Dynamics of Flow Avalanches Over Curved and Twisted Channels

Theory, Numerics and Experimental Validation

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It is an inevitable fact that the life sometimes is like a shock phenomenon. To smooth and diffuse it one needs a sufficient amount of courage. Time was very difficult for me when, first my father, and then in about two years period, my mother passed away. Being far away, I was not able to speak with them face to face at those last and critical moments. That was a great grief for me in my life.

Therefore, I dedicate this work to my parents, my wife and my daughters.

Shiva P. Pudasaini
Darmstadt, December 20, 2003
Abstract

This thesis presents a new theory and discussions about the motion of avalanches from initiation to run-out over a generally curved and twisted complicated mountain topography, its numerical simulation and comparison with well controlled, advanced laboratory experiments. It is hoped to be demonstrated that today’s method of determination of the avalanche motion along its track promises to give to the avalanche practitioner a tool with the aid of which fairly reliable predictions of avalanche motion along its track can be made, from initiation to run-out. The model computations and experiments also allow inferences as to the distribution of the mass of different granulates, like gravel or snow, in the deposition zone as well as to the forces exerted on structures that are affected by the motion of the avalanche.

To achieve this aim, a well known depth integrated avalanche model of Savage & Hutter is generalised to arbitrary channelised topographies, the intention being that the model would be able not only to describe the flow of snow, gravel, debris or mud, down a corrie of arbitrary curvature and twist and arbitrary cross sectional profile, but equally also the transportation of grains or pills in the agricultural and pharmaceutical industry, respectively. For the first time we were able to include the simultaneous effects of the curvature and torsion in the avalanche motion, which could not be achieved by previous models. The applicability of the present model equations is, therefore, much broader than in the previous cases. The flow down an inclined plane or within a channel with its axis in a vertical plane which may be curved can be described, as can the flow down complicated mountain valleys with arbitrarily curved and twisted talwegs and bed topographies. The new theory is ideally suited to realistic situations in connection with the use of Geographical Information and Visualisation Systems. Thus, the theory provides an entirely new direction in the field of avalanche and debris flow research. It also opens a large spectrum of applications in different industrial and geophysical problems.

The emerging equations for the distribution of the avalanche thickness and the topography-parallel depth-averaged velocity components consist of non-linear hyperbolic partial differential equations with discontinuous coefficients. To avoid any spurious oscillations and include naturally induced shock phenomena we introduced shock-capturing numerical schemes. To this end, two-dimensional Non-Oscillatory Central schemes with higher order cell reconstructions and second order accurate Total Variation Diminishing limiters were implemented. One of the most interesting aspects of avalanche dynamics is the study of avalanching motion over different bed structures and the effect of topography on their motion and deposits. We performed several numerical tests for avalanching masses down curved and twisted bed topographies. Uniformly and non-uniformly curved and twisted channels as well as channels which incorporate confined and unconfined continuous transition zones with constant and variable cross-sectional topographies merging into the horizontal run-out zones are considered. They demonstrate the combined effects of curvature, torsion and the radial acceleration associated with the bed topography. Thus, we are able to quantify the intrinsic effects of the topography and, finally, disclose the unknown physics of flows of avalanches through generally curved and twisted channels. Such sophisticated studies have not been carried out before, and it was possible here only with the new model equations.
In order to acquire confidence in new model equations it is vital to corroborate them by direct observation. In this spirit, we performed several laboratory experiments for different granular materials to check the validity of the theory. We used a modern measurement technique, the Particle Image Velocimetry, to measure the velocity field of the flowing particles at the free-surface and the bottom of the free-surface and unsteady motion of an unconfined avalanche over a chute that is curved in the main flow direction merging continuously into the horizontal run-out zone. We are able to demonstrate the fact that there are excellent agreements between the theoretical predictions of the model equations and the experimental measurements. This, ultimately, proves the applicability of the theory and efficiency of the numerical method and code and establishes a nice and strong correlation among the theory, numerics and the experiments.
Zusammenfassung


uniform gekrümme und tordierte Kanäle, wie auch Kanäle, welche offene, bzw. begrenzte, kontinuierliche Übergangszonen mit konstanter bzw. variabler Quertopographie aufweisen und in eine horizontale Auslaufzone münden. Die Resultate demonstrieren die kombinierten Effekte der Krümmung, Torsion, Radialbeschleunigung sowie variabler Topographie. Wir sind also in der Lage, die intrinsische Wirkung der Topographie zu quantifizieren und können so die unbekannten physikalischen Eigenschaften der Lawinenbewegung durch gekrümme und tordierte Kanäle ergründen. Solch komplexe Studien sind bis dato noch nicht durchgeführt worden; es war hier nur aufgrund des neuen Modelles und seiner Gleichungen möglich.

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Part I

Introduction, Conception & Importance of Avalanche Research
Chapter 1

Introduction

1.1 Motivation

Avalanches, debris and mudflows but equally also landslides are natural phenomena that occur in mountainous regions on our Globe on a regular basis. They are as such therefore a common phenomenon to inhabitants of mountainous regions such as the Alps or the Himalaya, who have learned to accept their occasional occurrence and to avoid the damages that are accompanied with them. Nevertheless, accidents involving damage of life and property and devastating singular incidences have regularly occurred in the past. These are the major reasons why, in such regions, the study of avalanches is a topic of public concern that is of permanent significance. The physics of the formation of the rapid motion of a large mass of soil, gravel or snow and the dynamics of the motion must be understood, if the danger induced by the release of a certain mass of gravel, snow or soil should be avoided or the impact of a moving mass on the avalanche track or on obstructing buildings be estimated. One hopes that understanding their physical basis will enable the appropriate defensive measures to be taken.

The last few years have witnessed increased efforts devoted to the physical understanding of the avalanche formation and motion in complex topography. More specially, whilst any forecast of avalanche occurrence and estimation of size is still largely a question of experience, the motion of a given loose mass of gravel, snow or soil is better amenable to analysis. This is so, because the physics of the motion of a finite mass of soil or snow is less difficult to understand than the physics of the mass release from a soil or snow slope at rest.

This thesis provides a new theory and discussions about the motion of avalanches from initiation to run-out over a generally curved and twisted complicated mountain topography, its numerical simulation and comparison with well controlled laboratory experiments. It is hoped to be demonstrated that today’s method of determination of the avalanche motion along its track promises to give to the avalanche practitioner a tool with the aid of which fairly reliable predictions of avalanche motion along its track can be made, from initiation to run-out. The model computations also allow inferences as to the distribution of the mass of different granulates, like gravel or snow, in the deposition zone as well as to the forces exerted on structures that are affected by the motion of the avalanche. This, in short is the aim of this thesis.
To achieve this aim, a well known depth integrated avalanche model is generalised to arbitrary channelised topographies, the intention being that the model would be able not only to model the flow of a finite mass of snow, gravel, debris or mud, down a corrie of “arbitrary” curvature and twist and “arbitrary” cross sectional profile, but equally also the transportation of grains or pills in the agricultural and pharmaceutical industry, respectively. The emerging equations for the distribution of the avalanche thickness and the topography-parallel depth-averaged velocity components, to be derived in this thesis, are a set of hyperbolic partial differential equations. Once they are derived, new significant technical problems must be solved in order to judge their adequacy: How are these equations solved numerically, and how are experiments conducted to compare theoretical results with corresponding experimental findings? Both subproblems pose challenging questions as we shall now briefly outline.

Successful modelling of strongly convective hyperbolic equations is one of the most challenging problems in computational fluid mechanics, particularly when large gradients of the physical variables occur, e.g., for a moving front and boundary or possibly arising shock waves in a granular avalanche. Shock formation is an essential mechanism in granular flows on an inclined surface merging into a horizontal run-out zone or encountering an obstacle when the velocity becomes subcritical from its supercritical state. It is therefore natural to apply conservative high-resolution numerical techniques that are able to resolve the steep gradients and moving fronts often observed in experiments and field events but not captured by traditional finite difference schemes. The NOC (Non-Oscillatory Central) differencing scheme with Minmod TVD (Total Variation Diminishing) limiter demonstrates the best numerical performance for simulating avalanche dynamics among all other limiters (e.g., Superbee and Woodward) and the ENO (Essentially Non-Oscillatory) cell reconstructions. Several numerical simulations of avalanching flows from simple to complex topographies incorporating curvature as well as torsion of the topography demonstrate fundamental and physically interesting and practically applicable results. The new theory and its numerical simulations disclose unknown physics of flows of avalanching debris through strongly curved and twisted channels and opens an enormous spectrum of applications. In principle, the theory can be applied to any kind of topography - from a simply inclined plane to very complicated arbitrarily curved and twisted channels in industrial as well as geophysical flows down mountain valleys from initiation to the deposits in the run-out zones. In fact, Geographic Information Systems (GIS) applied to mountainous avalanche-prone regions can be applied to the newly proposed model equations to simulate avalanching debris down complicated mountain valleys. In this way we serve a purpose of practitioners for hazard mappings and the protection of the life and property of the people.

