Micromechanical Analyses of Sturzstroms (Rock Avalanches) on Earth and Mars

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BERND IMRE

Mag. rer. nat., Karl-Franzens-Universität Graz

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Angenommen auf Antrag von
Prof. Dr. Sarah M. Springman
Prof. Dr. Timothy R.H. Davies
   Dr. Gunther Heißel
   Dr. Suzanne Lacasse

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The “Geoforum Umhausen” in Tyrol is a small (but beautiful) annual meeting offering a forum for high standing intellectual exchange on theoretical and practical topics related to geology, geotechnics, civil engineering, and natural hazards mitigation. From its very beginning in 1999, sturzstrom research stood on the agenda of this meeting. Furthermore, the nearby sturzstrom of Kofels and its impact—still felt today on the Ötztal Valley, served as a nucleation point for the conference. The importance of this topic is also emphasised by the regular attendance of the well known ETH Professor and researcher on sturzstroms, Theodor H. Erismann, who sadly died in 2002. I attended the tenth anniversary meeting in 2008 which provided me the opportunity to meet Dr. Heißel, head of the Geological Survey of the federal state of Tyrol. For the following correspondence which ensued I am very grateful, as I am for his agreement to act as a co-reviewer of this thesis.

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“He soon perceived, however, that the battles which Sir Miles and the rest had waged against armed knights to win a kingdom, were not half so arduous as this which he now undertook to win immortality against the English language. Anyone moderately familiar with the rigours of composition [and science!] will not need to be told the story in detail; how he wrote and it seemed good; read and it seemed vile; corrected and tore up; cut out; put in; was in ecstasy; in despair; had his good nights and bad mornings; snatched at ideas and lost them; saw his book plain before him and it vanished; acted his people’s parts as he ate; mouthed them as he walked; now cried; now laughed; vacillated between this style and that; now preferred the heroic and pompous; next the plain and simple; now the vales of Tempe; then the fields of Kent or Cornwall; and could not decide whether he was the divinest genius or the greatest fool in the world.”
(Excerpt from Virginia Woolf “Orlando”. Wordsworth Editions 1995, p. 39)

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Abstract

Sturzstroms are very fast landslides of very large initial volume and extreme run out, which display intensive fragmentation of blocks of rock due to inter-particle collisions within a collisional flow. An investigation of the behaviour and energy budget of such sturzstroms has been carried out using physical, analytical and numerical modelling techniques. Results from centrifuge model experiments, based on a guided experimental rock slide imposed by a dynamic acceleration field, provide strong arguments to allow the micro-mechanics and energy budget of sturzstroms to be described quantitatively by a fractal comminution model. This deterministic comminution model has been incorporated within a numerical distinct element (DEM) code allowing for the computationally efficient simulation of fragmenting rock masses at true scale. This DEM experiment indicates rock mass and boundary conditions, which allow an alternating fragmenting and dilating dispersive regime to evolve, and to be sustained for long enough to replicate the spreading and run out of sturzstroms. The fragmenting spreading model supported here is able to explain the run out of a granular flow, which is free of volatiles, beyond the travel distance predicted by a Coulomb frictional sliding model, without resorting to explanations by mechanics that can only be valid for certain, specific of the boundary conditions. This, and its strong relation to internal fragmentation, suggests that a sturzstrom constitutes a landslide category of its own. This study provides a novel framework for the understanding of the physics of such sturzstroms.
Kurzfassung

1 Introduction

“Einerseits zu einer stillen Harmonie fähig, welche als eine heitere Macht sich auf ihn übertrug, dann wieder zu leicht kränkbar von den übermächtigen Tatsachen, kannte er die Verlorenheit, wollte die Verantwortung und war durchdrungen von der Suche nach Formen, ihrer Unterscheidung und Beschreibung, über die Landschaft hinaus, wo („im Feld“, „im Gelände“) diese oft quälende, dann auch wieder belustigende, im Glückfall triumphierende Tätigkeit sein Beruf war.”
(Excerpt from Peter Handke “Langsame Heimkehr”. Suhrkamp Taschenbuch 1069, 1984, p. 9)

1.1 Nomenclature

In modern international literature, the gravity-driven movement of a mass of soil or rock is generally denoted as a landslide (Cruden, 1991). If bedrock constitutes the type of landslide material and if the landslide displays a sliding or falling motion of the first, initial movement, it may be classified as rock slide or rock fall (Cruden and Varnes, 1996). Rock slides will initially displace along a planar (translational slide) or curved (rotational slide) surface of rupture, whereas rock falls detach from a steep slope along a surface on which little or no shear displacement takes place.

1.1.1 Sturzstrom

The mechanics of the subsequent down slope movement of dry, loose rock slides or falls is generally well understood in terms of the competition between gravity, inertia and inter-granular friction (e.g. Carson and Kirkby, 1972; Duncan, 1996; Scheidegger, 1991; Wyllie et al., 2004 and others). However, a rare category of dry rock slides, or in few cases rock falls, exists, with rock debris subsequently travelling vast horizontal distances with only a comparatively small vertical drop in height. During run out, such dry, loose rock slides or falls exhibit a flow like behaviour and appear to travel as if the inter-granular coefficient of friction is temporarily reduced by an order of magnitude or more (Collins and Melosh, 2003; Eisbacher and Clague, 1984; Hsü, 1975 and others; Figure 1.1).

The first modern description of this kind of landslide is due to the Swiss geologist Albert Heim (Buss and Heim, 1881; Heim, 1882; Heim, 1932) following the catastrophic sturzstrom of Elm/Canton Glarus, in 1881. Originally, Heim used several synonyms to describe the “flowing” nature of a mass of broken rock fragments. The term sturzstrom, the most appropriate to describe this type of rapid flowing debris,
has been defined by Hsü (1975), following Heim (1932), as: “... a stream of very rapidly moving debris derived from the disintegration of a fallen rock mass of very large size; the speed of a sturzstrom often exceeds 100 km/h, and its volume is commonly greater than \(1 \times 10^6\) m\(^3\).” What has to be added to this definition is that sturzstroms originate most commonly from rock slides, and only rarely from falls. A more general version of this definition has found its way into the Dictionary of Geological Terms (Bates and Jackson, 1984).

The term *rock avalanche* is equivalent to sturzstrom (e.g. Melosh, 1990), and is used more commonly in international literature. Nevertheless, Albert Heim described this landslide process first and invented the term sturzstrom to match it. Due to his apt description of the phenomenon of the post-failure behaviour of a very large, disintegrating rock slide or rock fall encompassed in the term sturzstrom (among others Collins and Melosh, 2003; Hsü, 1975; Hsü, 1978; Hutchinson, 1988; Hutchinson, 2006; Kilburn, 2001; Melosh, 1986; Melosh, 1990) this denotation will be used throughout this thesis. There is no reason why this term should not remain part of the anglophone geological vocabulary, which includes many foreign words such as cirque, graben, horn or karst.

![Figure 1.1: Excessive travel distance \((L_e)\) related to rock fall (or rock slide) volume. \(L_e\) is the horizontal distance travelled by the tip of a sturzstrom beyond a limit based on dry frictional sliding with a nominal coefficient of friction of \(\tan 32^\circ\). The distance \(L_e\) is defined by \(L_e = L_{(travel\ length)} - (H_{(fall\ height)} / \tan 32^\circ)\). \(L_d\) denotes the deposit length (Eisbacher and Clague, 1984; Hsü, 1975). Selected data on sturzstroms based on Shaller (1991).](image-url)
1.2 Relevance of Sturzstroms as a Natural Hazard

Although rare (Figure 1.2), the high mobility of sturzstroms in terms of velocity and run-out, make these phenomena extremely hazardous (Kilburn, 2001). Such events have been known to devastate populated areas and cause death of victims located at what would seem to be safe distances from potentially safe mountainsides (Figure 1.3; Eisbacher and Clague, 1984; Heim, 1932).

![Figure 1.2: Summary diagram derived from numerous case histories illustrating the effective use of measures in reducing the impact of destructive landslides in developed mountain regions, depending on their volume and projected recurrence (modified after Eisbacher and Clague, 1984); shading denotes the area in which sturzstroms occur. Beside land use restrictions, monitoring and the possible evacuation of endangered areas may be a necessary measure to avoid loss of life, which would require profound knowledge about the run out mechanisms valid for sturzstroms.]

1.3 Motivation for Thesis Research

The US probe Mariner 9 (1972) was the first to take pictures of gigantic rock slides and sturzstroms (Figure 1.4) in the vast trough system of Valles Marineris, displaying travel distances of up to 100 km (Lucchitta et al., 1992). Their formation, and whether these rock slides or sturzstroms were emplaced in a wet or dry environment, has not yet been resolved (e.g. Lucchitta, 1979; Carr, 1981; Lucchitta, 1987; McEwen, 1989; Shaller et al., 1989; Lucchitta et al., 1992; Baker, 2001; Jakosky and Phillips, 2001; Legros, 2002; Schultz, 2002; Harrison and Grimm, 2003; Quantin et al., 2004a; Quantin et al., 2004b; Barnouin-Jha et al., 2005; Bulmer and Zimmerman, 2005; Lajeunesse et al., 2006; Soukhovitskaya and Manga, 2006). This question has profound implications regarding the presence, extent and timing of ground ice reservoirs and liquid water on Mars, essential for an understanding of the evolution of the Martian climate (Baker, 2001; Jakosky and Phillips, 2001; Lucchitta, 1987; Peulvast et al., 2001; Quantin et al., 2004 and others). Earlier research on the stability of the very high wall slopes of Valles Marineris (Imre, 2004a) led to the author’s exposure to the phenomenon of Martian sturzstroms, and the discovery that existing theories were not yet able to explain many characteristics related to their formation.
The key approach to study such geomorphologic features on an Earth-like planetary surface is the formulation of a working hypothesis, which is deduced (but not proven) from analogies of landscape features of known origin and those under scrutiny. Victor R. Baker writes: “In the retroductive reasoning on inferences of geomorphology, analogy serves merely to suggest fruitful working hypotheses, thereby leading to completely new theories that bind newly discovered facts. Mars’s landscape provides particularly stimulating opportunities to practise geomorphological reasoning, generating hypotheses that may initially strike some researchers as outrageous. Nevertheless, it is the productive pursuit of such hypotheses that leads ultimately to new understanding, not only of Mars, but also of Earth itself” (Baker, 2001).

The challenge is now that hypotheses on the high mobility of terrestrial analogies of Martian sturzstroms are of highly speculative origin also, striking some researchers as outrageous too. The motivation of this thesis is therefore twofold:

a) to reveal the mechanics of sturzstroms in more detail in order to contribute to the development of Type A (Lambe, 1973) run out prediction models, which are necessary for successful mitigation of this natural hazard.

b) to contribute to the understanding of the formation of Martian sturzstroms by contributing to the understanding of the high mobility of terrestrial sturzstroms.
1 Introduction

Figure 1.3: Contemporary painting of the Goldau sturzstrom of 1806 modified after W. U. Oppermann (1810 or 1820), seen from the Mt. Rigi Kulm. The outline of the deposit is indicated by a dotted line. (S1) denotes the centre of mass of the source at an altitude of ~ 1300 m a.s.l and (S2) the ~ centre of mass at about 500 m a.s.l. The horizontal distance between S1 and S2 amounts about to 3500 m (Berner, 2004). (G) indicates the former position of Goldau village (~ 510 m a.s.l.), which was annihilated completely by the sturzstrom together with several other hamlets. (LL) indicates Lake Lauerz (447 m a.s.l). The positive $x^\prime(t)$-axis points in the direction parallel to the main flow of the sturzstrom, to define the sign convention. It defines a moving coordinate system, whose origin is dependent on time $t$. In perpendicular directions, the $y^\prime(t)$-axis defines the horizontal width of the flow, and the $z^\prime(t)$-axis, its thickness.

Figure 1.4: Perspective image of a giant sturzstrom in the Ophir Chasma, Valles Marineris, Mars. Image taken by the European Mars Express probe (image width approx. 70 km, height of the failed cliff approx. 8 km; image credit: ESA/DLR/FU Berlin; courtesy E. Hauber, 2009).
1.4 Structure of this Thesis

1.4.1 Cumulative Dissertation

This thesis has been compiled using the option in article 8b of the ETH regulations “Ausführungsbestimmungen der Rektorin vom 1. Sept. 2008 zur Doktoratsverordnung ETH Zürich vom 1. Juli 2008”, permitting published or submitted research manuscripts to form the backbone of the written thesis. Three peer-reviewed journal articles and two peer-reviewed conference proceedings articles have been published by the author (as first author) or are currently under review. These five publications have been incorporated into this written thesis and form the body of it, extended with additional explanations and graphs. All sections in the thesis text, which are based on one of these publications, are indicated by the relevant reference.

1.4.1.1 Peer Reviewed Journal Publications


1.4.1.2 Peer Reviewed Conference Publications


1.4.2 Further Publications Related to this Thesis

1.4.2.1 Initiation of Failure of Large Rock Slides

This thesis research deals with the run out mechanism of sturzstroms only. The initiation of failure of large rock slides or falls eventually turning into sturzstroms is not covered. But this topic has also been investigated indirectly by a “spin off” of the author’s study at the University of Graz. This publication features a danger characterisation (Fell et al., 2005) of a large rock slide in the Fusch Valley in Salzburg, Austria of about 1 km$^3$ in volume:

1.4.2.2 Distinct Element Modelling

Further peer reviewed articles, which contain results of the author’s masters thesis research deal with the true scale numerical modelling of large rock masses and have been published before the beginning of the thesis research. They served as a conceptual basis for the development of the numerical modelling environment in this research.


1.4.2.3 Centrifuge Modelling

The author had the opportunity to gain experience in the task of modelling landslides within the ETH Geotechnical Drum Centrifuge at the beginning of the thesis when assisting Dr. Elisabeth T. Bowman. Results have been published recently as:

2 Aim of this Research Project

"Die Schriftsteller sehen früher als die Wissenschaft, wohin wir uns bewegen. Bei dem, was wir in der Natur finden, geht es nicht sosehr darum, was da zu finden ist. Was wir finden, entscheidet sich einfach dank unserer Möglichkeit zu verstehen."
(Excerpt from Peter Hoeg „Fräulein Smillas Gespür für Schnee“. Novel translated by Monika Wesemann. © 1994 Carl Hanser Verlag München)

2.1 Constructionism and Prediction in Epistemology

A modern view in philosophy on the aim of increasing knowledge is that new knowledge is constructed by comparing/adding new empirical observations to previous knowledge. Such constructionism means that a scientific theory is refined based on the empirical data gained by the attempt to verify or falsify the predictions made by that theory. This standpoint is summarised within the so called epistemic realism (Boyd\(^1\) and Devitt\(^2\) in Lauth and Sareiter, 2005). It postulates that advance in science displays, again, a successive convergence to veracity. But because empirical data themselves are never perfectly error-free, a definite verification or falsification (Popper\(^3\) in Lauth and Sareiter, 2005) of a theory may never be achievable. Therefore the ideal-theoretic Cartesian veracity (Descartes\(^4\) in Lauth and Sareiter, 2005) of a theory may also never be achieved. Instead of verification or falsification, it is therefore more appropriate to talk about confirmation of a theory. If the prediction of a theory can be shown to be true in the light of empirical observations, then the theory is confirmed by those observations and remains in contention for truth. Oreskes et al. (1994) conclude: “The greater the number and diversity of confirming observations, the more probable it is that the conceptualisation embodied in the model is not flawed. But confirming observations do not demonstrate the veracity of a model or hypothesis, they only support its probability. Confirming observations give therefore a warrant for a certain degree of belief (Carnap\(^5\) in Oreskes et al., 1994). In the Bayesian theory of probability, this degree of belief can be expressed as the prior probability of a theory. It expresses the probability of the

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\(^3\) Popper, K.R., 1984. Objektive Erkenntnis
\(^4\) Descartes, R., 1641. Meditationes de prima philosophia
\(^5\) Carnap R., 1968. The Problem of Inductive Logic
predictions made by a model to be true before empirical observations are available (Lauth and Sareiter, 2005). In the 13th Rankine lecture, the prior probability is denoted for the field of civil engineering as a Type A prediction by Lambe (1973).

Strom (2006a) therefore rightly notes that a “proposed model to explain their peculiarities [of sturzstroms] must not contradict any of the observable phenomena, which should be regarded as constraints with which to check a model’s reliability.” In other words, models of the emplacement of sturzstroms have to be confirmed based on empirical evidence.

But confirmation is not all. Practical needs go beyond this call. The inherent danger to the growing communities in alpine valleys below future potential sites of sturzstroms must be examined and results of predictions of endangered zones allowed to impact upon the planning processes in these areas. This calls for the ability to make, according to Lambe (1973), Type A predictions, which are done before an event. But Type A predictions need a sufficient understanding of the mechanisms involved in a process whose outcome has to be predicted, whereas confirmation alone may also be achieved without detailed knowledge on the mechanism involved. The Bayesian theory of probability recognises in this context the posterior probability of a theory. It expresses the probability of a model to be true after empirical observations have been available (Lauth and Sareiter, 2005). This correlates to so the called type C1 predictions after Lambe (1973) where predictions are made after the empirical observations have been available. Lambe (1973) is critical of C1 predictions and writes: "Our professional literature contains the results of more type C1 predictions than of any other type [It will be shown that this also applies to sturzstrom research]. [They] can of course be very helpful in contributing to our knowledge. However, one must be suspicious when an author uses type C1 predictions to prove that any prediction technique is correct."

Literature that postulates theories and models on the emplacement of sturzstroms will be reviewed in order to formulate the research aims of this work, based on two questions:

a) Has the model postulated been confirmed based on empirical evidence? Hence, has any experimental confirmation been achieved? Does it not contradict commonly observable phenomena (type features) of sturzstroms?

b) If it has been attempted to achieve confirmation, does the model postulated contribute to a deeper understanding of the mechanism involved? Therefore has it the potential to become a type A prediction tool?

### 2.2 Observable Type Features of Sturzstroms

To answer the questions posed above, it is necessary to define type features of sturzstroms, which are common to all, or at least the vast majority, of known natural events. Such features will allow for a confirmation of models proposed without relying on peculiar features, which might otherwise mislead the researcher into the development of imaginative theories on sturzstroms, which are applicable to very scarce boundary conditions only. Such boundary condition specific models do not
contribute to a better overall understanding of sturzstroms, which is necessary for the development of reliable type A prediction tools.

In the theory of epistemology, single localizable and datable events are referred to as “tokens”. General and repetitive processes and features, referred to as “types” may be induced from these tokens (e.g. Lauth and Sareiter, 2005). Based on literature review and own observations, three types can be identified which, seem to be common to all known cases of sturzstroms (Strom, 2006a; Strom, 2002):

a) Run out increases significantly with failure volume (Figure 1.1; among others Davies, 1982; Davies and McSaveney, 1999; Hsü, 1975; Legros, 2002; Scheidegger, 1973).

b) Sturzstrom deposits are intensively fragmented (Figures 2.1, 2.2; among others Couture et al., 1998; Di Luzio et al., 2004; Eppler et al., 1987; Erismann and Abele, 2001; Friedmann et al., 2006; Harp et al., 2003; Heim, 1932; Pollet and Schneider, 2004; Schneider et al., 1999; Shoaei and Ghayoumian, 1998; Smith et al., 2006; Strom, 1994; Strom, 1996; Strom, 2006b).

c) The initial stratigraphy of the source is preserved in the deposits, suggesting little turbulence within the flow (Heim, 1932; Hsü, 1978; McSaveney, 1978).

Figure 2.1: Present day view on the detachment zone of the Goldau sturzstrom of 1806 at the top of Mt. Rossberg (1558 m a.s.l.). The large blocks of conglomerate, bounded by widely spaced joints, are clearly visible (a person serves as a scale).
2.3 Literature Review

Sturzstroms and their “unexpected” run out have exerted fascination on the scientific community ever since the famous works by Buss and Heim (Buss and Heim, 1881; Heim, 1882; Heim, 1932). Public attention was already drawn to this topic since the 1806 Goldau sturzstrom, especially due to the report by statesman and physician, Karl Zay (1807), which encompasses the first modern scientific record of a sturzstrom. This was written in the spirit of the Enlightenment (Aufklärung), centred upon the preceding eighteenth century. After some decline in interest on this topic during the forties, fifties and sixties of the 20th century, the number of publications increased again in the seventies. Since then, a stream of publications, whose number has increased again since the nineties, transformed sturzstrom research to a well acknowledged, heavily debated scientific field. A comprehensive, but surely still incomplete review is attempted below, on the current state of sturzstrom research in the light of the questions developed in Section 2.1 and the type features presented in Section 2.2, to deduce the scientific gap and aim as scientific motivation for this doctoral research project.

2.3.1 Theories about the Mobility of Sturzstroms Proposing the Presence of Volatiles

A number of (classical) hypotheses have invoked the presence of a fluidising volatile such as air, water, vapour, volcanic gases or melted rock to explain the long run out of sturzstroms by reducing the effective stresses between the rock particles.

Kent (1966) proposed that entrapped air could fluidise landslides, a proposition which is supported by Shreve (1966; 1968). This concept has attracted the largest
public perception since then. A similar hypothesis was formulated by Goguel (1978), who proposed that vaporisation of water at the base of landslides could produce pore pressure in excess of lithostatic values and thus strongly reduce contact stresses between solid matter thereby reducing frictional resistance.

Erismann et al. (Erismann et al., 1977; Erismann, 1979; Erismann, 1986) describe the presence of fused rocks (pumice) within the Köfels sturzstrom (AUT) and its contribution to long run-out within a concept of self-lubrication. This concept belongs to the more peculiar theories on the emplacement of sturzstroms because, apart from the Köfels event, the occurrence of fused rocks have been reported for only few other events (e.g. De Blasio and Elverhøi, 2008). De Blasio and Elverhøi reach the conclusion that self-lubrication by fused rocks may not have general validity.

Voight and Sousa (1994) presented evidence for undrained shear within the water saturated base of a sturzstrom. Also Legros (2002; 2006) strongly supports the presence of fluids (water) under undrained conditions, as an explanation for the long run out of sturzstroms. The studies of Legros are especially notable, because they not only reject the popular air cushion hypothesis but also the hypothesis of self-lubrication of dry granular flows based on Bagnold’s work on solid particle flow (see below).

The most comprehensive is the work by De Blasio. Beside the above mentioned possibility of the production of fused rock (De Blasio and Elverhøi, 2008), models explaining the mobility of sturzstroms based on vapour (De Blasio, 2008) or excessive pore water pressure in combination with rock fragmentation (De Blasio, 2009) are also proposed.

2.3.1.1 Summary on 2.3.1

Physical experiments play a decisive role in achieving confirmation of theories presented to explain the long run out of sturzstroms. But except for the role of water under undrained conditions (e.g. Section 2.3.3) and the possibility of fused rock in principal (Erismann et al., 1977), no attempts have been made to achieve such confirmation, because most of these theories remain rather hypothetical. It is argued, without repeating criticisms, especially those coming from researchers promoting volatile-free mechanisms of sturzstrom run out (Section 2.3.2), that except for the possible presence of excessive pore water pressures (Legros, 2002; 2006), all other proposed mechanisms will be applicable to very specific boundary conditions only. But even excessive pore water pressure is unlikely to constitute a general mechanism because it requires both saturated conditions and a non-dilating environment. Both are improbable in sturzstroms, which display intensive fragmentation (Section 2.2) hence, creating a large number of new particle surfaces and therefore pore spaces that require saturation in a very short time, within a most probably dilating regime! Finally, in view of the giant landslides on planet Mars, these mechanisms do not provide an explanation for their extreme run out either. During the time when these giant landslides occurred, the climate on Mars was probably as dry as today and the atmospheric pressure as low as today (about 1/100th of the atmospheric pressure on Earth). It is therefore unlikely that volatiles were ever present, but if they were present, it is unlikely that they would have been under high enough pressure, or that these pressures would have been sustained for long enough to reduce the effective stresses sufficiently to promote long run out (e.g. Section 1.3).
2.3.2 Theories about the Mobility of Sturzstroms Proposing the Absence of Volatiles

A number of other authors have attempted to explain landslide mobility using granular models, in the absence of a volatile.

The first analysis originates from Heim (1932). His explanation is based on a velocity-dependent frictional bulk flow. According to his review of the 1881 Elm sturzstrom, the rock blocks remain in close contact with each other, pushing each other forward during run out due to momentum transfer. An analytical description of such a frictional rock mass spreading due to momentum transfer, applying Newton's second law of motion, has been published by Gassen and Cruden (1989) together with a subsequent reply to critics of their concepts (Gassen and Cruden, 1990). They claim that their analysis can well explain the run out of sturzstroms, such as the 1881 Elm event. But in the light of the author's own numerical experiments shown below, this proposition is doubted.

Hsü (1975), hypothesised that the fine particles which form in sturzstroms could fluidise the coarser, moving debris without the help of a supporting fluid. This concept has close similarities with the works by Campbell, 1989; Campbell et al., 1995 and Straub, 1997. They propose self-lubrication, assuming that the sturzstrom slides on a thin layer of highly agitated particles. This assumption reverts to Bagnold's work on solid particle flow (e.g. Bagnold, 1954). This view is also supported by the analytical analysis of Dent (1986). These concepts postulate that sturzstroms slide on a thin layer with reduced friction rather than as flow.

Melosh (1986; 1990; 1979) and Collins and Melosh (2003) hypothesised fluidisation by acoustic waves as a cause for abnormally long run-outs. Their concept is also related to the solid particle flow model (e.g. Bagnold, 1954). The major difference between the two is that, in Bagnold’s model, shear is concentrated at the base of flow within a zone of highly agitated, colliding particles whereas in the acoustic fluidisation model, particles remain in close contact to each other, organised within compressional wave packets. The claimed advantage of the latter concept is that the recovering of elastic energy stored within particles organized within compressional wave packets is viewed as much more efficient than particles within a collisional regime (Melosh, 1986). This claim can be justified for a single block and, to some degree, for within the proposed assemblage of many blocks under compression. But a sturzstrom does not display a continuum, and no tensile strength may be mobilised between the blocks. Therefore unpredictable effects may occur due to reflections at the boundary interfaces between the numerous particles involved. Additionally, because a sturzstrom constitutes a discontinuum at macro-scale of, to a large degree fine grained material, such pressure waves packets may likely be highly damped too (e.g. Studer et al., 2007). At the end particles organised within a wave packet may not behave differently energetically than particles in Bagnold’s collisional regime. It is therefore questionable if wave packets may contribute to an increased run out of sturzstroms.

All the theories about the mobility of sturzstroms proposing the absence of volatiles neglect the intensive fragmentation occurring within sturzstroms or identify it as side effect. Kobayashi (1998) attempted to bridge this gap by extending the concept of acoustic fluidisation, suggesting that the compressional stress within a wave packet may exceed the compressional strength of rock particles within that
packet. This concept finds also support by Strom (1994), based on field evidence, but without any further analytical considerations.

Davies and McSaveney recognized fragmentation as a key factor in the mechanics of the run out of sturzstroms (Davies et al., 2003; Davies and McSaveney, 1999; Davies and McSaveney, 2002; Davies and McSaveney, 2004; Davies and McSaveney, 2006; Davies et al., 2006; Davies et al., 2007; Davies et al., 1999; Dufresne and Davies, 2009; McSaveney and Davies, 2007; McSaveney and Davies, 2002; McSaveney and Davies, 2009; Smith et al., 2006). Their dynamic fragmentation-spreading model postulates that shear resistance within a sturzstrom is reduced by energy release due to dynamic fragmentation (e.g. “rock-bursts”, Linkov, 1996; Vardoulakis, 2006).

Purely geometrical effects contributing to the mobility of sturzstroms are proposed for example by Wassmer et al. (2002; 2004). But these effects seem to be applicable to few cases of sturzstroms only.

2.3.2.1 Summary on 2.3.2
Volatile free theories about the mobility of sturzstrom gained much attention in recent years. In particular the fragmentation-spreading model seems promising, because it combines long run out – one type feature of sturzstroms, with intensive fragmentation – an other type feature of sturzstroms.

2.3.3 Physical Models of the Mobility of Sturzstroms
Physical models play, from the epistemological position, a decisive role for achieving confirmation of theories on the long run out of sturzstroms.

- Hsü (1975) presents results of 1g flume experiments with Bentonite suspensions, which resemble the geometry of a sturzstrom event, namely the one of Elm in 1881, well. Advocating the view of sturzstroms as flow of dry rock, he supports the grain flow postulated by Bagnold (1954) as physical explanation for the fluid-like behaviour of real sturzstroms. He proposes that the apparent excessive run out of sturzstroms might be related to a reduction in frictional resistance of colliding blocks dispersed by a dust suspension as interstitial “fluid”.

- The concept of acoustic fluidisation by Melosh (1986; 1990; 1979) and Collins and Melosh (2003) has been supported by physical experimenting with a special shaking table by Davies (1982).

- Systematic and important sources of experimental observations concerning granular flows down an inclined plane have been published by Savage and Hutter (1991); Hutter et al. (1995); Manzella and Labiouse (2007), Davies and McSaveney (1999), and Davies et al. (1999).

- An obvious approach in modelling a granular material physically, which experiences rapid shear strain, is to perform ring shear tests. Such tests have been performed and published by Wang and Sassa (1998) and Deganutti (2008). Both report a drop in the shear resistance which can be related particle crushing. This effect is also rigorously analysed by others like Einav et al. (2006) and Einav (2007a; 2007b).
• In 1g physical flume experiments, fragmentation of the particles can hardly be observed because of the low level stress regime of such configurations. The performance of such experiments in the increased g-field of a centrifuge apparatus is therefore reasonable. Bowman (2006) presented data on the fragmentation of coal particles within a centrifuge experiment. But this very preliminary set up more closely resembled a single impact event than a slide or a flow of granular material, similar to gun-shot experiments like those presented by Tomas et al. (1999); Schubert et al. (2005); Reddish et al. (2005) or Wu et al. (2004). Similar centrifuge experiments resembling rock fall events accompanied by fragmentation have been performed by Itoh et al. (2006). But these experiments suffer from a lack of a thorough evaluation of the boundary conditions present.

2.3.3.1 Summary on 2.3.3
Despite the claim of good fit with empirical prototype data, long run out of dry granular materials remains enigmatic in 1g flume experiments. The mobility of sturzstroms cannot be easily reproduced by such physical experiments (Friedmann et al., 2006). Ring shear experiments and centrifuge experiments display promising approaches because they may allow simulations to be performed under a stress regime similar to that of prototype situations. But so far the ring shear experiments have revealed the presence of previously known residual shear strength of granular materials, but which is higher than the apparent friction coefficient of sturzstroms. On the other hand, the set up of the centrifuge experiments so far does not resemble slides or flows of granular material well.

2.3.4 Discontinuum Mechanical Numerical Models of the Mobility of Sturzstroms
The rapidly evolving field of distinct element modelling (DEM) becomes important as a numerical tool in analysing granular flows like sturzstroms, because it allows the explicit simulation of the aggregate response of discrete grains.

• Self-lubrication, assuming that the sturzstrom slides on a thin layer of highly agitated particles (e.g. Section 2.3.2) has been simulated numerically using a DEM, by Straub (1997).

