GRANT AGREEMENT NO.: 289911

MUMOLADE

MULTISCALE MODELLING OF LANDSLIDES AND DEBRIS FLOWS

Seventh Framework Programme

The People Programme

WORK PACKAGE 4 - Model tests, case studies and best practice

Work Package Leader: UNOTT

DATABASE OF HYDROLOGICALLY-DRIVEN SLOPE FAILURES

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1. Introduction

The MUMOLADE research program deals with debris flows and rainfall induced landslides. This report discusses hydrological driven, (spontaneous) landslides and in particular the development of a case study database, designed to meet the specific needs of testing and evaluating advanced numeric simulation landslide models.
Since there is no generally accepted uniform classification of landslides and to avoid misunderstandings, first the different landslide- types which will be processed within MUMOLADE are briefly described and defined followed by an abstract describing different aims and applications of models. However, the main part of this chapter is about the parameters needed for various model applications versus the parameters that are available from case studies in the field and suggestions how to bridge this gap. A suggestion for a data base to meet the specific requirements of model testing, -calibration and -evaluation is introduced, discussed and completed with data-examples.

2. Definition of terms regarding the landslide-process

There are different types of landslides and thus different landslide processes which need to be specified to support the choice of appropriate simulation approaches. For the needs for the MUMOLADE project the landslides will be distinguished as suggested in Keusen et al. (2004) in continuously moving landslides and spontaneous occurring landslides.

2.1 Continuous mass movements

Continuous mass movements are (in our context) deep seated more or less continuous movements in complex geological systems. The movement is not triggered but influenced by the water input (Figure 1), whereat the sums of water input in the system over long periods is relevant. The movement is according to the classification of Cruden & Varnes (1996) slow to extremely slow.

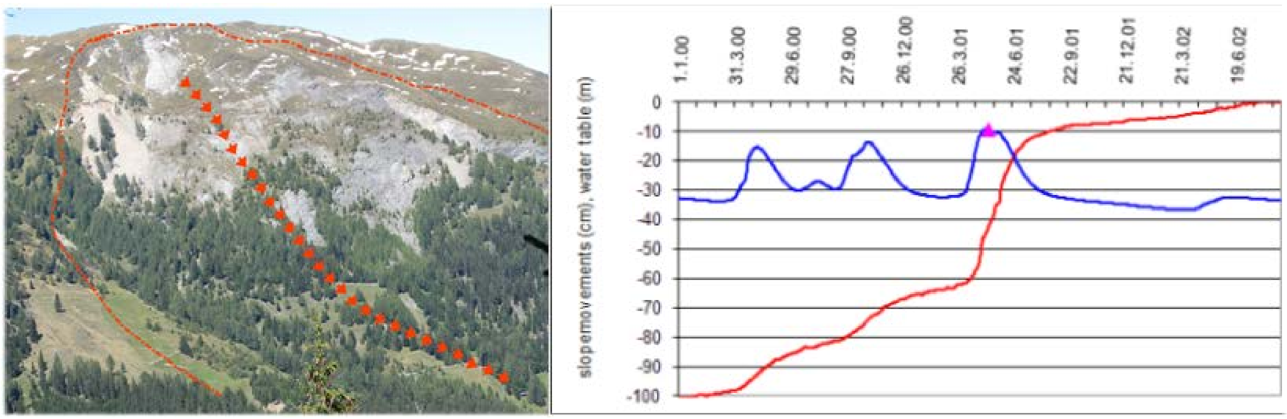


Figure 1: The movement rates of continuous landslides are influenced but not indicated by the water input respectively the slope water table, Eggerwiesenkopf/Gradenbach (Austria), Source: BFW

This type of mass movements is not in the focus of MUMOLADE and therefore not further discussed here. However, it has to be considered for the delimitation to shallow spontaneous landslides. It is noted that continuous mass movements often cause secondary movement processes on the surface as e.g. shallow, seemingly spontaneous landslides.