One of the dynamical aspects of an avalanche is its velocity distribution. It is very important for the practitioners to have proper knowledge of the velocity field in order to estimate the impact pressures (on obstructions and infrastructures), stress and strain rates and so on, in the course of a sliding avalanche down a mountain topography. From a structural engineering and planning point of view one must know the velocity field properly in order to design buildings, roadways and rail transportations in mountainous

\*We use the “.” marks because there are still some restrictions that must be observed in this general model.
regions. Equally important is the fact that one is always keen to know the velocity field of flowing granular materials and the fine granulates through various channels in process engineering scenarios in order to predict the flow dynamics. In this regard, the final task is the corroboration of the physical adequacy of the model equations, efficiency of the numerical method and the harmony of them with the (laboratory) experiments performed under essentially well controllable circumstances together with an advanced measurement technique. The Particle Image Velocimetry (PIV-measurement technique) is used to measure the dynamics of the velocity distribution of the free-surface flows of avalanches down curved chutes merging into horizontal planes. To our knowledge, such experiments have not been performed before. Ultimately, it is demonstrated that the theory, numerics and the experimental results are in excellent agreement.

1.2 Goals, Methods and Structure

Goals

There are three main aims in writing this thesis. They are as follows.

- Creation of a quite new theory that can model the flows of debris and avalanches down non-trivial and complicated mountain topographies in geophysics as well as flows of powder and granulate bulk materials through general channels in process engineering scenarios.

- Solving the complicated time-dependent non-linear hyperbolic model equations thus developed to describe flow avalanches from initiation to deposit in the run-out zones. Solutions of these equations should capture the underlying physics of the whole process. Therefore, we need to develop and apply some sophisticated and modern numerical methods, namely, the Total Variation Diminishing (TVD) shock-capturing methods with various TVD-limiters. As one of the major challenges of debris flow is concerned with the underlying topography, we must be able to apply these numerical schemes to different topographic configurations - from simple to complex bed geometries so that they serve as benchmark status for the practitioners.

- Do the model equations represent the physics we are looking for? Or, are they merely some useless calculations? Are the numerical schemes we are using reliable and able to cope with the physics of the model equations? The proper answers to these questions can only be established through field and/or laboratory experiments. The ultimate goal should thus be the corroboration of the theory and numerics with the experimental measurements regarding the velocity distribution and the evolution of the depth profile as an avalanche slides down over a given topography from initiation to the deposit, describing the entire dynamics. For this, some modern measurement techniques, like Particle Image Velocimetry, should be utilised.

Methodology

In order to achieve these lofty goals various advanced methodologies must be used. For the physical-mathematical modelling of avalanches one needs advanced knowledge of differential geometry, partial differential equations, material properties, flow rules and dynamical
aspects of large as well as small scale geophysical fluid dynamics. Due to the hyperbolicity and non-linearity of the model equations, they can only be solved properly with the help of Non-Oscillatory Central (NOC) differencing schemes together with various TVD limiters. Furthermore, the Particle Image Velocimetry (PIV)-measurement technique is used to measure the velocity distribution of the particles at the free-surface and at the bottom of the avalanching mass. PIV-measurements can also be used to determine the evolving boundary, whereas penetrometers can be used to measure the depth profile of the deposit of the avalanche.

Structure

The entire thesis is divided into four parts: introduction, theory, numerics and experimental validation.

**Part I** consists of two Chapters. The first Chapter presents the introduction and motivation for avalanche research and necessities for avalanche studies. Snow avalanche hazards and fatalities and casualties from different kinds of avalanches are reported. The major international scientific activities in avalanche and debris flow research are discussed in brief which provides a forum for researches in the international community to exchange the ideas on how to cope with avalanche and debris flow hazards. Chapter two provides a wide and general definition of avalanche dynamics as a rapid motion of large scale geomaterials like snow and debris down the side of a complicated mountain terrain. Dynamical aspects of avalanches like its track, run-out zone and impact pressure, are discussed in short. Some important and fundamental applications of avalanches, both in geophysics and process engineering scenarios, are presented. Other aspects contained in this Chapter are the division of avalanches into flow and powder types, and intermediate states between them. A survey on some classical avalanche models is presented. The limitations and drawbacks of the classical models indicate the necessity of a new model.

**Part II** contains three Chapters, all dealing with developments of continuum mechanical theories for different topographic descriptions. A short review of a continuum mechanical theory of granular avalanches flowing down a basal topography whose talweg lies essentially in a vertical plane aligned parallel to the steepest descent (main flow direction) is presented in Chapter three. For the first time we have put the Savage-Hutter avalanche model equations into a frame of a theory that is well defined and well structured from both a mathematical and a physical point of view. The assumptions, inputs and outputs of the theory are listed in a systematic manner. Generalisation of the theory for two and three dimensional basal topographies are presented. Advantages and limitations of the theory are explicitly and systematically listed which can not be found in other existing literatures. Chapter four is one of the most important parts of the present research work. This Chapter presents a complete and detailed derivation of a recently developed theory for the gravity-driven free-surface flow of an avalanche over arbitrarily curved and twisted topography which is a very important extension of the original Savage-Hutter model. The new theory includes the simultaneous effects of the curvature and torsion on the flow avalanche in channels which could not be investigated before. This makes the present theory applicable to realistic avalanche motions down arbitrarily guided topographies such as valleys and channelised corries. Digital data from Geographical Information Systems (GIS) of mountainous avalanche-prone regions can be applied to this model in
order to construct the hazard maps. Special features and the importance of the new theory are presented. It is shown that these new model equations can reproduce all previous extensions of the Savage-Hutter equations as special cases. The theory is developed from a completely different topographical point of view in which not only the talweg but also the entire basal topography can be curved and twisted. The model equations are put into standard conservative form to analyse the flow behaviour. Finally, comparison of these model equations with previous equations is presented. Analogously, Chapter five presents a short review of yet another new theory, specially designed for particular bed topographies, helicoidal surfaces. Such surfaces are used in industrial and technical applications in the transportation of solid bulk materials like capsules and pills in the pharmaceutical industries, grains in the agricultural and food producing industries, and powder substances in chemical process engineering. This then provides proof that the Savage-Hutter model equations can also be extended for flow avalanches through a very special channel that serves the purposes of investigations of the flow through particularly designed chutes. A short discussion is presented in order to differentiate this model from other model equations.

Part III, which deals with the numerical methods and simulations of the model equations presented in Chapter four for different topographic situations, is divided into three Chapters. (These are the hyperbolic partial differential equations mentioned earlier.) High resolution shock-capturing numerical methods are developed in Chapter six. Numerical difficulties of the model equations with traditional numerical methods are discussed and appropriate modern numerical methods, like NOC, ENOC (Essentially Non-Oscillatory Central Differencing) schemes with different TVD limiters, are presented in detail for non-linear one-dimensional conservation laws. Similarly, Chapter seven extends the one-dimensional shock-capturing numerical scheme of Chapter six to a two-dimensional system of conservative equations. This two-dimensional shock-capturing method is applied to the extended Savage-Hutter equations of Chapter four. Chapter eight deals with the numerical simulations of avalanches in topographies ranging from simple to complex configurations. The performances of various numerical schemes are discussed here. It is shown that the NOC scheme with Minmod TVD limiter demonstrates the best numerical results for simulating avalanche dynamics, with among others (e.g., Woodward and Superbee), limiters and ENO cell reconstructions. First, numerical simulations are presented for simple and torsion-free topographies which include the basal surfaces: curved down-hill but laterally flat; cylindrically curved down-hill and channelised in the cross-slope direction - for both cases with constant and variable cross-slope curvatures. Simulations are presented for superimposed basal topographies with laterally flat and curved reference topographies. For all these cases, results are presented and discussed in detail. Second, a large number of simulations are performed for complex and non-trivial topographies. These topographies include uniformly and non-uniformly curved and twisted channels with constant and variable channel widths. It is shown via different numerical simulations that the new theory developed in Chapter four is able to include the simultaneous effects of curvature and torsion in the dynamics of an avalanching mass over (generally) curved and twisted (mountain) topography. This is an entirely new aspect in the field of avalanche research. These numerical simulations disclose the unknown physical processes and discover some fundamental aspects of the avalanches in order to judge about the applicability of the new-model equations in reality. Similarly, simulations are presented to investigate the
sensitivity of the phenomenological parameters and the pressure dependence of the friction angles. It is shown that the dynamics of the avalanche is fairly sensitive to variations of the bed friction angle but less sensitive to the variation of the internal friction angle. Also, we have introduced a linear dependency of the bed friction angle with the over burden pressure of the granular pile. However, this destroys the scale invariance of the model equations.