• It will be shown below that the DEM code, PFC, by Itasca Consultants has been applied in the present study. 2D and 3D versions of this code have been utilised in a number of publications related to sturzstroms (among others Calvetti et al., 2000; Poisel et al., 2007; Poisel and Preh, 2006; Preh and Poisel, 2007; Tommasi et al., 2008). In principle, these studies comprise nothing else than the numerical representation of the 1g flume experiments shown above. The differences are that the numerical experiments are performed at true scale, at least of the bulk volume of the rock mass involved. All models consist of rigid particles, which can not experience fragmentation. Only the work by Tommasi et al. (2008) allows for a very coarse scheme of fragmentation.
2.3.4.1 Summary on 2.3.4

DEMs represent a very promising tool in simulating granular slides and flows. They also allow for the explicit representation of dynamic fragmentation, as shown for example, by Cheng et al. (2004; 2003). But these simulations are restricted to very small samples. With the current computational power available, it is impossible to model a true scale sturzstrom and to allow for explicit fragmentation down to silt-size particles simultaneously.

2.3.5 Continuum Mechanical Numerical Models of the Mobility of Sturzstroms

Continuum mechanical models in contrast to DEMs, offer a calculation efficient method to simulate the dynamic of sturzstroms, these days even in 3D and at true scale.

• Scheidegger (1973) regresses the logarithm of the volume of 33 cases of sturzstroms with the logarithm of their apparent coefficient of friction, yielding quite a good correlation. This work has been continued and extended by Tianchi (1983), by regressing 76 cases of Alpine sturzstroms.

• Denlinger and Iverson (2004), Iverson (2002; 2003; 2006), and Iverson et al. (2004) propagate both, the regression of empirical observations on the run out of granular avalanches, and their continuum mechanical modelling.

• Trunk et al. (1986) entered the field of continuum mechanical modelling of the run out of sturzstroms by considering also the topography while conducting back-analyses of the 1959 Madison Canyon event (Montana, U.S.A.).

• Continuum mechanical modelling based on a Newtonian fluid has also been done for the Chaos Jumbles sturzstrom (California, U.S.A.) by Eppler et al. (1987). This work is very notable because the three Chaos Jumbles events may be considered as the prototype sturzstroms par excellence. They occurred on completely flat terrain without any confinement. Additionally, the later two events were emplaced on their antecessor deposits. Hence, these sturzstroms moved on very rough, blocky and dry terrain, challenging all theories proposing a low frictional basal layer to explain the exceptional run out of sturzstroms. Finally Eppler et al. (1987) provide good arguments to consider sturzstroms rather as being emplaced like a liquid flow, than sheet-like as a slide.

• To demonstrate the proposed effects of dynamic fragmentation, Davies and McSaveney (2002) incorporated dynamic fragmentation within a mass-referenced continuum model for dynamic analysis of rapid mass movement.

• Hungr and Evans start in 1996 with the publication of the continuum mechanical back-analysis of cases of sturzstroms based on various types of rheologies. They modelled the 1987 Val Pola event (Italy) also utilising a Voellmy rheology. This event has subsequently been modelled by Crosta et al. (2004) and Pirulli and Mangeney (2008) again applying Voellmy rheology. This is notable because, in all three studies, a good agreement of the model result with the prototype situation could be achieved, but the input parameters, especially the turbulence coefficient differs quite significantly between all three works. Still, Hungr (2006) claims that: “...in about 70% of [sturzstrom] cases, good “first order” predictions of the total run out distance can be obtained.
using the Voellmy model, with a fixed pair of resistance parameters (friction coefficient of 0.1 and a turbulence coefficient of 500 m/sec²).

2.3.5.1 Summary on 2.3.5

Continuum mechanical simulations are quite successful in representing run out and spreading of sturzstroms. They therefore represent today’s state of the art of prediction the mobility and run out of eventual sturzstroms. The works of Scheidegger (1973) and Tianchi (1983) is cited under this heading because it deduces its prediction power in principle from the same approach as the continuum mechanical model: fitting of a mathematical formulation to empirical observations. Nevertheless both remain, like the cited continuum mechanical models, type C1 predictions (e.g. Section 2.1) and reveal, except for the work by Davies and McSaveney (2002), little about the underlying mechanical processes which lead to the unusual run out of sturzstroms.

2.4 Scientific Gap

An overview of mechanisms and methods proposed to explain and to predict the high mobility of sturzstroms has been given above. For a more detailed discussion, the interested reader is invited to consult detailed reviews on the mechanisms proposed above, given in Campbell et al., 1995; Davies et al., 1999; Deganutti, 2008; Erismann and Abele, 2001; Hungr, 2006; Legros, 2002; Legros, 2006; Pirulli and Scavia, 2007; Shaller and Smith-Shaller, 1996. Additionally, all studies presented above which propose volatile-free mechanisms to explain the long run out of sturzstroms (Section 2.3.2), include reviews and discussions, criticising the mechanisms that depend on the presence of volatiles (Section 2.3.1). Repeating all of these discussions here would not promote the definition of a scientific gap allowing for an advance in sturzstrom research.

However, to recall the discussion of Section 2.1, the two main questions, on which the hypotheses and theories presented above about the mobility of sturzstrom are reviewed, are repeated:

a) Have the models postulated been confirmed based on empirical evidence? Hence, has any experimental confirmation been achieved?
   Does the model contradict commonly observable phenomena of sturzstroms?

b) Does the model postulated contribute to a deeper understanding of the mechanism involved? Therefore, does it have the potential to become a type A prediction tool?

About a): Unfortunately, many of the proposed mechanisms lack any experimental confirmation. They retain therefore in the status of a hypotheses often based on a few empirical observations of real sturzstrom deposits. From the point of view of commonly observable type features, only the dynamic fragmentation-spreading model constitutes a promising approach to bridge the type feature of fragmentation with the type feature of long run out of (dry) rock masses.

About b): On the one hand, many successful attempts have been made at least to confirm geometrically, predictions made by continuum mechanical simulations. They therefore represent today’s state of the art of sturzstrom run out prediction. On the
other hand, most of these models do not contribute to a deeper understanding of the mechanism behind the high mobility of sturzstroms. They remain therefore purely Type C1 predictions with all the risks associated when such models are applied to make “real” predictions of the run out of a potential future sturzstrom site.

Finally, the Swiss geologist Albert Heim posed the key question: “Wie kann dieses Blockwerk sich auf diesem ebenen Talboden so ausgebreitet haben? Wasser, Schlamm-Muhrgänge könnten das nicht tun; und das Blockwerk ist trocken und war trocken!” (“How can a blocky rock mass spread itself in such a way? Debris flows could not do it; and the rock mass was dry and is dry!”; Heim, 1932). In our opinion, this question still remains largely unresolved today.

2.4.1 Aim of this Thesis

The motivation of this research project is to reveal the mechanics of sturzstroms in more detail in order to contribute to the development of a Type A (Lambe, 1973) run out prediction model, as declared in Section 1.3. Such a model is necessary, both for the successful mitigation of sturzstroms as a natural hazard, and for a contribution to the understanding of the formation of Martian sturzstroms. To begin with the development of such a Type A prediction model, it has been decided to proceed within this thesis with the aim of finding and confirming physical mechanisms governing the run out of sturzstroms. An alternative approach may to collect and to back-calculate case studies to increase the prediction power of continuum mechanical models, as proposed by Hungr (2006), with the drawback of revealing little about the underlying mechanical processes that lead to the excessive run out of sturzstroms.

It is obvious that a sturzstrom represents a highly dynamic collisional granular regime. Thus particles do not only collide but will eventually crush each other. Erismann and Abele (2001) describe this process as dynamic disintegration, where kinetic energy is the main driver for fragmenting the rock mass. In this case, and according to the literature review show above, the most promising approach is represented by the dynamic fragmentation-spreading model (Davies et al., 2003; Davies and McSaveney, 1999; Davies and McSaveney, 2002; Davies and McSaveney, 2004; Davies and McSaveney, 2006; Davies et al., 2006; Davies et al., 2007; Davies et al., 1999; Dufresne and Davies, 2009; McSaveney and Davies, 2007; McSaveney and Davies, 2002; McSaveney and Davies, 2009; Smith et al., 2006). This hypothesis has the potential to combine all type features of sturzstroms presented above (Section 2.2) within one theory. This model also has the potential to explain the extreme run out of Martian sturzstroms without relying on the presence of volatiles under high pressure.

The aim of this thesis research is therefore defined as:

- to study the concept of dynamic fragmentation in more detail by increasing the understanding of the role of rock fragmentation within the mechanics of highly mobile rock masses like sturzstroms.

This aim is considered as a promising precondition for the further development of a Type A run out prediction model of sturzstroms as declared in Section 2.1. Fell et al. (2005) developed a general flow chart depicting the risk management of natural hazards by a pyramid (Figure 2.3). In their definition of managing the risk of slope instability, whether of natural or anthropogen origin, is defined as: “The systematic
application of management policies, procedures and practices to the tasks of identifying, analysing, assessing, mitigating and monitoring risk”. Within this framework of risk management, the study aim represents the desire to contribute to the top of that pyramid (Figure 2.3), where the danger of a potential landslide, in the present case of a sturzstrom, is characterized. This requires, among other, a deep understanding of the mechanics of sturzstroms! The motivation for this thesis, as declared in Section 1.3, represents the desire to contribute to the subsequent step of that pyramid (Figure 2.3), below the danger characterisation. The hazard originating from a potential landslide is characterized at this level. This demands a Type A prediction model of the velocity profile and run out of sturzstroms.

Figure 2.3: General flow chart of landslide risk management according to Fell et al. (2005).

2.5 Methods to Address the Scientific Gap  
(modified after Imre et al., 2009a)

During this thesis project, and independently of it, Davies and McSaveney developed their fragmenting spreading model further. This study is therefore not a continuation of their work but an independent attempt at investigating the role of rock fragmentation within sturzstroms by adopting highly specialised methods and tools, which allow fundamental research to be performed.

Shaller and Smith-Shaller (1996) very rightly suggest that: “…experimental simulations, in which sturzstroms are modelled with flowing granular material, properly scaled by use of exotic materials or by centrifuge techniques, offer a possible means of bridging from present conceptual models to a suitable complex computer model.” Better knowledge of the mechanics of sturzstroms therefore
demands rigorous modelling, in particular of the transition from static to dynamic behaviour. And like theories which are constructed and confirmed in epistemic circles (Section 2.1), the study aim will be addressed by a three-step approach in which each step is built or constructed on the previous one (Figure 2.4; Janich, 1997). A more rigorous language is therefore necessary to describe the epistemological implications of the present study (among others Lauth and Sareiter, 2005; Oreskes et al., 1994; Rosenberg, 2005), which goes beyond the usual needs and requirements of civil engineering (e.g. among others Lee, 2002; Mayne et al., 2009).

Figure 2.4: Construction of the thesis research depicted by epistemological circles. Each circle feeds into the next, acting like interlocking gears.

2.5.1 Field Work (modified after Imre et al., 2009a)

The Goldau sturzstrom (Figure 1.3) that occurred in 1806 (canton Schwyz/Switzerland; Berner, 2004; Buxtorf et al., 1916; Buxtorf et al., 1912; Erismann, 1979; Heim, 1932; Thuro et al., 2005; Thuro et al., 2006a; Thuro et al., 2006b; Thuro et al., 2008; Thuro and Eberhardt, 2003; Zay, 1807; Zehnder, 1988) is a single sturzstrom event or, from the epistemological view point, a token. It displays
all type-features of sturzstroms as mentioned above, paired with an excellent availability of data and written first hand eyewitness accounts (Zay, 1807). The site is easily accessible and exhibits a simple geometry, reducing the impact of unwanted boundary effects (in contrast to the more recent events of Elm 1881 or Val Pola 1987). Additionally, the Goldau sturzstrom exhibits a geometry comparable to Martian sturzstroms of scientific interest. This sturzstrom was therefore selected to serve as prototype for the present research project (in civil engineering, a “prototype” is an idealized representation of an object of study and its type-features; e.g. Lee, 2002). Data of the fabric, particle size distributions and particle shapes have been collected for this study from this site. Further samples have been collected from the deposits of sturzstroms in Flims (canton Graubünden/Switzerland; Bieler, 2006; Erismann, 1979; Pollet and Schneider, 2004; Poschinger, 2002; Poschinger, 2005; Poschinger et al., 2006; Schneider et al., 1999; Wassmer et al., 2002; Wassmer et al., 2004), Grächen (canton Valais/Switzerland; Eisbacher and Clague, 1984; Montandon, 1933) and Köfels (Tyrol/Austria; Brückl and Brückl, 2006; Brückl et al., 2001; Erismann et al., 1977; Erismann, 1979; Kilburn, 2001; Sørensen and Bauer, 2003; Stini, 1941). The deposits sampled from all these sites are characterized by a fairly uniform matrix supported fabric. Despite intense fragmentation, large rock boulders can be found at any depth (Figure 2.2; Campbell et al., 1995). All sampled particles, of any size, display sharp edges with angular shape, while virtually no signs of abrasion can be found. Instead white, lunette shaped impact marks appear regularly, which are most visible on the micritic Malm limestone of the Flims sturzstrom (Figure 2.5). These features are not new. Heim (1932) described them quite accurately already, but the resulting implications on the thermodynamics of sturzstroms have not been fully elaborated since then.

Figure 2.5: Chunks of massive, micritic Malm limestone sampled from the Flims sturzstrom. This sample is representative of the angularity of particles forming in sturzstroms—independent from their diameter and geology. The rough fracture surfaces are not pre-existent in the source rock but are newly formed by fragmentation during the transition of the sturzstrom. These two chunks fit together like a “jigsaw puzzle” (Campbell et al., 1995; Shreve, 1966; Voight, 1978). The white spots are lunette shaped impact marks by other rocks, but no signs of abrasion are observable (a 27 mm diameter coin serves as scale).
2.5.2 Physical Modelling of Fragmentation (Epistemological Circuit I; modified after Imre et al., 2009a; Imre et al., 2010)

It is obvious that a sturzstrom represents a highly dynamic collisional granular regime. Particles not only collide but eventually crush each other. Fundamental research on the failure of rock (among others Ashby and Jones, 1980; Engelder and Fischer, 1996; Harder, 1992; Hillerborg, 1985a; Hillerborg, 1985b; Schubert et al., 2004; Schubert et al., 2005; Tomas et al., 1999; van Vliet, 2000; van Vliet and van Mier, 2000) reveals that fragmentation constitutes a path of energy dissipation. Because sturzstroms are accompanied by intensive particle fragmentation (Section 2.2), it is therefore necessary to consider it for the understanding of the thermodynamics of sturzstroms. Unfortunately, fragmentation within sturzstroms can not be observed directly in a real event because of their long "reoccurrence time" and the obvious difficulties in placing measuring devices within such a rock flow.

Physical experiments on rock slides have been performed within the ETH Geotechnical Drum Centrifuge (Springman et al., 2001) to enable significantly higher kinetic energies and stresses levels, much closer to the prototype situation, to be applied to rock material, in contrast with so-called 1g (gravity) laboratory experiments (Figure 2.5). The intention of these experiments is to make fragmentation within sturzstroms observable and reproducible. Hence, they have been performed to provide empirical data on which a hypothesis on the run out of sturzstroms may be induced. These experiments are not intended to test, or to deduce predictions on the run out of true sturzstroms; for the difference between induction and deduction (see e.g. Lauth and Sareiter, 2005).

2.5.3 Analytical Modelling of Fragmentation (Epistemological Circuit II; modified after Imre et al., 2009a)

To link field evidence and results of physical modelling with numerical modelling an idealised, deterministic comminution model after Sammis and co-authors (Sammis, 1996a; Sammis et al., 1987; Sammis, 1996b; Steacy and Sammis, 1991) is introduced.

The usefulness of this model is that it allows the reasonable quantitative description and prediction of key parameters necessary for understanding the energy budget of sturzstroms. At the same time, this comminution model is simple enough to represent key features of fragmentation and make progress in sturzstrom research, while not getting lost in mechanical or mathematical details.

2.5.4 Mechanical Rock Properties

An entire chapter (Chapter 5) is devoted to the thorough measurement, or reasonable selection, of quantitative mechanical intact rock properties, which are fed both into the analytical modelling of fragmentation, and the subsequent numerical modelling of the effects of fragmentation.

2.5.5 Numerical Modelling of the Effects of Fragmentation (Epistemological Circuit III; modified after Imre et al., 2009a)

A 3D Distinct Element Code will be adapted to model sturzstroms. These models will allow a closer look to be taken at the dynamic processes and stress regimes.
Constitutive models can be defined and inserted as required, based on results and experience obtained from the laboratory experiments.

As stress conditions in dynamic rock masses such as sturzstroms are difficult to model at laboratory scale, it is even harder to monitor their micromechanical response in analogue models. Therefore this study will complement the analogue models with numerical models. The 3D Particle Flow Code PFC-3D (based on the works by Cundall, 1988; Cundall and Strack, 1979) has been selected (Itasca, 2005a) for this purpose. This distinct element code allows a rapidly moving rock mass to be simulated. A great advantage is that the stress states, position and velocity of all particles are known and can be recorded for any particle at any time. This will allow micromechanical processes in the interior of sturzstroms to be analysed.
3 Physical Model

“The Geologic and Tectonic Inventory”
N-S cross section of the upper crust within the proximity of Goldau. Part I of a cycle of paintings on the sturzstrom of Goldau 1806, by the author, for the exhibition “Der Berg kommt! Risikokultur in den Alpen”; Musée Suisse, Schwyz, 2006.

3.1 Introduction

Boundary conditions, instrumentation and results of a physical experiment to simulate fractal fragmentation within the collisional flow regime of sturzstroms are presented in this section. The mechanical set up of this physical model delivers a guided experimental rock slide imposed by a dynamic acceleration field. Analogue rock material is stored in a hopper and released in-flight by a pneumatic trap door into an acceleration chute. The rock material progresses to a run out chute—reflecting the prototype situation of a sturzstrom, which includes a source, transit, and deposition zone. The instrumentation includes light barriers, a triaxial force sensor, frictional heat sensors, and high and low speed cameras with illumination provided by light emitting diodes.

Three contributions have been published about the attempt to model a sturzstrom or parts of it, physically. The work by Imre et al. (2010) provides a description of the centrifuge apparatus, the experimental set up, its boundary conditions and the sensing devices applied. The study by Imre et al. (2009b) presents the development, characterisation and application of an analogue material for rock, which has been used in the centrifuge experiments. Finally the study by Imre et al. (2009a) presents and discusses the results that have been achieved by the physical modelling of sturzstroms.
3.2 Mechanical Set Up (Imre et al., 2009a; Imre et al., 2010)

The physical model in the geotechnical centrifuge is designed to expose two litres of rock to a stress and kinetic energy regime comparable to that of true sturzstroms. It is not intended to scale masses and dimensions completely, as in the classical sense (e.g. Schofield, 1980) of modelling a prototype. The experiment simulates an environment of a virtual unconfined run out in the direction of the $x'(t)$-axis, plane strain conditions in the local $y'(t)$-axis, a free surface in the positive $z'(t)$-direction and a smooth sliding surface in the negative $z'(t)$-axis of the sliding mass (Figures 3.1, 3.2). This basic set up is inspired by the direction of the stresses of sturzstroms in nature (Figure 1.3). The thickness of a sturzstrom is small compared to its lateral and longitudinal extensions. The propositions are made that the largest normal stress will act in the flow direction along the $x'$-axis. The intermediate normal stress will act horizontally, perpendicular to the flow direction along the $y'$-axis, where plane strain conditions may be assumed in the middle of the sturzstrom. The minimum normal stress, mainly due to the limited overburden of the rock mass, will act in the direction of the $z'$-axis.

During flow, the model material is loaded externally through an interplay of radial and tangential acceleration fields, and surface friction in the plus/minus $y'$ and minus $z'$-directions, only. No other interaction between the model device and the sliding rock mass occurs, in contrast to ring shear apparatuses, which are also used in sturzstrom research (Deganutti, 2008), where deformations are imposed on a rock material by a rigid plate boundary. A maximum velocity of about 15 m/s can be achieved in the $x'$-direction of the centrifuge model, allowing fully dynamic experiments to be performed. This maximum velocity is limited by the mechanical strength of the centrifuge apparatus, which is designed for 440 times earth’s gravity at a radius of 1.1 m, and is still about 5 times smaller than the estimated peak velocity of the Goldau sturzstrom in 1806 (Berner, 2004). Preliminary centrifuge experiments revealed that the kinetic energies have been too low under such conditions to enable fragmentation of natural rock to occur through inter-particle collisions. A solution to this problem was to scale the strength of the rock material. For this reason, the ETH Analogue Material for Rock (ETHAR) was developed and applied in form of cubes with side lengths $\nu_0$ of 19, 32, or 48 mm. Data of the properties of ETHAR, which are of interest here, are given in Section 3.3. A detailed description and characterisation of that material, together with an analysis of its performance within the boundary conditions provided by this physical model environment, is discussed in Imre et al. (2009b).
Figure 3.1: 3D sketch of the experimental set-up: (a) hopper; (b) acceleration chute; (c) run out chute segments; (d) compressed air tank; (e) tool plate; (f) drum; (g) high speed camera mounted vertically; (h) lighting system; (i) data acquisition box. The entire system rotates clockwise around the vertical $y$-axis with an angular velocity $\omega$. The displacement of the experimental rock material is described by a moving coordinate system, with the $x'(t)$-axis parallel to the channel base.

Figure 3.2: Top view into the drum centrifuge: two experiments are performed during each run with diametrically opposed channel sections (a), (b), and (c) for balance. The high speed camera (g) is shown on this image in an alternative, horizontal, mounting. The hopper (a) is inclined at 12° to the radius of the drum; the acceleration channel (b) has a radius of 0.325 m; and the run out channel (c) a radius of 1.06 m.
3.2.1 The Hopper (modified after Imre et al., 2010)

The hoppers (Figures 3.1–3.3) are Aluminium boxes that are designed to store two litres of test material each. They are equipped with a pneumatic system, operated under an air pressure of 800 kPa, for releasing the trap doors in flight. The compressed air is stored, pre-flight, within a two litre steel tank (Figure 3.1). The trap door release is triggered via an electromagnetic valve, which opens the air flow to the pneumatic pistons linked to the locking bolts.

The trap doors swing open under self weight after releasing the locking bolts pneumatically. It takes 0.07 seconds after triggering for the doors to reach their fully opened positions at an angular drum velocity $\omega$ of 30.4 rad/s. In this position, the doors direct the blocks of rock into the adjacent acceleration channel. The experiment is performed within two diametrically opposed channels to ensure balance in the drum, requiring a reliable, simultaneous release of the two trap doors. The failure of one door would otherwise lead to strong dynamic imbalance, potentially destructive to the centrifuge apparatus at a whole. The release system was designed, and also tested statically, for loads up to 2.5 kN to prevent this (Figure 3.4), according to the expected loading conditions during the experiment.

After removal of the covering lids, the hoppers are filled with blocks of rock pre-flight, from the top (Figure 3.3). After filling, the lids are placed again, fully enclosing the rock material from all six sides. Large air intake lids are located opposite to the trap doors to prevent depression of air pressure while the blocks leave the hoppers (Figure 3.3).

![Figure 3.3: The hopper section of the experiment (cover lid removed). (a) trap door and its hinge (b); (c) pneumatic piston to unlock the door in-flight; (d) swing delimiter with attached acceleration sensor; (e) acceleration chute; (f) air intake lid.](image)
3.2.2 The Acceleration Channel (Imre et al., 2010)

The acceleration channels (Figures 3.1, 3.2, and 3.5) are located adjacent to the hoppers (Figure 3.3). The channel base, made out of stainless steel, has a circular curvature with a radius of 0.325m. The side walls are made out of anodized aluminium. A Coulomb friction model was assumed to be appropriate to describe the sliding behaviour of the rock during the experiment, therefore the friction coefficient \( \mu \), on the interface channel/rock material, plays a vital role in the experiment. The friction coefficient is predominantly controlled by adhesion (in the sense of molecular attraction between contiguous surfaces of materials of different compositions) and ploughing (Mate, 2008). If the rock material would cause substantial grooving in the channel surface, this would alter the roughness and therefore the frictional behaviour of the channel faces during each test, changing this crucial boundary condition in each test. The frictional response of varying surfaces under different loading conditions was investigated prior to the design of the experiment, leading to selection of the materials presented (Räbsamen, 2007).

A number of sensors are mounted on the model apparatus in order to monitor the experiment in flight (while the centrifuge is spinning) and to validate the analytically derived boundary conditions (Section 3.2.6).

Three light barriers are placed at the end of the channel to measure the point in time at which a light beam is disturbed, so that the front velocity of the experimental rock slide can be determined (Figure 3.5). Additionally, four frictional heat sensors
are mounted flush with the channel base (Figures 3.5, 3.6). These sensors were made in house using NiCr/NiAl type K thermocouples (DIN, 1995). The intention was to sample quasi point measurements on the frictional heat development at the channel base, which may then be integrated over the entire channel surface to gain at least a measured range of frictional energy dissipated during the experiment. Although a few readings yielded reasonable results, the frictional heat sensors failed in general. The main reason is found in the insufficient shielding against electromagnetic noise of the very sensitive thermocouples (Figure 3.7).

**Figure 3.5:** Elevation view into the acceleration channel (a) and the first section of the run out channel (b). (c) main light source; (d) light barriers. The force (e) and temperature sensors (f) are mounted flush with the channel base allowing frictional force and heat of the rock material to be measured.

**Figure 3.6:** The PVC block (a, c) provides a thermally and electrically insulated mounting for the temperature sensor. The sensor consists of a friction-plate (b); (d), made out of the same steel as the chute base, in which an electrically insulated thermocouple is glued. The glue is a resin with a high thermal conductivity, which was increased by adding brass powder (e) (scale in cm).
Figure 3.7: A representative example of the frictional heat measurements whereby the centrifuge has been spun up and down before the experiment. The measurements shown represent the relative change in temperature compared to the absolute room temperature within the centrifuge. It can be seen clearly that electromagnetic noise, partially dependent on the angular velocity of the centrifuge (expressed by the “Gravity” curve of an acceleration sensor attached to the centrifuge drum), exceeded the signals, obtained during the sliding. Even the signal of the absolute room temperature, which serves as reference for the measurements, indicates disturbance due to noise.

3.2.3 The Run Out Channel (Imre et al., 2010)

Three run out channels segments, each 0.416 m long, are located adjacent to the acceleration channels (Figures 3.1, 3.2, and 3.5). The stainless steel channel base has a circular curvature with a radius of 1.06 m. The first channel segment is instrumented with a combined temperature and three-axial force sensor (Figure 3.8) and equipped with a side window, allowing for observation of the sliding rock material in the minus $y'$-direction by a high speed camera (Figures 3.1, 3.2).

3.2.4 The Force Sensor (Imre et al., 2010)

A three-axial force sensor$^6$ is mounted flush with the channel base (Figures 3.5, 3.8C). The construction principle of the device requires a preloading of the sensor through its centre hole by a plunger. Forces acting on it cause deformations within the plunger, which are then measured by the force sensor. Such a loading configuration requires in situ calibration of the sensor in order to be able to make accurate absolute measurements. Because an in situ calibration can not be achieved if the sensor is mounted within the centrifuge, a loading frame was constructed to “simulate” the in-situ mounting conditions of the sensor in every detail (Figure 3.9). The sensor was calibrated for a maximum force of 100 N in the plus/minus $y$ axis.

$^6$ www.kistler.com, data sheet # 000-173d-07.01, type 9602
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\((x\text{-axis of the sensor})\), 500 N in the plus/minus \(x\) axis \((y\text{-axis of the sensor})\) and 1000 N in the minus \(z\)-axis \((z\text{-axis of the sensor})\) (Appendix 8.1).

The sensor is shock resistant up to 2000 \(\text{m/s}^2\) and was successful in measuring force components dynamically at 10 kHz and quasi statically at 0.5 Hz (Figure 3.10).

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\(\text{Figure 3.8: A) The triaxial force measuring device consists of a sensor (a) which is mounted by a steel plunger (b) on a holding frame (c). B) The mounting frame (c) itself is attached to the backside of the first segment of the run out chute (d). C) The plunger (b) pops through the base of the run out chute (d) to its front side. During the experiment the plunger is loaded by the rock in compression in the minus \(z\)’ direction and primarily in the \(x\)’ direction by shear due to friction. Since the force sensor requires minute amounts of deformations to allow for force measurements, a gap (e) is kept free around the plunger, which is filled with silicon (scales in cm).}\)
Figure 3.9: A) Sensor measurement of force is dependent on the stiffness of its mounting. The sensor (a) has therefore to be calibrated in all three axes prior to the experiment. The calibration was achieved by mounting the sensor (a) together with the plunger (b) and the mounting frame (c) on a test frame (d) (including the silicone filled gap shown in Figure 3.8C). The sensor is then loaded by a steel bar (e). B) Both the frame (c) and the bar (e) were attached to a standard electromechanical test frame (f) to load the sensor (a) in the minus $z'$, C) $\pm x'$ and D) $\pm y'$-directions (scales in cm).
Figure 3.10: Representative example of a force measurement of an experiment with $\omega$ of 30 rad/s (low-pass, Butterworth, 6th order, 200 Hz cut-off frequency filtering applied). The measurement can be split into three phases: phase (a) denotes the measurement between the triggering of the experiment and the point in time when the rock material front reaches the sensor, which is located at the beginning of the first segment of the run out chute (Figure 3.5). During this phase the forces in the minus $z'$-direction (radial force) remain $\approx$ constant whereas the force in the $x'$-direction (tangential) becomes negative. No conclusive explanation has been found for the latter. The rock material passes the force sensor during phase (b). The beginning of phase (c) marks the end of the experiment, after less than 0.2 seconds. When the rock material has stopped, it applies a static load in the minus $z'$-direction on the sensor. This load prevents the force sensor from snapping back into its zero position due to friction, hence the loading remains in $x'$-direction as well. The arc tangent of the force $x'$ over force $-z'$ yields a friction angle of 20° during the phases (b) and (c). This value is very close to the frictional response of the stainless steel channel base of 18 ± 1°, investigated in preliminary experiments on a slip table (Figure 3.30; Imre et al., 2009c), proving the constancy of this boundary condition during the experiment.

3.2.5 The Side Window (Imre et al., 2010)

The experiment is monitored with a high speed camera either from the side, through an observation window (Figure 3.11), in the minus $y'$-direction (Figure 3.2) or from top in the minus $z'$-direction (Figure 3.2). The velocity of the rock material during the experiment requires high frame rates in the order of 2000 frames/s. The resultant short shutter times necessitate strong lighting to illuminate the images sufficiently, which often leads to very perturbing reflections. It was necessary to adjust the components of the light source, observation window, and camera carefully relative to each other. Twelve, 5 W, 160 lm light emitting diodes (LED), with a spectral power maximum at 505 nm (cyan), have been used as a light source (Figures 3.11, 3.12).
Such LEDs are much smaller than standard light bulbs, which provide the same luminous flux and can therefore be mounted within a more confined configuration. The spectral power maximum was selected to meet the spectrum of the maximum quantum efficiency of the black and white high speed camera. The quantum efficiency describes the fraction of photon flux that contributes to the photocurrent in a photodetector (Fowler et al., 1998). The illuminance of ~ 19000 lx emitted by the LEDs in the configuration applied is used more effectively due to the improved sensor signal to noise ratio.

The LEDs are glued with a high thermal conductivity resin to an aluminium mounting frame, which itself is attached to a heat sink for cooling the LEDs. The vertical distance and the angle between the LEDs and the observation window are chosen so that their optical paths neither cause reflections to the camera nor total reflection within the glass itself (Figure 3.11B). The mounting frame also acts as an aperture focusing the light beam of the LEDs to prevent light scatter, which again would cause reflections on the window. Finally, to exclude all other sources for light scatter, all metal parts in proximity to the LEDs and the observation window are finished with a rough, sand blasted and black anodised surface (Figure 3.11A).