2.2 Spontaneous movements

Spontaneous movements are triggered by the increase of shear stress (e.g. erosion at the toe of the slope, earthquakes, modification of slope), the decrease of shearing resistance (e.g. water infiltration, weathering, removal of forest vegetation) or both together (e.g. earthquake shaking, Van Asch et al. 2008). However, the most frequent triggering factors are heavy rainfall and earthquakes. Interaction of these triggering events can be observed in reality; they increase the probability of the landslide occurrence. Anyhow, MUMOLADE focuses on hydrological driven (usually rather shallow) landslides. Saturation of the loose material layer occurs either due to snow melting in spring e.g. in combination with rainfall or in summer due to long intensive rainfalls (e.g. 1999, 2002 and 2005 in Tyrol and Vorarlberg, Austria). The movement speed according to the classification of Crunden & Varnes (1996) is very rapid to extremely rapid.
Figure 2 shows the nomenclature suggested by the USGS (Geology.com, state 2015, based on WP/WLI (1993)) which is used in this text.

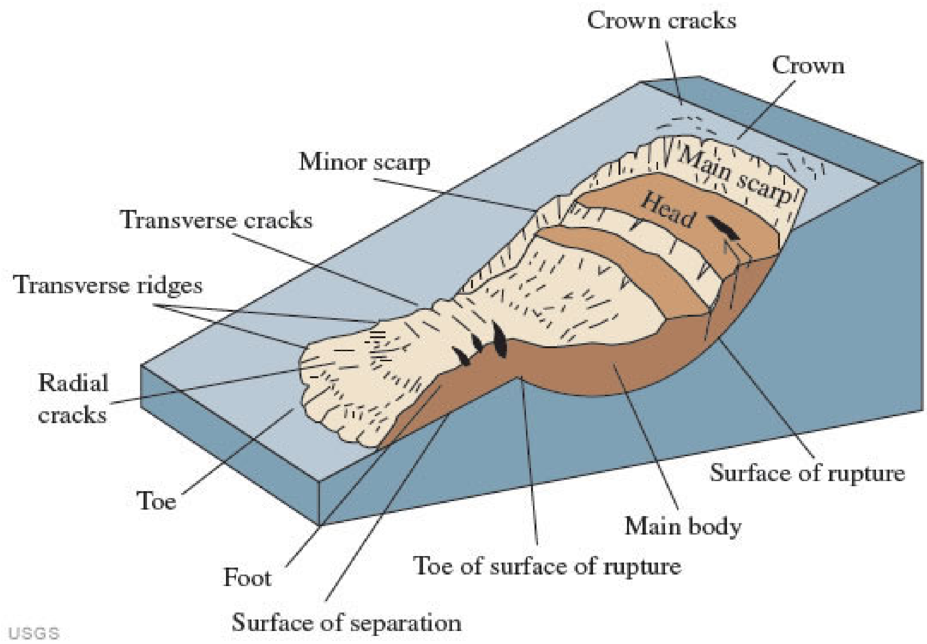


Figure 2: An idealized landslide showing commonly used nomenclature (USGS Geology.com, state 2015)

2.3 Model-relevant process mechanisms

Within the process type shallow landslide, three major processes have to be considered (Figure 3):

- Initial process (triggering, start),
- transportation (movement) and
- deposition.

In the case of shallow landslides, the transportation and deposition process often overlaps. Thus, during field survey or by aerial images interpretation, there is not always a distinct identification possible. Hence these two process types may be classified as one. Anyhow, most model approaches are able to deal also with this type of information.