**Part IV** deals with the experimental validation of the theoretical prediction of the model equations. There are three Chapters in this part. Chapter nine gives a brief review of the theory of the PIV-measurement technique mainly designed for the velocity measurements in transparent fluids. Next, we introduce a “Granular-PIV” in order to measure the velocity distribution of the particles at the surface and bottom of the free-surface motion of an avalanche. Technical details, such as the set-up of the “Granular-PIV” and particular and general problems arising in the Granular-PIV are pointed out in brief. Chapter ten presents experimental results and brings all items together (i.e., theory, numerics and experiments). It is very important for the practitioners to have proper knowledge of the velocity field in order to estimate the impact pressure on the obstructions and infrastructures. The PIV-measurement technique is used to measure the dynamics of the velocity distribution of an avalanching flow down a curved chute that merges continuously into the horizontal run-out zone. Similarly, the evolution of the avalanche boundary and the depth profile of the deposit are measured. Experimental details are explained and the problems are outlined. Excellent agreements between the theoretical predictions and experimental measurements are established. Finally, Chapter eleven contains the summary of the present work and provides an outlook for future research.

### 1.3 Necessities of Avalanche Studies

Snow avalanches, landslides, rock falls and debris flows are extremely destructive and dangerous natural calamities. The frequency of occurrence and amplitudes of these disastrous events appear to have increased in recent years, possibly due to an increase in land use and development activities, anticipated warming of the Earth’s atmosphere, the associated increase of extreme storms, poor forestry practices and land misuse in the mountainous areas. This implies an increase in damage and consequently leads to large casualties. Mountainous regions are always gravely affected by such phenomena as they endanger the public life and properties and infra-structures. Reliable methods for the prevention and/or reduction of the effects of such disasters are therefore in great need. Evidently, civil engineers, forestry engineers and concerned authorities who are responsible for the planning and development in these regions have considerable interest in it.

#### 1.3.1 Snow Avalanche Hazards and Fatalities

The number of avalanches falling annually in the United States is on the order of $10^5$. And the number of avalanches falling annually world wide is on the order of $10 \times 10^5$. According to U. S. statistics (around 1986) about one percent of the total avalanches causes serious problems: injury, death, and destruction of property. Based on this report, about 140 people are caught annually in avalanches, 60 – 70 are partly or wholly buried, 12 sustain injury, and 17 are killed. Austria, Switzerland each report 35 – 40 persons killed.
by avalanches per year, France 31, Italy 20 – 30, Japan 30, Norway 10 – 15, Germany 10 and Canada 7 [4]. Furthermore, HUTTER [52] explains that the capital that is invested for direct and indirect prevention of damage and casualties due to snow avalanches is much more than the average money spent for insurance claims, more than 50 Mio Swiss francs per year in Switzerland alone.

Snow and debris avalanches are natural hazards that occur in many parts of the world. They have been responsible for casualties of insured and dead people as well as the destruction of railways, bridges, and houses. Avalanches are typically associated with steep mountainous areas. The early avalanche victims were travellers and soldiers. By the Middle Ages, the mountain valleys of the Alps were inhabited but its dramatic population increase occurred in the 20th century. The earliest reference of avalanche deaths is from the year 1118 in Iceland [5, 6]. FLURY SPRECHER VON BERNEGG (who was responsible for recording all kinds of unusual events occurring in the Davos environs) recorded the first avalanche prone death in Davos, Switzerland. In 1449, he described an avalanche which destroyed 4 buildings and killed 11 people. Four people were buried for 24 hours but were rescued alive. This was the first entry in the Swiss avalanche history. The next entry was made on January 16, 1602 to describe a similar type of avalanche hazard in which 13 people were found dead under the snow; a fourteen year old girl was found alive after being buried in the snow for 36 hours. Two of the worst years in the avalanche history of Norway were 1679, which killed between 400 – 600 people, and 1755, which killed about 200 people, as records show [4]. McClung [79] reports about the avalanche deaths in the Himalaya. From 1895 to 1979 some 200 mountaineers and porters had died by avalanches, making this the greatest killer of a number of expeditions to the world’s highest mountains. The Mt. Everest leads the list with 34 killed, followed by Nanga Parbat (20), Dhaulagiri (17), Manaslu (17), and Annapurna (12). Avalanche history in North America is just over a century old but full of devastating property damage and loss of human life. As for the US in 1898, during the month of April alone, 72 gold seekers died in an avalanche, while another 49 were buried or caught in Alaska. “The worst disastrous avalanche in the history of the United States occurred in March 1, 1910 near the town of Wellington in Washington. The final death toll was 96, with 22 survivors among 118 victims. Beneath the snow lay two trains, three steam locomotives four electric locomotives, a rotary snowplow, several boxcars, an engine shed, a water tower, and telegraph poles and wires!” [4]. Also a surprising fact is that during World War II, soldiers were fighting battles in the mountains of alpine regions, and avalanches were used as weapons of destruction. Fraser [24, 25] estimates that some 40,000 – 80,000 soldiers were lost in the avalanche warfare. From the winters 1940/41 to 1987/88 more than 7000 snow avalanches were recorded in Switzerland with damaged property leading to a total of 1269 deaths. The deadliest avalanches in recent years struck Southeast Turkey in 1992. Heavy snowfall resulted in about 10 m of snow. The thick layer of snow, on the steep mountain side, triggered numerous devastating avalanches over several days. Whole villages were buried and hundreds of people were killed. Included in that total are as many as 104 paramilitary police officers, [138, 145]. In Europe, a suddenly released debris flow in North Italy in August 1998 buried 5 German tourists on the superhighway “Brennerautobahn”.
1.3.2 Different Avalanche and Debris Flow Types & Casualties

According to the American Avalanche Association, AAA, millions of snow and ice avalanches occur each year in the entire world and cause numerous casualties. It is evident that with increasing population, popularisation of the tourism and recreational activities in the mountainous countries, the damage equally increases leading to large casualties. Debris flows, like snow avalanches, are common and worldwide phenomena of mass wasting and they often cause serious hazards. Debris-flow hazards including mudflows, hyperconcentrated flows and volcanic debris flows (called lahars: a lahar is a hot mud flow) are often caused by exceptional meteorological and geological events and then are only part of the natural disaster. Furthermore, landslides, rockfalls and snow and ice avalanches that initiate on steep slopes can travel large distances before they come to rest. Their occurrence is largely unpredictable and in mountainous regions, like the Alps and the Himalaya, they often continue to be a threat both to human life and property. Research in avalanche prevention and the study of their dynamics are therefore important responsibilities of most mountainous nations.

Figure 1.1a shows a view of the Gondo spitting mudflow of 14th October 2000, and destruction of the village of Gondo (Switzerland) and roadways [141]. The rain which had been falling incessantly in the area around the village of Gondo for 48 hours triggered off a 10,000 m$^3$ spitting mud flow. The flow composed of mud and blocks caused 14 deaths and destroyed a dozen buildings including the 400 year old Stockalper tower.

Being a mountainous country, Nepal is frequently and badly affected by hundreds of landslides each year during the rainy season. The biggest and massive landslides triggered by heavy monsoon rains in the year 2002 buried alive at least 44 persons and displaced nearly 228 families of two villages in the eastern hilly district of Khotang, 200 km south-east of the Nepalese capital Kathmandu. Forty-two persons were buried in their sleep.
1.3 Necessities of Avalanche Studies

(a) Debris flow in Kirgizstan – Glacier moraines in Tuyk Valley, Alaarcha basin North Tien Shan. The moraine to the left has been displaced by a (probably seismically induced) debris flow. (courtesy of Dr. V. Aizen, University of California, at Santa Barbara).