A 10 mm thick, blue-violet antireflective coated float glass, with about 90% reduced reflectivity compared to acrylic glass, has been selected to reduce the amount of light that is lost due to reflections on the observation window (Figure 3.12). An additional advantage of selecting glass as a side window is its hardness, with much more resistance against scratching than acrylic glass. Severe scratching would have both significant influence on the mechanical strength of the float glass window and therefore on the security of the experiment as well on the quality of the images taken through the window. Some minor scratching still occurred, although within acceptable limits (Figure 3.13). A 10 mm thick, very hard aluminium oxide (sapphire) window could have been an available alternative.

Reference marks have been attached to the outside of the window, to allow particle velocity tracking to be carried out. The marks are made out of precise custom-made friction foils, which can be ordered in virtually any colour and at a resolution of up to 1200 dpi (Figure 3.13).

![Figure 3.11](71x160 to 525x297)

**Figure 3.11:** **A)** Side view onto the first segment of the run-out channel showing the mounting frame (a) of the 12 LEDs (b) together with the observation window (c) and heat sink (d). **B)** Exploded drawing of the mounting frame (a), optical paths (e).
camera (f), notch (g) in the mounting frame (a) acting as an aperture.

Figure 3.12: Comparison of the reflectance of coated and uncoated observation windows made of float glass (a⁸) or acrylic glass (b⁹) with the relative spectral power of the light source (c¹⁰) and the quantum efficiency of the CMOS camera (d¹¹) used.

Figure 3.13: View from the position of the high speed camera through the observation window onto the experiment. Six LEDs (a) are hidden at each side within the mounting frame. (b) numbered friction foil reference marks at one cm orthogonal spacing. (c) rock material deposit at the end of the experiment. (d) scratches on

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⁸ www.schott.com, data sheet # 1003-5d/08/06-P
⁹ www.roehmschweiz.ch, data sheet # 50/0102/01133 (d), 211-1 January 2002
¹⁰ www.luxeon.com, data sheet #: DS34 (09/19/04)
¹¹ www.mikrotron.de, data sheet # MC13xx User’s Manual Rev. 1.11
3.2.6 The Acceleration Field (Imre et al., 2010)

The most important boundary condition in the centrifuge model is the acceleration field applied to the model material during the experiment. For a single point of mass, at time \( t \), for a constant angular velocity \( \omega \) of the centrifuge, the centrifuge acceleration \( a_{cfr}(t) \), causing dislocation of the particle in the radial direction, is defined by:

\[
a_{cfr}(t) = \frac{v_{t,channel}^2(t - dt)}{r(t - dt)} \text{[m/s}^2], \tag{3.1}
\]

where \( v_{t,channel}(t) \) is the tangential velocity of the channel at the radial position \( r(t) \) of a particle. The centripetal acceleration \( a_{cpr}(t) \) at time \( t \) which forces the mass point in a new radial trajectory is defined by:

\[
a_{cpr}(t) = \frac{v_{t,channel}^2(t - dt) + v_r^2(t - dt)}{r(t - dt)} \text{[m/s}^2], \tag{3.2}
\]

where \( v_r(t) \) is the radial velocity of a particle within the experiment. The tangential acceleration \( a_{t,cp}(t) \) at time \( t \) forcing the mass point in a new tangential trajectory is defined by:

\[
a_{t,cp}(t) = 2 \cdot \frac{(v_{t,channel}(t - dt) - v_r(t - dt)) \cdot v_r(t - dt)}{r(t - dt)} \text{[m/s}^2], \tag{3.3}
\]

where \( v_r(t) \) is the radial velocity of a particle within the experiment. The tangential velocity \( v_r(t) \) at time \( t \) is defined by:

\[
v_r(t) = v_r(t - dt) + a_{cfr}(t)dt \text{[m/s]}, \tag{3.4}
\]

and the radial velocity \( v_r(t) \) at time \( t \) by:

\[
v_r(t) = v_r(t - dt) + a_{t,cp}(t)dt \text{[m/s]}, \tag{3.5}
\]

with the radial position \( r(t) \) of the particle within the experiment at time \( t \):

\[
r(t) = r(t - dt) + v_r(t)dt + a_{cfr}(t) \frac{dt^2}{2} \text{[m]}. \tag{3.6}
\]

The last term in Equation (3.6) describes the change in \( r \) during a time step \( dt \). This term is omitted in the following solution because \( dt \) will be kept small. Resulting from the above equations, the angular velocity \( \omega_{\text{particle}} \) of a particle within the experiment at time \( t \) can be expressed as:

\[
\omega_{\text{particle}}(t) = \frac{v_r(t)}{r(t)} \text{[rad/s]}, \tag{3.7}
\]

which equals, following Equations 32 and 33, the angular velocity \( \omega \) of the centrifuge itself only, if the particle experiences no dislocation in the tangential direction. These equations are solved iteratively by a MatLab® script.
To point out the complexity of the acceleration field acting on a mass point within the centrifuge experiment, the numerical solution of Equations (3.1) to (3.7) is depicted below graphically. But for better understanding, this solution scheme is split into three parts, as shown in Figures 3.14 to 3.16.

Figure 3.14: Radial centrifuge acceleration $a_{cf}(t)$ (Equation 31), radial centripetal acceleration $a_{cp}(t)$ (Equation 32), and tangential centripetal acceleration $a_{ct}(t)$ (Equation 33) acting on point of mass sliding along a chute within the centrifuge experiment at time $t$. The system rotates within a plane perpendicular to the $y$-axis at an angular velocity $\omega$. The position of the point mass is defined by the polar coordinates $r(t)$ and $\theta(t)$. The slope angle $\chi(t)$ remains constant for the hopper section at 12° but changes with the polar position of the point mass for the acceleration channel and run out channel sections according to the circle functions for the channel radii of 0.325 m and 1.06 m respectively. $a_{cf}(t)$, $a_{cp}(t)$, and $a_{ct}(t)$ are split into their radial (index $r$), tangential (index $t$), channel parallel (index $p$) and channel normal (index $n$) components.
Figure 3.15: Coulomb friction $\mu$ is assumed to be valid. Because $\mu$ is finite, the components $a_{cp}(t)$ and $a_{tp}(t)$ can only be mobilized as a function of the effective accelerations normal to the channel. $a_{cp, mobilized}(t)$ and $a_{tp, mobilized}(t)$ are therefore calculated as $(a_{n,cp}(t) + a_{t,cp}(t)) \cdot \mu$. Over the intermediate step of calculating the effective resulting radial and tangential accelerations $a_{r,cp}(t)$ and $a_{t,cp}(t)$, the effective radial accelerations acting on the mass point in radial direction $a_{r,cp}(t)$ and in tangential direction $a_{n,cp}(t)$ can be calculated with the effective tangential accelerations acting on the mass point in radial direction $a_{r,cp}(t)$ and in tangential direction $a_{n,cp}(t)$.
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3.2.6.1 Example Calculation of an Acceleration Field

For a mass point, moving along the hopper section, the acceleration channel and the run out channel within the centrifuge experiment, the result of an example calculation is depicted in Figure 3.17. The geometry (channel radii) of the simulated experiment equals the geometry of the true physical experiment (Figure 3.2). The graphs show the development of the tangential, radial, and normal accelerations during the experiment. In this example, the centrifuge drum rotates at an angular
velocity $\omega$ of 30.7 rad/s. A static mass point, located at a radial position of 1.06 m, which equals the radius of the run out chute (Figure 3.2), would experience a radial acceleration field of 1000 m/s$^2$ at such an angular velocity of the experimental apparatus. Figure 3.17 shows that the entire experiment would last about 0.08 seconds only, a value which could be well confirmed in the centrifuge model tests (Räbsamen, 2007). The graphs start at time null = 0.07 seconds. The reason is that after triggering the pneumatic opening mechanism of the trap door (Figure 3.3), it takes about 0.07 seconds to release the locking bolt and for the trap door to swing to its final open position. This value has been measured with the high speed camera. After that the mass point will start to displace from the centre of the base of the hopper section.

- Figure 3.17, hopper section (a): due to the inclination of 12° of the hopper to the radius of the centrifuge (Figure 3.2), the mass point experiences a centripetal [cp] acceleration normal to the hopper base of about 100 m/s$^2$ from the very beginning of the experiment. This ensures that the rock material applied in the real experiments also remains in close contact with the channel base from the very beginning. The radial centrifugal [cf] acceleration, which amounts at the beginning of the experiment to about 600 m/s$^2$, causes the mass to displace, eventually leaving the hopper section and entering the acceleration chute section.

- Figure 3.17, acceleration channel section (b): the mass point reaches its maximum velocity within this section (in this example about 15 m/s parallel to the channel base), but also its highest centripetal [cp] acceleration normal to the chute base of about 1800 m/s$^2$. This means that the frictional resistance reaches its maximum around the peak velocity of the particle, expressed by the negative centrifugal [cf] tangential and radial accelerations. At the end of this section, when the acceleration chute merges smoothly into the run out chute, which is mounted parallel to the drum, the centripetal [cp] radial acceleration becomes equal to the centripetal [cp] acceleration normal to the channel base. Also the centripetal [cp] tangential acceleration becomes equal to the centrifugal [cf] tangential acceleration, whereas the radial centrifugal [cf] acceleration now becomes zero.

- Figure 3.17, run out channel section (c): the mass point loses velocity very rapidly within this section until it stops. Accordingly, the centripetal [cp] acceleration normal to the channel bases eventually reaches its static value of 1000 m/s$^2$. The centrifugal [cf] acceleration acting tangential to the channel base, responsible for the eventual stop of the mass point, reaches its static value as well. This value is controlled by the friction angle of the channel base of 20° (Section 3.2.4). Hence, it can be calculated by multiplying the static centripetal [cp] acceleration normal to the channel of 1000 m/s$^2$, with the tangent of 20°, which yields a value of about -370 m/s$^2$. A negative sign has to assigned to this number, because it acts as resistance.
3.2.6.2 Discussion about the Acceleration Field

This numerical simulation of the acceleration field represents a simplification of the real physical experiment. The predictions obtained were quite accurate in comparison with experiments performed within the centrifuge, as long as the rock mass sliding behaviour within the centrifuge experiment can be described by Coulomb friction (Räbsamen, 2007). Still, interactions of even a single rock block with the chute (canting etc.) occurred in the real physical experiments, which are not taken into account by the algorithm. Therefore, the numerically derived accelerations and velocities can be seen as upper boundary values, because the idealised numerical simulation slightly overestimates the data obtained from the physical experiment by trend.

Nevertheless, this numerical model provides useful insight into the boundary conditions of a centrifuge model, where mass points change their radial and tangential position rapidly during the experiment. Knowledge about these boundary conditions was crucial for planning and interpretation of the physical centrifuge experiments at various points during the study:

a) The theoretical insight gained answered the controversially debated question of whether the acceleration chute should point in the sense of rotation of the centrifuge drum or in the opposite direction. The result is that the acceleration chute has to point in the direction of rotation of the drum (Figure 3.2). This assures that the trajectory of a particle is always undercut by the acceleration chute, which keeps the particle in contact with the chute and therefore of the acceleration field of the centrifuge. Otherwise a particle may hit the acceleration chute once after release from the hopper, but would then lose contact to the chute. Due to the Coriolis effect, it may still appear as if the particle would slide along the chute, but in reality the particle would be free of acceleration and therefore of stresses. It appears that this is the case in the centrifuge rock fall experiments presented by Itoh et al. (2006).
b) The numerical model of the acceleration field has been confirmed in preliminary centrifuge experiments, with a preliminary set up by Räbsamen (2007). The numerical model was then used to plan and to design the final set up, as shown in Figure 3.2. The decisive advantage was that due to the numerical simulation, the dynamic peak acceleration, necessary for the design of the stability of the final mechanical set up, could be predicted.

c) The numerical simulation also revealed that the centrifuge experiment is not capable of predicting run outs of dry granular flows or slides. One reason is that the acceleration field does not resemble a natural prototype situation. The second reason is that any process which may reduce the apparent friction of the model slide (for example dynamic fragmentation-spreading) would cause higher radial and tangential centrifugal accelerations (and hence velocities) of a particle. But, at the same time, this would increase the centripetal radial and tangential centrifuge accelerations also. This would then increase the effective stresses and therefore the frictional resistance of a particle moving on the chute. This feedback mechanism keeps the run out a dry rock mass more or less constant, also when the angular velocity $\omega$ of the centrifuge is varied.

d) The numerical simulation was then also helpful in the interpretation of the results of the centrifuge experiments performed in this thesis (e.g. Section 3.4).

3.3 The ETH Analogue Material for Rock (ETHAR) (Imre et al., 2009b)

A physical analogue material is presented as a synthetic rock for use in centrifuge experiments. Although the stresses within the experimental set up in the centrifuge are significantly enhanced due to acceleration forces, compared to 1g laboratory experiments, the original rock of an historic sturzstrom event is still too strong and does not display fragmentation when allowed to run out in the centrifuge under enhanced gravity. Therefore, it is necessary to develop a material that will exhibit mechanical properties analogue to the natural prototype rock, but with reduced strength. A literature review on the development of analogue materials is included and the recipe of the newly developed synthetic soft rock, which is convenient to manufacture and requires only short curing times, is provided, together with a comprehensive mechanical characterisation of this material. In addition, it is shown that this material may serve as a physical prototype for the numerical simulation of soft rock within distinct element codes.

3.3.1 Introduction (Imre et al., 2009b)

The failure of rock is an important process accompanying many natural or man made events or actions, which is controlled by the mechanical strength of the rock. In the event that physical experiments at laboratory scale are adopted to investigate certain aspects, natural rock is often found to be stronger than the stresses that can be applied. This is especially true for experiments aimed to simulate mass movements, which are accompanied by rock fragmentation in nature. Very large rock slides or rock falls generate extensive fragmentation during transition and deposition when they turn into sturzstroms.
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Such sturzstroms are notably for far reaching run-out, which can not be explained by simple frictional models. The comparatively new fragmentation-spreading model identifies fragmentation as a key parameter for long run-out of sturzstroms (Davies, 1982; Davies and McSaveney, 1999; Davies and McSaveney, 2002; Davies and McSaveney, 2004; Davies and McSaveney, 2006; Davies et al., 2006; Davies et al., 2007; Davies et al., 1999; Dufresne and Davies, 2009; McSaveney and Davies, 2007; McSaveney and Davies, 2002; McSaveney and Davies, 2009; Smith et al., 2006). Despite preliminary efforts (e.g. Bowman, 2006; Deganutti, 2008) to confirm it, this promising theory still lacks convincing experimental validation.

The contact area and contact stresses between particles during fragmentation, as well as the degree of confinement of the rock mass, play a role in the response during a sturzstrom event. The centrifuge experiment simulates an environment defined with positive sign convention according to the arrows in Figure 1.3 with a virtual unconfined run out in the direction of a local $x'$-axis, with plane strain conditions in a local $y'$-axis, a free surface in a positive $z'$-direction and a smooth sliding surface in a negative $z'$-axis of the sliding mass. The rock mass is loaded externally through an interplay of radial and tangential acceleration fields, and surface friction in the plus / minus $y'$ and minus $z'$-directions, only. No other interaction between the experimental apparatus and the sliding rock mass occurs. The underlying approach is not to scale such a giant prototype event down to laboratory size but to take a small "virtual sample" of rock particles, with a mass $m$ and to load it under enhanced stress and kinetic energy conditions within an experimental setup.

The enhanced acceleration field causes stresses to be applied to the model material that are much closer to the prototype situation than in so called 1g (gravity)-laboratory experiments. Still, preliminary experiments showed that even an acceleration field of 200 times the natural gravity field does not lead to significant fragmentation, if natural rock is employed as a model material. Therefore a material that displays consistent mechanical properties analogue to natural rock, but of reduced strength, has to be sourced or developed.

This chapter provides a recipe of a synthetic analogue material, together with a comprehensive characterisation of its mechanical properties. This material has been named ETH Analogue material for Rock (ETHAR). It will be shown that ETHAR is capable of representing brittle rock failure due to inter-particle collisions within a model sturzstrom. It will also be shown that it can be applied very flexibly both for physical modelling and, as a physical representation for validating distinct element numerical models (DEM).

3.3.2 Scaled Mechanical Similitude Properties of the Analogue Material (Imre et al., 2009b)

The Goldau sturzstrom in 1806, serves as a prototype (e.g. Langhaar, 1951) for the planned centrifuge modelling efforts. During this event, an estimated volume of about $35 \times 10^6$ m$^3$ was mobilised, which reached a back-calculated maximum velocity of up to 70 m/s, where this represents the prototype velocity $v$. The most prominent rock constituting this sturzstrom was an Oligocene molasse conglomerate (Hantke, 2006; Stürm, 1973; Vogel and Hantke, 1988). The so-called “Bunte Rigi-Nagelfluh”, named after its type location in Switzerland, is a colourful limestone-dolomite conglomerate,
with about 5-10% content of plutonic components (Figure 3.18A). This material is the prototype for the selection and manufacture of an analogue material.

The appropriate scaling factor $k$ is addressed by using a kinetic energy approach. It is obvious that a sturzstrom represents a highly dynamic collisional granular regime. Yet particles not only collide, but eventually they crush each other. Erismann and Abele (2001) describe this process as dynamic disintegration, where kinetic energy is the main driver for fragmenting the rock mass.

Of particular interest is the intensity of fragmentation of particles within the collisional granular regime. For the sake of the later evaluation of the amount of energy required to create new fracture surfaces, the fragmentation intensity is defined as a dimensionless surface area ratio $P$:

$$P = \left[ \frac{A}{A_{\text{frag}}} \right] = \left[ \frac{A}{A_{\text{frag}}} \right]^* [\cdot], \quad (3.8)$$

where $A$ and $A_{\text{frag}}$ represent the surface area of particles within the sample volume before and after fragmentation respectively, both for the prototype and model cases. The model case is denoted by superscript $^*$. The rough assumption is made, when attempting to reproduce the same ratio $P$ within the model, that the formation of new fracture surfaces within a sturzstrom is a yet unspecified function of the kinetic energy $E_{\text{kin}}$ and the uniaxial compressive strength $\sigma_{c,f}$ of the individual rock particles:

$$P = f(E_{\text{kin}}, \sigma_{c,f}) [\cdot] \quad (3.9)$$

The maximum acceleration field of about 200 times earth gravity level corresponds to a maximum achievable particle velocity of about 15 m/s within the experimental set-up. The kinetic scaling factor $k$ between reported maximum bulk velocities of the prototype sturzstrom $v$ (Berner, 2004) and the maximum model velocity $v^*$ is:

$$k = \frac{v}{v^*} = \frac{70 \text{ m/s}}{15 \text{ m/s}} \approx 5 [\cdot], \quad (3.10)$$

The bulk model velocity is therefore about 5 times slower than the prototype velocity. The prototype kinetic energy $E_{\text{kin}}$ can be calculated by:

$$E_{\text{kin}} = \frac{1}{2} m \cdot (v^* \cdot k)^2 \text{ [Nm, J]} \quad (3.11)$$

The model kinetic energy $E_{\text{kin}}$ is therefore scaled by $k^2$:

$$k^2 = \frac{E_{\text{kin}}}{E_{\text{kin}}} \approx 25 [\cdot], \quad (3.12)$$
Preliminary tests suggest that if the model uniaxial compressive strength $\sigma_{c,f}$ of the analogue material is scaled by the factor $k^2$, fragmentation can be simulated successfully within the given modelling environment, which forms a focus of these investigations:

$$k^2 = \frac{E_{\text{kin}}}{E_{\text{kin}}} = \frac{\sigma_{c,f}}{\sigma_{c,f}} \approx 25$$  \[3.13\]

Further fundamental scaling laws for similitude properties of the analogue material may then be derived by applying dimensional analysis (e.g. Langhaar, 1951). The first step is to define a set of parameters that describe the problem sufficiently. It is obvious that the strength and deformation properties of the analogue material have to be scaled consistently to the prototype material. The effective compressive strength $\sigma'_{c,f}$ is a function of the shear strength $\tau_f$ of the material at failure, which can be described by the Mohr-Coulomb shear failure criterion (e.g., among others, Parry, 1995) with:

$$\tau_f = \sigma'_n \tan \varphi'_{\text{max}} + c' \quad [\text{MPa}], \quad (3.14)$$

where $\sigma'_n$ denotes the effective normal stresses, $\varphi'_{\text{max}}$ the effective maximum internal friction angle and $c'$ the effective cohesion respectively. The strain of the material may be described by a linear elastic strain model with:

$$\varepsilon_a = \frac{1}{M'}(\sigma'_a - 2\nu'\sigma'_r) \quad [-], \quad (3.15)$$

where $\varepsilon_a$ denotes the axial strain, $M'$ the effective Young’s modulus, $\nu'$ the effective Poisson’s ratio and $\sigma'_a, \sigma'_r$ the effective axial and radial stresses respectively. Since all materials tested in this research study are in a dry state, for the sake of simplicity, all apostrophes, representing the effective stress state of parameters, will be omitted from now on. Finally, it is necessary to define the tensional strength $\sigma_{t,f}$ of the material due to mode I failure, which can be expressed as (e.g. van Vliet, 2000):

$$\sigma_{t,f} = \sigma_{t,\text{max}} = \frac{F_{t,\text{max}}}{A} \quad [\text{MPa}], \quad (3.16)$$

where $\sigma_{t,\text{max}}$ denotes the maximum measured tensional stress, $F_{t,\text{max}}$ the maximum measured tensional force, and $A$ the cross-sectional area of the specimen. Equations (3.14) to (3.16) are considered sufficiently accurate to describe the mechanical response of the material in the first instance. Hence the stress / strain material behaviour is a function of the following parameters:

$$\text{stress / strain} = f\left(c, \sigma_{c,f}, \sigma_{t,f}, M, \varphi_{\text{max}}, \nu\right). \quad (3.17)$$

To reproduce mechanical similitude (e.g. Langhaar, 1951) between the prototype conglomerate and the analogue material, the parameters in function (3.17) have to be scaled according to their dimensions. Scaled standard deviations are calculated utilizing Gauss’ error propagation law. The references indicate the data source for mechanical properties of the prototype conglomerate. The number of samples taken is denoted by $n$. 

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3.3.2.1 Cohesion [dimension of stress] (Imre et al., 2009b)

\[ k_c = k^2 = 25 \Rightarrow c^* = \frac{c}{k^2} = \frac{6 \pm 2}{25} = 0.24 \pm 0.1 \text{ [MPa]} \quad \text{(n = 25)} \] (3.18)

The cohesion \( c \) of the “Bunte Riginagelfluh” conglomerate has been derived from triaxial compression tests (Figure 3.18B) by calculating the offset (intercept) \( b_{mc} \) (3.1±0.8 MPa) and slope \( \beta_{max} \) (41.4±0.6°) of the maximum strength failure envelope \( K_{f,max} \) (Figure 3.19) as:

\[ c = \frac{b_{mc}}{\cos(\arcsin(\tan \beta_{max}))} \text{ [MPa].} \quad \text{(3.19)} \]

3.3.2.2 Uniaxial Compressive Strength [dimension of stress] (Imre et al., 2009b)

\[ k_{\sigma,c} = k^2 = 25 \Rightarrow \sigma_{c,f}^* = \frac{\sigma_{c,f}}{k_{\sigma,c}} = \frac{84 \pm 19}{25} = 3.4 \pm 0.7 \text{ [MPa]} \quad \text{(n = 3)} \] (3.20)

The uniaxial compressive strength of the conglomerate has been obtained by Berner (2004) on 84 mm diameter specimens at 0.5 kN/s loading rate (Figure 3.19).

3.3.2.3 Tensile Strength [dimension of stress] (Imre et al., 2009b)

\[ k_{\sigma,t} = k^2 = 25 \Rightarrow \sigma_{t,f}^* = \frac{\sigma_{t,f}}{k_{\sigma,t}} = \frac{3.6 \pm 1.9}{25} = 0.14 \pm 0.07 \text{ [MPa]} \quad \text{(n = 4)} \] (3.21)

The tensile strength was derived from Brazilian splitting tests by Berner (2004) on 84 mm diameter specimens at 0.5 kN/s loading rate (Figure 3.19).

3.3.2.4 Young’s Modulus [dimension of stress] (Imre et al., 2009b)

\[ k_M = k^2 = 25 \Rightarrow M^* = \frac{M}{k_M} = \frac{18 \pm 4}{25} = 0.7 \pm 0.1 \text{ [GPa]} \quad \text{(n = 6)} \] (3.22)

The Young’s modulus was derived as the tangent modulus at ~50 % uniaxial compressive peak strength \( \sigma_{c,50} \) according to VSS (2005) or ASTM (2007) on 48, and 98 mm diameter specimens at 0.05 and at 0.1 mm/min loading rate respectively.

3.3.2.5 Maximal Internal Friction Angle [dimensionless] (Imre et al., 2009b)

\[ k_\varphi = 1 \Rightarrow \varphi_{max}^* = \frac{\varphi_{max}}{k_\varphi} = 62 \pm 2 \text{ [deg]} \quad \text{(n = 25)} \] (3.23)

The maximal internal friction angle of the “Bunte Riginagelfluh” conglomerate has been derived from triaxial compression tests (Figure 3.18B), calculated from the slope \( \beta_{max} \) (41.4±0.6°) of the maximum strength failure envelope \( K_{f,max} \) (Figure 3.19) as:

\[ \varphi_{max} = \arcsin(\tan \beta_{max}) \]. \quad \text{(3.24)}
The prototype conglomerate displays a high maximum internal friction angle. This can be explained by looking at the failure surfaces. Under the applied intermediate level triaxial stress regime, the residual shear failure surface consists of failed aggregates, which form an undulating face and therefore exhibit strong interlocking and dilatancy (Figure 3.18A; Barton, 1976). Only the cohesive bonds have been broken, even at higher strains, whereas interlocking remains widely intact, which leads to a high residual internal friction angle of about 62 ± 2 degrees (Figures 3.18B, 3.19).

![Figure 3.18: A) Shear band development during triaxial testing at a loading rate of 0.05 mm/min and a radial pressure $\sigma_r$ of 5 MPa (scale in cm) of a core of “Bunte Riginagelfluh” conglomerate, diameter 48 mm, height 101 mm. The large clasts of the matrix supported conglomerate add scatter to the test data—nevertheless this specimen size is valid because it occurs in the prototype situation also. Failure surfaces develop both in matrix and clasts and, in a few cases, at the clast/matrix interface. The heterogeneity of the conglomerate causes the formation of a very rough shear surface that displays high residual shear strength. B) stress/strain behaviour during triaxial testing of cores of “Bunte Riginagelfluh” conglomerate with diameters of 48 mm and 98 mm and heights of 101 mm and 200 mm respectively. The peak shear strength is measured as $(\sigma_a - \sigma_r)_{\text{max}}$ of each test. The residual shear strength $(\sigma_a - \sigma_r)_{\text{res}}$ is measured where the distortion of a sample continues at constant deviatoric stress.](image)
Figure 3.19: Compiled strength data measured on “Bunte Riginagelfluh” conglomerate samples shown in mean stress $s$ / deviatoric stress $t$ space. Triaxial compressive strength data obtained on 48 mm diameter specimens at $\sigma_\epsilon$ of 5 MPa and 0.05 mm/min loading rate (a); triaxial compressive strength data obtained on 98 mm diameter specimens at $\sigma_\epsilon$ of 5 MPa and 0.1 mm/min loading rate (b); uniaxial compressive strength data obtained on 84 mm diameter specimens at 0.5 kN/s loading rate (Berner, 2004) (c); residual shear strength obtained on 48 and 98 mm diameter specimens at $\sigma_\epsilon$ of 5 MPa and 0.05 or 0.1 mm/min loading rate; (e) Brazilian splitting strength data obtained on 84 mm diameter specimens at 0.5 kN/s loading rate (Berner, 2004). The maximum and residual failure envelopes $K_{f,max}$ and $K_{f,res}$ have been obtained by least squares regression.

3.3.2.6 Quasi-Static Poisson’s Ratio [dimensionless] (Imre et al., 2009b)

$$k_v = 1 \Rightarrow \nu^* = \frac{\nu}{k_v} = 0.06 \pm 0.03 [-] \quad (n = 3; \text{Lama and Vutukuri, 1978}) \quad (3.25)$$

The quasi-static Poisson’s ratio $\nu$ has not been evaluated for the prototype conglomerate. Therefore data have been drawn from literature for conglomerates of similar strength. These rocks display a low radial expansion under uniaxial loading.

3.3.2.7 Uniaxial Strength Ratio [dimensionless] (Imre et al., 2009b)

In extension to the above scaled parameters, the uniaxial strength ratio $SR$ is suggested in the work by Indraratna (1990) as an additional dimensionless material parameter for an analogue material:

$$SR = \left[ \frac{\sigma_{e-f}}{\sigma_{t-f}} \right] = \left[ \frac{\sigma_{e-f}}{\sigma_{t-f}} \right]^* = \left[ \frac{84 \pm 19}{3.6 \pm 1.9} \right]_{\text{m}} = 23 \pm 7 [-] \quad (3.26)$$
3 Physical Model

The uniaxial strength ratio is of particular interest to this study because it is a way of quantifying the brittleness of a material (e.g. Becker and Lemmes, 1984; Harder, 1992; Spaun and Thuro, 1994). A variety of definitions exist in the literature, for the brittleness of a material that can bear tensile loading in principle. Harder (1992) defines a material to be brittle if its load-displacement curve does not show a descending branch during displacement controlled loading; otherwise it is described as being ductile. Such a curve can be obtained for rock and concrete, and these materials are often determined to be quasi-brittle. Although the definition of the brittleness by Harder (1992) is clear, the axial strength ratio by Becker and Lemmes (1984) or Spaun and Thuro (1994) is preferred for its simplicity and the availability of data for comparison with other materials. The brittleness of the prototype conglomerate is described by its axial strength ratio $SR > 20$ as “very brittle” according to Spaun and Thuro (1994).

3.3.3 Selection of an Analogue Material (Imre et al., 2009b)

Indraratna (1990) suggests excellent guidelines for the selection of an appropriate model material—the analogue material should meet the following specifications when adapting these guidelines to this research programme:

a) The analogue material or its constituents should be universally and economically obtainable, and should not be toxic.

b) The mechanical properties of specimens must be identical to one another and easily prepared under laboratory conditions.

c) Specimens of the analogue material have to be shaped easily or cast into varying dimensions.

d) The physical properties of the analogue material have to be insensitive to heat and humidity.

e) The strength and deformation properties of the analogue material satisfy the mechanical scaling criteria above.

f) The analogue material must feature a short manufacturing and / or curing time.