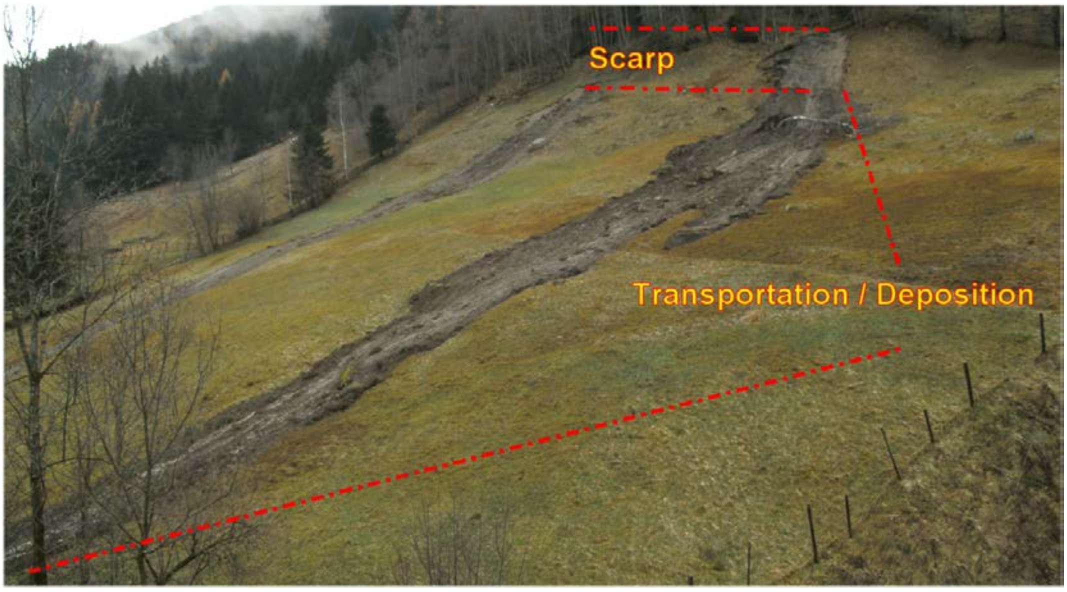


Figure 3: Spontaneous, shallow landslide in loose material, scarp and transportation/deposition zone, Upper Mölltal (Austria) 2012, BFW/Pichler & Hagen

2.4 Classification of hydrological driven, spontaneous landslides:

There are different sub-types of hydrological driven landslides, which can be characterized by the shape of the scarp, the surface of rupture, the form and depth of slide and the water content of the moving mass (Tilch et al. 2011, Hübl et al. 2009, Krummenacher & Tobler 2009, Girty 2009, USGS 2004, Cruden & Varnes 1996, Varnes 1978). The identification of the landslide type is necessary for a proper assignment of models. Here, the rather basic but widely accepted classification for mass movement processes from Varnes (1978) / USGS (2004) was chosen as the basis for classification.

TYPE OF MOVEMENT		TYPE OF MATERIAL		
		BEDROCK	ENGINEERING SOILS	
			Predominantly coarse	Predominantly fine
FALLS		Rock fall	Debris fall	Earth fall
TOPPLES		Rock topple	Debris topple	Earth topple
SLIDES	ROTATIONAL	Rock slide	Debris slide	Earth slide
	TRANSLATIONAL			
LATERAL SPREADS		Rock spread	Debris spread	Earth spread
FLOWS		Rock flow (deep creep)	Debris flow	Earth flow
			(soil creep)	
COMPLEX		Combination of two or more principal types of movement		

Figure 4: Types of landslides. Abbreviated version of Varnes classification of slope movements (Varnes 1978, USGS 2004)

2.4.1 Translational slides

Translational slides (Figure 5, Figure 6) are usually shallow landslides with a planar surface of rupture. The fault plane already exists before the event, it is often bedrock. The main scarp is commonly (more or less) straight, the shape of the slide is almost rectangular.