(b) A white death: Snow avalanches killed 38 people in the tiny town of Galtür, Austria in 1999, picture sources [138, 139]

Figure 1.2: (a): Debris deposition in Taiwan, (From [43], courtesy Sino-Geotechnique Research and Development Foundation, Taipei, Taiwan). (b): Debris flow in Kirgizstan – Glacier moraines in Tuyk Valley, Alaarcha basin North Tien Shan. The moraine to the left has been displaced by a (probably seismically induced) debris flow. (courtesy of Dr. V. Aizen, University of California, at Santa Barbara).
(c) A white death: Snow avalanches killed 38 people in the tiny town of Galtür, Austria in 1999, picture sources [138, 139]

at Sanmal village including seven members of a family and 13 travellers lodged for the night in one house. Another landslide buried two others in Dipsey village. The incessant rains triggered the landslides at 2 am. July 15, 2002. The landslides had fallen about two kilometers above the villages. Sixteen victims were rescued and airlifted to Kathmandu and nearby hospitals for treatment. Around 300 livestock were also killed by the landslides. A week later, in a period of 5 days, 94 persons were killed in Makwanpur district in floods and landslides triggered by rains while 26 died in Kathmandu Valley, see Fig. 1.1b. Similarly, in the last week of August, 2001, in Khotang and Okhaldhunga districts, a landslide buried 15 houses. In the year 2000, floods and landslides triggered by incessant rains claimed at least 160 lives across the country [144].

Fig. 1.1c shows the destruction of settlement and roads caused by debris flow in the Aosta-Valley in Italy [137]. Figure 1.2a shows another debris deposition in a forest area of Taiwan with a huge amount of boulders on the surface of the depot. Figure 1.2b represents a quite different situation. The picture demonstrates a moraine debris in Kirgizstan that is transported by a glacier in Tuyk Valley, Alaarcha basin North Tien Shan. The moraine to the left has been displaced by a debris flow. Geologists conjecture that this debris could probably have been induced by a strong seismic wave.

The Alpine region of Europe suffers more avalanches than anywhere else in the world. In two months (January and February, 1999), more than 70 people have been killed in avalanches throughout resort towns in France, Italy, and Switzerland, and the rest of Europe, [140]. A four-week period beginning in late January 1999, provided a tragic reminder that ski resorts were an environment prone to natural disaster, in Galtür, Austria, see Figs. 1.2c and elsewhere in Europe. It was the worst alpine natural disaster in more
1.3.3 Common Properties of Natural and Industrial Avalanches

Usually, granular avalanches occur when a large layer of granular material becomes unstable. Rockfalls, landslides, debris flows and snow-slab avalanches are examples of granular avalanches in geophysical contexts. Similarly, flows in silos, hoppers, rotating drums and slag heaps are examples of granular avalanches in industrial applications, see Fig. 1.3. Although there is an enormous difference in length-scale between the geophysical and industrial avalanche flows, the dominant and principal physical mechanisms that drive the flow are similar. Dense flow avalanches of rock, ice and snow are gravity-driven flows that are observed in the natural environment on a very wide range of length scales. Gray et al. [31] mention that in geophysical contexts, rockfalls, landslides and snow-slab avalanches may set in motion up to $10^{10}$ m$^3$ of material whereas in industrial flows in silos, hoppers, rotating drums or on slag heaps the volume of the material is of the order of several cubic centimetres to several hundreds of cubic meters. Three key prehistoric events in rockslides are presented in Table. 1.1. These are huge events in the history of rockslides. In fact, it is believed that size effects enter only for very large avalanches [111].

1.3.4 International Scientific Activities

Within the scientific community, the field of snow and avalanche research is a relatively new and young field. Until the 20th century scientists had not attempted any systematic studies of the physical aspects of the mountain snowpack, mechanical forces causing avalanches and avalanche dynamics. Winter mountaineering and skiing seems to have become fashionable only at the beginning of the last century. Interest in avalanche research developed gradually due to mountaineering and skiing. First avalanche studies took place than 40 years. On 25 February, 1999, heavy snow in the central Alps provoked avalanches which killed more than 30 people. A snowslide hit the village of Galtür at more than 160 kmh$^{-1}$ $\approx$ 44 ms$^{-1}$, while an avalanche as tall as a house plunged down the Chamonix valley in France. The heavy death-toll was the result of the avalanches penetrating inhabited areas; as a rule, the victims are climbers, skiers and snowboarders on the slopes.

Figure 1.3: Piling of a mixed bed of granular materials in a cement industry, an example of granular flow and avalanche in process engineering. Different grey scales of the heap correspond to different ingredients of the mixture of cement. The material is continuously deposited from a quasi-static point source. The material flows rapidly down the faces of the heap in shallow layers. During the downward flux of the fine mixture of granular material, particle segregation according to size, density or resilience takes place. (courtesy of MVT Maschinen- und Verfahrenstechnik Bernhard Blatton GmbH, Dillingen)
1.3 Necessities of Avalanche Studies

Table 1.1: The table represents the three key and huge rockslides in the prehistoric period. The table also indicates the fact about long run-out of large events in terms of the total overall slope corresponding to the total overall distance travelled by the moving mass in the longitudinal flow direction. The data are taken from [23].

<table>
<thead>
<tr>
<th>Event</th>
<th>Volume</th>
<th>Material</th>
<th>Overall Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flims (Switzerland)</td>
<td>$10^{12}$ m$^3$</td>
<td>Limestone</td>
<td>0.07</td>
</tr>
<tr>
<td>Köfels (Austria)</td>
<td>$10^{10}$ m$^3$</td>
<td>Augengneiss</td>
<td>0.18</td>
</tr>
<tr>
<td>Langtang (Nepal)</td>
<td>$10^{10}$ m$^3$</td>
<td>Migmatite/gneiss</td>
<td>-- --</td>
</tr>
</tbody>
</table>

in the European Alps around the beginning of the 20th century, and half a century later in the United States. Serious research on this field was started in 1936 when the Swiss founded their own Snow and Avalanche Research Institute in Davos [107]. Subsequently, similar centres were established in France, Canada, USA, Russia and other countries as well. These institutes are now leading centres for fundamental and applied avalanche research.

European scientists built the foundation of snow and avalanche knowledge in the late 1930s and 1940s. The Swiss Federal Institute of Snow and Avalanche Research (SFISAR) was founded in 1936 and the French institute (CEMAGREF) followed in 1949. The Americans and Canadians joined these efforts in the 1950s. Modern research has made advances and refinements of the basic principles, and we now have a fairly detailed understanding of the physical and mechanical processes in the snow pack which led to avalanche formation.

The large number of calamities expressed in huge economic losses and insured as well as dead people are the reasons why the general assembly of the United Nations passed a resolution on December 11, 1987, designating the 1990s as the International Decade for Natural Disaster Reduction. This resolution was aiming at promotion of international awareness and the scientific research activities on natural and man-made disasters, for more details, see [116]. In Germany, there is the Deutsches Komitee für Katastrophenvorsorge e. V., an active committee, for disaster reduction within the International Strategy for Disaster Reduction (ISDR). The UN marked 2002 as The International Year of Mountains, IYM-2002, in order to increase global awareness of how important mountains are to life on earth, and accidents or damages arising from natural hazards. For this purpose, national committees were formed in 78 countries. Special international conferences are devoted and held regularly on these topics, e.g., the CALAR-Conference on Avalanches, Landslides, Rock Falls and Debris Flows, Vienna, January 2000; INTERPRAEVENT-annual conferences on the protection of habitants from floods, debris flows and avalanches; (DFHM)- International Conference on Debris-Flow Hazards Mitigation, the first and second, respectively, held in San Francisco, California, U. S. A., and Taipei, Taiwan and the third held in September 10 – 15, 2003, Davos, Switzerland, in order to provide forums for debris-flow researchers in the international community to exchange ideas on how to cope with debris-flow hazards using the most advanced state-of-the-art methodology both in mechanics and hazard prediction and risk assessment. This has drawn attention to the importance
of reliable recognition of natural avalanche paths and predicting deposition zones.