Strain rate dependent effects are not considered. The reasons for this are discussed below. It can be seen from the above scaling laws that a properly scaled analogue material basically has to display very low strength with high brittleness at the same time. From the strength point of view, a natural, weakly cemented sandstone may be considered (e.g. Lama and Vutukuri, 1978). But natural rock does not fulfil criteria a) b) and c) simultaneously (e.g. among others van Vliet, 2000). Carnallite ($\text{K}_2\text{MgCl}_3 \cdot 6\text{H}_2\text{O}$), a colourless, extremely brittle salt of low strength, which can be obtained commercially, for example, from Germany, was considered initially. This material has a massive, crystalline texture and a very low porosity and may therefore serve as an analogue for marble or many igneous rocks. However, Carnallite was ruled out quite early due to criteria d), because it displays pronounced hygroscopic behaviour, so that its mechanical properties remain constant only in a very dry environment. Finally, coal was considered as an analogue material, as described by Kaiser et al. (1985) or Bowman (2006), although it is unclear how the frictional behaviour of coal changes with heat. In the proposed experimental set-up, the analogue material is supposed to slide on a stainless-steel chute within the centrifuge. Friction is therefore a very
important boundary condition of the system. To keep control of that boundary condition, the most important requirement of the frictional behaviour of the analogue material is that it remains constant during the experiment.

As a consequence, the manufacturing of an artificial material with defined scaled mechanical properties as an analogy to the prototype conglomerate was seen as a feasible solution. The classical work by Stimpson (1970) gives a comprehensive review of various constituents that have been used in the past to manufacture synthetic materials. Subsequently, Abdulla and Kiousis, 1997; Dass et al., 1994; Dunham and Valsangkar, 2005; Dykeman and Valsangkar, 1996; Indraratna, 1990; Itoh et al., 2006; Kosar et al., 1997; Monteiro et al., 1993; Nakagawa and Myer, 2001 among others, have published properties and constituents of synthetic sandstones lightly cemented by sodium silicate, plaster, or Portland cement/clay mixtures with strength and deformation properties very similar to the required scaled model properties described above.

Based on this review, it was decided to formulate a synthetic soft rock (ETHAR) with Portland cement as cementing agent, with the added advantage, in comparison with the synthetic analogue materials described in the literature, of reducing the preparation and curing times. ETHAR consists of only 3 constituents and can be used in experiments within 3 days. This allows test specimens to be produced close to a scheduled test day.

3.3.4 Constituents (Imre et al., 2009b)

3.3.4.1 Aggregate (Imre et al., 2009b)

The Pleistocene, aeolian, Bassendean sand, from the Perth basin in Western Australia, is selected to be the aggregate. Due to the marine origin and subsequent leaching processes, this material represents a quartz sand of very high purity (Kendrick et al., 1991; Low et al., 1980). The marine origin and aeolian depositional environment created a well rounded (Figure 3.20) and poorly graded (ASTM, 2006, Figure 3.21, Table 3.1) sand.

![Rounded Bassendean sand quartz grain with numerous aeolian type v-shaped pits (Kenig, 2006; magnification 20 times).](image)

*Figure 3.20: Rounded Bassendean sand quartz grain with numerous aeolian type v-shaped pits (Kenig, 2006; magnification 20 times).*
3.3.4.2 Cement (Imre et al., 2009b)

A white Portland cement type CEM I 52.5 N, meeting European Standard (CEN, 2000), is used. This cement features a high nominal uniaxial compressive strength of \( \geq 20 \text{ N/mm}^2 \) after 2 days and \( \geq 52.5 \text{ N/mm}^2 \) after 28 days of curing. The hardening of
the cement sets in after about 45 minutes. The high albedo of the white cement yields, together with white aggregate, a bright material, which can be monitored well under difficult lighting conditions, or coloured with cement colours for special applications such as monitoring the mixing behaviour of a sliding rock mass within the centrifuge. Blocks of ETHAR were coloured using commercially available cement colours such as, “Pieri®Kaolor by Grace Constructions Products SA. These pigments comply with European Standard (CEN, 2006) and do not alter the strength properties of the analogue material.

3.3.4.3 Mixing Proportions (Imre et al., 2009b)

A mixture of ETHAR, which satisfies the above scaling criteria, contains constituents in the following proportions:

- a) White Portland cement 10 % of aggregate mass (Bassendean sand)
- b) Water 40 % of cement mass (water/cement ratio of 0.4)
- c) Pigments 3 % of cement mass

All dry components were mixed initially prior to the addition of water to ensure a homogeneous mixture. The water/cement ratio of 0.4 ensures thorough hydration of the cement, with a good workability of the final mixture at the same time. It provides a moist material, which does not release any bleed water, even under vibration.

3.3.4.4 Casting and Curing (Imre et al., 2009b)

The compaction and shaping of ETHAR was carried out in two different moulds. A small mould (Figure 3.22) was used to manufacture cylindrical specimens of high precision with a diameter of 50 mm and a length of 100 mm, in accordance with European Standards (CEN, 2003; CEN, 2004). The large mould (Figure 3.23) was employed to manufacture up to ten prismatic specimens at once, separated by plates, with an edge length of 100 mm. These prisms (Figure 3.24) have then been cut into cubic blocks (Figure 3.25), which are designed to fit into the hoppers of the centrifuge experiments (Figures 3.2, 3.3). All specimens were compacted within the moulds, which were firmly attached onto a vibratory table at a frequency of 3600 Hz and an amplitude of 0.1 mm in accordance with ASTM (2000 (reapproved 2006)). Standard weights used for testing the maximum index density and unit weight of soils in accordance with ASTM (2000 (reapproved 2006)), were applied to achieve compaction in the moulds on the vibratory table. The small specimens were loaded with a weight of 8 kg leading to application of a surcharge stress of ~ 40 kPa (Figure 3.22). The large specimens were loaded with a weight of 23 kg, applying a surcharge stress of ~ 23 kPa (Figure 3.23).

All moulds, except for the mounting structure, have been made from rigid Polyvinylchloride (PVC), which has a non-porous surface and is insensitive to the alkaline cement, so that separating agents such as silicone oil were not required. The PVC material showed sufficient stiffness and strength during vibration of the sample.

The sand/cement mixture hardened within the moulds for 3 days at 20° Celsius and 95 % relative humidity, and, after extraction from the moulds, this was continued if a longer hardening time was desired.
Figure 3.22: Small mould. a) vibratory table deck, b) mould made of two half-shells, which also act as a guide sleeve, c) the piston for compacting the sand/cement mixture has three notches to permit expulsion of entrapped air, d) surcharge weight.

Figure 3.23: Large mould. a) vibratory table deck, b) mould made with four retaining walls, also which act as guide sleeve, with numerous small holes to permit expulsion of entrapped air, c) compacting piston, d) surcharge weight, e) separation plates.
Figure 3.24: Dismantled large mould (a) with six layers of coloured, readily cured prismatic specimens of ETHAR, separated by PVC plates (b) (scale in cm on label).

Figure 3.25: “Ready to use” cubes made by separating cured prismatic specimens of ETHAR (scale in cm on label).
3.3.5 Mechanical Properties (Imre et al., 2009b)

It is necessary to evaluate the mechanical similitude of ETHAR according to the mixing properties, casting and curing, and scaling laws described above.

3.3.5.1 Texture (Imre et al., 2009b)

The texture of a material influences its mechanical parameters and can be described best in sedimentary petrography terms. Because of the poor grading of the aggregate and the relatively low cement content, ETHAR constitutes a weakly cemented, grain-supported, psammitic of high effective porosity (e.g. Bates and Jackson, 1984). Cementation of the aggregates occurs only at direct grain contacts (Figure 3.26). Although the small and the large specimens have been compacted to different shapes under different surcharge stresses (Section 3.3.4.4), their dry densities $\rho_d$ remain at 1690 ± 5 kg/m$^3$ ($n = 25$) with a void ratio $e$ of 0.59. This is advantageous because mechanical properties do not change very much despite different mould and compaction conditions.

A further and interesting advantage of the particulate nature of ETHAR is the geometry of its cemented grain contacts, which can be reasonably interpreted as quasi-circular. These contacts display a striking similarity to the numerical representation of rock within distinct element codes (DEM) (Figure 3.27). In numerical codes, for example like the Particle Flow Code (PFC) (Cundall and Strack, 1979; Itasca, 2005b), rock is simulated as an assemblage of spherical particles “cemented” at their contacts by disk shaped bonds. Hence ETHAR can replicate a DEM based representation of soft rock (e.g. Imre, 2004b; Potyondy and Cundall, 2004). The average trace length of the cemented quasi-circular contacts have been measured on three thin sections (e.g. Figure 3.26), manufactured under differing cutting directions. These trace lengths are interpreted as the cemented contact’s average diameter, determined as 91 ± 27 μm ($n = 87$).

![Figure 3.26: Thin section of the analogue material depicting its internal texture parallel to the direction of compaction. The bright grains are Bassendean sand quartz grains. The black shading shows the cement that encloses the sand grains. Voids are coloured in grey.](image)
3.3.5.2 Measured Uniaxial Compressive Strength (Imre et al., 2009b)

The uniaxial compressive strength tests were performed based on Swiss Standards (VSS, 2005). The specimens of 50 mm diameter and 100 mm length were loaded under strain-control at a rate of 0.05 mm/min (Figure 3.28). The material showed a strain-hardening behaviour that is quite typical for sandstones, as the pore-volume is first reduced before shear-bands develop (Vutukuri et al., 1974). The target uniaxial compressive strength of the analogue material was obtained by varying the cement content. The uniaxial compressive peak strength $\sigma_{c,f}$ was determined as $3.5 \text{ MPa} \pm 0.4 \ (n = 5)$ and matched the specified target strength $\sigma_{c,f}^*$ of 3.4 MPa (Equation (3.20)) sufficiently well after 3 days of curing.

3.3.5.3 Measured Internal Friction Angle and Cohesion (Imre et al., 2009b)

The internal friction angle $\phi_{\text{max}}$ and the cohesion $c$ of ETHAR were derived from triaxial compression tests (Figures 3.28, 3.29) according to Equations (3.23) and (3.18). These tests were performed following European and Swiss Standards (CEN, 2003; VSS, 2005). As expected, it was not possible to create an analogue material that achieves such a high maximum internal friction angle as demanded from the scaled maximum internal friction angle (Equation (3.23)). Nonetheless, a maximum internal friction angle of $53 \pm 1$ degrees was obtained for ETHAR, which is still higher than many other analogue soft rocks quoted in the literature (e.g. Section 3.3.3). The cohesion was determined to be $0.44 \pm 0.03 \text{ MPa}$. After failure, and under high strains, all cohesive bonds break and any cohesion is eliminated, whereas the friction angle decreases only slightly, implying that the material displays minor dilation only along the shear zone. This behaviour of ETHAR is advantageous in terms of similitude to the prototype material. It can be explained by the narrowness of the shear zone developed, which was found to be only about 2–3 grain diameters wide (Figure 3.29A).
Figure 3.28: Compiled strength data measured on ETHAR samples shown in mean stress \( s \) / deviatoric stress \( \tau \) space. (a) triaxial compressive strength data obtained on 50 mm diameter specimens at \( \sigma_f \) of 0.8, 0.4, 0.2, 0.1, and 0.05 MPa and 0.05 mm/min loading rate; (b) uniaxial compressive strength data obtained on 50 mm diameter specimens at 0.05 mm/min loading rate; (c) residual shear strength obtained on 50 mm diameter specimens at \( \sigma_f \) of 0.8, 0.4, 0.2, 0.1, and 0.05 MPa and 0.05 mm/min loading rate; (d) Uniaxial tensile strength data obtained on notched specimens at 1 \( \mu \text{m/min} \) loading rate. The maximum and residual failure envelopes \( K_{f,\text{max}} \) and \( K_{f,\text{res}} \) have been obtained by least squares regression.
Figure 3.29: A: Shear band development during triaxial testing at a loading rate of 0.05 mm/min and a radial pressure $\sigma_r$ of 0.8 MPa of a moulded sample of ETHAR, diameter 50 mm, height 100 mm (scale in cm). Failure occurs by breakage of cemented grain contacts within a thin, 1–3 grain diameter wide, shear zone. The intact grains of the aggregate form a rough shear surface displaying high residual shear strength. B: Stress/strain behaviour during triaxial testing on specimens of ETHAR. The peak shear strength is determined from measured values of $(\sigma_d - \sigma_r)_{\text{max}}$ for each test. The residual shear strength $(\sigma_d - \sigma_r)_{\text{res}}$ is obtained from where the distortion of a sample continues at constant deviator stress.

3.3.5.4 Measured Dynamic Surface Friction Coefficient (Imre et al., 2009b)

The frictional response of ETHAR has been measured dynamically, on a motor driven slip table with a strain gauge measuring the friction force (Räbsamen, 2007; Stachowiak et al., 2004), for differing slip surfaces and loading conditions (Figures 3.30, 3.31). Based on these experiments, it was decided to select stainless steel as sliding surface within the centrifuge experiments, because it provided the most constant dynamic friction coefficient over a range of different loading conditions that are representative of the loads anticipated in the subsequent centrifuge tests. The
average friction coefficient $\mu$ of ETHAR on stainless steel was found to be $0.32 \pm 0.02$ [-] (equivalent to a surface friction angle of $18 \pm 1$ degrees).

![Figure 3.30](image1.png)

**Figure 3.30**: Dynamic interface friction angle of ETHAR on stainless steel and anodised Aluminium, as a function of sliding velocity and normal force (Räbsamen, 2007).

![Figure 3.31](image2.png)

**Figure 3.31**: Dynamic interface friction angle of ETHAR on Polytetrafluorethylene as a function of sliding velocity and normal force (Räbsamen, 2007).

### 3.3.5.5 Measured Quasi-Static Elastic Properties (Imre et al., 2009b)

The quasi-static Young’s modulus $M$ and the Poisson’s $\nu$ ratio were derived according to VSS (2005) or ASTM (2007) from uniaxial compressive tests at a loading at a rate of 0.05 mm/min. Axial and radial strains, $\varepsilon_a$ and $\varepsilon_r$, have been measured by strain gauges located in the middle of the specimens (Figure 3.32A). The Young’s modulus has been obtained as a tangential Young’s modulus $M_{50}$ to the stress-strain curve at an axial stress range $\Delta\sigma_a$ at 50% of the mean peak-uniaxial compressive stress $\sigma_{c,f}$ of 3.5 MPa as:

$$M_{50} = \frac{\Delta\sigma_a}{\Delta\varepsilon_a} \text{ [GPa]}$$

The quasi-static Young’s modulus $M_{50}$ was determined to be $12.2 \pm 2.8$ GPa ($n = 5$) with this method. The quasi-static Poisson’s ratio $\nu$ was obtained within the same stress range, and was derived as $0.09 \pm 0.04$ [-] ($n = 5$), indicating only a small radial expansion under uniaxial loading, which provides a good analogy to the scaled
Poisson’s ratio according to Equation (3.25). But it is unclear how much local radial confinement the strain gauges themselves induced in the relatively soft ETHAR, causing systematic errors to the strain measurements (Figure 3.32A). For this reason, the quasi-static Young’s modulus $M_{50}$ was also calculated, for the same range of $\Delta \sigma_a$, utilizing strain data calculated from an external axial deformation sensor (Figure 3.32A). The comparative quasi-static Young’s modulus $M_{50}$ was then determined to be $3.9 \pm 0.9$ GPa ($n = 7$). Combining the external axial strain data with the radial strain data measured with the strain gauges yields a quasi-static Poisson’s ratio $\nu$ of about 0.01, which is an unrealistic value as is the Young’s modulus $M_{50}$ obtained from the axial strain gauge measurements. The conclusion is drawn that obtaining radial strain data from a weak but still stiff material needs very sensitive measuring devices which impose none or very small forces only on ETHAR. Obvious solutions like laser transducers (Messerklinger and Springman, 2007) or particle image velocimetry (PIV; White et al., 2003) may also yield unsatisfactory results, because the radial deformations are expected to be in the order of magnitude of surface roughness of the specimen itself. Because $\nu$ is of minor importance to this research, it was decided to take no further steps to measure the radial expansion with more sensitive devices and to obtain $M_{50}$ from external strain measurements, a method which turned out to be reliable during the entire testing campaign of ETHAR.

3.3.5.6 Measured Fracture Energy and Tensile Strength (Imre et al., 2009b)

The energy consumption by the creation of new fracture surfaces within a fragmenting rock slide is considered to be an important factor for understanding the
energy budget of such a slide. The fracture surface energy $G_F$ of ETHAR was measured to achieve an educated estimate of this path of energy dissipation. These measurements, as all other measurements presented here, can only provide an approximate guide, because particles of all sizes, and therefore fractures of all dimensions, are created during fragmentation of rock particles in nature or in an experiment. But whether or not the fracture surface energy is a material property, independent of fracture dimension, is still a matter of research (e.g. among others Ashby and Jones, 1980; Engelder and Fischer, 1996; Harder, 1992; Hillerborg, 1985a; Hillerborg, 1985b; Schubert et al., 2004; Schubert et al., 2005; Tomas et al., 1999; van Vliet, 2000; van Vliet and van Mier, 2000).

The fracture surface energy $G_F$ is calculated according to Hillerborg (1985b) as:

$$G_F = \frac{E_{\text{frag}}}{A}, \text{[Nm/m}^2, \text{J/m}^2\text{]} \quad (3.28)$$

where $A$ is the projected crack area and $E_{\text{frag}}$ is the work or absorbed energy due to fracturing (fragmentation), computed as:

$$E_{\text{frag}} = \int_0^w F \cdot \delta w, \text{[Nm, J]} \quad (3.29)$$

where $F$ denotes the mode I loading force and $w$ is the crack width (opening). The crack width is defined as being zero at peak load (Figure 3.33A).

![Figure 3.33: A) Definition of the work or absorbed energy due to fracturing (fragmentation) $E_{\text{frag}}$, modified after Hillerborg (1985b) from an axial tensile force $F$ /deformation $\delta$ diagram. $E_{\text{frag}}$ is calculated as the area beneath the tensile force curve from peak $F_f$ as the crack width $w$ develops. The deformation at peak tensile force $\delta_f$ is the sum of the elastic deformation component $\delta_e$ and the plastic deformation $\delta_p$. $E_p$ denotes the plastic deformation energy that can not be recovered during failure of the specimen. B) Results of the four successful axial tensile force tests for which a full pre- and post peak force/displacement curve could be measured.](image)

The assessment of the mode I fracture surface energy has been made by performing uniaxial tension tests on cylindrical analogue material specimens, following recommendations by van Mier and van Vliet (2002). A number of technical
problems had to be overcome to achieve reliable results from this direct method of measuring fracture properties, which will be described briefly below.

An electro-mechanical test frame was used as a loading device (Figure 3.34). Aluminium cylinders of the same diameter as the test specimens were glued holohedrally and centrically to the test specimen ends prior to testing to reduce the stiffness contrast between analogue material and loading platen. The loading platens were then connected to the loading frame via well aligned hinges on each side of the specimen so that the specimen ends were allowed to rotate freely during testing. The boundary effects are minimized under these loading conditions, compared to fixed or fixed-controlled boundary conditions (van Vliet, 2000). Hence the resulting tensile strengths and fracture surface energies represent a lower boundary for the tensile strength and surface energy of a material (van Mier et al., 1995).

The analogue material specimens were notched radially to a depth of 10 mm and a width of 1.5 mm to 40 % of the diameter of the test specimen, so that the position of the mode I crack could be predefined to concentrate the strain within the notched area. Two strain transducers were clipped on opposite sides of the specimen to measure the deformation within the notch. The measuring length of each strain transducer was kept as small as possible (e.g. van Mier and van Vliet, 2002) although it was still 36 mm. All these measurements have been applied to allow for a stable, quasi-static mode I crack growth within the specimen. In other words, it has been intended to prevent elastic strain energy exceeding the energy \( E_{\text{frag}} \) necessary to form a mode I crack, which would be stored within the fracture zone, and which otherwise would lead to so-called unstable snap-back behaviour (van Mier and van Vliet, 2002).

Still, it was not possible to achieve stable crack-growth and a complete softening diagram with the machinery available. One reason was found in the test control, which did not allow for a true deformation controlled loading of the specimen (e.g. van Vliet, 2000). The loading-cross beam was set to move at a constant velocity of 1 \( \mu \)m/min instead. Another reason may have been the loading frame, which was possibly not stiff enough compared (e.g. Friedman et al., 1972; Hillerborg, 1985b) to the minute strain necessary to fracture this very sensitive analogue material.

Two steel pull-rods, tensioned parallel to the test specimen, have been attached to increase the stiffness of the loading “chain” (Figure 3.34) to overcome the inadequacy of the set up. The advantage is that even when the test specimen fails completely, the loading frame remains under tensional loading. Otherwise relaxation of the loading frame (or even of the force transducer alone) may have been sufficient to cause unstable crack growth within the analogue material. The pull-rods were preloaded by tightening the end-nuts with a moment of 1 Nm. Thus the specimen was slightly pre-loaded compressionally, so that the precise origin of the force/deformation curve could be located (e.g. van Vliet, 2000; Figure 3.35). Additionally, it prevented accidental pre-test failure of the specimen during test preparation (e.g. Hillerborg, 1985b) and increases the possibility that the crack opens directly at one of the two strain transducers. A draw-back of the pull-rods is that the test specimen can not rotate freely anymore, but only normal to the plane of the pull-rods. Hence the resulting tensile strengths and fracture surface energies probably do not represent a perfect lower boundary for the tensile strength and surface energy of this material anymore.
Figure 3.34: A) Test set-up for measuring the tensile strength and the fracture surface energy by uniaxial tensile loading. (a) notched analogue material specimen. (b) notch. (c) cylindrical loading platens holohedrally glued to the specimen. The loading platens are attached to steel cross-beams (d) and to the loading frame by hinges (e) on both sides of the specimen. The load is measured with a 10 kN force transducer (f) and applied by a moving cross-beam (g) of the loading frame. (h) steel pull-rods of 4 mm diameter with hinges (i) in the same plane as the notch. (j) displacement transducers clamped to the specimen diametrically opposite to each other (scale in cm). B) Enlarged detail showing notch (b).
Figure 3.35: Typical stable and complete tensile force/strain curve retrieved from a uniaxial tensional test with parallel pull-rods. The compressional pre-loading of the specimen is denoted as $F_{\text{pre}}$. The shaded area is the force/strain curve of the analogue material is "riding" on the force/strain curve of the pull-rods. It represents the force/strain curve of Figure 3.33A. The compressional pre-loading and the linear force/strain relationship, governed by the stiffness $M_{\text{pull-rod}}$ of the pull-rods have to be subtracted to retrieve the force/strain curve of the analogue material alone.

The tensile strength $\sigma_{t,f}$ of eight specimens could be determined as $0.25 \pm 0.07$ MPa ($n = 8$) by adopting this improved set up. Four of these tests yielded complete force/deformation curves (Figure 3.33B) from which the fracture surface energy $G_F$ could be determined as $1.28 \pm 0.59$ J/m² ($n = 4$).

Compared to the tensile strength of the “Bunte Rigi-Nagelfluh” (derived from Brazilian Tests (Berner, 2004), the tensile strength $\sigma_{t,f}$ of the analogue material is about one order of magnitude lower. The fracture surface energy $G_F$ is two orders of magnitude smaller than the values published by van Vliet (2000) or Hillerborg (1985a) for concrete or sandstone, but only one order of magnitude smaller compared to data for sandstone, as published by Friedman et al. (1972), which have been derived from notched beam tests.

3.3.5.7 Measured Brittleness (Imre et al., 2009b)

The axial strength ratio $SR$ of ETHAR is calculated as:

$$SR = \frac{\sigma_t}{\sigma_{t,m}} = \left[ \frac{3.5 \pm 0.4}{0.25 \pm 0.07} \right]_{m} = 14 \pm 4.2 \ [-]$$

(3.30)

ETHAR can be described as “brittle “ with $10 < SR < 20$ according to Spaun and Thuro (1994), although it is less brittle than the prototype conglomerate with $SR < 23 \pm 7$ (Equation (3.26)). In comparison: natural red “Felser” Sandstone displays an axial strength ratio ranging from 30 to 50, whereas concrete mobilises an axial strength ratio ranging from 10 to 20 (van Vliet, 2000). The brittleness of ETHAR is therefore of the same order as unreinforced concrete, but slightly less than that of natural rock.

3.3.5.8 Measured Coefficient of Restitution (Imre et al., 2009b)

Finally, the coefficient of restitution of ETHAR has been measured. It quantifies a pathway of elastic energy dissipation in a collisional regime; hence it is of interest for
Research on the energy budget of a fragmenting particle flow such as a sturzstrom. At a macroscopic scale, even pure elastic loading and unloading of rock is accompanied by energy dissipation. This hysteretic damping may be quantified as the ratio between the elastic energy invested during loading and that recovered during unloading. This ratio is defined as the coefficient of restitution \( \text{COR} \) (e.g. Imre et al., 2008). The coefficient of restitution \( \text{COR} \) was determined according to Imre et al. (2008) as 0.73 [± 0.03] at a confidence interval > 95 %. For comparison, the \( \text{COR} \) of the prototype conglomerate ranges from 0.801 to 0.915 (Imre et al., 2008).

### 3.3.6 Summary about the Development of ETHAR (modified after Imre et al., 2009b)

To provide an overview, measured and derived material properties of both the prototype conglomerate and ETHAR are given in comparison in Table 3.2. All features of ETHAR are related to 3 day old samples. It was clear from the beginning that a perfect match of all mechanical properties would be an unlikely achievement. Nevertheless, the uniaxial compressive strength, the high maximum internal friction angle, relatively low cohesion and the pronounced brittleness of ETHAR reflect the nature of the prototype conglomerate quite well. The standard deviations presented for the mechanical properties suggest that ETHAR demonstrated relatively uniform performance within the manufacturing and curing process.

**Table 3.2: Comparison between mechanical prototype and model properties.**

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Unit</th>
<th>ETHAR</th>
<th>Prototype</th>
<th>Demanded scaling</th>
<th>Achieved Scaling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cohesion</td>
<td>( c )</td>
<td>MPa</td>
<td>0.44 ± 0.03</td>
<td>6 ± 2</td>
<td>1:25</td>
<td>1:13</td>
</tr>
<tr>
<td>Uniaxial compressive strength</td>
<td>( \sigma_{c,f} )</td>
<td>MPa</td>
<td>3.5 ± 0.4</td>
<td>84 ± 19</td>
<td>1:25</td>
<td>1:24</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>( \sigma_{t,f} )</td>
<td>MPa</td>
<td>0.25 ± 0.07</td>
<td>3.6 ± 1.9</td>
<td>1:25</td>
<td>1:14</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>( M_50 )</td>
<td>GPa</td>
<td>3.9 ± 0.9</td>
<td>18 ± 4</td>
<td>1:25</td>
<td>1:4.6</td>
</tr>
<tr>
<td>Max. internal friction angle</td>
<td>( \varphi_{\text{max}} )</td>
<td>deg</td>
<td>53 ± 1</td>
<td>62 ± 2</td>
<td>1:1</td>
<td>1:1.2</td>
</tr>
<tr>
<td>Quasi-static Poisson’s ratio</td>
<td>( \nu )</td>
<td>--</td>
<td>0.09 ± 0.04</td>
<td>0.06 ± 0.03</td>
<td>1:1</td>
<td>1:0.66</td>
</tr>
<tr>
<td>Dynamic friction coefficient</td>
<td>( \mu )</td>
<td>--</td>
<td>0.32 ± 0.02</td>
<td>0.29 ± N/A</td>
<td>1:1</td>
<td>1:0.9</td>
</tr>
<tr>
<td>Axial strength ratio</td>
<td>( SR )</td>
<td>--</td>
<td>14 ± 4.2</td>
<td>23 ± 7</td>
<td>1:1</td>
<td>1:1.6</td>
</tr>
<tr>
<td>Coefficient of restitution</td>
<td>( \text{COR} )</td>
<td>--</td>
<td>0.73 ± 0.03</td>
<td>0.801–0.915</td>
<td>undefined</td>
<td>~1:1.17</td>
</tr>
<tr>
<td>Fracture surface energy</td>
<td>( G_F )</td>
<td>J/m²</td>
<td>1.28 ± 0.59</td>
<td>n/a</td>
<td>undefined</td>
<td>n/a</td>
</tr>
<tr>
<td>Dry density</td>
<td>( \rho_d )</td>
<td>kg/m³</td>
<td>1690 ± 5</td>
<td>2600 ± 90</td>
<td>undefined</td>
<td>1:1.5</td>
</tr>
<tr>
<td>Void ratio</td>
<td>( e )</td>
<td>--</td>
<td>0.59</td>
<td>n/a</td>
<td>undefined</td>
<td>n/a</td>
</tr>
</tbody>
</table>
Since ETHAR was readily prepared within 3 days, it could be employed very flexibly in terms of changing colours and block sizes, in accordance with the scientific and scheduling requirements of the centrifuge experiments.

The texture of ETHAR shows, in terms of aggregate particle size distribution, particle shape, and geometry of cemented contacts, striking similarities to the numerical representation of rock in DEMs as an assembly of spherical particles “cemented” by disk-shaped bonds (Figure 3.27; for example e.g. Potyondy and Cundall, 2004).

3.4 Results and Confirmation of the Physical Model (Imre et al., 2009a)

Applying ETHAR within the centrifuge experiments, resulted in the successful formation of fragmented rock mass deposits. The most striking features of these deposits are the texture and the particle size distributions of the fragmented material. These results are compared with samples of natural sturzstrom deposits. For a better understanding of the fragmentation achieved, data on the particle velocity during the centrifuge experiment are presented, and discussed first in the light of the acceleration field (Section 3.2.6).

3.4.1 Particle Velocity (Imre et al., 2009a)

Videos taken with a high speed camera (Figure 3.2) revealed that the rock masses are sliding virtually as one block (Figure 3.36), hence the differential velocities between the individual rock blocks are very small compared to the absolute sliding velocities of the rock masses tested. However, the rock mass experienced simple shear deformation in the x’-direction, which can be recognized by the distribution of layers of coloured rock blocks (Figure 3.37). The rock mass therefore moved, at least to a small degree, as a flow. Another important observation is that, except for the very top layer in the z’-direction, the rock blocks do experience intensive fragmentation (Figure 3.37C). The acceleration and velocity profiles (Figure 3.17) show that the rock mass experiences strong slope parallel acceleration and subsequent deceleration in the direction of the x’-axis during the experiment. The acceleration field acts therefore as a virtual, soft “obstacle” capable of decelerating the rock mass rapidly. The effects interpreted from the image data (Figures 3.36, 3.37) are that the rock mass experiences, due to inertial effects, shear displacements not only at the contact with the basal interface but also internally within the rock mass itself. Because the bottommost layers of the rock mass experienced the fastest deceleration, shear and collisional impacts of these rocks with the overriding hanging wall layers caused intensive fragmentation within this “process” zone. Further implications, which can be derived from these observations, are discussed in more detail below.

It should be noted that stresses generated by the artificial acceleration field alone turned out not to be sufficient to exceed the strength of the experimental rock material. This has been confirmed from a test set up where the extension of the rock mass was kept short in the x’-direction but constant in the z’-direction. Hence, the entire rock mass was sliding as one block and no fragmentation occurred. Thus,
overburden pressure in the minus $z'$-direction can be ruled out as a cause of particle failure.