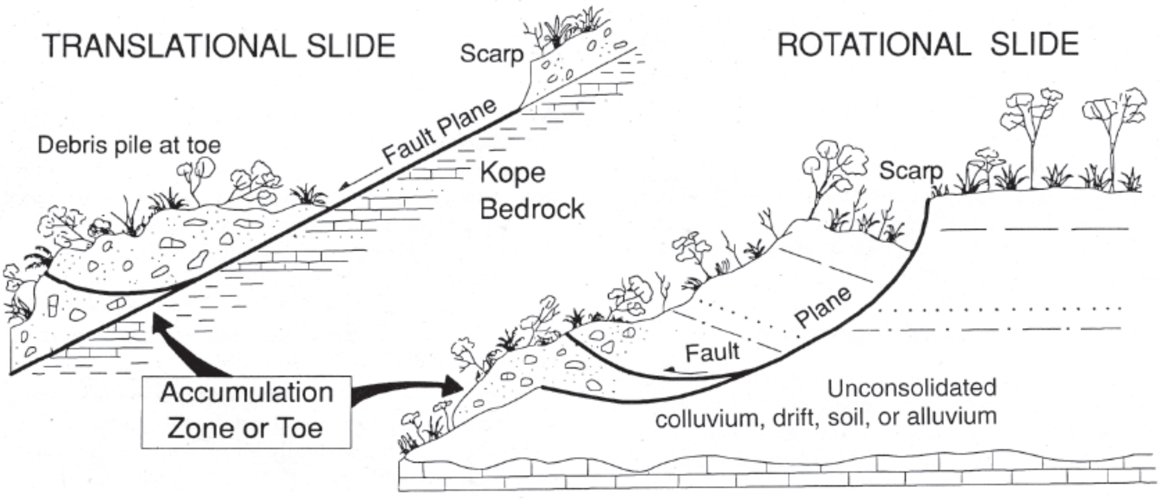


Figure 5: Definition diagrams for principal types of landslides, cross section (Potter 2007)

Figure 6: Translational landslide with planar slide plane (bedrock), Laterns 1999, BFW/ Hagen

2.4.2 Rotational slides

Rotational slides (Figure 5, Figure 7) are usually deeper. They occur in the loose material layer and show a curved, concave-shaped fault plane (surface of rupture), which develop in the moment of sliding. The scarp of rotational slides is roughly kidney formed.

Figure 7: Rotational landslide with concave shaped slide plane and sliding material transportation (Gasen 2005) BFW/ Hagen

2.4.3 Irregular forms ("slope explosions")

So called "slope explosions" (Figure 8) do not fit in the scheme of translational / rotational classification. They are caused by hydrostatic effects (pore water pressure) when only sliding as initial processes is unlikely. Often water outlets (springs etc.) can be observed in the scarp. Subsequent, flows frequently develop (even by moderate slope angles) because of the high water content and low consistency of the material.

Figure 8: "Slope explosion", with high water content (and subsequent earth flow), Gasen 2005, BFW/ Priesch

However, in the field, transition forms of the described landslide-types occur and hinder sometimes a clear classification. Thus, the relevant specific parameters, on which the identification of the processes is based, should be documented as well.

2.5 Transport-processes subsequent to initial landslides (transportation and deposition)

It is best to document transport and deposition separately. However, in the field they are often not clear to delineate. There are indistinct transitions caused by small scale spatial and temporal changes.
The types of mass movements can be classified according to means of the speed of the process and the water content of the moving mass (Carson & Kirkby 1972) or with respect to physical issues (Girty 2009, USGS 2004 based on Varnes 1996 and 1978, Figure 4).