Within the avalanche research community regular conferences, workshops and symposia are held that are exclusively devoted to snow behaviour in its cover and to avalanching motion of snow. The International Glaciological Society has held two conferences, 1992 and 2000 that were exclusively devoted to snow and additional conferences in 1996 and 1998 in which the dynamics and thermodynamics of snow and ice were central topics of interest. The International Glaciological Society held an *International Symposium on Snow and Avalanches* in Davos, Switzerland, 2 – 6 June 2003. The reason for this is that in most mountainous areas, avalanches pose a significant threat to human life and property. Profound knowledge of avalanche initiation and avalanche dynamics opens up new and powerful prospects for improving avalanche forecasting, hazard mapping and technical measures for an integrated risk-management approach. The conference proceedings, *Annals of Glaciology*, are a continuing flow of source of the most recent research both from a fundamental and applied point of view.

Many universities throughout the world offer special courses in snow and avalanche research at various levels of their education. These courses are offered in Departments of Civil and Environmental Engineering, Geography, Natural Sciences or Geophysics. In the department of Civil Engineering, Montana State University, the research specialities contain snow mechanics – particularly avalanche dynamics; flow of granular materials and physical properties of snow and ice. Different programmes are conducted in research fields such as measuring snow avalanche flow properties like flow velocity, density, stress and other mechanical properties within a flowing avalanche; modelling avalanche dynamics as granular fluid flow and the development of models of avalanche motion based upon the mechanics of granular material which is useful for the prediction of avalanche runout and impact pressures. These educational efforts guarantee for a continuous flow of young scientists that are willing to carry the avalanche science into the future.

An important area for future research is probably the measurement of speed and temporal spatio evolution of the depth profile as well as density of the flowing avalanche. This information is critical for researchers who seek to model moving avalanches, and avalanche practitioners who must use the research for decision-making, such as evaluating maximum avalanche path run-out distances and zones for determining where to allow construction or highway development and where and how to use protection measures against avalanches.
Chapter 2
Granular Avalanches: Definition, Related Concepts and a Review of Classical Models

2.1 The Complexity of Granular Materials

A granular material is a collection of a large number of discrete solid particles with interstices filled with a fluid or gas. Granular materials show distinctive behaviour that manifests itself either as that of solids or liquids or gases. For instance, powders pack like solids and flow like liquids. All these effects originate in the ability of granular materials to form a hybrid state between fluid and solid. In fields such as process engineering and production technology, feeding and discharging particulate materials into and from storage systems of any kind (e.g., silos and hoppers) are typical operations of bulk solid handling that give rise to granular flows. Snow, rock or powder avalanches, debris or pyroclastic flows or the formation of dunes are typical examples of granular flows in the geophysical context. Many interesting properties of granular materials can be observed through granular flows. Among these are species segregation, avalanches, dilatancy, reverse grading, formation of shear bands, Brazil nut effect and fluidisation, all important phenomena arising in cohesionless particle systems of geophysical or industrial applications.

2.2 Applications of Granular Flows

There are numerous applications of flows of granular materials both in Nature, technology and engineering applications. Here we will explain some of them that we often encounter in process engineering and geophysical flow systems of particulate materials.

2.2.1 Chemical Process Engineering

Particles are important products of chemical process industries, agricultural products, pharmaceuticals, paints, dyestuffs and pigments, cement, ceramics, and electronic materials. Solids handling and processing technologies are thus essential to the operation and competitiveness of these industries. In chemical engineering mention might be made of fluidised beds, spouted beds and manufactures of pharmaceuticals. All these arise in one
form or another when bulk matter has to be moved. Methods of xerography (called electrophotography, method of dry photocopying in which the image is transferred by using the attractive forces of electric charges; ionised plastic particles, called toner is introduced that sticks to the charged areas, the powder is then fused to the paper with heat), powder material forming (development of new materials by means of powder consolidation), powder metallurgy processes (material forming processes based on powders which are used in various industries like automobile industries to produce motors, gears and break pads; in abrasives for polishing and grinding wheels; in manufacturing for cutting and drilling, etc.) and ultra-structural processing of ceramics and novel coating techniques (advanced coating technology for granular and other materials) are just a few examples which require the knowledge of granular flows.

2.2.2 Geophysical Flows

In natural sciences one can find examples from geophysical applications such as landscape formation by landslides, rock, ice and snow avalanches, debris and pyroclastic flows. Although these examples might seem to be of very disparate nature they in fact have many similarities. This is why during the past three decades research into the fundamental mechanisms of granular and geophysical flows have increased both in space and scope. Despite their everyday familiarity granular flow systems have become paradigmatic systems of complexity. Because of the practical importance, granular flows and avalanches have been studied by many researchers from different disciplines who have presented their own models on it. A collective review on it can be found in [41, 50, 97].

2.3 Granular Avalanches

2.3.1 Definition

By the term avalanche we mean a rather large mass of snow, ice or rock that slides rapidly down the side of a mountain. When great masses of snow, ice, rock or soil crash down the side of a mountain, the result is an avalanche. Avalanches are most often huge and sweep down the mountain-sides with tremendous impact force and roar like thunder. Everything in their path is swept away – railways, highways, buildings, trees, people, and animals. Nevertheless, many times they may be small and simply block a path. An avalanche will continue down a mountain until the elevation of the mountain starts to decrease and flatten out where the avalanche will then pile up. It can also lose speed down the mountain depending on how large the slope is and how much snow or debris is in the mass. The more mass, the longer an avalanche will travel.

The word avalanche is directly derived from the old French avalanste, meaning to let down, lower, or go downstream. Similarly, the Latin derivative of “Lavina” gives rise to the German word for avalanche which is Lawine, meaning to slip or glide down. There are different types of avalanches: rock avalanches, which can bring down millions of tons of granite or other mountain-forming materials, which may change the land forever; soil avalanches and mudslides which are caused when water-saturated soils break loose and flow down a mountain side; also ice avalanches, which always contain some snow but are primarily made up of glacier ice. More generally and broadly speaking, a granular
avalanche represents the gravity-driven free surface flow of a continuum granulate medium down a steep slope, often initiated by an instability of a granular layer. For better understanding we refer to Fig. 2.1a, b. It shows (panel a)) a deposit of (wet) snow from a flow avalanche and (panel b)) a snapshot of a laboratory avalanche: a mixture of sand and gravel (40 kg) is released from a spherical plexiglass cap and moves down the gully. Both pictures indicate similarities at least in the run-out zones which may be a good motivation to model avalanches from a physical–mathematical point of view and validate the model from a well controlled laboratory test.

Possible motional mechanisms for rockfalls, rockslides, landslides, mud flows and avalanches are gravity driven, potentially catastrophic, fast displacements of more or less considerable debris masses. The most characteristic feature of such events consists in the dominance of a rapid descent over a steep mountain slope. If the displacement takes place in a very steep slope it is often called fallings. For a rockslide or a rockfall, while descending, a high amount of the total weight acts as a motor and only a limited one is able, by generating friction, to produce a breaking effect. The result is not only a high rate of acceleration (in
extreme cases; depending on, e.g., the material properties, topographic conditions and its slope; it is practically nearly equal to the gravitational acceleration) but also an almost equal velocity of all moving elements is observed as long as the atmospheric drag is not a substantial limiting factor. An interesting fact in case of a rockslide is that sometimes the event can be triggered neither by a particularly heavy earthquake nor by abnormal precipitation but entirely by long term degradation of the rock material’s strength.

These phenomena, collectively referred to as avalanches, can be physically characterised as multiphase gravity flows, which consist of randomly dispersed, interacting phases, whose properties change with respect to both time and space. An avalanche can be described as the transient, three-dimensional motion of a variable mass system made up of a non-rigid, non-rotund, non-uniform assemblage of granular (snow) fragments flowing down a non-uniform slope of varying surface resistance [71]. In this sense, an exact analysis of the motion of an avalanche is perhaps an unattainable goal. Thus, we may define the avalanche as follows:

**Definition:** An avalanche can be described as a transient, three-dimensional gravity-driven free surface motion of a mass system made up of an assemblage of granular fragments initiated by an instability of a granular layer and flowing down to the run-out zone on an arbitrarily steep topography with any surface resistance.

### 2.3.2 Avalanche Dynamics

How does an avalanche move, how fast, how far and with how much destructive power? The answer to these, and similar, questions are contained in the topic avalanche dynamics. The science of avalanche dynamics was not well advanced till the middle of the 20th century. Perhaps, the main reason could be a lack of measured data for avalanche velocity, height and impact pressures and the complicated geometric features on which the flow takes place. Methods to predict avalanche velocity, run-out zones and associated impact forces were first developed in Switzerland in the 1950s due to the availability of historical and initial experimental data of their own [1]. Here we address some important aspects of avalanche dynamics.

