapid mass movement of granular solids, water and air as a single phase system. The presence of water in a granular flow distinguishes '*mud and debris flow*' from '*granular avalanches*'. Debris flow is a rapid mass movement of liquefied, unconsolidated, saturated soil. The speed of the debris flow varies from 50 $\mathrm{km\,h^{-1}}$ to 80 $\mathrm{km\,h^{-1}}$ in extreme cases, transporting 100 to 100,000 cubic meters of unconsolidated sediments down very steep slopes. Figure 1.1 shows the catastrophic effect of a debris flow that occurred during an earthquake-triggered landslide in Las Colinas, El Salvador. On the other hand, Submarine landslides transport sediments across continental shelves even on slopes as flat as $1^\circ$ and can reach speeds of 80 $\mathrm{km\,h^{-1}}$. Figure 1.2 shows the Storegga Landslide, the largest recorded continental slope failure, which struck off the coast of central Norway, transporting materials over 500 km (Ward and Day, 2002).

Granular avalanches, debris flow and submarine landslides cause significant damage to life and property. Globally, landslides cause billions of pounds in damage, and thousands of deaths and injuries each year. On 2 May 2014, a pair of mudslides killed at least 2000 people, 3000 houses were buried and over 14,000 affected after a landslide hit the north-east Afghan province of Badakhshan. Rescuers responding to the initial mudslide were struck by a second mudslide which trapped or killed a large proportion of potential rescuers, (Source: BBC, 2014). The consecutive slides levelled the village, and left the area under 10 to 30 metres of mud. A week of torrential rain might be a plausible reason for the mudflows. Understanding the triggering mechanism and the granular flow process provides an insight into the force and velocity distribution in a granular flow, enabling us to design appropriate defensive measures.

Figure 1.1 Initiation, channelling, spreading and deposition of debris slide in Las Colinas, El Salvador, January 2001. The debris flow buried as many as 500 homes. (Source: USGS report on '*Landslides in Central America*', 2001)