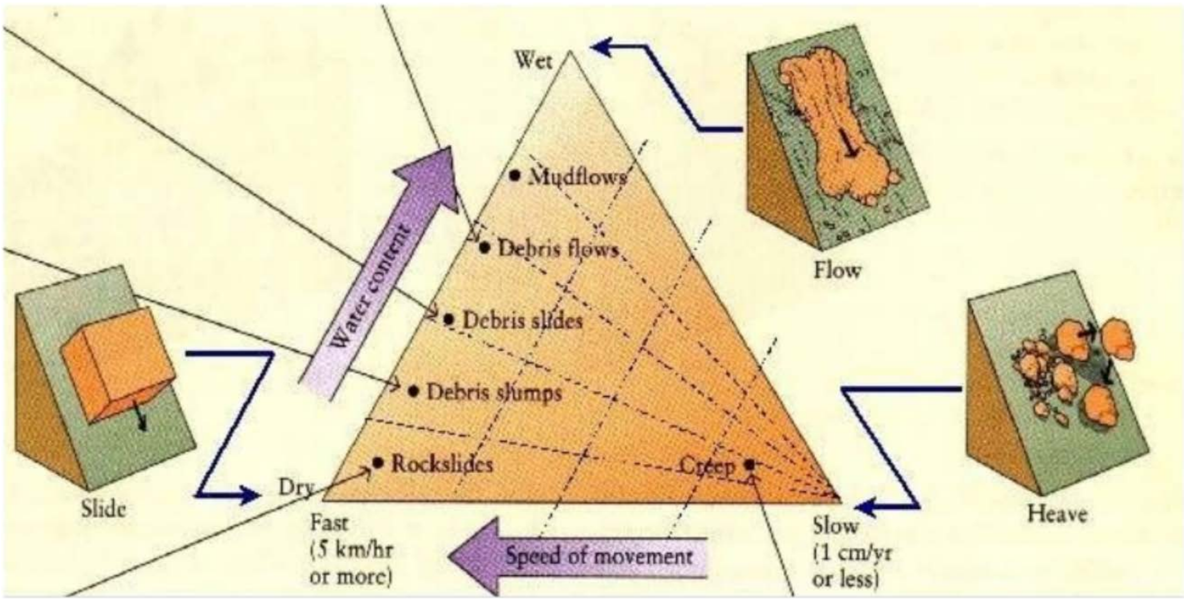


Figure 9: Classification of slope processes in dependence on the speed of the movement and the water content, after Carson & Kirkby (1972)

According to the classification of Varnes (1978 / USGS 2004, Figure 4
Figure 9) and Carson & Kirkby (1972, Figure 9) the movement processes include:

- Falling: e.g. rockfall etc.
- Sliding, usually rapid to very rapid movements (Cruden & Varnes 1996, Figure 10), accumulation of the transported material typically in or close to the scar area (Kienholz et al. 2006, e.g. Figure 7)
- Flows:
    - Moderate movement (creeping)
    - Very rapid to extremely rapid movement (Cruden & Varnes 1996) especially in the case of high water contents ("slope explosions") with long run out distances and high damage potential. Up to now, there have no commonly accepted classification prevailed. However, the different transport processes are predominantly defined by the concentration of solids and the percentage of the different grain size fractures, explicit of the fines (e.g. Girty 2009: debris flow (20 – 80 % of particles > 20 mm), earth flows and mud flows (approx. 80% of particles < 0,06) or Cóussot 2003 (Figure 11)
- Lateral spreading caused by ground liquefaction (plastic ground deformation)
- Complex movements – combination of two or more principal types of movement

In terms of the MUMOLADE project, rapid mass flows are of highest interest.

Velocity Class	Description	Velocity (mm/sec)	Typical Velocity	Probable Destructive Significance
7	Extremely Rapid			Catastrophe of major violence; buildings destroyed by impact of displaced material; many deaths; escape unlikely
		5×10^{3}	5 m/sec	
6	Very Rapid			Some lives lost; velocity too great to permit all persons to escape
		5×10^{1}	3 m/min	
5	Rapid			Escape evacuation possible; structures; possessions, and equipment destroyed
		5×10^{-1}	1.8 m/hr	
4	Moderate			Some temporary and insensitive structures can be temporarily maintained
		5×10^{-3}	13 m/month	
3	Slow			Remedial construction can be undertaken during movement; insensitive structures can be maintained with frequent maintenance work if total movement is not large during a particular acceleration phase
		5×10^{-5}	1.6 m/year	
2	Very Slow			Some permanent structures undamaged by movement
		5×10^{-7}	15 mm/year	
	Extremely SLOW			Imperceptible without instruments; construction POSSIBLE WITH PRECAUTIONS

Figure 10: Classification of process velocities according to Cruden & Varnes (1996)