**Avalanche Paths**

They are divided into three parts with respect to the dynamics. The *starting zone* is usually the steepest part of the entire path. Here the avalanche breaks away, accelerates down the slope and picks up additional material (snow or debris) as it moves. From the starting zone the avalanche moves into the *track*, where the velocity generally remains more or less constant and little or no additional snow or debris is added to the moving avalanche and the average slope angle has become less steep. This is where small avalanches stop, because they do not have enough inertia to flow further. After travelling down the track it reaches the *run-out zone* where the avalanche motion ends, either abruptly as it crashes into the bottom of a gorge or deep narrow valley with deep sides, see Fig. 2.2a. Or it can stop slowly as it decelerates across a gradual slope. As a general rule, the slope angle of starting zones is in the range of 30° to 45° or more, of the track it is 20° to 30° and of the run-out zones it is less than 20°. In most cases the avalanche simply flows a path down the steepest route on the slope while being guided or channelled by terrain features, such
as the side walls of a gully, which normally direct the flow of the avalanche to the bed. This holds for so-called flow avalanches but not for powder snow avalanches.

**Run-out Zones**

Large masses, like rockslides and avalanches, move more economically and thus reach farther than smaller ones. The effect was first investigated by Heim [40]. The existence of long-run-out events is a significant obstacle for a reliable mathematical modelling of such flows with the intention of predicting the threatened area.

One of the most complicated and practically relevant aspects of avalanche dynamics is the effort to predict how far an avalanche will continue to flow or travel after it has reached the run-out zone. An equally important question for avalanche practitioners and civil engineers is how much area it will hit and how the deposition profile may look like. These areas are important from an infrastructure point of view.

**Impact Pressures**

Besides the reach of an avalanche, or a rockslide, also the velocity at any point of its travel is of outstanding importance. The destructive power of an avalanche may be estimated by
its velocity $v$ and density $\rho$, since $\rho v^2 / 2$ has the dimension of a pressure. This is called the impact pressure by avalanche dynamicists and stagnation pressure by fluid mechanicians, and it shows that the speed is a decisive variable in determining the forces exerted on the structures by the moving snow. Smaller and medium sized events may have impact pressures of $10^4$ Pa (0.1 bar), but in very large avalanches they may reach as much as $10^7$ Pa ($10^2$ bar) and are then able to uproot a large part of the forest and destroy solid buildings. Sometimes it can even derail an entire train transport, see Fig. 2.2b.

2.3.3 Pattern Formation by Granular Avalanches

In this section we will give a brief account on small scale avalanches in a thin gap between two vertical plates, rectangular or circular. Development of patterns and mixing, demixing and segregation of particles in silos, hoppers, heap formations and in transportation of mixtures of fine grains are related to the nature of avalanches. This justifies the fact that the study of avalanches is important not only in nature but equally also in process engineering scenarios.

A successive deposit of granular avalanches may exhibit strong pattern formation. Continuous deposition, erosion or rotation gives rise to intermittent avalanche release at low flow rates. Once in motion kinetic sieving of a bi-disperse granular mixture creates two-layer shear bands in which the larger particles overlie the smaller particles. When this motion is suddenly brought into rest by the upstream propagation of a shock wave a pair of stripes is generated in the deposition. Successive releases of the granular materials create a large scale pattern reflecting the strong history of the flow [29]. In the following paragraphs, we describe three mechanisms for avalanche initiation and particle size segregation together with shock waves that bring the avalanche quickly to rest. These phenomena lead to pattern formation within the deposited material. All the experiments take place between parallel plates with a spacing of 3 mm, which prevents lateral spreading of the avalanche and exerts an additional wall friction that slows the avalanche speed. A binary mixture of cohesionless (white) sugar crystals and (dark) spherical iron powder with mean grain diameters of 0.5 mm and 0.34 mm, respectively, is used with mixing ratio by volume 1 : 1.

Particle Size Segregation and Shock Waves

One of the most fundamental characteristics of an avalanche is that it has the ability to act as a kinetic sieve; this, in turn, sorts the granular material by its grain size distribution. Consider a typical roll wave configuration on an inclined slope as shown in Fig. 2.3a. As the grains are sheared gaps between the particles are continuously created and destroyed completely. Under the action of gravity the smaller particles are more likely to fall into the space available in the granular heap. An inverse grading of the particles rapidly develops in which the larger particles overlie the smaller particles. The white particles overlie the dark (smaller) particles, thus forming two-layered shear bands (i.e., stripes). The larger grains are transported to the front whilst the smaller grains concentrate at the rear of the avalanche. This phenomenon, as shown in the picture, Fig. 2.3a, is due to the fact that the surface of avalanche moves faster than the base. Dispersed shock waves (see Fig. 2.3b) in granular avalanches, which bring the granular material rapidly to rest, are important agents for pattern formation. Shock waves are initiated when the avalanche front reaches the base of the slope, or a solid wall, and propagates rapidly upslope freezing the particle
2.3 Granular Avalanches

Figure 2.3: Pictures showing pile formation by pouring a mixture of (white) large and (dark) small particles between the slit of two parallel plexiglass plates. a) Photograph and schematic diagram of a granular avalanche in a typical roll wave configuration. An inverse graded particle size distribution rapidly develops in which the large particles overlie the small particles forming a stripe. Shearing of the velocity through the avalanche thickness transports the larger particles to the front of the deposit. b) Photograph and schematic diagram of the upward propagating dispersed shock wave. The material below the shock is at (or nearly at) rest, whilst the grains above it are flowing rapidly downslope. (From [29], courtesy of Continuum Mech. and Thermodyn., Springer Verlag, Berlin, Heidelberg)

size distribution into the deposited granular material, thus preserving the pattern formed during the avalanche motion.

Avalanches in thin Vertical Piles of a Mixture of Fine Granules

In a first experiment, consider two vertical plexiglass plates forming a narrow gap. Together with a basal plate and two side walls they form a plane two-dimensional “silo”. The mixture is poured into this silo of dimension 70 cm high by 34 cm wide from a point source at the top-center. Although the material is continuously deposited at the top of the pile, it does not flow immediately down the faces because of the difference between the static and dynamic internal friction angles. Once the static friction angle is exceeded the avalanche flows down the face of the pile and forms a roll-wave, in which kinetic sieving takes place, see Fig. 2.3a. As soon as the avalanche reaches either the base or the side walls of the silo, it is rapidly brought to rest by the upslope propagating shock wave, as shown in Fig. 2.3b. These upslope moving shock waves freeze the particle size distribution created by the inverse grading into the deposited granular material and thus preserve the pattern formed during avalanche motion. Successive and alternating avalanche releases on both faces of the triangular pile build up a sequence of such layers giving rise to a pine-tree pattern, as shown in Fig. 2.4a. It is worth mentioning that there is a tendency for the upslope propagating shock wave to destabilise the granular material on the opposite face of the pile, so that avalanches tend to form first on one side and then on the other.

A small whole of 5 mm length is opened at the center of the silo base. The granular material then develops into an internal core flow, and a vee-shaped rat-hole is quickly formed, as shown in Fig. 2.4b. The granular material on either side of the core is at rest and the pine tree pattern is preserved there. Material is fed to the core by a sequence of intermittent avalanches that flow down the faces of the rat-hole and are initiated by erosion at the base of the avalanche slope. As before, kinetic sieving takes place within
a) A pine tree effect is built up through successive stripe formation and burial. b) When a small hole is opened at the base a core flow develops with the large (white) particle at the center and the small (dark) at the side. c) At low flow rates intermittent granular avalanches penetrate into the central core leaving a straight stripe on the free surface that acts as a tracer particle in the flow. (From [29], courtesy of Continuum Mech. and Thermodyn., Springer Verlag, Berlin, Heidelberg)

the avalanche and the larger particles concentrate in the center of the core whilst the smaller particles are drawn into a dark shear band on either side of the central white core of the silo. If the flow rate is low avalanches can penetrate into the center of the core and come to rest when they hit the opposite side of the rat-hole. A series of initially straight stripes have been sheared and deformed due to the discharge of material from the bottom hole of the silo, as shown in Fig. 2.4c.