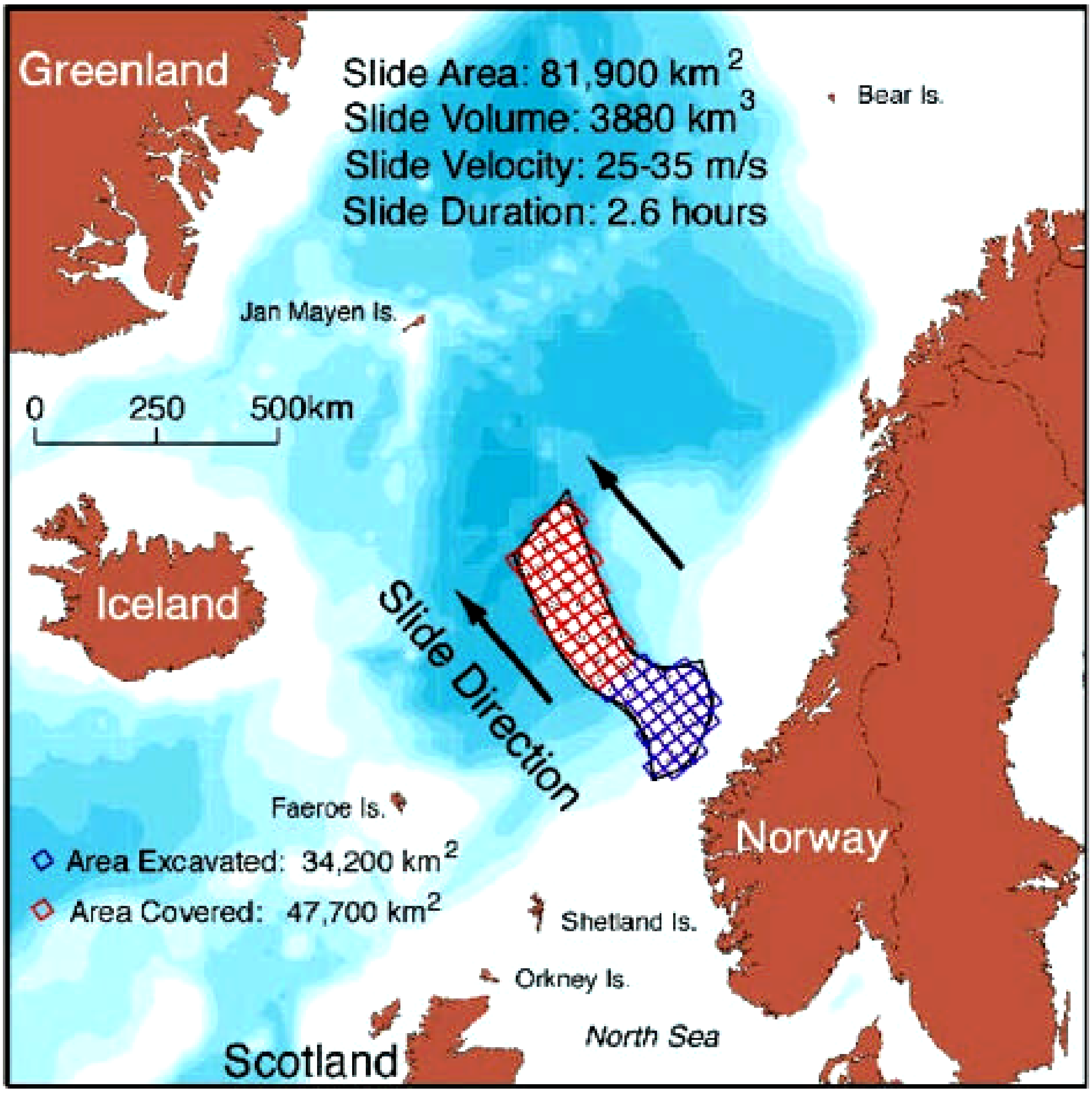


Figure 1.2 The extent of the Storegga landslide (Source: School of geoscience, University of Sydney)

## 1.1 Modelling the granular flows

The dynamics of a homogeneous granular flow involve at least three distinct scales: the *microscopic scale* which is characterized by the contact between grains, the *meso-scale* which represents micro-structural effects such as grain rearrangement, and the *macroscopic scale*. In a submarine landslides, which is of 100,000 km$^3$ in volume is influenced by the grain-scale dynamics happening at the scale of a few $\mu$ meters to millimetres. This poses a question of how to appropriately model the various scales of behaviour observed in a granular flow.

Typically, continuum laws are only used when there is a strong separation of scales between the micro-scale and the macro-scale sizes of the flow geometry. Although granular materials are composed of discrete grains which interact only at contacts, the deformations of individual grains are negligible in comparison with the deformation of the granular assembly as a whole. Hence, the deformation is primarily due to the movements of grains as rigid bodies. Therefore, continuum models are still widely used to solve engineering problems associated with granular materials and flows.

Conventional mesh-based approaches, such as Finite Element (FE) and Finite Difference (FD) methods, involve complex re-meshing and remapping of variables, which cause additional errors in simulating large deformation problems. Mesh-free methods, such as the Material Point Method (MPM) and Smooth Particle Hydrodynamics (SPH), are not constrained by the mesh size and its distortion, and hence are effective in simulating large deformation problems such as debris flow and submarine landslides. The analytical and finite-element-like techniques which consider granular materials as a continuum cannot take into account the local geometrical processes that govern the mechanical behaviour of non-homogeneous soils, and pose subtle problems for statistical analysis.

The grain level description of the granular material enriches the macro-scale variables that happen to poorly account for the local rheology of the materials. Numerical models based on the Discrete Element Method (DEM) allow us to evaluate quantities which are not accessible experimentally, thus providing useful insight into the flow dynamics. Grain-fluid interactions can be simulated by interfacing discrete-element methods with a Lattice Boltzmann solver or a Computational Fluid Dynamics solver, however these methods have their inherent limitations. Even though millions of grains can be simulated, the possible length of such a grain system is generally too small to regard it as '*macroscopic*'. Therefore, methods to perform a micro-macro transition are important and these '*microscopic*' simulations of a small sample, i.e. the '*representative volume element*', can be used to derive a macroscopic theories which describes the material within the continuum framework.