Figure 3.36: View into the “A” channel of the model. Image taken by the black and white high speed camera during the experiment. The arrow indicates the flow in the $x'$-direction and serves as a scale. Its length is 32 mm, which equals the initial side length $r_0$ of the intact blocks. The rock blocks remain in contact during the entire experiment. This simulation was performed at an angular velocity $\omega$ of the centrifuge of 30.4 rad/s.
Figure 3.37: A characteristic example of the internal deformation of the rock “flow” simulated within the centrifuge experiment. This simulation was performed at an angular velocity $\omega$ of the centrifuge of 30.4 rad/s. **A)** The hopper section of the experiment (cover lid removed). (a) trap door and its hinge (b); (c) pneumatic piston to unlock the door in-flight. The hopper is filled in the positive $z'$-direction with layers of red, blue, and green blocks of ETHAR. **B)** View into the acceleration and run out channels of the model showing a total view of the rock “flow” deposit at the end of the experiment. As depicted in Figure 3.36, the rock blocks remain in contact during the entire experiment. **C)** Magnification of the rock “flow” deposit but with the approx. upper half, in $z'$-direction of the rock mass, stripped. Whereas the uppermost rock blocks remained widely intact, the bottommost layer displays intensive fragmentation. The dotted lines mark the perimeter of ± intact blocks still existing in that matrix supported deposit. The arrow indicates the flow in the $x'$-direction and serves as a scale with a length of 32 mm, which equals the original side width $r_0$ of the rock blocks applied in this experiment.
3.4.2 Fabric of the Fragmented ETHAR (Imre et al., 2009b)

The most striking result of the fragmentation of rock particles within the centrifuge experiments is the fabric of the deposit achieved which is characterized by a matrix supported texture of the material: except for the approx. upper half of the deposit, which is only slightly fragmented, no particles of the same size were found in contact with each other (Figure 3.37C). This observation is consistent with those made in nature (Figure 3.38), providing powerful evidence to validate this centrifuge model. The physical reasons for such a fabric are still under discussion. McDowell and co-authors (McDowell, 2001; McDowell and Bolton, 1998; McDowell et al., 2002) showed that the particle (tensile) strengths of single particles reduces as their size increases, whereas the works of Sammis et al. (1987), McDowell and Daniell (2001) or Einav (2007a; 2007b) suggest that smaller particles “shield” larger particles and prevent their failure by distributing the loading more evenly over them likewise a hydrostatic stress field (Tsoungui et al., 1999). Therefore particles of similar size in contact with each other are more likely to fail than those of different sizes. This process leads to a fabric of the deposit where larger particles float in a matrix of finer ones. Like the natural deposits of sturzstroms (Figures 2.2, 2.5, 3.38), particles of the fragmented ETHAR, whatever their size, have an angular shape with sharp edges (Figure 3.37).

![Figure 3.38: Outcrop detail of the intensively fragmented deposit of the post Pleistocene Flims sturzstrom, close to the railway station “Versam-Safien”. Note that all particles are surrounded by smaller ones, therefore no particles of a similar size appear to touch each other (scale in cm).]

3.4.3 Particle Size Distribution of the Fragmented ETHAR (modified after Imre et al., 2009a; 2009b)

The deposits from the centrifuge experiments have been collected and dry sieved carefully by hand to reveal their cumulative mass of particle size distribution $m(<R)$, where $m$ denotes the mass of particles of size $r$ smaller than the sieve aperture $R$ (CEN, 2005). These data are plotted in Figures 3.39A and B. The samples from the Flims, Grächen, Goldau and Köfels sturzstroms have been examined in the same fashion. These data are plotted in Figure 3.39B for % passing normalized by aperture size $< 8$ mm, together with those of the fragmented ETHAR. Within the sampled orders of magnitude of $r$ obtained from the experiments
conducted in the centrifuge, the data of ETHAR fit well to the cumulative mass of particle size distributions of the Grächen, Goldau and Köfels sturzstroms, but not well to those of Flims.

**Figure 3.39:** A) Initial and final cumulative mass particle size distributions $m(r<R)$ resulting from the centrifuge experiments performed at an angular velocity $\omega$ of 31 radians/sec., utilizing blocks of ETHAR with initial dimensions $r_0$ of 19 mm (small), 32 mm (medium), and 48 mm (large). The final cumulative mass particle size distributions comprise fines $\leq 8$ mm, which can be determined from standard sieve analysis, only. Larger particles represent either non- or only partially fragmented blocks. B) Cumulative mass particle size distributions, normalized over the cumulative mass particle size distributions at $R=8$ mm, of various sturzstroms, compared with the results from the centrifuge experiments.
3.4.3.1 Fractality of the Particle Size Distributions (Imre et al., 2009a)

Comparing the particle size distributions achieved in the centrifuge experiments with the distributions revealed by sieving samples of deposits of true sturzstroms (Figure 3.39B), provides insight. If the size distribution of the particles of a rock mass is proportional to a power law relation with the slope \( \nu \), where:

\[
N(r \geq R) \propto R^{-\nu},
\]

then a fractal is defined (Mandelbrot, 1982; Turcotte, 1986; Tyler and Wheatcraft, 1992). \( R \) is a measure of length (e.g. sieve aperture) in this equation, \( N(r \geq R) \) is the cumulative number of particles with a length \( r \geq R \). The fractal dimension \( D \) can be calculated from the relationship given in Equation (3.31) as (Turcotte, 1997):

\[
D = 3 - \nu \quad [-].
\]

However, it is more practical to work with the percentage of cumulative mass of particles \( m \) of size \( r \) “less than” \( R \)—\( m(r < R) \), because measurements are obtained directly from sieve analyses. Under the assumption of uniform particle density, Tyler and Wheatcraft (1992) showed that a valid and robust way of obtaining the mass based fractal dimension \( D \) from real sieve data, is to regress \( m(r < R) \) on \( R \) expressed in the log/log space according to the power law relation:

\[
m(r < R) = kR^\nu,
\]

where \( k \), is the offset of the regression line.

Turcotte (1986) developed the proposition that \( D \) is sensitive to a particular mode of fragmentation. Hence comminution processes can be interpreted and compared in terms of \( D \). The fractal dimension has been calculated according to Equations (3.32) and (3.33) for all natural and artificial particle size distributions presented in Figure 3.39. The result is that, within the two orders of magnitude of \( r \) for these data, \( D \) ranges from 2.60–2.86. These values of \( D \) obtained from the centrifuge experiments fit well to the fractal dimensions of the Grächen, Goldau and Köfels sturzstroms, but again not well to those of Flims. They are also in the range of values of \( D \) for other natural sturzstroms also, as presented in the data compiled by Crosta et al. (Crosta et al., 2007) for particles with \( r \) up to 1000 mm. An interesting observation for this centrifuge experiment in particular is that most of the slopes of the cumulative mass-particle size distributions tend to decrease (while \( D \) increases) for particles with \( r < 8 \) mm, which may be interpreted as a change in the mode of fragmentation.

3.4.4 Confirmation of the Centrifuge Experiment (modified after Imre et al., 2009b)

The dynamically changing acceleration field of the experiment creates a challenging boundary condition, which has to be mastered. Care has been taken to incorporate this boundary condition into the development of the theoretical and mechanical design of a scientifically sound and mechanically reliable experiment. This is also reflected by the efforts to monitor the experiment, where the light barriers and the force sensor are primarily intended to allow for a comparison between the theoretically derived boundary conditions and its real physical representation during the experiment. While monitoring of the experiment with the high speed camera was
successful, it turned out that the frictional heat sensors did not yield enough useful results.

Although the mobilized strength of rock may vary significantly with strain rate (for example Howe et al., 1974 in the case of marble) or may not vary significantly with strain rate (for example Zhao, 2000 in the case of granite), it was not attempted to scale ETHAR for dynamic similitude properties. Estimating strain rates generated between colliding rock particles in a true sturzstrom with any accuracy would be extremely difficult in practice, because a very wide range of particle sizes occur in sturzstroms, which are interacting with each other on very irregular interfaces. Estimates of dynamic rock properties may therefore rather contribute to indeterminacy than to solving problems. So standardized quantitative rock material tests have been adopted for the primary characterization. However, in the context of sturzstroms, these standardized parameters are only index parameters, because they are derived from tests that require samples whose shapes and sizes do not occur in sturzstroms in nature. The value of these standardized tests is to allow comparison between the prototype conglomerate and ETHAR.

It must be kept in mind that the indeterminacy of the given problem calls for a focus on few, well established properties. This is thought to be far more useful than to give undue emphasis to the intricacies of a particular test (e.g. Pollack, 2003). How is it then possible to evaluate the usefulness of ETHAR as a homogenous laboratory rock material under these circumstances? How can the physical experiment as a whole be confirmed? This may be done by looking at what is reasonably well known in terms of valid boundary conditions and properties: the prototype initial conditions, the prototype kinetic energy level, and the prototype final situation. The centrifuge experiment must then be capable of delivering comparable results in terms of fabric, shape and (fractal) particle size distribution of the resulting fragmented model deposit, under model boundary conditions that replicate the prototype situation (Section 3.2).

This could be achieved indeed. The most noticeable results of the fracturing of rock particles within the centrifuge experiments are the fabric (Section 3.4.2) and the fractal particle size distribution (Section 3.4.3) of the fragmented material achieved.

It can be therefore “inferred to the best explanation” (Lauth and Sareiter, 2005) that ETHAR and the centrifuge experiment as whole displays, at least approximately, a valid representation of the prototype situation. The epistemic loop depicting this abductive reasoning is shown in Figure 3.40. The performance of the centrifuge experiment allows this physical model to be proposed for performing meaningful experiments on the mechanics of sturzstroms.

It is pointed out again that the centrifuge experiment is scaled to the maximum kinetic energy level that can be achieved within this set up! This approach is very different to classic centrifuge modelling. It means that neither the mass, nor the volumes of the experimental rock material are scaled. Hence, one litre of ETHAR represents one litre of rock within a sturzstrom, like one kilogram of ETHAR represents one kilogram of rock within a sturzstrom. The intact rock blocks of the Molasse conglomerate of Goldau and of ETHAR, as depicted in Figure 3.40A and B, therefore do not need to be in scale. In contrast, the fragmented rock blocks of the Molasse conglomerate and of ETHAR, as depicted in Figure 3.40C and D, are in
scale. This is no contradiction, especially when the particle size distributions of the fragmented materials are fractal and therefore scale invariant.

Figure 3.40: Epistemic research path of this study. A) Present day view on the detachment zone of the 1806 Goldau sturzstrom. The large blocks of the “Bunte Rigi-Nagelfluh” conglomerate, bounded by widely spaced joints, are clearly visible, a person serves as scale, see Figure 2.1. B) see Figure 3.25, scale on the note in cm. C) see Figure 3.38, scale in cm. D) see Figure 3.37C, the arrow serves as scale and amounts 3.2 cm. The centrifuge model is not a direct model representation of the prototype (a) but it provides a similitude initial condition in the form of intact rock blocks (b) and a similitude kinetic energy level expressed by a maximum achievable bulk velocity (c). A comminution process causes the fragmentation of the initially intact rock blocks both in the prototype and model situation (d). The resulting deposits are compared in terms of deposit texture, particle shape, and particle size distribution (e). This comparison allows for an “inference to the best explanation” (Lauth and Sareiter, 2005) that ETHAR and the centrifuge experiment as a whole displays, at least approximately, a valid representation of the prototype situation of a small portion of rock fragmented within a sturzstrom.
4 Analytical Model (modified after Imre et al., 2009a)

4.1 Introduction

The most noticeable results of the centrifuge experiments shown above are the fabric and the fractal particle size distribution of the fragmented material achieved in this physical experiment. What insights may be gained from the fabric and the fractal dimensions derived? How are sturzstroms, especially their emplacement, influenced at macro-scale by these micro-scale features? To answer these questions, it has been suggested to perform true scale numerical experiments on the run out of sturzstroms (Section 6). But to do so, it is necessary to find an analytical description of the fragmentation of rock particles and of the resulting evolution of their fabric and the fractal dimension of their particle size distribution.

4.2 Fragmentation Model (Imre et al., 2009a)

Sammis and co-authors (Sammis, 1996a; Sammis et al., 1987; Steacy and Sammis, 1991) presented an idealised, deterministic comminution algorithm to model fragmentation within fault gauge formation. The hypothesis underlying this model is that a fragmentation process will cause the failure of one of two fragments of near
equal size contacting each other. That small fragments will break large fragments or that large fragments will break small fragments, is assumed to be unlikely.

The mathematical algorithm simulating fragmentation according to this comminution model begins with an “initiator” (Mandelbrot, 1982), which is a cube with an initial side length of \( r_0 \). The mass conserving “generator” operation then retains two diagonally opposite cubes at each cycle \( n \) or scale, but fragments others. The result is that no blocks of equal size are in direct contact with each other (Figure 4.1). After a few cycles, the fabric of such a virtually fragmented material displays striking similarities to the fabric of natural sturzstrom deposits and artificial deposits achieved within the centrifuge experiment (Section 3.4.2).

The net number of blocks \( N_n \) that are newly created during a cycle \( n \), are calculated by this model as:

\[
N_n = 8 \cdot 6^{n-1} [-].
\] (4.1)

The number of blocks \( N_{n,ret} \) that are retained within the initiator volume during cycle \( n \), can be calculated as:

\[
N_{n,ret} = 2^n \cdot 3^{n-1} [-].
\] (4.2)

The side length \( r_n \) of the newly created blocks can be calculated as:

\[
r_n = \frac{r_0}{2^n} [m].
\] (4.3)

The fractal dimension \( D \) of this deterministic comminution model can now be directly calculated as (Turcotte, 1997):

\[
D = \frac{\log \left( \frac{N_{n+1,ret}}{N_{n,ret}} \right)}{\log \left( \frac{r_n}{r_{n+1}} \right)} [-].
\] (4.4)

To calculate \( D \), Equation (4.2) yields \( N_{1,ret} = 2 \) for cycle \( n = 1 \) and \( N_{2,ret} = 12 \) for cycle \( n = 2 \). Equation (4.3) yields \( r_1 = 0.5 \text{ m} \) for cycle \( n = 1 \) and \( r_2 = 0.25 \text{ m} \) for cycle \( n = 2 \), assuming \( r_0 \) to be \( 1 \text{ m} \). Inserting these numbers into Equation (4.4) yields a fractal dimension \( D \) of 2.584. This number is very similar to the fractal dimension of the particle size distribution of natural sturzstrom deposits and artificial deposits achieved within the centrifuge experiment (Section 3.4.3). This fact can be depicted by plotting the particle size distribution calculated within this comminution model together with the particle size distribution derived from natural sturzstrom deposits and artificial deposits (Figure 4.2).

This comminution model is therefore successful, in describing and predicting both the fabric and the particle size distribution of rock experiencing fragmentation within a sturzstrom, to a sufficient degree. The usefulness of this analytical model of fragmentation is now that it allows the quantitative description and prediction of key parameters necessary for understanding the micromechanical energy budget of sturzstroms. In the view of this model, fragmentation changes from a continuous to a periodic process, hence the fragmentation of the initiator occurs in cycles.
Figure 4.1: An idealized, deterministic model for fractal fragmentation after Sammis et al., (1987). A zero order cubic cell with the dimension \( r_0 \) is divided into eight cubic elements with dimensions of \( r_n = r_{n-1}/2 \). This process is repeated to higher orders whereas two diagonally opposite cubes are retained at each scale. The basic structure is fractal, yielding a \( D \) of 2.58. \( \sigma'_{1,f} \) symbolises the maximum effective principal stress at failure. \( \sigma_{\text{disp},n}' \) symbolises the dispersive stresses at failure in the direction of the minimum effective principal stress \( \sigma'_{3,f} \) which is discussed in detail below in Section 4.3.

Figure 4.2: Cumulative mass particle size distribution calculated by the comminution model, plotted together with the cumulative mass particle size distributions, normalized for \( R=8 \) mm, of natural sturzstroms and the deposits from the centrifuge experiments (as depicted in Figure 3.39B).

4.3 Dispersive Stress Model (Imre et al., 2009a)

The fragmentation–spreading model of sturzstroms (Davies et al., 2003; Davies and McSaveney, 1999; Davies and McSaveney, 2002; Davies and McSaveney, 2004; Davies and McSaveney, 2006; Davies et al., 2006; Davies et al., 2007; Davies et al., 1999; Dufresne and Davies, 2009; McSaveney and Davies, 2007; McSaveney and Davies, 2002; McSaveney and Davies, 2009; Smith et al., 2006) is based on the violent phenomenon of "rock bursts", especially known in mining (among others Herget, 1988; Linkov, 1996). Linkow describes a rock burst as an: "[...] explosion-like fracture which usually occurs at the edge of a seam or in a pillar. Highly stressed
rock disintegrates suddenly in a violent, dynamic manner. Fragments of fractured rock acquire velocities of more than 10 m/sec, sufficient to cause injury and even death to miners, damage to equipment and openings, and substantial disruption and economic loss to mining operations.” The micro-mechanics of rock burst is still under debate (e.g. among others Cook, 1965; Linkov, 1996; McSaveney and Davies, 2009; Vardoulakis, 2006). The concept of rock bursts proposed in this thesis can be envisioned by referring back to Section 3.3.5.6, measuring the fracture surface energy $G_F$ of ETHAR. This test had to be performed extremely carefully and slowly to allow for a stable, quasi-static mode I crack growth within that brittle material (e.g. Section 3.3.2.7). If this is the case, the elastic energy $E_{elas,f}$ stored within the tensionally loaded specimen at failure, equals the fracture surface energy $E_{frag}$ necessary to split this specimen apart. That means that all $E_{elas,f}$ will be dissipated during crack formation and the crack width $w$ will remain as permanent plastic deformation of the specimen (Figure 3.33). If the loading rate is too high, an excessive amount of $E_{elas,f}$ will be stored within the specimen. In this case, unstable crack growths will occur, resulting in so called “snap-back” behaviour. This means that the excessive elastic strain, not dissipated by the crack formation, will be recovered instantly, causing the newly created two halves of the specimen to snap back. What is snap-back in tensional loading is none other than rock-burst in quasi-uniaxial loading of brittle materials. In both cases, loading, and therefore elastic deformation is applied to a material at higher rates than crack growth occurs. When the material finally fails, a potentially large amount of excessive elastic energy $E_{elas,f}$ is available, which, during relaxation, may be converted into kinetic energy of the particles originating from the failed material. The conversion of excessive elastic strain energy into kinetic energy, with dissipation of energy for the formation of new fracture surfaces at the failure of a material, is a common process confirmed experimentally and is also in accordance with “daily life” experience (Figure 4.3) and with the arguments of McSaveney and Davies (2009). A sophisticated and illustrative study covering this conversion can be found, for example, in Bergstrom (1963).

Linkov (1996) acknowledges, in his key-note lecture, the importance of the loading rate dependency in the occurrence of rock-burst. But he roots his lecture on rock-bursts on the work done on this topic by Cook (for example Cook, 1965). Cook develops his theory on rock-bursts by applying the Griffith yield locus (Griffith, 1921). He comes to the conclusion that: “The most important aspects of this concept are that amounts of energy, large in relation to the stored elastic strain energy, are necessarily dissipated during the failure of rock, […]. These factors are of vital importance in understanding any process concerning rock failure such as rock drilling or rock bursts.” In this view, rock-bursting is a process that dissipates vast amounts of energy and can not be driven by the elastic energy stored within the material. It requires a large amount of energy applied to the material from outside post failure, which exceeds the elastic energy stored within the material at its failure. As a consequence, fragmentation would be a tremendous energy sink and a completely passive process. Based on this view, the dynamic fragmentation-spreading model (Dufresne and Davies, 2009; McSaveney and Davies, 2009), which depends on an active role of rock fragmentation and on the efficient recovery of elastic strain energy at failure, is rejected, for example, by Hungr (2006). But due to the empirical evidence presented above, and the fact that excessive run out of sturzstroms occurs despite the intensive fragmentation of the rock material involved, the view advanced by Hungr is rated, in this thesis, as a misconception.
As explained above, rock-bursts occur when quasi-brittle rocks are loaded compressionally up to their failure strength in uniaxial direction. In that case their stored elastic strain energy is to a large degree recovered as kinetic energy of the failed particles. In the case of ideal uniaxial compressional loading, failure occurs as mode I tension cracks, oriented parallel to the loading direction. Relaxation and the simultaneous conversion of the elastic excessive energy stored within the fragments originating from the failed material, will therefore take place perpendicular to the direction of the loading. This proposition is also in accordance with both empirical observations gained from uniaxial compressional strength tests. This behaviour is depicted for example by Bergstrom (1963) also. Within true sturzstroms, perfect uniaxial stress conditions may not prevail always, but quasi uniaxial conditions have to be assumed to allow for rock-bursting to occur. In this case, relaxation and the simultaneous conversion of the elastic excessive energy stored within the fragments originating from failed rock particles will take place in the direction of the minimum effective principal stress $\sigma'_3$ (Figure 4.3). Thus a dispersive stress or “granular pressure” (Davies and McSaveney, 2006) $\sigma_{disp,n}$ may evolve from such a cloud of failed rock particles. Assuming the maximum effective principal stress $\sigma'_1$ to act predominantly in the $x$-direction of a sturzstrom, would therefore cause the reduction of effective stresses predominantly along a plane spanned by the $y$ and minus $z$-axis and hence reduction of frictional resistance $\tau_x$ mobilised within the $x$-direction:

$$\tau_{x,n} = \left(-\sigma_z + \sigma_{disp,n}\right) \cdot \mu,$$

This expression allows the dispersive stress concept to be combined with the effective stress concept (Terzaghi, 1960) and the Coulomb frictional model, where the friction coefficient is denoted as $\mu$.

The elastic strain energy $E_{elas,f}$ stored just before failure may be calculated for a triaxial principal stress state, during a fragmentation cycle $n$, utilizing the comminution model presented here, as (modified after Jaeger and Cook, 1979):

$$E_{elas,f,n} = \frac{1}{2M} \left(\sigma_{1,f}^2 + \sigma_{2,f}^2 + \sigma_{3,f}^2 - 2 \cdot \nu \cdot \left(\sigma_{2,f} \cdot \sigma_{3,f} + \sigma_{3,f} \cdot \sigma_{1,f} + \sigma_{1,f} \cdot \sigma_{2,f}\right)\right) \cdot \gamma_n^3 \cdot N_n$$

[Nm],

where $M$ denotes the elastic modulus, $\sigma'_{1,2,3,f}$ the effective principal stresses at failure and $N_n$ the number of particles affected, which is calculated by Equation (4.1).

The energy $E_{frag}$ dissipated due to fragmentation can be calculated for a cycle $n$ as:

$$E_{frag,n} = A_n \cdot G_F \ [Nm],$$

where $G_F$ denotes the fracture surface energy (Hillerborg, 1985b) and $A_n$ the net surface area, which is newly formed during a cycle $n$.

The net surface area $A_n$ can be again derived from the comminution model and is calculated as:

$$A_n = \frac{3^n}{2^{n-1}} \cdot r_0^2 \ [m^2]$$

(4.8)
The dispersive kinetic energy $E_{disp}$ released at failure may be calculated for a cycle $n$ as:

$$E_{disp,n} = E_{elas,f,n} \cdot COR - E_{frag,n} \text{ [Nm]},$$

(4.9)

where $COR$ denotes an elastic coefficient of restitution of rock (Imre et al., 2008).

Figure 4.3: Hitting a rock block with a hammer: conversion of kinetic energy into elastic strain energy and reconversion of the elastic strain energy into kinetic energy after failure of the rock. An interesting effect of fragmentation is that the maximum effective principal stress $\sigma'_{1}$ is deflected quasi-perpendicular, in direction of the minimum effective principal stress $\sigma'_{3}$. The resulting cloud of particle fragments may then induce a load on surrounding particles, which will cause a dispersive stress $\sigma_{disp}$. The behaviour of quasi-brittle rocks within this very simple experiment can be confirmed, by any standard laboratory compressive strength test.

4.4 Summary on the Analytical Fragmentation Model

The fractal comminution model after Sammis and co-authors offers a sufficient mathematical description of the fabric and the fractal particle size distribution of the fragmented material achieved in the physical experiments and of natural sturzstrom deposits. It displays, therefore, the basis on which the energy budget, including the occurrence of the dispersive kinetic energy $E_{disp}$ of distinct rock blocks experiencing cyclic fragmentation, may be calculated at micro-scale. Such an analytical description may then be implemented within a discontinuum numerical modelling environment for studying the effects of dispersive stresses at macro-scale.
5 Mechanical Rock Properties

5.1 Introduction

At this point, it is necessary to consider the fracture surface energy $G_F$ going into Equation (4.7), the compressive strength of rock, which will affect the principal yield stresses $\sigma'_{1,2,3,f}$ (Equation (4.6)), and the coefficient of restitution $COR$ going into Equation (4.9) in more detail. Although the mobilized strength (among others Howe et al., 1974; Li et al., 2005; Zhao, 2000) and the elastic properties of rock may vary with strain rate, it was deliberately decided not to endeavour to consider any dynamic properties at the present stage of the work for the same reasons as discussed previously above in context with the development of ETHAR (Section 3.3.6). Estimates of strain dependent rock properties may therefore rather contribute to indeterminacy than to solving problems. An additional reason is that the tremendous geometric irregularity of rock particles forming sturzstroms may have a higher influence on their mechanical behaviour than strain rates do (among others Jaeger and Cook, 1979; McDowell and Bolton, 1998), but this dependency can be incorporated in an analysis more simply.
5.2 The Elastic Coefficient of Restitution (Imre et al., 2008)

5.2.1 Introduction (Imre et al., 2008)

The stress/strain curve of practically any rock material under elastic deformation shows a hysteretic loading/unloading path. In the present context, the term “elastic” means that all material deformation will be fully recovered during unloading. But at the same time, the hysteretic loading/unloading path means that the energy stored as elastic deformation cannot be fully recovered during unloading. This hysteretic damping may be quantified as the ratio between the elastic energy invested during loading and recovered during unloading. This ratio is denoted as the coefficient of restitution (COR) (e.g. Stronge, 2000).

This response to impact between rocks can be represented in computational models, either indirectly by constitutive models or directly via splitting the model into structural units, so-called distinct elements. Depending on their fidelity, the advantage of distinct element models (DEM) is that they can explain many aspects of mechanical behaviour of intact rock without a preformulated, global constitutive relationship. These features can permit distinct element modelling to become an appropriate research tool to investigate the complex micro- and macromechanical behaviour of intact rock and rock masses.

A high resolution DEM consisting of elements, not even of grain size but of the size of individual atoms, may also simulate hysteretic damping properly without constitutive formulations. Yet because of computational limitations, it is not possible to represent a block of rock at such a resolution. Therefore the size of the rigid elements must be enlarged to improve calculation efficiency.

Hysteretic damping can then be introduced within the contact constitutive model of a DEM. A simple contact constitutive model simulating hysteretic damping has been provided, for example by Itasca, 2005b. The model simulates a strain-rate independent, collinear normal contact between rigid elements, which can be envisioned as a linear spring with higher stiffness during unloading than that during loading. Collinear (e.g. Stronge, 2000) means, that the loading configuration between two bodies is oriented so, that each centre of mass is on a common normal line passing through the initial point of contact. The contact is frictionless in the normal direction. To calibrate such a contact model, the damping could be back-calculated by fitting the computer model to a real case. A more direct approach is to feed a computer model with physical parameters that can be measured.

This research supports the latter approach of feeding in physical parameters by providing data of the COR for such a collinear, strain-rate independent normal contact, measured for various components of a molasse conglomerate. These data are useful to calibrate or validate (Oreskes et al., 1994) the response to contacts between rigid particles within a DEM calculation.

5.2.2 The COR of Rock (Imre et al., 2008)

In reality, a rock sample may be deformed elastically, either due to a slow, quasi-static loading or fast, due to an impact. The difference between the two is that in the first case, the strain-rate is so small that strain and strain-rate are constant throughout the entire body at any time. In the second case, any loading and
unloading occurs over such a short time period, that only a very small portion of the body may be deformed during contact.

5.2.2.1 Quasi-Static Coefficient of Restitution (Imre et al., 2008)

A quasi-static hysteresis curve can be obtained by plotting the axial stress versus the axial deformation of a rock body (Cross, 1999). In this study, the COR of an Oligocene (Hantke, 2006; Stürm, 1973; Vogel and Hantke, 1988) molasse conglomerate has been investigated. The so-called “Bunte Rigi-Nagelfluh” is a colourful limestone-dolomite conglomerate, with about 5-10% content of plutonic components (Stürm, 1973). Specimens were sampled as drill-plugs (e.g. Figure 5.1) from Mt. Rossberg, close to Goldau, Switzerland. Six specimens were then loaded and unloaded axially in a triaxial test apparatus, within their elastic yield locus, at an axial strain velocity of 0.05 %/min. This strain velocity corresponds to recommendations by the Swiss Standard (VSS, 2005) for determining the quasi-static uniaxial strength of rock-bodies. The corresponding stress/strain curves display the work done during a loading and unloading cycle (Figure 5.2).

The work $W$ done per unit cross-sectional area $A$ of the specimen during loading or unloading can be expressed as follows:

$$W = A \cdot \int_1^3 (\sigma - \sigma ') \, d\varepsilon [\text{kNm, kJ}] \quad (5.1)$$

where $\varepsilon_1$ is the axial strain, $l$ is the initial specimen length, and $\sigma_1 - \sigma_3$ is the deviatoric stress. The work $W$ is represented by the area below the loading and unloading curves (Figure 5.2). The energy loss is described by the coefficient of restitution (COR), which is the ratio between the energy released during unloading ($W_{UL}$) and the energy spend during loading ($W_L$):

$$COR = \frac{W_{UL}}{W_L} [-]. \quad (5.2)$$

The resulting quasi-static CORs for all six conglomerate specimens were in the range of 0.65 to 0.70. These values contain three main sources of error: firstly, the contacts between rock specimen and loading platens are not frictionless. Therefore the radial displacement of the rock specimen near the loading platens is restrained and frictional work has to be done. Secondly, by deforming an entire rock sample, internal plastic deformations caused by the minute growth of pre-existing flaws may develop, without this becoming apparent, even at very small strains. Thirdly, the testing machine displays a small amount of damped elastic internal deformation, slightly altering the stress/strain curves.
5.2.2.2 Coefficient of Restitution (COR) During Impact (Imre et al., 2008)

This approach adopted to measure the dynamic COR during impact has been based on previous work (Bernstein, 1977; Schnurmann, 1941; Smith et al., 1981; Sondergaard et al., 1990; Stensgaard and Lægsgaard, 2001), modified and adopted for natural, inhomogeneous materials like rock. A colliding particle, which does not behave perfectly elastically during unloading, displays an impulse during compression, that is larger than the impulse during expansion. For a normal collinear impact of smooth bodies, this kinetic COR (Poisson, 1811) is equivalent (Stronge, 2000) to the definition of the kinematic COR (Newton, 1726).
The latter definition means that the particle rebound at a speed less than the incident speed (Figure 5.3) or in other words: the kinematic COR, can be written as the ratio between the speed of separation $v_{n+1}$ and the speed of approach $v_n$:

$$\text{COR}_i = \frac{|v_{n+1}|}{v_n}, \quad (n=1, 2, 3, \ldots) \quad [-]. \quad (5.3)$$

If the collision is represented by the bounce of a ball on a half space under gravity $g$, then the flight time from the top of the trajectory to the surface is one-half of the total flight time $T_n$ between the $n^{th}$ and $(n+1)^{th}$ bounces (e.g. Bernstein, 1977):

$$v_n = \frac{gT_n}{2}, \quad (n=1, 2, 3, \ldots) \quad [\text{m/s}]. \quad (5.4)$$

Consequently, it is valid to substitute the velocity terms of Equation (5.3) by Equation (5.4) for the $n^{th}$ and $(n+1)^{th}$ bounces. The kinematic COR$_i$ can now be expressed as the ratio between the total flight times $T_{n+1}$ and $T_n$ (Figure 5.3):

$$\text{COR}_i = \frac{T_{n+1}}{T_n}, \quad (n=1, 2, 3, \ldots) \quad [-]. \quad (5.5)$$

Consequently only measurements of the flight times $T_n$ between the bounces are now required, to measure the kinematic COR$_i$ and to solve this equation. These times $T_n$ were measured in the subsequent experiments. Since the kinetic COR, kinematic COR and also the energetic definition of the COR are equivalent for a normal collinear impact of smooth bodies (Stronge, 2000), the COR$_i$ measured herein will now be denoted simply as the coefficient of restitution (COR).