A Catherine Wheel Effect

Consider a thin closed circular disk of diameter 25 cm which is filled with the same granular mixture as before with a free surface that lies above the center as shown in Fig. 2.5. In order to emphasise the pattern formation due to the small avalanches, the disk is first laid horizontally and then gently shaken so that all the small dark particles fall to the bottom. Once turned to the vertical position one side of the disk is completely dark, whilst the other is completely white. When the disk is rotated at a constant rate of 100 seconds per revolution intermittent avalanches are formed at the free surface. The intermittency again stems from the difference between static and dynamic internal friction angles. The central circular core of the material remains completely undisturbed due to the slow rotation of the disk. Each avalanche release sorts the granular material, forming a stripe, which is frozen into the deposit by the shock wave and subsequently rotated and buried in the undisturbed material below the free surface. Subsequent releases create a sequence of stripes tangent to the central core, see Fig. 2.5a. This process ultimately creates a Catherine wheel effect after a complete revolution, as shown in Fig. 2.5b.

At faster rotation rates (here < 20 seconds per revolution) the intermittency of the avalanche release, the shock waves and the stripes disappear and a steady-state flow regime dominates, see Fig. 2.5c. The material is continuously released on the upper side
2.4 Types of Granular Avalanches

Figure 2.5: The consecutive pictures demonstrate the formation and collapse of Catherine wheel effect. a) At low rotation rates intermittent avalanche release in a thin rotating disk filled with the granular mixture leads to the formation of stripes tangent to the free surface. b) The disk is rotated to a full revolution to form a Catherine wheel effect. c) At faster rotation speed a quasi-steady flow develops. d) In such a situation the free surface is fixed in space and there is a continuous distribution of particle sizes outside the center core. (From [29], courtesy of Continuum Mech. and Thermodyn., Springer Verlag, Berlin, Heidelberg)

and continuously deposited on the lower side of the concave free surface and is transported between the two positions by a quasi-steady avalanche in which kinetic sieving takes place. The smaller particles are the first to get deposited on the lower half of the free surface because they are concentrated at the bottom of the avalanche and a new pattern develops in which the central core is undisturbed. There is a continuous distribution of grain sizes outside the central core. The distribution starts with a high concentration of small particles near the core and ending with a high concentration of large particles near the outer wall, see Fig. 2.5d.

2.4 Types of Granular Avalanches

There are two limiting cases of avalanche, landslide and rockfall dynamics depending upon the form of motion rather than the quality of the material. Between the two limiting cases
discussed below, a wide variety of avalanches can be found which are sometimes referred to as mixed-type avalanches.

2.4.1 Flow Avalanches

The so-called flow avalanche, see Figs. 2.1a,b can also be understood as a dense gravity driven “laminar type flow” avalanche. In this case the role of the solid particles dominates while that of the interstitial fluid is minor or even negligible. Such flows are typical for many debris- and mud-flows, rockslides, landslides and snow avalanches. On average, the density is fairly high, for snow avalanches it ranges from 150 kgm$^{-3}$ to 500 kgm$^{-3}$. The typical mean velocity ranges from 18 kmh$^{-1}$ to 90 kmh$^{-1}$ $\cong$ (5 ms$^{-1}$ to 25 ms$^{-1}$). Most snow and ice avalanches, when they are formed from a fractured snow pack, develop as flow avalanches. Fresh dry snow tends to form small granules of perhaps, $2 - 3$ mm diameter, wet snow develops into hard snow balls (of several tens of mm diameter), and old snow in the spring which has undergone several metamorphoses (so-called “greasy snow”) consists of ice grains of $5 - 10$ mm diameter. While their behaviour under flow must be different simply because of their different appearance in the deposit, they enjoy the similarities of dense granular flows.

2.4.2 Powder Avalanches

A powder avalanche occurs in a very cold, dry climate. The light powdery snow grains do not stick together well. Sometimes, when strong winds cause this snow to move down a mountain side, it swirls and spins like a huge white cloud. They can be so violent as to uproot large trees and carry them along like match-sticks. A powder avalanche also develops induced and added wind, and much damage to houses is caused by the wind alone. These are less dense and may be called “turbulent type flows” of airborne particles. They are very rapid flows of snow clouds. In this case the role of the fluid and particles is of similar significance, and the flows are termed turbulent two phase flows. These flows are typical for density and turbidity currents, e.g., dust clouds occurring in the desert, in pyroclastic volcanic eruptions in subaquatic turbidity currents and in snow and ice avalanches, see Figs. 2.6 and 2.7. However, such avalanches are less frequent than flow avalanches. Typically, the mean-flow depth, velocity, and density are of the order of magnitude $10 - 100$ m, $50 - 100$ ms$^{-1}$ and $5 - 50$ kgm$^{-3}$, respectively [2].

The above mentioned two situations actually present idealised, limiting cases. Neither of the two types of avalanches is less dangerous. Once either has been triggered off, there is usually little or no chance of walkers, skiers, or climbers to escape its path. By far the most often occurring avalanche is of mixed type, e.g., a flow avalanche overlain by some snow dust. Or a powder snow avalanche may consist at its bottom of a boundary layer of a flow avalanche. Nevertheless, their separate study is helpful because the relevant physics can be more easily described which makes it easier to understand the corresponding physical processes.
2.5 Landslides and Avalanches on other Planets

Like on the Earth, on the other planets of our solar system, such as Mars and Venus, scientists have also observed avalanches, debris flows and landslides. The reason is that these planets also consist of large ranges of mountains covered by ice, glaciers, rocks and soil.

Mars has (perhaps) the largest avalanches in the Solar System. Mars has so many large avalanches that underlying processes are concealed. The landslides on this planet are very wide, typically about 100 km. The volume of the landslide debris of Ophir Chasma, a large west-northwest-trending trough, is more than 1000 times greater than that from the May 18, 1980 debris avalanche from Mount St. Helens [146]. Figure 2.8a shows a close-up view of a landslide on the south wall of Valles Marineris. This landslide partially removed the rim of the crater that is on the plateau adjacent to Valles Marineris. Several distinct layers can be seen in the walls of the trough. These layers may be regions of distinct chemical composition or mechanical properties in the Martian crust. Similarly, Fig. 2.8b shows debris of Canyon landslide. Mass movements on Venus, seen in radar images acquired by the Magellan spacecraft during its first mapping cycle, are easily interpreted within the scheme commonly used to classify terrestrial landslides. Rock slumps, rock and/or block
slides, rock avalanches, debris avalanches, and possibly debris flows are seen in areas of high relief and steep slope gradients, and are most abundant in the tectonic troughs that crisscross much of the equatorial region of Venus. Venusian landslides, like those found within the Valles Marineris on Mars, tend to come from escarpments typically higher than those on Earth. Faulting and seismically-induced accelerations are probably responsible for the majority of non-volcanic mass movements. The atmosphere may participate in promoting the movement of some of the landslide debris, but environmental factors (e.g., rainfall, temperature cycling) do not appear to play as dominant a role as they do on Earth. Venus shows clear and unambiguous evidence of mass movements at a variety of scales. Measurements and observations show that Venus is covered by, at most, a very thin mantle of debris. Similar avalanches are also found on the moon.

2.6 Survey on Avalanche Models

In this section we present an account of some avalanche models that are in use. They range from molecular dynamics models to continuum mechanical models. The main purpose is to discuss about the inherent properties of these models and outline their applicabilities depending upon the specific situations in our real life. Finally, the necessity of a new continuum mechanical model is presented which will be the main focus in subsequent chapters.

2.6.1 A View on Some Classical Avalanche Models

Statistical Models

In mountainous regions mapping models are used to determine avalanche zoning for land use and planning. It normally demands either accurate knowledge of past avalanche
spreads or methods for computing boundaries of the avalanches. There are several statistical methods for that. Two widely used stochastic models are due to Lied & Bakkehøi and by McClung & Lied [76, 80]; they establish correlations between the run-out distances and the underlying topographic parameters. These parameters include the location of the initiation point (A), an intermediate point (B) somewhere in the transition zone (to the run-out) and the position of the stopping point (C), see Fig. 2.9a. A simple continuous curve (e.g., parabola) is used to fit the natural path of the avalanche in the downhill direction by assuming that the longitudinal profile of the avalanche path governs its dynamics. The average inclination angle, $\beta$, to the horizontal of the avalanche path is determined by a straight line, $L'$, joining the initial point and the intermediate point, the point at which deceleration of the avalanche starts. The position of the stopping point of the avalanche motion is described by using a stopping angle, $\alpha$, that is the angle of a straight line, $L$, joining the starting and stopping point to the horizontal. This angle is called Pauschalgefälle as shown in Fig. 2.9b. Using regression methods, this angle can be explicitly expressed as a function of the average inclination angle, thus providing the one-dimensional extent and consequential boundaries of the avalanches. The model equation can explicitly be written as $\alpha = \lambda \beta + \gamma$, where the regression coefficient $\lambda$, and the pure constant $\gamma$ are to be determined by the real field data [76, 77].