Granular flows have been extensively studied during the past two decades through experimental and numerical simulations (Andersen and Andersen, 2010; Denlinger and Iverson, 2001;

Iverson et al., 1997; Jaeger et al., 1996; Tang et al., 2013). In most cases, granular flows exhibit three distinct regimes: the slow quasi-static regime, a dilute collisional regime and an intermediate regime. Many theories and phenomenological models have been developed to model the behaviour the different flow regimes. One approach is to use the Kinetic theory, (Jenkins and Savage, 1983; Savage and Jeffrey, 1981) which assumes binary collision between particles. Kinetic theory is able to capture the rapid-collisional regime, however is incapable of predicting the dense quasi-static behaviour. Granular flows exhibit fluid like behaviour, using a simple analogy from fluid dynamics one can model granular flows as non-Newtonian fluids using a variant of the Navier-Stokes equation; one such approach is the depth-averaged shallow water equation (Savage and Hutter, 1991). This approach has been applied to solve granular flow dynamics with a reasonable amount of success. However, the basic assumption of neglecting the effect of vertical acceleration restricts the approach from describing the triggering mechanism, in which the vertical acceleration plays a significant role such as collapse of a vertical cliff.

In certain cases, classical theories are incapable of describing the flow kinematics. Hence, rheologies have been used to describe the mechanical behaviour of granular flows through an empirical relation between deformations and stresses. Midi (2004) proposed a new rheology for granular flows based on extensive experimental and numerical investigation on gravity-driven flows. The $\mu(I)$ rheology describes the granular behaviour using a dimensionless number, called the *inertial number* $I$, which is the ratio of inertia to the pressure forces. Small values of $I$ correspond to the critical state in soil mechanics and large values of $I$ corresponds to the fully collisional regime of kinetic theory. The spreading dynamics are found to be similar for the continuum and grain-scale approaches, however the rheology falls short in predicting the run-out distance for steeper slopes and in the transition regime where the shear-rate effect diminishes. The flow of granular materials in a fluid remains largely unexplored.

In addition to the scale-effects, most geophysical hazards usually involve multi-phase interactions. The momentum transfer between the discrete and continuous phases significantly affects the dynamics of the flow. In order to describe the mechanism of multi-phase granular flows, it is important to consider both the dynamics of the solid phase and the role of the ambient fluid. Most models which simulate submarine landslides assume a single homogeneous grain-fluid mixture governed by a non-Newtonian fluid behaviour (Denlinger and Iverson, 2001; Iverson, 2000). Although successful in accounting for the general phenomenology on analytical grounds, such models fail to capture certain phenomena such as porosity gradient and fluid-induced size-segregation. Moreover, application of these models involves additional assumptions about the boundary/interface between the grains and the fluid, and the transition between high and low shear stresses.

The simple $\mu(I)$ rheology is found to capture the dense submarine granular flows, if the inertial time scale in the rheology is replaced with a viscous time scale (Pouliquen et al., 2005). However, the transition from a rapid granular flow down a slope to the quasi-static regime when the granular mass ceases to flow, where the shear rate vanishes, is not captured by the simple model. The flow threshold or the hysteresis characterizing the flow or no-flow condition is also not correctly captured by this model. When the scale of the system is larger than the size of the structure, a simple rheology is expected to capture the overall flow behaviour, however in granular flows, the size of the correlated motion is of the same size as the system, causing difficulties in modelling the flow behaviour. Hence, it is essential to study the behaviour of granular flows at various scales, i.e. microscopic, meso-scale and continuum-scale levels, in order to describe the entire granular flow process.

## 1.2 Objectives

This study is motivated by a simple question: If a granular column collapses and flows in a dry condition and within a fluid, in which case would the run-out be the farthest? The collapse in a fluid experiences drag forces which tend to retard the flow, this might result in a longer run-out distance in the case of dry condition. However, the collapse in fluid might experience lubrication effects due to hydroplaning and this reduces the effective frictional resistance, which might result in a longer run-out distance in the case of fluid than the dry condition. Would the effect of lubrication overcome the drag forces and result in the farthest run-out in fluid? or would the drag forces predominate resulting in dry condition having the farthest run-out distance. Although, a simple problem by description, the influence of various properties such as slope angle, initial packing density, permeability on the run-out behaviour makes it a complex phenomenon.

The other important question is how to model the granular flow behaviour, which exhibits complex fluid-like and/or solid-like behaviour depending on the initial state and the ambient conditions. Despite advances in numerical tools,

The aim of this research work is to understand and describe the mechanism of granular flows in dry and submerged conditions using a multi-scale approach. This research work involves identification of fundamental microscopic parameters that control the granular flow dynamics. Continuum and discrete-element modelling of granular flows are performed to understand the limits of the continuum approach in modelling large deformation granular flow problems. This study provides an insight into the mechanics of granular flows, and enables us to understand the mechanisms involved in geophysical hazards, such as avalanches, debris flows and sub-marine landslides.

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