![Figure 5.3: Schematic representation of a ball bouncing on a fixed surface, illustrating notation used in formulations.](image)

5.2.3 Explanations for Occurrence of Hysteretic Damping (Imre et al., 2008)

Jaeger and Cook (1979) offer an explanation for this behaviour with the inherent presence of tiny flaws within the apparently intact rock. Within the elastic yield locus, the compressional loading in terms of an effective deviatoric stress $\sigma'_1 - \sigma'_3$ of a rock
sample may cause an elastic relative motion between the surfaces of a closed crack if the induced shear stress is higher than the frictional resistance of these surfaces. In this case, sliding proceeds up to the conclusion of the loading. A relaxation shear stress at the crack surfaces is induced at the beginning of unloading due to the elastic deformation of the crack walls. This stress now has to overcome both the reversed frictional resistance and the shear stress still induced due to the deviatoric effective stress $\sigma_1' - \sigma_3'$. This is not possible instantaneously, but only after a decrement $\Delta(\sigma_1' - \sigma_3')$ of the compressional loading. Therefore, Jaeger and Cook, 1979 state that the work against friction during a complete cycle of loading and unloading is divided between these portions in the ratio of $(\sigma_1' - \sigma_3')/((\sigma_1 - \sigma_3) - \Delta(\sigma_1' - \sigma_3'))$. Because of energy dissipated due to friction, the elastic work stored within the crack walls can not be recovered fully. This implies that the relaxation of an elastically deformed rock particle does not set in immediately, but with a time lag. This leads to the definition of the kinetic COR by Poisson (1811) where the impulse during compression is larger than the impulse during expansion.

Additionally energy may be transformed into elastic wave propagation, light, heat and sound. Energy dissipation due to elastic wave propagation will only be significant if at least one of the colliding entities is slender (Stronge, 2000). Measurements to prevent energy transformation into elastic wave propagation are discussed below. Energy transformed into light, heat and sound is neglected because they account for only a small fraction of the total energy of an impact (Goldsmith, 1960).

5.2.4 Mechanical Set Up of Drop Test Apparatus (Imre et al., 2008)

Because of the difficulties in determining the boundary conditions in quasi-static loading tests of rock specimens, the approach of deriving the COR from impact response has been chosen. Furthermore, the region of significant deformation within the rock specimen during impact loading is localized to the contact region (e.g. Stronge, 2000). Consequently this contact process and the applied rigid body theory represent the contact processes modelled by the DEM closely, in which deformation is calculated for the small (but not infinitesimal) area of a single body/body contact.

The drop test apparatus enables a normal collinear impact between a spherical drop ball and the planar, polished surface of a material of interest to be imposed. The apparatus consisted of an arm to which a drop ball was attached, which was either released by switching off an electromagnet or a vacuum. The vertical position of the arm was adjustable for drop heights ranging from between 1 to 200 mm. The base of the apparatus was a massive (20 kg) dead weight made of steel, to ensure that the momentum of the drop ball did not transfer into any part of the drop test apparatus and that elastic wave propagation does not lead to significant energy dissipation (Figure 5.4).

It was also possible to perform the drop tests within a sealed chamber, in which air pressure could be lowered, because it was expected that air resistance would decelerate the bouncing ball. Since preliminary tests proved that a low air pressure did not lead to any measurable influences on the resulting COR, the following experiments were performed under normal atmospheric pressure and a temperature of 20°C. To achieve accurate measurement of the COR, the deformation of the impactor and the impacted surface has to be purely elastic. Plastic deformation and energy loss due to elastic waves must be kept small.
Schnurmann (1941) showed that, if a particle impacts a polished steel surface, plastic deformation was seen due to the occurrence of lunette-shaped impact marks. To find an appropriate impact energy for drop tests on rocks, preliminary experiments were conducted by dropping steel balls of various diameters (2-8 mm) and materials (steel, granite) from various heights (50-200 mm) onto a disc \((D=48 \text{ mm}, \ h=20 \text{ mm})\) of polished Carnallite. Pure Carnallite \((\text{KMgCl}_3\cdot6\text{H}_2\text{O})\) is a colourless, very brittle salt. Inelastic deformations due to high impact energies can be observed in terms of cracks formed at the impact site. To compare the effect of impactors of differing sizes and materials, the energy concentration \(E_A\) of the impact energy \(E\) normalized over the surface \(A\) of the impacting particle was calculated:

\[
E_A = \frac{mgh}{A} \quad [\text{Nm/m}^2, \text{J/m}^2].
\]  
(5.6)

In this formula, \(h\) denotes the fall height, \(m\) the mass of the impacting particle and \(A\) the spherical surface area of the impactor. No damage to the Carnallite surface was observable at a 10 times optical magnification below an energy concentration of about 2.5 J/m\(^2\).

A carbon chromium steel ball bearing of 3 mm diameter, with a content of approximately 1 % carbon and 1.5 % chromium, displaying a Rockwell Hardness of 58 to 65 HRC\(^{12}\), released from a height of 50 mm, satisfies this requirement (Figure 5.5). This set up yielded a planar impact energy concentration of about 1.9 J/m\(^2\) (e.g. Equation (5.6)). To check the applicability of this set-up to the molasse conglomerate, the specimen 46975_2, zone 2 (e.g. Table 5.1) was impacted by this steel ball from different fall heights. Figure 5.6 shows the result where the 3 mm steel ball was released from a height of 1, 25, 50, 100, 150 and 200 mm. The diagram reveals a clear dependency on the impact energy, as is reported in literature (e.g. among others Coaplen et al., 2004; Goldsmith, 1960; Schnurmann, 1941; Sondergaard et al., 1990; Stensgaard and Lægsgaard, 2001). The COR reaches a maximum and almost constant value at a drop height of 50 mm and reduces continually with increasing drop height (and impact energy concentrations greater than 2.5 J/m\(^2\)). The almost horizontal linear fit for drop heights of 1, 25 and 50 mm over mean COR, with an offset of COR 0.895 ± 0.026, supports this interpretation (e.g. Stensgaard and Lægsgaard, 2001). It also implies that this set-up, with a release height of 50 mm and below, is practically strain-rate independent. Therefore a release height of 50 mm was selected to perform the series of drop tests.

All samples to be measured were holohedrally glued onto the dead weight to prevent energy dissipation by elastic waves due to unwanted dynamic responses. Due to the massive nature of the rock base and the small, spherical impactor, elastic wave propagation is not considered to be relevant for this impact mode.

\(^{12}\) SKF Bearings.

http://www.skf.com/
Figure 5.4: Drop test apparatus, (a) electromagnet for holding steel ball, (b) signal amplifier, (c) ball trigger, (d) dead weight.

Figure 5.5: Detailed view of 3 mm steel ball and electromagnet.

Figure 5.6: Graph showing dependency between COR and drop height. CORs were obtained for drop heights of 1; 25; 50; 100; 150 and 200 mm. Their standard deviations and related numbers of measured bounces are indicated.
5.2.4.1 Measurement of Time Interval $T_n$ (Imre et al., 2008)

A small transverse wave is generated when the ball collides with the surface of the rock specimen, which propagates through the rock. This wave was captured by an acceleration sensor (Figure 5.7). The resulting analogue signal was then amplified, converted into a digital signal and stored as text file (Figure 5.8).

The acceleration signal $\lambda$ (Figure 5.9) was recorded at a sample rate of 40 kHz. The insertion times $t_n$ and related intervals $T_n$ were calculated automatically by a computer algorithm applied to the unfiltered signal records:

$$
t_n \leftarrow \text{if } |\lambda_n| \geq \sum_{i=n-20}^{n-1} |\lambda_i| \text{ [sec]}, \quad T_n = t_{n+1} - t_n \text{ [sec]}.
$$

For the measurement set up used (Figure 5.8), this algorithm determines $t_n$ with a precision of $\pm 5 \cdot 10^{-5}$ sec.

5.2.4.2 Calculation of Dynamic Elastic COR (Imre et al., 2008)

According to Equation (5.5), the COR may be calculated from a single drop test, if the ball bounces at least three times on a perfect surface. However, the polished surface of a natural material like rock is seldom perfectly smooth. Grain boundaries and tiny fissures are likely to deflect the ball, altering the time interval $T_n$. A guiding tube may be used to keep the ball bouncing vertically. In this case, friction between the bouncing ball and the tube will result in unwanted ball deceleration and rotation. Therefore, the problem of irregular ball bouncing was addressed by increasing the number of drop tests on a single specimen without a guiding tube and statistically estimating the population average of the COR. The measured individual COR$_i$ of a single drop test are normally distributed. The normality was tested by quantile-quantile plots. The overall COR$_t$ of a single drop test was then calculated as the arithmetic average of its individual COR$_i$ according to Equation (5.5):

$$
\overline{\text{COR}}_t = \frac{1}{n} \sum_{i=1}^{n} \text{COR}_i,
$$

The standard deviation $s$ of a single drop test is calculated as follows:

$$
s_{\text{COR}} = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \left( \text{COR}_i - \overline{\text{COR}}_t \right)^2}.
$$

The drop test was repeated such that the sample average of the test set (COR) matched the true, population average COR within a confidence interval of at least 95%. The number of valid bounces of each single drop test varied within one test set and as a result of this, so did the population size of each single drop test. The sample average of the test set (COR) must therefore be calculated as a weighted ($w_i$) average of its individual drop tests:

$$
\overline{\text{COR}} = \frac{\sum_{i=1}^{n} \left( w_i \cdot \text{COR}_i \right)}{\sum_{i=1}^{n} w_i}, \quad w_i = \frac{1}{s_{\text{COR}}^2}.
$$
The sample standard deviation of the test set was calculated as follows:

\[
\sigma_{\text{COR}} = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} (\text{COR}_i - \overline{\text{COR}})^2}.
\]

(5.11)

Figure 5.7: Disc of molasse rock glued to basal dead weight, with acceleration sensor attached on the left hand side.

**Signal Recording and Analysis**

**Ball Triggering**

(a) Electromagnet 24V Isolizer®

(b) Rubber Socket Water Jet Pump -50 kPa

Figure 5.8: Signal recording and analysis chain. Ball triggering: (a) in case of a steel ball, impactor is released by turning off an electromagnet. (b) in case of a rocky impactor, the impactor is released by turning off a vacuum.

Figure 5.9: Acceleration signal for a drop test on a Sandstone sample (sample # 46975-2, zone 2). White stars indicate insertion times of signal when the impactor contacts half space.
5.2.5 Drop Tests (Imre et al., 2008)

5.2.5.1 Drop Test: Steel Impactor on a Glass Surface (Imre et al., 2008)

Generally, research on the COR has focused on collisions between bodies of the same material. In the present case, where the attempt is to measure the COR of rock material, this approach is problematic because of technical difficulties in obtaining truly spherical particles of rock, which are necessary to generate collinear collisions. This can be overcome by dropping a highly accurate and homogenous steel ball onto the polished surface of a rock drill core, which is technically much easier to achieve. The underlying assumption is now that the steel ball behaves perfectly elastically and displays an own COR of 1 (Cross, 1999) whereas the COR of the rock material is generally < 1. The composite COR measured for the collision between a steel ball and a rock surface is therefore completely controlled by the individual COR of the rock surface (Cross, 2000). In other words: the individual COR of the rock surface is thought to be equal to the composite COR.

These proof tests were now intended to verify the individual COR of the steel ball and the accuracy of the drop-test apparatus in general. The tests were performed with an object slide as a fixed half space, holohedrally glued onto the dead weight (Figure 5.10). A regular soda-lime glass\textsuperscript{13} served as the slide, since the surface is very smooth and homogenous. It is one of the materials that responds as closely to truly linear elastic behaviour as possible within its yield locus due to the minuteness of its flaws, typically with a length of only about 1000 Å (Jaeger and Cook, 1979). The individual COR of the glass slide is therefore expected to be 1.00. The 3 mm steel ball, released from a height of 50 mm served as the impactor, so that the composite COR of this system is again expected to be 1.00. These experiments yielded a composite COR of 0.999 ± 0.001. Therefore, neither the steel ball nor the glass surface displayed considerable energy dissipation for the given drop-height.

\textbf{Figure 5.10: Glass slide glued to dead-weight base plate by epoxy resin glue. Acceleration sensor (small cylinder) is attached to glass slide with same glue.}

5.2.5.2 Drop Test: Steel on Molasse Conglomerates (Imre et al., 2008)

The elastic COR of various components of the molasse conglomerate (Figures 5.11, 5.12, 5.13, and 5.14) was measured by loading discs (D=48 mm, h=20 mm) that were holohedrally glued to the dead weight (Item d in Figure 5.4) dynamically. The

\textsuperscript{13} Marienfeld Laboratory Glassware.

http://www.marienfeld-superior.com/
upper sides of the discs were polished with 1 µm sandpaper. The 3 mm steel ball, released from a height of 50 mm served as the impacting projectile. Momentum transfer of the impacting ball into the measured components of the conglomerate was neglected, since only such components that displayed a non-weathered and well cemented contact to the matrix of the conglomerate were investigated. The test results for each of the three rock types and their lithological description are summarized in Table 5.1.

Figure 5.11: Rock sample # 46975_2.

Figure 5.12: Rock sample # 46975_3.
Figure 5.13: Rock sample # 46975_4.

Figure 5.14: Rock sample # 46975_5.
<table>
<thead>
<tr>
<th>Sample #</th>
<th>Zone #</th>
<th>Lithology</th>
<th>mean COR [-], (Equation (5.10))</th>
<th>s, (Equation (5.11))</th>
</tr>
</thead>
<tbody>
<tr>
<td>46975-2</td>
<td>1</td>
<td>massive, micritic marly-limestone of yellow-greyish colour</td>
<td>0.896</td>
<td>0.001</td>
</tr>
<tr>
<td>(Figure 5.13)</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>46975-3</td>
<td>1</td>
<td>coarse-grained, fine-grained, sandstone (psammite), quartz (max. 2mm),</td>
<td>0.895</td>
<td>0.002</td>
</tr>
<tr>
<td>(Figure 5.14)</td>
<td>2</td>
<td>poorly rounded (psammite), components of made up of quartzite, redish,</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>marble, limestone, chert, quartz and mica-slate, embedded in a dark greenish,</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>calcitic matrix</td>
<td></td>
<td></td>
</tr>
<tr>
<td>46975-4</td>
<td>1</td>
<td>fine-grained, quartz-sandstone (psammite), made up of quartzite, redish,</td>
<td>0.817</td>
<td>0.024</td>
</tr>
<tr>
<td>(Figure 5.15)</td>
<td>2</td>
<td>marble, limestone, chert, quartz and mica-slate, embedded in a calcitic</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>matrix</td>
<td></td>
<td></td>
</tr>
<tr>
<td>46975-5</td>
<td>1</td>
<td>coarse-grained, fine-grained, sandstone (psammite), quartz (max. 5mm),</td>
<td>0.809</td>
<td>0.017</td>
</tr>
<tr>
<td>(Figure 5.16)</td>
<td>2</td>
<td>poorly rounded (psammite), components of made up of quartzite, redish,</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>marble, limestone, chert, quartz and mica-slate, embedded in a calcitic</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>matrix</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The components were grain supported and cemented by a calcitic matrix. This sandstone itself formed the matrix of the matrix-supported molasse conglomerate.
5.2.5.3 Drop Test: Granite Impactor on Granite and Sandstone (Imre et al., 2008)

To round off the experiments, the collision of an impactor and a fixed surface, both of similar composition, was investigated by dropping a granite sphere onto components of the molasse conglomerate. Due to technical difficulties, the impactor was not made out of exactly the same material as the conglomerate components tested and was not of a perfectly spherical shape, but the granite sphere (D ≈ 10 mm) was of comparable mineralogy and texture (Figure 5.15). This impactor was also dropped from a height of 50 mm onto sample # 49675-3, zone 2 (granite, Figure 5.12) and sample # 49675-5, zone 1 (sandstone, Figure 5.14). This system represented an energy concentration $E_A$ of 2.2 J/m², which is below the threshold of 2.5 J/m². Within a confidence interval of at least 95%, the drop test yielded a COR of 0.844 ± 0.018 for sample # 49675-3, zone 2 and a COR of 0.831 ± 0.012 for sample # 49675-5, zone 1. These values are comparable with the COR of these zones obtained in the experiments using a steel ball as impactor. It could be seen that if two particles, each displaying the similar individual COR, collide, the resulting composite COR remains almost the same.

Figure 5.15: Granite impactor before release, held in place by vacuum.

5.2.6 The Fracture Surface Energy $G_F$ and the Compressive Strength $\sigma'_{cf}$ (modified after Imre et al., 2009a)

5.2.6.1 Particle Size Independence (modified after Imre et al., 2009a)

Taking quasi-static mechanical rock properties of the “Bunte Rigi-Nagelfluh” conglomerate, the predominant rock constituting the 1806 Goldau sturzstrom, as an example (Tables 3.2, 6.1), and assuming in the first instance that the mechanical properties are independent of particle size (Figure 5.16A), the balance between $E_{frag,n}$ and $E_{disp,n}$ available is depicted in Figure 5.16B. In this case, the development of $E_{frag,n}$ would serve as a stopping criterion for the mechanical fluidization of a sturzstrom because all elastic strain energy $E_{elas,f}$ available would be dissipated in fragmentation energy. Taking $3.5 \cdot 10^7$ m³ as the volume of the Goldau 1806 sturzstrom (Berner, 2004), and assuming an initial rock block side length $r_0$ of 1 m, it can be estimated for constant mechanical rock properties, that approx. $2 \cdot 10^5$ MNm of $E_{frag}$ may be consumed to comminute that rock mass down to a particle size of $1 \cdot 10^{-5}$ m. This amounts to approx. 1/3 of the potential energy available within that event, based on
the fall height of its centre of mass of about 700 m (Berner, 2004). This value lies close to the estimations reported in Locat et al. (2006). In this case, fracturing would constitute, beside friction, a significant energy sink within the energy budget of sturzstroms.

5.2.6.2 Particle Size Dependence (modified after Imre et al., 2009a)

Assuming a dependence of $G_F$ and $\sigma_{c,f}$ on the particle size $r_n$, a different picture evolves. $G_{F,n}$ may vary, based on the input parameter shown in Table 6.2, according to:

$$G_{F,n} = k_{G_F} \cdot r_n^{n_{G_F}} \Rightarrow k_{G_F} \cdot \left(\frac{r_0}{2}\right)^{-n_{G_F}} \text{[J/m}^2\text{]}, \quad (5.12)$$

based on a power law regression of data presented in van Vliet (2000) with $\alpha_{G_F} \sim 0.4$ as its slope (Figure 5.16C). The offset $k_{G_F}$ is calculated from a matching pair of values, in the present case, with the specimen dimension $r$ of 1 m, for which a $G_F$ of 400 J/m$^2$ has been measured (e.g. van Vliet, 2000), as:

$$k_{G_F} = r^{-\alpha_{G_F}} \cdot G_F \Rightarrow 1^{-0.4} \cdot 400 = 400 \text{[J/m}^2\text{]}.$$

(5.13)

The particle size dependence of $\sigma_{c,f,n}$ may be described as (Figure 5.16C):

$$\sigma_{c,f,n} = k_{\sigma_{c,f}} \cdot r_n^{n_{\sigma_{c,f}}} \Rightarrow k_{\sigma_{c,f}} \cdot \left(\frac{r_0}{2}\right)^{-n_{\sigma_{c,f}}} \text{[MPa]}, \quad (5.14)$$

based on data from the literature for uniaxial compression (Jaeger and Cook, 1979) and also for tensile particle splitting (McDowell and Bolton, 1998). According to these data, the slope $\alpha_{\sigma_{c,f}}$ of the power law regression can also be set to 0.4. This is not surprising because both the uniaxial compression and, as the name already says, the tensile splitting test, cause the formation of mode I tensile cracks within the material tested. The offset $k_{\sigma_{c,f}}$ is calculated from a matching pair of values, in the present case with the specimen diameter $r$ of 0.05 m, for which a $\sigma_{c,f}$ of 84 MPa has been measured (e.g. Section 3.3.2.2), as:

$$k_{\sigma_{c,f}} = r^{-\alpha_{\sigma_{c,f}}} \cdot \sigma_{c,f} \Rightarrow 0.05^{-0.4} \cdot 84 = 25.3 \text{[MPa]}.$$

(5.15)

The resulting balance between $E_{\text{frag}}$ and $E_{\text{disp}}$ is depicted in Figure 5.16D. The increase of $\sigma_{c,f}$ would serve as stopping criterion for the mechanical fluidization of a sturzstrom because the increasingly smaller particles would become too strong to experience further fragmentation within the collisional environment of a sturzstrom (Figure 5.16C). Again, taking $3.5 \cdot 10^7 \text{ m}^3$ as the volume of the Goldau sturzstrom Berner, 2004 and assuming an initial rock block size $r_0$ of 1 m, it can be estimated for this case, that approx. $2 \cdot 10^8 \text{ MNm}$ of $E_{\text{frag}}$ may be consumed to comminute that rock mass down to a particle size of $1 \cdot 10^{-5} \text{ m}$. This would not even be 1% of the potential energy available. In this case, fracturing would constitute an almost negligible energy sink within the energy budget of sturzstroms. Estimations yielding such a low value have also been reported by McSaveney and Davies (2009).
Figure 5.16: A) Assumption of a particle size independence of the fracture surface energy $G_F$ and uniaxial compressive strength $\sigma_{c,f}$. B) The increase of newly created fracture surfaces (Equation (4.8)) demands $E_{\text{frag},n}$ (Equation (4.7)) to exceed the elastic strain energy $E_{\text{elas},n}$ (Equation (4.6)) after a few cycles $n$, which sharply reduces the dispersive strain energy $E_{\text{disp},n}$ (Equation (4.9)) available. The energies in this example are calculated for a volume of 1 m$^3$ of rock with an initial side length $r_0$ of 1 m. C) Assumption of a particle size dependence of $G_F$ (Equation (5.12)) and $\sigma_{c,f}$ (Equation (5.14)). D) The particle size dependent decrease of $G_F$ causes only a gentle increase in energy necessary to create new fracture surfaces $E_{\text{frag},n}$ (Equation (4.7)). The energies in this example are calculated for a volume of 1 m$^3$ of rock with an initial side length $r_0$ of 1 m again.

5.2.7 Discussion

5.2.7.1 The Coefficient of Restitution (modified after Imre et al., 2008)

Measured values for the COR of a range of rock materials have been measured. They are shown to be higher than those obtained for the quasi-static COR derived from triaxial tests. One reason might be that the COR was obtained on individual components or the matrix of the conglomerate instead of the bulk of the samples. The second, more important reason was that in the triaxial tests, energy may have been dissipated not only due to internal friction, but also due to external friction between loading platens and sample and internal plastic deformations caused by minute growth of pre-existing flaws. In contrast, the COR during dynamic loading was obtained in these drop tests as a practically strain-rate independent, direct collinear impact, affecting only a localized area of the rock material within the contact region. As a result, crack growth was assumed to have been prevented. A COR measured in this way is not only similar to a collinear contact simulated in the DEM, but may also be considered to be useful for calibrating the numerical contact behaviour of rigid
particles in a DEM. The CORs of the rock samples tested never reached 1.00 even at very small fall heights. This stands in contradiction to general statements drawn from experimental results of collinear impacts between the same metals (Goldsmith, 1960; Stronge, 2000). This may be due to the higher homogeneity (or minuteness of flaws) of metals compared to natural materials like rock.

5.2.7.2 The Fracture Surface Energy $G_F$ and the Compressive Strength $\sigma_{c,f}$

Of these two simple examples of mechanical rock properties, the second, non-linear, particle size dependent case is more realistic, because it is closer to empirical evidence. But it is clear that this assumption still does not cover all concerns that arise around the complex field of fracture mechanics. Turcotte (1997) concludes: “Fragmentation involves the initiation and propagation of fractures and is a highly non-linear process requiring complex models even for the simplest configuration.”

This must be even truer for combining fragmentation with sturzstroms.

The indeterminacy of the given problem calls for a focus on a few, established properties. This is thought to be the far more successful way than giving undue emphasis to the intricacies of a particular theory or approach (e.g. Pollack, 2003). The next step will be the combination and implementation of the fragmentation model, the dispersive stress model, and the relationships of size-dependent rock properties within a distinct element numerical code (DEM).
6 Numerical Model

6.1 Introduction

A more direct approach than attempting to calculate a dispersive stress $\sigma_{disp}$ is to take the post failure kinetic energy of the fragmented particles to analyze the influence of fragmentation on the emplacement of sturzstroms. This is done by implementing Equations (4.6)–(4.9), and (5.12)–(5.15) within a distinct element model (DEM). This code models the movement and interaction of assemblies of rigid spherical particles among themselves and/or with boundary walls (Figure 6.1), which is performed by an alternating calculation of Newton’s second law of motion and a force-displacement model at the contacts. A detailed description of this DEM is given by Cundall (1988), Cundall and Strack (1979), and Hart et al. (1988). A simple linear elastic contact model, with the possibility for representing energy dissipation by elastic hysteretic damping and frictional slip, has been adopted as force-displacement constitutive relationship for this study (Figure 6.2). Such a numerical description offers the possibility to describe a granular medium, like a sturzstrom, via a “granular”, iterative comminution model, within a “granular” DEM. This DEM may simulate fragmentation of bonded rigid spheres numerically, with bonds that would fail if their strengths would be exceeded either in the normal or shear directions. Representing rock in this way, in order to model shear localization, was successfully applied in numerous studies (e.g. Baumgarten, 2006; Cheng et al., 2003; Clayton and Reddy, 2006; Cundall and Strack, 1979; Imre, 2004b; McDowell and Harireche, 2002; Potyondy and Cundall, 2004; Robertson, 2000; Whittles et al., 2006 for example). The drawback of such a formulation is that it would require small rigid model spheres (in the range of centimetres or smaller) to simulate the behaviour of real intact rock successfully. This would limit, with the computational power available today, the true model volume within a range of much smaller than one cubic metre.
The elegance of the solution presented here is to apply the comminution model after Sammis et al. (1987) within the continuum of a rigid sphere itself to allow for its “virtual” fragmentation. Such a formulation enables the usage of larger, unbonded particles and, eventually, the simulation of sturzstroms at true scale.

Figure 6.1: Sketch symbolizing the interaction of rigid particles A and B within the DEM (modified after Itasca, 2005b). $R^{[A]}$, $R^{[B]}$ denote the particle radii and $[A-B]$ the distance between the particle centroids, which are described by the 3D positional vectors $x^{[A]}$, $x^{[B]}$. The vector $x^{[A]}$ describes the position of the contact plane between the particles A and B. The orientation of the contact plane and of $[A-B]$ is described by the unit normal vector $n_i$. $u^n$ denotes the contact overlap.

Figure 6.2: Sketch representing the action of the linear elastic contact constitutive model (modified after Itasca, 2005b), as implemented in the DEM, with the possibility for representing energy dissipation by elastic hysteretic damping and frictional slip. $F^n$ denotes the normal force and $\Delta F^s$ incremental elastic shear force. $K_n^{\text{load}}$ denotes the normal contact stiffness during the loading phase and $K_n^{\text{unload}}$ the normal contact stiffness during the unloading phase where $K_n^{\text{load}} < K_n^{\text{unload}}$. The same applies to the shear contact stiffness during loading $K_s^{\text{load}}$ and unloading $K_s^{\text{unload}}$. $u^n$ and $u^s$ denote the contact overlap in normal direction and the shear displacement respectively. $n_i$ denotes the unit normal vector defining the orientation of the contact in space. Finally, $\mu$ denotes the friction coefficient of the Coulomb slip constitutive model.
6.2 Implementation of the COR within the DEM

The DEM code “Particle Flow Code PFC 3D” (Itasca, 2005a) contains an algorithm to implement energy dissipation by elastic hysteretic damping within its contact constitutive model library (Itasca, 2005b). The major drawbacks of this algorithm are:

a) that the COR can not be directly assigned as a contact property but has to be calibrated by varying the contact normal secant stiffness $K_{n,m}$.

b) This contact model does not allow for hysteretic damping in the shear direction of particle contacts, which may cause instabilities within simulations of large, compact particle assemblies.

c) Finally, this contact model contains no algorithm to monitor the energy dissipated by hysteretic damping.

An attempt has been made to overcome these problems by extensive rewriting of this contact constitutive relation. The required contact stiffnesses on loading $K_{n,load}$ and unloading $K_{n,unload}$ are now directly calculated from a given value of COR for compressional normal loading as (e.g. Figure 6.2):

$$K_{n,load} = K_{n,m} \, [N/m] \text{ and }$$

$$K_{n,unload} = \frac{K_{n,m}}{\text{COR}} \, [N/m],$$

(6.1)

where $K_{n,m}$ is the contact normal secant stiffness resulting from the contact normal secant stiffnesses assigned to the contacting entities (ball/ball or ball/wall contacts; Itasca, 2005b).

The required contact stiffnesses on loading $K_{s,load}$ and unloading $K_{s,unload}$ are now directly calculated from a given value of COR for shear loading as:

$$K_{s,load} = K_{s,m} \, [N/m] \text{ and }$$

$$K_{s,unload} = \frac{K_{s,m}}{\text{COR}} \, [N/m],$$

(6.2)

where $K_{s,m}$ is the contact shear tangent stiffness resulting from the contact shear tangent stiffnesses assigned to the contacting entities (ball/ball or ball/wall contacts; Itasca, 2005b).

For loading in normal direction, the elastic energy $E_{elas}$ stored within a contact at time $t$ is calculated as:

$$E_{elas}(t) = \frac{1}{2} \cdot \left( \left( u^n(t) - u^0 \right)^2 \right) \cdot K_{n,load} \, [Nm],$$

(6.3)

where $u^n$ is the current overlap (e.g. Figure 6.1) of the contacting entities and $u^0$ the overlap at the beginning of the normal loading phase.
For unloading in the normal direction, the hysteretic damping energy \( E_{\text{hys}} \), dissipated within a contact at time \( t \), is calculated as:

\[
E_{\text{hys}}(t) = 0.5 \cdot \left( \frac{F^n + (K_{n,\text{load}} \cdot (u^{00}(t) - u^{\text{max}}) + u^{\text{max}})}{K_{n,\text{load}}} \cdot (1 - COR) \right)^2 \cdot K_{n,\text{load}} \quad \text{[Nm]},
\]

where \( F^n \) is the current contact normal force and \( u^{\text{max}} \) is the maximum contact overlap during the loading phase of the contact. The current overlap \( u^{00} \) is calculated as:

\[
u^{00} = \frac{F^n}{K_{n,\text{load}}} \quad \text{[m]}.
\]

To calculate the elastic energy \( E_{\text{elas}} \) stored within a contact at time \( t \) during the unloading phase, a “virtual” elastic energy \( E_{\text{elas, virt}} \), pretending no hysteretic damping, is calculated first:

\[
E_{\text{elas, virt}}^n(t) = 0.5 \cdot \left( \frac{F^n + (K_{n,\text{load}} \cdot (u^{00}(t) - u^{\text{max}}) + u^{\text{max}})}{K_{n,\text{load}}} \cdot 1 \right)^2 \cdot K_{n,\text{load}} \quad \text{[Nm]}.
\]

The elastic energy \( E_{\text{elas}} \) stored within a contact at time \( t \) during unloading can now be calculated from Equations (6.4) and (6.6) as:

\[
E_{\text{elas}}^n(t) = E_{\text{elas, virt}}^n(t) - E_{\text{hys}}^n(t) \quad \text{[Nm]}.
\]

For loading in the shear direction, the elastic energy \( E_{\text{elas}} \) stored within a contact at time \( t \) is calculated as:

\[
E_{\text{elas}}^s(t) = 0.5 \cdot (\Delta u)^2 \cdot K_{s,\text{load}} \quad \text{[Nm]},
\]

where \( \Delta u \) is the incremental shear displacement during one calculation cycle.