In the last two decades, several extenstions of this method have been made. They consist in variations of the parameters and a fit of the model with a particular topography. Although such simple statistical models have been extensively used in practice and give fairly reliable and objective results for fixed sites, many shortcomings are attached with these approaches. This method needs a long-return period, typically 100 years, of avalanches for a given avalanche track. The dynamics of avalanches is governed not only by topographic features of its paths, but it also depends on many other rheological and mechanical features of its paths, but it also depends on many other rheological and mechanical
properties of the material such as basal and internal angles of friction of the base and the material, respectively. The model is also limited to one-dimensional path profiles and thus cannot predict the spread of the avalanche which, among others, is one of the most important features of avalanche mapping. The topographic parameters cannot be measured in the laboratory or in the field, and the results rely on past events.

Mass Point Models

Until 1989, the most widely used and applied avalanche models utilised a center of mass approach and were based on the ideas first suggested by Voellmy [127] who related the shear traction at the base of the flow to the square of the velocity and postulated an additional Coulomb friction contribution to it. On the one hand, Voellmy assumed uniform and steady conditions, whilst on the other hand, in this model a number of subjective parameters must be predetermined in order to obtain results which match observational data. The simplicity of the model constitutes its power, because, depending upon the parameter choice, it may be applicable to flow as well as powder snow avalanches, but this flexibility makes it also difficult to handle. Many attempts were undertaken to improve Voellmy’s model, e.g., by Salm, Gubler, Perla, Cheng, McClung and Mellor [2, 82, 88, 109]. Unfortunately, none of these extensions could be advanced beyond the center of mass approach. They are not able to provide information as to the spatial and temporal properties of an avalanche such as the velocity distribution and the evolution of the avalanche height and spread. These are certainly not constant, neither in space nor in time [18, 19]. The height of the flow may merely be included as a parameter value, but is not calculated as a function of space and time.

Hydraulic Models

Some other, hydraulic, models attempt to idealise these complicated materials as linear Newtonian fluids, as discussed by Brugnot, Dent & Lang, leading to the Navier-Stokes equations which may be solved numerically [11, 18]. Although it is perhaps not feasible to assume that this type of constitutive relation adequately describes the media, some success has been achieved in modelling certain aspects, like the geometric properties of the motion of the avalanche, with this approach. Several hypotheses were proposed to explain the mechanisms for fluidisation which occurs in a thin layer close to the basal surface [22, 36, 42, 65, 114]. For fluidised granular materials, apparent viscosities may be measured [115] but the range of conditions which sustain fluidisation vary greatly among solid-fluid gravity current systems [72].

Kinetic Theory and Molecular Dynamics Models

Such models were developed by Haff, Jenkins & Savage, Jenkins & Richman, Lun et al., Hwang & Hutter, and many others, to describe the rheology of the granular materials [37, 54, 58, 59, 78]. However, these theories are difficult to apply to avalanche flows as shown by Gubler, Hutter, Szidarovszky & Yakowitz, Salm & Gubler [36, 44, 45, 110]. A kinetic theory would involve the solution of an additional energy equation for granular temperature, velocity and density variations. These solutions entail to involve the use of rather complex boundary conditions, e.g., for granular temperatures, velocities and stresses. It has been demonstrated by Hutter, Szidarovszky &
Yakowitz [44] that the construction of solutions to the related problem, even of steady chute flows, is very complicated.

Jenkins outlined a hydraulic theory applied to a debris of a dry granular mass in which the greater part of the depth is assumed to behave as a frictional plastic material [60]. This frictional plastic material is supported at its base on a thin shear layer in which collisional transfers of momentum and energy dominate. Assuming the heap to be deformed by frictional shearing while supported at its base by a relatively thin region of intense shear in which grains interact through collision, he described the frictional shearing by using the Mohr-Coulomb yield criterion. Together with balance laws and boundary conditions of the kinetic theory for dense granular flows to describe the region of colliding grains at the base, he determined the relationship between the shear stress, normal stress and relative velocity of the boundaries in this shear layer using an analysis of a steady shear flow between identical bumpy boundaries. The model has not further been pursued.

2.6.2 Necessity of a New Model

The simple two parameter mass point models, e.g., of Voellmy [127], Salm [109] and Perla et al. [88] have only been tested against experimental data as far as runout distances are concerned, and this comparison shows considerable scatter. This means that the field data against which theoretical models could be tested were too scarce to calibrate the existing models of that time with sufficient certainty: the classical theoretical formulations of Voellmy [127] and Salm [109] are known to be oversimplified. Obviously, because of the mass point assumption, the temporal evolution of the geometry of the moving avalanche can not be calculated in these models. The reasons for why the runout distances and deposition areas cannot be predicted by these models with significant accuracy can be attributed to the difficulties of the parameter identification but more likely to an inadequate description of (i) the physical (rheological) properties, (ii) the sliding conditions and (iii) the geometries of the moving avalanches [49]. Furthermore, these models do not allow the determination of the spreading of the avalanching mass and thus cannot give information on the mass distribution in the runout zone [51]. There are other models describing the avalanches as linear Newtonian fluids [11, 18] leading to Navier-Stokes equations. These are in principle able to somehow describe the geometrical properties of the motion. However, real avalanches are governed by nonlinear constitutive relations, so that the above ansatz can only serve as a very rough approximation. Alternatively, statistical models are limited to one-dimensional situations and depend on both the topographic feature and long-run period. They cannot incorporate rheological and mechanical behaviour of the material. Moreover, kinetic theory and molecular dynamics models are very complicated to handle even for simple geometries [36, 44, 45, 110].

It is very difficult to postulate a constitutive relation for the stress tensor in terms of a deformation measure that correctly describes avalanche behaviour under rapid motion and possible large shearing for which the phenomenological parameters can be identified. Fortunately, observations suggest that the major part of the shearing in many avalanches takes place in a very thin boundary layer near the bottom and it is therefore possible to circumvent the detailed determination of the constitutive response by depth averaging the field equations with the result that the material behaviour only needs to be known at the base. Instead of prescribing a detailed constitutive relation (stress-stretching relation), a
Coulomb-dry friction law for the basal friction and a Mohr-Coulomb yield criterion for the interior behaviour can be used. The information obtained in this way is sufficient to essentially reduce information about the stresses to the traction conditions at the free and basal surfaces and thus involving only a closure relation for the basal shear traction (depth-averaged equations). Based on these prerequisites, dynamic equations can be derived that describe the temporal-spatio evolution of the height and the depth-averaged streamwise velocity of the moving avalanche pile [35].

In the last three decades, new mathematical descriptions for the motion of rock falls, ice and snow avalanches have been presented for the obvious reason, namely the need for a better prediction of the runout distances and deposition zones. Earlier attempts of such geophysical flows had either dealt with hydraulic-type models which treat the problem as a gradually varying open channel flow of infinite mass or a mass point model of Voellmy. As explained above, the existing avalanche models before 1988 were generally inadequate [72]. The trend at that time, and till now, in the research of flowing snow and other granular materials is directed at determining the predominant mechanisms governing the motion of flow avalanches. Despite the significant role of avalanches in the mountainous regions like the Alps and the Himalaya, where accurate predictions of forces exerted by, and the travel distances arising in, avalanches are important, the other existing avalanche forecast models seemed to be weak and fraught with uncertainties.

The Savage-Hutter-theory [112] and its various extensions and generalisations for real as well as complicated topographies incorporate a great number of the above discussed important features of granular avalanches [31, 99, 101, 131]. It is a complete theory in the sense that it provides a clear formulation of the problem in physical-mathematical terms and leads to well defined initial boundary value problems in problems of practical relevance, (also, see, Section 3.3.4). Thus, advanced numerical techniques can be developed and successfully implemented. Consequently, theoretical predictions can be and have been validated by many different laboratory experiments. Thus, it may, in many situations provide a complete knowledge of the avalanche motion from initiation on a steep slope to run-out on a shallow slope.