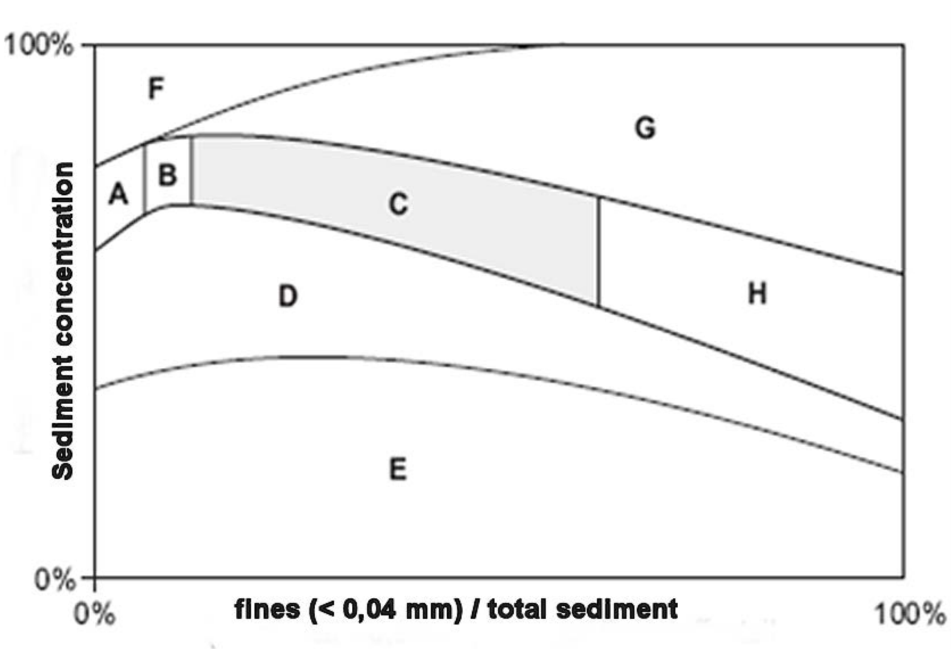


Figure 11: Classification of movement types regarding fine grain concentration and sediment concentration according to Cóussot (2003), modified: A: Granular flow, B: Viscous-granular flow, C: Viscous flow, D: Hyper-concentrated flow, E: Fluviatil bed load, F: Rockfall, G: Landslide, H: Mudflow

In fact, combinations of flows and slides may occur, which hinder a clear classification of the processes (Lotter & Haberler 2013). At least for the purpose of modeling a further differentiation between

- granular flows (friction between particles) and
- viscous flows (rheological behavior)

based on the percentage of fines is suggested (specification Figure 11).

Occasionally “slope debris flows (Hangmuren, Figure 12)” are classified as a separate movement-type (e.g. Losey 2013, Krummenacher & Tobler 2009, Hübl et al. 2009). They are defined as flows on morphologically almost flat slopes, without developed channel-structures. Frequently they occur especially subsequently to the slide type “slope explosion”, discussed before. Thus it is likely that they are viscous flows with comparatively high water contents.

Figure 12: “Slope debris flow”, (Gasen 2005), BFW/ Lang

3. Applications and models for landslide modeling: An overview

3.1 General remarks

To apply models successfully, the framework and aims of the modeling activity have to be expressed in advance (e.g. Soeters & Van Westen 1996):

- What is required (landslide distribution and potential, landslide run out, potential damage, model calibration and evaluation through back analyses).
- Scale of analysis (national, regional, local, site investigation)
- Available data and resources (landslide inventory, spatial data)

The available database and resources have to be checked whether they allow achieving the aims set (theoretically).
In the case of advanced modeling of slope instability on a local scale, the identification of the relevant (physical) process is crucial for the choice of an adequate approach respectively to assess, if an available model is adequate to describe the observed process.