For unloading in the shear direction, the hysteretic damping energy \( E_{\text{hys}} \) dissipated within a contact at time \( t \) is calculated as:

\[
E_{\text{hys}}^s(t) = 0.5 \cdot (\Delta u \cdot (1 - COR))^2 \cdot K_{s,\text{load}} \quad \text{[Nm]}.
\]

To calculate the elastic energy \( E_{\text{elas}} \) stored within a contact at time \( t \) during the unloading phase in shear direction, a “virtual” elastic energy \( E_{\text{elas, virt}} \), pretending no hysteretic damping, is again calculated first:

\[
E_{\text{elas, virt}}^s(t) = 0.5 \cdot (\Delta u \cdot 1)^2 \cdot K_{s,\text{load}} \quad \text{[Nm]}.
\]

For unloading in the shear direction, the elastic energy \( E_{\text{elas}} \) stored within a contact at time \( t \) can now be calculated from Equations (6.9) and (6.10) as:

\[
E_{\text{elas}}^s(t) = E_{\text{elas, virt}}^s(t) - E_{\text{hys}}^s(t) \quad \text{[Nm]}.
\]

Note: the energy calculations in normal and shear direction during unloading are all performed by using stiffnesses at loading. This has to be done because the
stiffnesses during unloading are already considered in the normal and shear contact force calculations during unloading, which subsequently goes into the calculation of the displacements $u$ during unloading (Itasca, 2005b). These overlaps and displacements during unloading are then transferred into the energy calculations, which are performed at last in a calculation cycle of the program.

### 6.3 Incorporation of the Fragmentation Model into the DEM

(Imre et al., 2009a)

The post failure, dispersive kinetic energy is now considered within the DEM by letting a dispersive velocity $v_{\text{disp},n}$ act on a single rigid particle of mass $m_{\text{particle}}$, in the direction of $\sigma'_{3}$ (Figure 6.3):

$$v_{\text{disp},n} = \frac{2 \cdot E_{\text{disp},n}}{m_{\text{particle}}} \text{[m/s]}, \quad (6.12)$$

if the three dimensional deviator stress $q'$ (Atkinson and Bransby, 1978):

$$q' = \frac{1}{\sqrt{2}} \left[ (\sigma'_{1,f} - \sigma'_{2,f})^2 + (\sigma'_{2,f} - \sigma'_{3,f})^2 + (\sigma'_{3,f} - \sigma'_{1,f})^2 \right]^{\frac{1}{2}} \text{[MPa]}, \quad (6.13)$$

exceeds $\sigma_{c,f,n}$ (Equation (5.14)). The input average normal and shear stress tensor $\bar{\sigma}_{ij}$ of a particle $(p)$ is calculated as:

$$\bar{\sigma}_{ij}^{(p)} = -\frac{1}{V^{(p)}} \cdot \sum_{N_c} \left| x_{i}^{(c)} - x_{i}^{(p)} \right| \cdot n_{i}^{(c,p)} \cdot F_j^{(c)}, \quad (6.14)$$

where $V$ is the volume of the particle, $N_c$ the number of particle/particle or particle/ground contacts acting on $(p)$, $x_{i}(p)$ and $x_{i}(c)$ are the locations of the particle centroid and its contacts, $n_i$ is the unit normal vector directed from a particle centroid to its contact location and $F_j$ is the force acting at a contact $(c)$ (Cundall, 1988). The magnitudes and the directions of the principal stresses $\sigma'_{1,f}$ and $\sigma'_{3,f}$ of particles undergoing fragmentation are calculated from Equation (6.14) as the eigenvalues and eigenvectors of the stress tensor $\bar{\sigma}_{ij}$ (e.g. Figures 6.3 and 6.4).
Figure 6.3: Rigid particle of the DEM with mass $m_{\text{particle}}$, located within a Cartesian coordinate system with the $x$-axis parallel to the flow of the simulated sturzstrom. The particle is loaded by the three principal stresses $\sigma'_1 > \sigma'_2 > \sigma'_3$. If the deviatoric stress $q'$ (Equation (6.13)) exceeds $\sigma_{c,f}$ (Equation (5.14)), a dispersive velocity $v_{\text{disp}}$ (Equation (6.12)) is applied in the positive direction of $\sigma'_3$. The number of “initiators” $N_{\text{initiator}}$ of side length $r_0$, which fits into the volume of the rigid particle of radius $r_{\text{particle}}$, is calculated by Equation (6.15).
Figure 6.4: Example of sturzstrom simulated within the DEM consisting of 9999 rigid particles. The orientation of principal stresses $\sigma_{1,f}$, $\sigma_{3,f}$ and $v_{disp,n}$ of particles undergoing failure are plotted in an isogonal, stereographic projection during a period of 4.211 x 10^-4 sec. at 0.21 sec. after the simulation starts. It can be seen that the maximum principal stresses are rarely oriented in the z'-direction. The overburden pressure is therefore smaller than the normal and shear stresses acting in the sub x'-direction. One rigid particle is indicated to serve as an example (marked by an "x"). Its maximum principal stress $\sigma_{1,f}$ numbers 38 MPa and displays a trend of 344° (in clockwise direction with the x-axis as zero) and a plunge of 40°. Its minimum principal stress $\sigma_{3,f}$ is oriented perpendicular to $\sigma_{1,f}$ and displays a trend of 305° and a plunge of 50°. $v_{disp,n}$ acts in the same direction as $\sigma_{3,f}$ and is 5.9 m/s in this example.

6.4 Effects of Fractal Fragmentation revealed by the DEM (modified after Imre et al., 2009a)

Exploring the full potential of the DEM applied would exceed, by far, the remit of the current study. Therefore, two simple examples will be shown to highlight the effects of dynamic fragmentation on fast moving rock masses such as sturzstroms. The simulations shown consist of a rock mass block with a volume of 1 x 10^7 m^3 (Goldau ~3.5 x 10^7 m^3) consisting of ~10000 unbonded rigid particles. The size ratio $r_{max}/r_{min}$ of
the rigid particles numbers 1.86 to prevent a reorganisation of the particles within a closed-packed lattice, which otherwise would dramatically alter the behaviour of the particle assembly (Potyondy and Cundall, 2004). The number of “initiators” $N_{\text{initiator}}$ of the comminution model by Sammis et al. (1987), with a side length $r_0$ and a volume $V_{\text{initiator}}$, which lie within a single rigid particle with a diameter $r_{\text{particle}}$ ($r_{\text{min}} \leq r_{\text{particle}} \leq r_{\text{max}}$) and a volume $V_{\text{particle}}$ (Figure 6.3) is calculated as:

$$
N_{\text{initiator}} = \frac{6 \cdot V_{\text{particle}}}{8 \cdot V_{\text{initiator}}} \Rightarrow \frac{6}{8} \cdot \frac{\left(\frac{4}{3} \cdot \pi \cdot r_{\text{particle}}^3\right)}{r_0^3}.
$$

Note that $N_{\text{initiator}}$ does not need to be an integer number and that only 6 blocks of an initiator split into a further 8 blocks (e.g. Equation (4.1), for $n=1$ and Figure 4.1), hence 75% of each $V_{\text{particle}}$ will experience further fragmentation according to the comminution model. The comminution model is now applied to every rigid particle of the DEM by multiplying Equations (4.7) and (4.9) with $N_{\text{initiator}}$.

This particle assembly in the examples is defined to move on a completely flat floor with an initial velocity of 70 m/s (according to maximum velocities proposed for Goldau; Berner, 2004). Two DEM simulations, case I, Test # 21d (Figure 6.5) and case II Test # 31d (Figure 6.6), will be compared. Their primary input parameters are presented in Tables 6.1–6.3. The only variation between case I and II will be the friction coefficient $\mu$ mobilized in the interface particle assembly/ground, which is considerably higher in case II.

Table 6.1: Quasi-static mechanical intact rock parameters of the “Bunte Rigi-Nagelfluh” conglomerate.

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniaxial compressive strength</td>
<td>$\sigma_c$</td>
<td>MPa</td>
<td>84 (± 19)</td>
<td>Berner, 2004; Imre et al., 2009b; specimen diameter 0.05 m</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>$M$</td>
<td>GPa</td>
<td>18 (± 4)</td>
<td>Imre et al., 2009b; specimen diameter 0.05 m</td>
</tr>
<tr>
<td>Coefficient of restitution</td>
<td>COR</td>
<td>--</td>
<td>0.89 (± 0.01)</td>
<td>Imre et al., 2008</td>
</tr>
<tr>
<td>Fracture surface energy</td>
<td>$G_F$</td>
<td>J/m²</td>
<td>400</td>
<td>estimation after van Vliet (2000) for characteristic specimen size of 1 m</td>
</tr>
<tr>
<td>Initiator size</td>
<td>$r_0$</td>
<td>m</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>
Table 6.2: Quasi-static, particle size dependent, mechanical intact rock parameters.

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fracture surface energy</td>
<td>$G_F$</td>
<td>J/m²</td>
<td>400</td>
<td>estimation after van Vliet (2000) for characteristic specimen size of 1 m</td>
</tr>
<tr>
<td>Offset $G_F$</td>
<td>$k_{GF}$</td>
<td>J/m²</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>Slope $G_F$</td>
<td>$\alpha_{GF}$</td>
<td></td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Uniaxial compressive strength</td>
<td>$\sigma_{c,f}$</td>
<td>MPa</td>
<td>84</td>
<td>Bermer, 2004; Imre et al., 2009b; specimen diameter 0.05 m</td>
</tr>
<tr>
<td>Offset $\sigma_{c,f}$</td>
<td>$k_{\sigma_{c,f}}$</td>
<td>MPa</td>
<td>25.3</td>
<td></td>
</tr>
<tr>
<td>Slope $\sigma_{c,f}$</td>
<td>$\alpha_{\sigma_{c,f}}$</td>
<td></td>
<td>0.4</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.3: Further input parameters for the DEM.

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of restitution of particle/ground contacts</td>
<td>COR$_{\text{floor}}$</td>
<td>---</td>
<td>0.3</td>
<td>Maximum, numerically stable, energy dissipation at particle/ground contacts</td>
</tr>
<tr>
<td>Friction coefficient of particle/particle contacts</td>
<td>$\mu_{\text{particle}}$</td>
<td>---</td>
<td>0.5</td>
<td>Together with an experimentally derived dilation angle of 6°, $\mu_{\text{particle}}$ yields an angle of repose of the total assembly of 32° (Appendix 8.2)</td>
</tr>
<tr>
<td>Friction coefficient of particle/ground contacts case I</td>
<td>$\mu_{\text{ground,I}}$</td>
<td>---</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Friction coefficient of particle/ground contacts case II</td>
<td>$\mu_{\text{ground,II}}$</td>
<td>---</td>
<td>9.5</td>
<td>Entrainment friction</td>
</tr>
</tbody>
</table>

6.4.1 Run Out Behaviour (modified after Imre et al., 2009a)

The run-out behaviour of case I is depicted in Figure 6.5. All particles move as a flexible sheet due to the relatively low frictional resistance at the base, showing very low relative displacements between the particles (e.g. Davies et al., 1999). This results in a low stress level within the particle assembly, causing an insufficient number of particles to reach their yield strength and to fragment. The lack of dispersive stress within the particle assembly causes it to move and to stop, as would be predicted by a simple frictional block model. Only inertial effects cause the front of the particle assembly to spread (Figure 6.5C).

Figure 6.6 shows the run-out behaviour for case II, whereby the high friction mobilized along the ground causes particles in contact with the floor to decelerate rapidly compared to the rest of the particle assembly (Figure 6.6A). The result is that the zone of highest shear displacement migrates from the ground into the particle...
assembly itself (Figure 6.6B, C). In this shear zone, the relative velocities between the particles are so high that stresses occur that are sufficient to yield fragmentation. As soon as this is the case, the dispersive stresses cause a dilation of the particle assembly with a simultaneous reduction of the shear resistance that can be mobilized in the shear zone. Because of the activities occurring within this zone, it is denoted as process zone. The particle assembly above the shear zone may now override the material below the shear zone (Figure 6.6B, C). High dilation and low shear resistance simultaneously cause fragmentation and the development of dispersive stresses to cease, which lays the ground for a new cycle of fragmentation. The development of a migrating shear zone is therefore a self-regulated process. The resulting spreading of the rock mass in case II (61%) is much more prolonged than in case I (42%). The resulting total run out of case II exceeds the case I by about 18%.

The displacement profiles (Figure 6.7) indicates also that the material in case I (Test 21d moves approximately as a single sliding block. The distal end only experiences slight spreading. In contrast, case II (Test 31d) displays prolonged spreading of the rock mass. The proximal end experiences almost no displacement whereas the distal end displays a pulsed, stop and go, spreading.

The analysis of the velocity profiles of case I and II given in Figure 6.8 is also very instructive. It is also possible to recognize from the velocity profiles that the material in Test 21d moves approximately as a single sliding block. Only the distal end displays a “bumpy” velocity profile due to inertial effects acting on the tip of the decelerating rock mass. On the contrary, in Test 31d, the proximal end experiences fast deceleration whereas the distal end displays a pulsed velocity profile. The behaviour of the distal end should not be confused with stick-slip behaviour. In the present case, after the tip has stopped, it will be overridden by the hanging wall rock masses above to form the new tip of the rock mass.

Case II highlights the fact that during run out the mass of the material in motion reduces with time. While Davies et al. (1999) rightly argue, that the right choice of a mass reduction rate may critical for a proper mathematical run out prediction, this is no concern at all within the current DEM. The reason is that within the current model such a rate does not need to be preset because, the migrating process zone and as a consequence, the reducing amount of material in motion develops naturally.
Figure 6.5: Simulation of a rock mass block with a volume of $1 \times 10^7$ m$^3$ consisting of ~10000 rigid particles moving with an initial velocity of 70 m/s in the $x$-direction (Test 21d). The initial dimensions are $x=629.46$ m, $y=209.82$ m, $z=75.72$ m. Only the right half ($y/2$) from the total assembly is shown. The colour coding of the particles indicates their deviator stress $q'$ state. The friction coefficient mobilized by the ground $\mu_{\text{ground},1}$ is set to 0.5 (Table 6.3). Gravity is acting in the minus $z$-direction. 

A) Initial particle assembly. B) Particle assembly at the halftime of the total simulation duration. C) Final particle assembly with all velocities < 0.1 m/s.
Figure 6.6: Simulation of a rock mass block with a volume of $1 \times 10^7 \, \text{m}^3$ consisting of ~10000 rigid particles moving with an initial velocity of 70 m/s in the $x$-direction (Test 31d). The initial dimensions are $x=629.46 \, \text{m}$, $y=209.82 \, \text{m}$, $z=75.72 \, \text{m}$. Only the right half ($y/2$) from the total assembly is shown. The colour coding of the particles indicates their deviator stress $q'$ state. The friction coefficient mobilized by the ground $\mu_{\text{ground}, I}$ is set to 9.5 (Table 6.3) representing “rugged” ground. Gravity is acting in the minus $z$-direction.

A) Particle assembly 0.42 sec. after simulation starts. The particles coloured in blue indicate a practically stress free, dispersed zone of the assembly where all particles move at the same velocity within a granular “cloud”. The reason for this can be found at the base, where particles in contact with the ground have been decelerated dramatically forming a “process zone” displaying high shear strain, stress and fragmentation (enlarged detail).

B) Particle assembly at the halftime of the total simulation duration. The dispersed assembly collapses, forming new “process zones” in which particle fragmentation will cause dilatancy of the assembly again (enlarged detail).

C) Final particle assembly with all velocities $< 0.1 \, \text{m/s}$. It can be seen that the “process zone” migrated from the ground all the way to the very top “layer” of the particle assembly which is still at that time of the experiment, in
a highly dispersed state, indicated by the blue colouring of the particles.

Figure 6.7: Displacement development of Test 21d ($\mu_{\text{ground},1}$ is set to 0.5 (Table 6.3)) in comparison with the displacement development of Test 31d ($\mu_{\text{ground},1}$ is set to 9.5 (Table 6.3)). Of each test the displacements in the $x$-direction of the centre of mass point, the distal and the proximal end of the rock mass are given.

Figure 6.8: Velocity development of test 21d ($\mu_{\text{ground},1}$ is set to 0.5 (Table 6.3)) in comparison with the velocity development of test 31d ($\mu_{\text{ground},1}$ is set to 9.5 (Table 6.3)). The velocities in the $x$-direction of the centre of mass point, the distal and the proximal end of the rock mass are given for each test.

6.4.2 Fragmentation Behaviour

As noted before, the key in understanding the differences between case I and case II lies in the amount of particles experiencing fragmentation during run out. In case I 55.8% of the particles have been loaded beyond their yield strength $\sigma_{c,f}$ (Equation (5.14)) at least once. The distribution of the number of particles $N_{\text{particle}}$ that have been fragmented during one or more cycles $n$ is shown in Figure 6.9 for case I. In this simulation, a maximum of 9 cycles $n$ has been reached, representing a minimum virtual particle size $r_{n=9}$ of 1.95x10^{-3} m (Figure 6.10; Equation (4.3)), based on an initiator size $r_0$ of 1.0 m (Table 6.1, refer again to Figure 6.3).
Figure 6.9: Distribution of the number of particles $N_{\text{particle}}$, which are plotted over the number of fragmentation cycles $n$, experienced for case I (Test 21d). 4418 particles experienced no fragmentation whereas the other 55.8% experienced up to 9 cycles $n$ (total number of particles: 9999).

Figure 6.10: Distribution of the number of particles $N_{\text{particle}}$, which are plotted over the minimum size or side width $r_n$ of their virtual internal blocks, reached for case I (Test 21d). 4418 particles experienced no fragmentation whereas the virtual internal blocks of five particles reached a minimum side width $r_{n=9}$ of $1.95 \times 10^{-3}$ m.

In case II, 100% of the particles have been loaded beyond their strength. The distribution of the number of particles $N_{\text{particle}}$ that have been fragmented during one or more cycles $n$ is shown in Figure 6.11. In this simulation, all particles have been fragmented at least two times and a maximum of 14 cycles $n$ has been reached, representing a minimum virtual particle size $r_{n=14}$ of $6.10 \times 10^{-5}$ m (Figure 6.12; Equation (4.3)), based on an initiator size $r_0$ of 1.0 m (Table 6.1). This result shows that fragmentation has been much more intense in case II compared to case I.
Figure 6.11: Distribution of the number of particles $N_{\text{particle}}$ which are plotted over the number of fragmentation cycles $n$ experienced for case II (Test 31d). 100% of the particles in the assembly experienced fragmentation, 2 up to 14 cycles $n$ (total number of particles: 9999).

Figure 6.12: Distribution of the number of particles $N_{\text{particle}}$ which are plotted over the minimum side width $r_m$ of their virtual internal blocks, reached for case II (Test 31d). All particles experienced fragmentation, whereas the virtual internal blocks of four particles reached a minimum side width $r_m=14$ of $6.1 \times 10^{-5}$ m.

So far, only the number of particles experiencing fragmentation within the DEM assembly has been analyzed. The comminution model applied to the DEM also allows for a view on the distribution of the numbers of virtual initiators $N_{\text{initiator}}$ within the particles (e.g. Equation (6.15); Figure 6.13), which will be done for the more interesting case II, and also to highlight the functionality of Equation (6.15). The entire particle assembly comprises 9999 particles, which contains $3.09 \times 10^6$ initiators of a side width $r_0$ of 1.0 m. Of these number of initiators $N_{\text{initiator}}$ 25%, experienced no fragmentation according to the comminution model (Figure 4.1). The other 75% experienced again, in analogy to their “mother” particles, between two to 14 cycles $n$ of fragmentation.
Figure 6.13: Distribution of the number of initiators $N_{\text{initiator}}$, which are plotted over their minimum side width $r_m$, reached for case II (Test 31d). 25% of the initiators experienced no fragmentation, whereas the rest experienced up to 14 fragmentation cycles $n=14$, which corresponds to a minimum side width $r_m=14$ of $6.10\times10^{-5}$ m.
6.4.3 Mixing Behaviour

The migration of the shear zone into the rock mass is reflected also by the mixing behaviour of the particle assembly. For Test 31d presented above, the mixing has been monitored by tracking particles that have been initially “coloured” according to a horizontal layering (Figure 6.14A) or vertical layering (Figure 6.15A).

For the horizontal layering, the final situation is depicted in Figure 6.14B. It reveals that spreading has occurred, with only minor mixing of the layers. The stratigraphic contact between the layers remains planar, but inclined, reflecting the shear or process zone which migrated from the bottom to the top during the run out of the rock mass.

For the vertical layering, an intermediate situation is depicted in Figure 6.15B and a final situation in 6.15C. The formerly vertical stratigraphic boundary between the layers becomes almost horizontal when the shear zone, which migrates from the bottom to the top, passes that boundary. The stratigraphic order of the layering remains intact although it may be interpreted in a field situation as inverse.
Figure 6.14: Mixing behaviour of Test 31d. A) Initial situation with equally thick horizontal layering indicated by a coloured bottom, middle, and top layer. The colour coding of the particles is now not indicating a stress state but the initial position within the particle assembly. B) Final situation of the experiment.
Figure 6.15: Mixing behaviour of Test 31d. 
A) Initial situation with equally thick vertical layering indicated by a coloured distal, middle, and proximal layer. The colour coding of the particles is now not indicating a stress state but the initial position within the particle assembly. 
B) Intermediate situation of the experiment. 
C) Final situation of the experiment.
6.4.4 Energy Budget Monitoring

It is proposed that the energy budget of a sturzstrom can be sufficiently well described in terms of the balancing equation:

\[ E_{pot} = E_{kin} + E_{elas} + E_{hys} + E_{frag} + E_{disp} + E_{fric}, \]  

(6.16)

where \( E_{pot} \) denotes the potential energy, \( E_{kin} \) the kinetic energy of the particle assembly, \( E_{elas} \) the elastic strain energy stored within the particle assembly, \( E_{hys} \) the hysteretic damping during elastic relaxation of the particle assembly, \( E_{frag} \) the energy dissipated by the formation of new fracture surfaces during fragmentation, \( E_{disp} \) the dispersive energy recovered due to rock bursts, and finally \( E_{fric} \), which denotes energy dissipated by friction.

In the current DEM simulation environment, \( E_{pot} \) is not monitored because it is largely constant and small compared to \( E_{kin} \), which comprises the initial energy input available for spreading and run out of the simulated sturzstrom. In other words, only the run out situation on a flat valley floor is simulated. Therefore the potential energy has been converted into kinetic energy already. The balancing equation is therefore written as:

\[ E_{kin} = E_{elas} + E_{hys} + E_{frag} + E_{disp} + E_{fric}. \]  

(6.17)

All energies mentioned in Equation (6.17) have been recorded either based on formulations intrinsic to the DEM code, or those which have been implemented in this research.

6.4.4.1 Kinetic Energy

The kinetic energy \( E_{kin} \) at time of the particle assembly of \( N_{particles} \) is calculated for a time step \( (t) \) as (Itasca, 2005b):

\[ E_{kin}(t) = \frac{1}{2} \left( \sum_{N_{particles}} \cdot m_{particle} \cdot v_{i, particle}^2 \right)(t) [Nm], \]  

(6.18)

where \( m \) denotes the mass of an individual particle and \( v \) a velocity scalar of an individual particle, including both 3D translational and rotational velocity components.

6.4.4.2 Elastic Energy

The total elastic energy \( E_{elas} \) stored within the particle assembly is calculated for a time step \( (t) \), as the sum of the Equations (6.3), (6.7), (6.8), and (6.11) as:

\[ E_{elas}(t) = \left( \sum_{N_{contacts,wall}} \cdot \left( \frac{1}{2} \sum_{N_{contacts,wall}} \right) \cdot \left( E_{elas}^{n,load} + E_{elas}^{n,unload} + E_{elas}^{x,load} + E_{elas}^{x,unload} \right) \right)(t) [Nm], \]  

(6.19)

where \( N_{contacts,wall} \) denotes the number of boundary wall contacts and \( N_{contacts,ball} \) the number of particle contacts, which a particle experiences. The latter is divided by half because particle/particle contacts are counted twice in the calculation scheme. Note that Equation (6.19) is calculated within the contact constitutive relation, based on the elastic strain stored within the \( contacts \). In contrast, the elastic strain energy \( E_{elas,f} \) stored within an \( initiator \) just before failure, is calculated by Equation (4.6), based on the principal stresses acting on the \( particle \) to which this initiator belongs to. The
reason is that in this numerical code, contact forces and contact strains are updated during each time step by cycling through the list of all contacts within the model. The contact constitutive relation is therefore not directly linked to the list of particles within the models, which means that the strain stored in a particle (with $N_{\text{contacts}}$) can not be directly derived without large programming effort, making the code computationally inefficient. But what can be directly derived from a particle is its principal stress state calculated from Equation (6.14). Because the elastic strain energy $E_{\text{elas},f}$ stored within an initiator is linked to the particle to which this initiator belongs, Equation (4.6) is calculated based on principal stress state of the particle (Equation (6.14)) and not from the strain energy stored in the contacts as calculated by Equation (6.19).

6.4.4.3 Fragmentation Energy

The particle based fragmentation energy $E_{\text{frag}}$, dissipated within the entire particle assembly by the creation of new fracture surfaces within the initiators, is calculated for a time step $(t)$ and based on Equation (4.7) as:

$$E_{\text{frag}}(t) = \left( \sum_{N_{\text{particle},f}} \sum_{N_{\text{initiators},f}} E_{\text{frag},n}(t) \right) \text{[Nm]},$$

where $N_{\text{initiators},f}$ (Equation (6.15)) and $N_{\text{particle},f}$ denotes the number of initiators and particles undergoing failure respectively at time $(t)$. Note: A particle under failure is decelerated in the 3D direction of its deviatoric stress tensor to an amount that:

$$E_{\text{kin,deceleration}}(t) = E_{\text{frag},n}(t) \text{[Nm]},$$

6.4.4.4 Dispersive Energy

The particle based dispersive energy $E_{\text{disp}}$ of the entire particle assembly at time $(t)$, which can be recovered during the virtual failure of $N_{\text{particle},f}$ is calculated, based on Equation (4.9), for the entire particle assembly as:

$$E_{\text{disp}}(t) = \left( \sum_{N_{\text{particle},f}} \sum_{N_{\text{initiators},f}} E_{\text{disp},n}(t) \right) \text{[Nm]},$$

where $N_{\text{initiators},f}$ (Equation (6.15)) and $N_{\text{particle},f}$ denotes the number of initiators and particles under failure respectively at time $(t)$.

6.4.4.5 Hysteretic Damping Energy

The total hysteretic damping energy $E_{\text{hys}}$, dissipated within the particle assembly is calculated for a time step $(t)$, according to Equations (6.4) and (6.9) as:

$$E_{\text{hys}}(t) = \left( \sum_{N_{\text{particle}}} \sum_{N_{\text{contacts,wall}}} \left( \frac{1}{2} \sum_{N_{\text{contacts,ball}}} \left( E_{\text{hys}}^{n} + E_{\text{hys}}^{b} \right) \right) (t) \text{[Nm]},$$

where $N_{\text{contacts,wall}}$ denotes the number of boundary wall contacts and $N_{\text{contacts,ball}}$ the number of particle contacts, which a particle experiences. The latter is divided by half because particle/particle contacts are counted twice in the calculation scheme.
6.4.4.6 Friction Energy

The friction energy $E_{\text{fric}}$ dissipated in the particle assembly of $N_{\text{particles}}$ is calculated for a time step $t$ as (Itasca, 2005b):

$$
E_{\text{fric}}(t) = \left( \sum_{i=1}^{N_{\text{contacts}}} F_{i}^s \cdot \Delta u^s \right)(t) \text{ [Nm]}, \tag{6.24}
$$

where $N_{\text{contacts}}$ denotes the number of contacts in the particle assembly, $F^s$ the shear force tensor and $\Delta u^s$ the incremental shear displacement.

6.4.5 Comparison of the Energy Budget of the DEM Simulations Performed

Also a comparison between the energy budget of case I and case II reveals significant differences.

In case I (Figure 6.16), practically all kinetic energy ($E_{\text{kin}}$) is dissipated by friction ($E_{\text{fric}}$). The particles in the assembly remain in close, almost in static contact which is represented by the presence of elastic energy stored ($E_{\text{elas}}$), and the absence of energy dissipated by hysteretic damping ($E_{\text{hys}}$), which occurs only during dynamic unloading of particles in contact. Almost no energy is dissipated in fragmentation ($E_{\text{frag}}$) and simultaneously recovered as dispersive energy ($E_{\text{disp}}$), because an insufficient number of particles experienced fragmentation (e.g. Figure 6.9).

In case II (Figure 6.17), most of the kinetic energy ($E_{\text{kin}}$) is dissipated by friction ($E_{\text{fric}}$) in two phases lasting from about 0 to 1 second and 4 to 8 seconds of simulation time. A large number of particles at the base or in a shear zone within the rock mass experience intensive fragmentation, mainly during these two phases. This causes significant dispersive energies ($E_{\text{disp}}$) to evolve, causing a dilatational unloading of the particles in the assembly (e.g. number of particles fragmenting in Figure 6.17 with the stress state of the particles in Figure 6.6AB), which then causes the energy dissipation by friction to decline rapidly. The dynamic of this regime is also reflected by the occurrence of significant amounts of energy dissipated by hysteretic damping ($E_{\text{hys}}$).

Integrating the changes in energy over time in Figure 6.17 for case II yields that:

- about $2.0 \times 10^{13}$ Nm of kinetic energy ($E_{\text{kin}}$) were available during this experiment,
- about $2.1 \times 10^{13}$ Nm of frictional energy ($E_{\text{fric}}$) were dissipated during the experiment. This number does not seem to be reasonable, however, the step-wise monitoring of the energies, as applied here, may cause errors of up to 10%. A refinement of the monitoring would be possible but at the price of loss of computational performance,
- about $7.6 \times 10^9$ Nm of fragmentation energy ($E_{\text{frag}}$) were dissipated for the formation of new fracture surfaces. This amounts to only about 0.04% of the kinetic energy available. Although important in the microscopic view on a single, fragmenting particle, viewing the fracture surface energy $G_F$ as being particle size dependent makes $E_{\text{frag}}$ a negligible path of energy dissipation within a sturzstrom at macroscopic scale.
- on the other hand about $2.0 \times 10^{11}$ Nm of dispersive energy ($E_{\text{disp}}$) were recovered amounting only to about 1% of the kinetic energy available, but
apparently sufficient to alter the run out and spreading behaviour of the rock mass.

- about 1% of the kinetic energy available were stored as elastic energy ($E_{elas}$) within particles that had not fragmented. This energy was therefore not converted into dispersive energy ($E_{disp}$),

- about 10% of the elastic energy ($E_{elas}$) was later dissipated by hysteretic damping ($E_{hys}$) during unloading. This is a reasonable, but not a very precise value. Again, although important in the microscopic view on a single, fragmenting particle, $E_{hys}$ constitutes a negligible path of energy dissipation within a sturzstrom at macroscopic scale.

Figure 6.16: Energy budget of case I (Test 21d). The changes in frictional work, fragmentation work, hysteretic damping work, elastic strain energy stored, and the dispersive energy recovered are plotted in a stacked area plot displaying their trends and the contribution of each value over time. The changes of the kinetic energy within the system and the number of particles under failure are plotted as trend lines over time.
Figure 6.17: Energy budget of case II (Test 31d). The changes in frictional work, fragmentation work, hysteretic damping work, elastic strain energy stored, and the dispersive energy recovered are plotted in a stacked area plot displaying their trends and the contribution of each value over time. The changes of the kinetic energy within the system and the number of particles under failure are plotted as trend lines over time. A) Plot of all data. B) Enlargement of the area indicated A.
6.4.6 The Concept of Inertial Entrainment Friction (Imre et al., 2009a)

The assumption of a very high friction coefficient at the base, as in case II, is reasonable, describing an “apparent” friction postulated as a concept of “inertial entrainment friction”. This concept is developed, based on own observations and literature that sturzstroms “and their deposits reflect strong interactions with rugged terrain and deformable, wet substrates” (Hewitt, 2006). Terrain may not only be considered as “rugged” due to the presence of obstacles, where a high “apparent” friction seems obvious, it could also apply to completely flat terrain in soft soil, in which material will be entrained by ploughing (Figure 6.18). In consequence, it may be assumed that every rock block in contact with the basal soil will accelerate a volume of soil of the same or even higher mass than the mass of the block itself. The result is that at the base of a sturzstrom, not only the drained or undrained internal frictional resistance of the soil has to be overcome, but also that the momentum of the rock particle is transferred into the ground, an effect which is pointed out also by Davies et al. (1999). This causes the basal layers of rocks to be decelerated dramatically compared to the rock mass above. The result is that the zone of the highest shear displacement will migrate upwards into the rock mass (Figures 6.6, 6.14), in which the momentum transfer between the rock blocks may cause their fragmentation.

This would mean that “soft” ground will mobilize a higher resistance than “hard” rock, above a critical relative displacement rate between the sturzstrom and the ground, due to momentum transfer. Such behaviour reverses when the sturzstrom eventually slows down. Without significant momentum transfer, soft ground will mobilize much lower shear strength than a hard rock surface. The concept of inertial entrainment friction therefore suggests an explanation for the presence of fragmentation during run out of a sturzstrom on soft ground but also of the occurrence of secondary features like, for example, transversal ridges or Toma hills (among others e.g. Abele, 1974; Poschinger et al., 2006; Prager et al., 2006). Such features seem to be related to situations where sturzstroms have been emplaced on very soft, saturated soils. The sturzstrom may already have come to rest (no or small displacement relative to the direct ground) whereas slabs of failed soft soil, accelerated due to the momentum transfer described above, may still move, deforming the sturzstrom deposit above. If the heavily fragmented rock mass of a sturzstrom reaches an open water surface, a suspension flow may evolve adding to an even more prolonged total run out. The late deposition phases of the Almtal sturzstrom in Austria (Reitner et al., 1993) or again the 1806 Goldau sturzstrom, when the rock mass reached Lake Lauerz (Heim, 1932; Zay, 1807), may serve as examples. But these suspension flows can not be considered as sturzstroms anymore in the strict sense.

The other extreme are rock blocks sliding on “hard” intact rock. In this case, momentum transfer into the base may be minor because, even at high velocities, substantial ploughing may not occur, preventing migration of the shear zone into the rock mass. This would cause all shearing to take place within this contact zone creating enormous frictional heat, occasionally leading to partial melting of the surrounding rock (“fused rock”; Erismann et al., 1977). In any case, the rock mass would move in this situation as a block or flexible sheet, displaying small amounts of fragmentation only.
A further inference, which may be drawn from the concept of inertial entrainment friction, is that, if for any reason, the shear resistance between the sturzstrom rock mass and the underground is significantly reduced (for example interstitial volatiles like air, water, fused rock, etc), the rock mass will move as a block or flexible sheet with all displacement taking place in that distinct shear zone. In this case, only minor fragmentation will occur, because the relative velocities between the particles within the rock mass are too small to generate sufficient impact forces. Because intense fragmentation is characteristic of sturzstroms, any process which may be proposed as a reason for a significant reduction of the basal shear resistance (below the angle of repose of the sturzstrom rock mass) may be ruled out from playing a major role in the displacement of sturzstroms. This inference may also allow a new view on the extremely large sturzstroms on the surface of the planet Mars. Their formation, and whether these sturzstroms were emplaced wet or dry, is still in discussion (e.g. Section 1.3). This question has profound implications regarding the presence, extent and timing of ground ice reservoirs and liquid water on Mars.

![Image of sturzstrom impact](image)

**Figure 6.18:** An example of how rugged terrain may be envisioned in context with flat, soft ground. The image shows a rock block from a sturzstrom, which ploughed through fine-grained fluvial and lacustrine sediments near the distal rim of the Yarrbah Tshoh event, Shigar valley Baltistan (Hewitt, 2006). The sturzstrom moved diagonally from the left to the right. Hewitt notes the “bow-wave” of crumpled alluvium in front of the largest boulder. This means that not only the internal frictional resistance of the alluvium had to be overcome (arrows) but also the momentum of the boulder with mass $m_1$ had to be transferred into the wedge of soil with mass $m_2$.

### 6.5 Discussion

In the introduction of the dispersive stress model (Section 4.3), it has been assumed that the maximum effective principal stresses $\sigma^\prime_1$ will act predominantly in the $x$-direction of a sturzstrom. The correctness of this assumption could be shown by recording the orientation of the principal stress states of particles experiencing fragmentation. The stereographic projection depicted in Figure 6.4 reveals that the maximum effective principal stresses $\sigma^\prime_1$ are truly predominantly oriented in the $x$-direction of a sturzstrom, if a process zone can develop, as in case II of the numerical experiments. This fact can be recognized by the stress distribution of the particles depicted in Figure 6.6A and B. For case I, in which no process zone developed, the
orientation of the maximum effective principal stresses $\sigma_1^\prime$ is much steeper, much closer in direction to the $z$-axis of the model sturzstrom, than in case II. As a consequence, the direction of $\sigma_1^\prime$ in case I is largely controlled by the overburden pressure of the rock mass as is generally the case in gravity driven mass flows. In case II, the direction of $\sigma_1^\prime$ is predominantly caused by particle impacts due to the velocity contrast between the hanging wall and foot wall material of the process zone. The direction of that zone, and therefore of $\sigma_1^\prime$, is a function of the orientation of the vectors of particle velocities within that zone.

At this point it is necessary to review the centrifuge experiments again. In Section 3.4.1, it was reported that the rock masses within that experiment moved as a flexible sheet (Figure 3.36) and displayed a mode of fragmentation, which is comparable to deposits of natural sturzstroms (Figure 3.37). From the DEM simulation, it is inferred that both at once may not be possible. At the time, when the centrifuge experiment was designed, it seemed essential to provide a modelling environment in which ploughing and therefore momentum transfer between the rock mass and the side walls of the experimental chute is prevented. The centrifuge experiment replicates therefore the “hard” ground case as discussed above. The observed fragmentation is interpreted to be the result of the dynamic acceleration field evolving from the boundary conditions as discussed in Sections 2.2.1 and 2.3, acting as a “soft” obstacle. Based on the evidence derived from the DEM, it seems promising to introduce truly “rugged” boundary conditions in the centrifuge in upcoming studies. This may allow momentum transfer, fragmentation and migration of the process zone to be simulated physically at laboratory scale. But also in the DEM numerical simulation environment, the concept of inertial entrainment friction has to be explored in more detail in future.

In all DEM simulations performed, no signs of highly agitated particles at the base of the simulated rock mass could be observed contradicting the granular flow model (Bagnold, 1954; Campbell, 1989; Campbell et al., 1995; Hsü, 1975; Straub, 1997). In case II of the DEM simulations, where dynamic fragmentation was active, a long wave kind of “breathing” of the rock mass during run out has been observed (Figure 6.17) indicating phases where a high or low frictional regime was prevailing within the self-regulating process zone. But, because velocity contrasts, and therefore shear displacement accompanied by particle fragmentation was localized within sub-horizontal, distinct process zones that were migrating upwards, this “breathing” is also not interpreted to represent pressure waves packets, as proposed by Melosh (1986). All simulations performed within the DEM, not accompanied by fragmentation, more or less moved as block slides with minor inertial effects (Figure 6.5). The strong relationship to dynamic fractal fragmentation of the sturzstroms simulated, the direction of their maximum principal stresses that are not predominantly oriented in direction of the overburden pressure, defines them as a landslide category of its own. The mechanics of such sturzstroms differs significantly from all other gravity driven mass flows.
7 Summary, Conclusion, Recommendations

„Es gibt keinen fertigen Prozess. Jeder Schaffensprozess wird eines Tages abgebrochen.“
(Alfred Hrdlicka - Austrian sculptor, draughtsman, painter and artist, 1928–2009)

7.1 Summary

7.1.1 Addressing the Aim of this Study in Terms of Epistemological Circles

Based on epistemological considerations, two questions had been formulated (Section 2.1) on which theories and models on the emplacement of sturzstroms were rated in the subsequent literature review:

a) Has the model postulated been confirmed based on empirical evidence? Hence, has any experimental confirmation been achieved? Does it contradict commonly observable phenomena (type features) of sturzstroms?

b) If it has been attempted to achieve confirmation, does the model postulated contribute to a deeper understanding of the mechanism involved? Therefore has it the potential to become a type A prediction tool?

The literature review (Section 2.3) revealed that on the one hand, many of the proposed mechanisms published aimed to explain the unusual run out of sturzstroms, although they often lacked any experimental confirmation or can not combine all type features of sturzstroms (Section 2.2) within a single theory. On the other hand, many successful attempts have been made to simulate sturzstrom run out by continuum mechanics models. They therefore represent today’s state of the art of sturzstrom run out prediction. But most of these models do not contribute to a deeper understanding of the mechanism behind the high mobility of sturzstroms. They remain therefore purely Type C1 predictions, with all the risk associated when such models are applied to make “real” predictions of the run out of a potential future sturzstrom site.

Rather than continuing with the method of back-calculating case studies to increase the prediction power of models based on continuum mechanics, it has been decided to proceed within this thesis with the aim of finding and confirming physical mechanisms governing the run out of sturzstroms. As the most promising hypothesis on the high mobility of sturzstroms, the dynamic fragmentation-spreading model (Davies et al., 2003; Davies and McSaveney, 1999; Davies and McSaveney, 2002; Davies and McSaveney, 2004; Davies and McSaveney, 2006; Davies et al., 2006; Davies et al., 2007; Davies et al., 1999; Dufresne and Davies, 2009; McSaveney and Davies, 2007; McSaveney and Davies, 2002; McSaveney and Davies, 2009; Smith et
al., 2006) has been identified (Section 2.4.1) due to its potential power of combining all type feature of sturzstroms (prolonged run out in relation with volume, intensive fragmentation, and preservation of stratigraphy; Section 2.2) within a single theory.

The aim of this thesis research developed in Section 2.4.1 was therefore to study the concept of dynamic fragmentation within sturzstroms in more detail, by increasing the understanding of the role of rock fragmentation within the energy budget of such massive landslides. The methods adopted to address the study aim within this thesis (Section 2.5) can be depicted as epistemic circles (Figure 2.4) where every method applied, feeds newly gained information into the next circle. These epistemic circles not only serve as a “logical thread” throughout the study, they also depict the construction of deeper knowledge on the mechanics of sturzstroms achieved, circle by circle.

7.1.1.1 Epistemological Circuit I – Physical Modelling of Fragmentation
The most noticeable results of the physical modelling of fragmentation within the ETH Geological Drum Centrifuge are the fabric (Section 3.4.2) and the fractal particle size distribution (Section 3.4.3) of the fragmented material achieved. For both, it was possible to achieve confirmation based on observations on natural sturzstrom deposits. The boundary conditions of the centrifuge model (close to real kinetic energy levels, with a free boundary in the \( z \)-direction and unconfined, obstacle-free run out in the \( x \)-direction), resemble therefore a useful research environment, enabling observation of particle fragmentation, as it most probably occurs during the run out of natural sturzstroms.

7.1.1.2 Epistemological Circuit II – Analytical Modelling of Fragmentation
The centrifuge experiment allows the fragmentation of a small volume of rock to be simulated within a kinetic energy regime similar to true sturzstroms. It can not simulate entire sturzstrom events, because of its rapidly changing acceleration field. That makes the experiment neither to scale nor capable of simulating excessive run out. Hence it is desirable to simulate sturzstroms at true scale numerically to gain understanding of the role and effect of rock fragmentation within such massive landslides.

It was shown in Chapter 4 that the fractal comminution model (Sammis et al., 1987; Steacy and Sammis, 1991) allows for a successful description and prediction of the fabric and fractal particle size distribution of true sturzstrom deposits and their representation in the centrifuge experiment. Extending this analytical model leads to the prediction of the micro-scale energy budget of a single particle, that is experiencing multiple cycles of fragmentation. This fractal comminution model therefore enables the results of physical experiments to be linked with numerical modelling, by providing a reasonable mathematical description of fragmentation. At the same time, this comminution model is simple enough to represent key features of fragmentation and make progress in sturzstrom research, while not getting lost in mechanical or mathematical details.

7.1.1.3 Epistemological Circuit III – Numerical Modelling of Fragmentation
To this point, the analysis of sturzstroms was micromechanical in scale and based on finite (distinct) particles, which may experience cyclic fragmentation. For the attempt at simulating sturzstroms numerically at true scale, it is therefore reasonable not to
leave that path and to allow for a micro scale, particle based, and cyclic description of
the mechanics of sturzstrooms in this numerical modelling environment also. By
choosing the Particle Flow Code PFC3D (Itasca, 2005a) as the numerical modelling
environment and incorporating the fractal comminution model (Sammis et al., 1987;
Steacy and Sammis, 1991), this task could be fulfilled (Chapter 6). The effects of
dynamic fragmentation within sturzstrooms can now be simulated at true (macro)
scale by allowing for a micro-mechanical, distinct particle based, and cyclic
description of fragmentation at the same time, without losing significant
computational efficiency.

It could be shown that dynamic fragmentation significantly influences the macro
scale energy budget, run out and spreading of a sturzstrom. It could be shown also
that the evolving mode of displacement, linked to a migrating upward shear or
process zone (Section 6.4.1), leads to a preservation of the initial stratigraphy of the
source rock of a sturzstrom in its final deposit, without significant mixing (Section
6.4.3). A further striking result is the observation at macro scale that these effects
may evolve under an almost negligible loss of potential energy, invested in the
formation of new fracture surfaces during fragmentation or in the hysteretic damping
which elastically deformed particles experience during relaxation (Section 6.4.5). A
final interesting observation is that the occurrence of dynamic fragmentation, the
evolving of process zones, and therefore prolonged spreading of a sturzstrom, are
causatively linked to the presence of a substrate on which the basal portions of a
sturzstrom are strongly decelerated. This may be due to the presence of rugged,
undulating and blocky terrain or of wet, soft soil. Both types of substrates are
interpreted as causing a rapid deceleration of the basal portion of a sturzstrom due to
intense momentum transfer of the rock mass into the ground (Section 6.4.6).

7.1.2 Addressing the Motivation of this Study
Although a state could be reached in which it became possible to simulate
sturzstrooms at true scale, the tasks defined in the motivation for this thesis research
(Section 1.3) could not be fulfilled:

a) It was not possible to develop a functioning Type A prediction model of the run
out of sturzstrooms as a tool in natural hazard mitigation. Therefore it was not
possible to contribute to the characterisation of the hazard, originating from a
potential sturzstrom (Figure 2.3).

b) Also the application of such a model on Martian sturzstrooms in terms of a
retroductive reasoning on inferences of geomorphology (Section 1.3) could not
be achieved. Both have their reason in the inability to prepare the distinct
element numerical modelling environment for simulations of sturzstrooms
displaying volumes exceeding 1.0x10^7 m^3. As a consequence, studies on the
volume / run out relationship, a final type feature of sturzstrooms, could not be
performed.

7.2 Conclusion
The proposition is made that the dynamic-fragmentation and its implementation in a
distinct element numerical model presented here, constitute a comprehensive model
combining prolonged run out, fragmentation, and preservation of stratigraphy as type
features of sturzstroms. A consequent focus has been laid on a micro-mechanical, distinct particle based, and cyclic analysis and simulation of the micromechanics of a sturzstrom. The result is twofold:

a) The mathematical algorithms implemented within the distinct element model (epistemological circle III) to simulate the effects of dynamic fragmentation, can be tracked causatively all the way through their analytical description (epistemological circle II), the results of physical modelling (epistemological circle I) to the empirical evidence gained from the observation of true sturzstroms.

b) It is believed that it was possible to meet the study aim defined in Section 2.4.1, which asks for an increased understanding of the role of rock fragmentation within the mechanics of a sturzstrom.

c) Hence, it is believed that it was possible within this thesis, to contribute to the danger characterisation (Figure 2.3) of a sturzstrom.

The conclusion is drawn that sturzstroms represent a type of landslide whose run out is not only controlled by friction but significantly by the initial size, intact strength and intact elastic properties of the rocks involved. This allows a number of interesting implications to be suggested on which further research may be based:

a) The mathematical descriptions of fractal comminution, and the resulting development of dispersive stresses presented here are suitable to be implemented as constitutive models within distinct element codes. A calculation-efficient numerical simulation of the effects of fragmentation within a particulate flow, under consideration of all effects of three-dimensional momentum transfer, may now be possible.

b) Sturzstroms will develop in situations where the majority of the host rock is constituted of hard, widely jointed blocks (e.g. ISRM, 1978). Otherwise the development of slow, deep seated gravitational slides is more likely (Imre et al., 2009a). The investigation of the structural inventory of the detachment zone of a sturzstrom therefore gains significance (for a study covering this topic e.g. Locat et al., 2006).

c) The sturzstrom model presented here depends on the presence of “rugged” ground to allow for fragmentation of the rock mass and a migration of the shear zone into the sturzstrom.

d) Particle impacts due to the velocity contrast between the hanging wall and foot wall material of the process zone, and not the overburden pressure, are the main cause for peak stresses leading to the fragmentation of rock particles. The spreading of the rock mass is therefore predominantly related to inertial effects and not the overburden pressure, as is generally the case in gravity driven mass flows.

e) The energy dissipated during fragmentation for the formation of new fracture surfaces $E_{\text{frag}}$ and during the damped relaxation of elastically deformed particles $E_{\text{hys}}$, plays a decisive role in the energy budget of a single block at micro scale. Frictional resistance or momentum transfer at and into the ground remains the overwhelming sink of potential energy at micro scale. At this scale, $E_{\text{frag}}$ and $E_{\text{hys}}$ may be considered as being almost negligible.
f) The evidence presented in this thesis suggest that the emplacement of Martian sturzstroms may have in fact taken place in a dry, volatile free environment. But, the presence of minor amounts of water in the form of wet, soft soil may not be excluded in accordance with the entrainment — friction concept presented here.

g) The empirical volume dependency of the run out of sturzstroms may have one physical reason in the amount and initial size of intact rock blocks available for fragmentation and therefore of dispersive stress generation. The volume of intact rock particles involved in such a flow can be envisioned as a “fuel” source consumed by fragmentation.

Together with the fractal comminution model implemented to describe natural and experimental sturzstrom deposits, the applied DEM turned out to be a useful tool for sturzstrom research. It allows type features of sturzstroms to be simulated successfully and consistently, based on standardised rock and rock mass properties. It also reveals the micro-mechanical and energetic aspects of sturzstroms, which suggests this DEM, as modified and developed in this thesis, is a promising tool for further research on sturzstroms.

The implications presented may suggest also, that a sturzstrom, because of its strong relation to internal fractal fragmentation and other inertial effects, constitutes a landslide category of its own, because its mechanics differs significantly from all other gravity driven mass flows. This proposition does not exclude the possible appearance of frictionites, Toma hills or suspension flows etc., but it considers them as secondary features.

As a consequence, it is suggested that the terminology of sturzstroms, as introduced in Section 1.1.1 is reviewed again. To recapitulate, Hsü (1975), following Heim (1932) defined a sturzstrom as: “... a stream of very rapidly moving debris derived from the disintegration of a fallen rock mass of very large size; the speed of a sturzstrom often exceeds 100 km/h, and its volume is commonly greater than 1x10^6 m^3.” In the light of the results of this thesis, the part “... derived from the disintegration of a fallen [or sliding] rock mass...” becomes most notable within this definition. In fact, Heim made a point of distinguishing very large rock falls (greater than 1x10^6 m^3 – denoted by Heim as Bergstürze) and sturzstroms evolving from them, and large rock falls (1x10^4—1x10^5 m^3 – denoted by Heim as Steinlawinen). In the first case, the broken rocks are generated through the fragmentation (disintegration) of the rock mass involved, whereas in the second case, the original rock block sizes largely remain unchanged during run out. According to the results of this study, fragmentation plays a key role in the mobility of sturzstroms. The definition by Hsü (1975), of a sturzstrom evolving from a disintegrating very large rock fall (or slide), appears therefore not only empirically but also theoretically accurate.

These may be the reasons why the term rock avalanche is much more prevailing in the international literature. Bates and Jackson (1984) define an avalanche as: “A large mass of snow, ice, soil, or rock, or mixtures of these materials, falling, sliding, or flowing very rapidly under the force of gravity.” If rocks display the dominating constituent of an avalanche, such a landslide may be denoted as rock avalanche. This term is more vaguely defined and can therefore apply to more cases of landslides. The vague definition is also important to allow its application in the context of the abundant number of theories about the mobility of sturzstroms
(Chapter 2.3), which do not necessarily consider fragmentation or disintegration of the rock mass as a relevant process.

The proposition is therefore made, that rock avalanche and sturzstrom should not be treated as equivalent. This proposition differs from what has been initially done in Section 1.1.1, but the results of this thesis support such a conclusion. In accordance with Bates and Jackson (1984), it is suggested, instead, that a sturzstrom can be put under the genus of rock avalanches, as may be done for a lahar which constitutes a landslide of similar volume, run out and velocity, but with different underlying mechanisms (e.g. among others Iverson et al., 1998). As a consequence, a sturzstrom may be described as a rock avalanche, but a rock avalanche is not necessarily a sturzstrom.

In view of the giant landslides on planet Mars, and according to the discussion above, these should be denoted as rock avalanches as long as their internal mechanism of emplacement has not been revealed. Nevertheless, the results presented here suggest that the dry, volatile free emplacement of true sturzstroms may have been possible on Mars.

7.3 Recommendations

7.3.1 Recommendations for Further Research

The conclusions drawn above suggest that the methods and results presented in this study may serve as a basis for further research as is depicted in Figure 2.4, following the constructionism introduced in Section 2.1.

A numerical study on the variance of the run-out, in relation to the volume of the rock mass, applying the DEM, adjusted in this study, is therefore considered as the most urgent next step. Furthermore, this DEM awaits an application to true sturzstroms on Earth and Mars. The back calculation of such events will reveal how successfully such a numerical code may predict sturzstroms based on the common rock mechanical and geometrical input parameter suggested in this study.

At the same time, the entrainment friction concept deserves further consideration. On the DEM side, it will be necessary to develop a more sophisticated particle/boundary wall contact constitutive relation to account for entrainment of soft soil under drained/undrained conditions. The most elegant solution would be a combination of the DEM with a continuum mechanical formulation (Itasca offers such a possibility by combining their code PFC-3D with their finite difference scheme FLAC-3D). On the side of physical modelling, it may be interesting to simulate dry rock slides moving on moist, undrained soft substrates within a centrifuge model. The experimental set up for the ETH Geotechnical Drum Centrifuge presented above may be adjusted for such a task.

7.3.2 Recommendations for a Danger Characterisation

The motivation of this thesis, as declared in Section 1.3, to contribute to the characterisation of the hazard originating from a potential sturzstrom could not be fulfilled. But at a level above, interesting preliminary recommendations for a danger characterisation (Figure 2.3) of a sturzstrom, may be derived from this thesis.
The pending back calculation of true sturzstrom events shall not be prejudged. But, by concluding the rock mechanical and geometrical input parameters suggested in this study, a guideline of how to investigate the danger of a rock slope, whose potential failure volume may rouse the apprehension of an eventual formation of a sturzstrom, is presented in terms of a check list. After careful geological and geotechnical mapping, the following questions should be answered:

a) What is the expected (estimated) rock slope failure volume? Is the development of a sturzstrom feasible according to Scheidegger (1973) or Tianchi (1983)? What will be the range of expected run outs according to these empirical run out volume relations?

b) Can the failure volume be subdivided in (geotechnical) rock units?

c) How widely jointed are these units on average within the failure volume? Hence, what is their average (estimated) rock block size (Kluftkörpergrösse)?

d) What is the average (estimated) quasi-static uniaxial strength $\sigma_{c,f}$ of these units?

e) What is the average (estimated) quasi-static Young’s Modulus $M$ of these units?

f) What is the average (estimated) fracture surface energy $G_F$ of these units?

g) What is the average (estimated) angle of repose $\varphi$ of these units?

h) What is the geometry of the transit and deposition zone of an eventual sturzstrom (digital elevation model)?

i) Can the potential transit and deposition zone be divided into zones of hard, soft/dry, and soft/undrained ground, with low, medium, and high entrainment friction?

The particle size dependence, hence the slope $k_{\sigma_{c,f}}$ of the quasi-static uniaxial strength $\sigma_{c,f}$, may be revealed by a series of Point Load Tests (ASTM, 2008; Bieniawski, 1975; Singh and Singh, 1993; Thuro, 2008) in the field. Measuring the fracture surface energy $G_F$ (and its particle size dependence) requires highly sophisticated, timely and costly tests which can not, in general, be applied in time for hazard mitigation. A sufficient alternative is to estimate these properties based on literature data (for example Friedman et al., 1972; Hillerborg, 1985a; van Vliet, 2000).
8 Appendix

8.1 Calibration Force Sensor

Figure 8.1: Calibration regression of the force sensor $x$-axis (2nd, fine measuring range) equalling the $y$-axis of the experiment (Figure 3.9D).
Figure 8.2: Calibration regression of the force sensor $y$-axis (2nd, fine measuring range) equalling the $x$-axis of the experiment (Figure 3.9C).

Figure 8.3: Calibration regression of the force sensor $z$-axis (2nd, fine measuring range) equalling the $z$-axis of the experiment (Figure 3.9B).
8.2 Angle of Repose (DEM)

Figure 8.4: Adjusting the friction angle of the particles and the boundary walls in the DEM to reach an angle of repose of 32°, according to the usual angle of repose of real rock masses (e.g. Eisbacher and Clague, 1984), within a numerical, vertical dump-test. Initially the heap of particles is bounded by walls at all sides. After removing two vertical walls, gravity, acting in the minus $z$-direction, will cause the particles to develop a slope at a stable angle. The height of the heaps initially amounts to about 70 m as the initial block height of case I and II in Section 6.4. A) A particle and wall friction angle of 30° yields an angle of repose of about 36°. B) A particle and wall friction angle of 26° yields an angle of repose of about 32°. The dilation angle amounts therefore to about 6°.
9 References


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# Curriculum Vitae

Mag. rer. nat. (KFU Graz) Bernd Imre
Gartenstrasse 67
CH - 4132 Muttenz
Tel: ++41-(0)44-633-2526
E-mail: bernd.imre@igt.baug.ethz.ch

Date & Place of Birth: 11 January 1976, Graz / Austria
Civil Status: married, two children
Citizenship: Austria

## Education

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<th>Date</th>
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| May 2004–Jan. 2010 | Doctoral Thesis in Civil Engineering | Thesis Title:
  “Micromechanical Analyses of Sturzstroms (Rock Avalanches) on Earth and Mars” | ETH Zurich / Switzerland |
| Feb. 2007–April 2009 | Study in Didactics                  | Teaching Certificate in Civil Engineering (26 ECTS) | ETH Zurich / Switzerland |
| Oct. 1997–July 2003 | Study in Engineering Geology        | Master of Science (MSc.) (honours degree)         | Karl Franzens and Technical University of Graz / Austria |
| Sept. 2001–Mai 2002 | Study in Geology                    |                                                   | University of Utah, Salt Lake City, Utah / U.S.A. |
| Sept. 1991–June 1996 | Study in Civil Engineering          | High school diploma (honours degree)              | HTL Ortweinschule Graz / Austria |
## Internships

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<td>Sedimentological core descriptions, Preparation of thin-sections</td>
<td>Vienna / Austria</td>
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<td>July 1998 and July 1996</td>
<td>Aluglas GmbH</td>
<td>Site Manager</td>
<td>Stainz / Austria</td>
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<td>July 1995–Aug. 1995</td>
<td>Porr Technobau AG</td>
<td>Assistant of the site manager “Semmering” Prospecting Tunnel</td>
<td>Mürzzuschlag / Austria</td>
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<td>Assistant of the site manager during reconstruction of two highway bridges</td>
<td>Graz / Austria</td>
</tr>
<tr>
<td>July 1992 and July 1993</td>
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<td>Assistant of the site manager</td>
<td>Graz / Austria</td>
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## Civil Service

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## Voluntary Assistance

<table>
<thead>
<tr>
<th>Date</th>
<th>Institution</th>
<th>Duties and Responsibilities</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005/2006</td>
<td>ETH Zurich, Inst. for Geotechnical Engineering</td>
<td>Elected member of the institute council</td>
<td>Zurich / Switzerland</td>
</tr>
<tr>
<td>2001/2002</td>
<td>University of Utah, International Student Council</td>
<td>Webmaster</td>
<td>Salt Lake City, Utah / U.S.A.</td>
</tr>
<tr>
<td>2000/2001</td>
<td>Karl Franzens University of Graz, Geological Institute</td>
<td>Elected member of the institute council</td>
<td>Graz / Austria</td>
</tr>
<tr>
<td>1995–2001</td>
<td>Abwassergenossenschaft Willersdorf e.G.</td>
<td>Wastewater plant operations manager</td>
<td>Willersdorf / Austria</td>
</tr>
</tbody>
</table>
Awards

<table>
<thead>
<tr>
<th>Date</th>
<th>Title</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb. 2009</td>
<td>International Conference “From Shear Bands to Rapid Flow”—Best presentation award</td>
<td>Centro Stefano Franscini, Monte Verità, Ascona / CH</td>
</tr>
</tbody>
</table>

Supervised Master Thesis Studies

Räbsamen, S, 2007. Die Energiebilanz von Rutschungen aus trockenem, nicht fragmentierendem Reibungsmaterial in der Geotechnischen Trommelzentrifuge am Institut für Geotechnik an der ETH Zürich. IGT/ETHZ. *Awarded with the ETH Zurich Culmann-Fonds Prize.*

Wildhaber, B. 2007. Synthese von Analogmaterialien zur Simulation fragmentierender Sturzströme in der Geotechnischen Trommelzentrifuge am IGT. IGT/ETHZ.

Supervised Bachelor Thesis Studies


Publications (peer-reviewed)

See Section 1.4 of this study.

18.03.2010  
Bernd Imre