3.2 Types of model approaches

Generally, there are three main types of approaches to compile landslide susceptibility and/or hazard maps (ÖREK 2015, Schwarz et al. 2014, Thiebes 2012, Tilch et al. 2011, Van Asch et al. 2008, Guzetti 2006, Baillifard et al. 2003):

- Heuristic
- Statistic
- Deterministic

3.2.1 Heuristic approaches

Heuristic approaches integrate the knowledge and experience of experts to derive maps of landslide susceptibility and hazard (Thiebes 2012). They are usually based on a geomorphologic survey of the terrain, collecting information on current and recent landslide activity in the area and on geomorphologic settings. Soeters & Van Westen (1996) distinguish between geomorphologic analysis and qualitative methods. Van Asch et al. (2008) qualified the assessment by direct mapping of the terrain as a heuristic approach. The qualitative methods of hazard assessment regarding landslide triggering are based on the superimposition of thematic maps like geological map, hydrological map, slope map, land use map, soil type and depth map etc. (Thiebes 2012, Van Asch et al. 2008).
Heuristic approaches to determine the range of landslides generally base on the determination of the flow path and a minimal slope angle according to the method of Heim (1932).
The heuristics approaches are indirect (or semi-direct), mostly qualitative methods, whose reliability depends on how well and how much the investigator understands the geomorphologic processes occurring in the area (Guzetti 2006). They are usually applied quickly to get a first rough impression of the spatial pattern of landslide disposition and range.

3.2.2 Statistical approaches

Statistical methods are presently the most frequently used method in case of regional landslide susceptibility and hazard modeling, raised by the rapid development of GIS (Zizioli et al. 2013, Bell 2007, Carrara et al. 2006). They provide quantitative results (as e.g. a susceptibility/hazard index) which are suitable for a quantitative assessment of landslide hazards (Guzetti 2006). The most important requirement to apply statistical approaches is an appropriate data base of landslide events. Statistical approaches to analyze landslide hazards consider the causative factors that led to the landslide occurrence in the past by the identification of stand characteristics, where landslides occurred. Relevant parameters are determined quantitatively. They are used to predict future landslides in the terrain by identifying areas with similar failure conditions (Frometta 2014, Guzetti 2006). Statistical approaches link input and output data by empirical parametric functions. The parameters used in these functions are mostly not related to physical parameters that can be determined in the field or in the laboratory (Van Asch et al. 2008).
A vast range of different methods has been developed so far. Bell (2007) provides an extensive list of statistical methods. Several authors compare and discuss the advantages and disadvantages of the various methods as well as the methods of evaluation (e.g. Tilch et al. 2011). Most frequently applied statistical approaches are bivariate regression, multiple regression, discriminate analyses, logistic regression, Bayesian statistic, fuzzi logic and likelihood ratio (Thiebes 2012, Cervi et al. 2010).

3.2.3 Deterministic approaches

Deterministic approaches to determine slope failures provide physically-based analyzes on slope stability, which links the theoretical framework of hydrology, geomorphology and geotechnical science with different degrees of simplification. They support the physical understanding of landslide location, timing and transport mechanism (Formetta et al. 2014,) and allow a quantitative estimate of slope stability respectively thresholds for precipitation (Zizioli et al. 2013, Van Asch et al. 2008). Thiebes (2012) distinguishes between regional deterministic models which use simplified stability calculation (e.g. infinite slope model) and local models for the analysis of single slope failures as the widely applied limit-equilibrium methodology. Latter have a long tradition in geotechnical slope stability practice (design of artificial slopes etc.). Because of the need of exhaustive data, deterministic approaches are generally recommended for mapping small areas (ÖREK 2015, Van Asch et al. 2008).

4. Database, inventories and case studies

4.1 General remarks

Landslide models need to be tested in order to confirm model assumptions and subsequently to adapt them for practical usage. To do so, well documented landslide events are indispensable. In contrast, landslide inventories generally aim on supporting planning of responsible actors in the field of hazard management (Naturgefahren.at 2015) and raising the awareness of public on a potential endangerment (Crawford 2014) but not on testing of modeling approaches.
Guzetti et al. (2012) specifies the scopes of landslide inventories as follows:

- Documenting the extend of landslide phenomena
- A preliminary step to gain maps on landslide disposition and resulting hazard and risk assessment
- The base to analyze the spatial pattern and the type of landslides based on geologic properties (bedding, mineral composition, thickness etc.) and geomorphologic characteristics (slope gradient) along with other data.
- Studying the evolution of landscapes with the viewpoint mass transport processes.

Guzetti et al. (2012) and Perzl et al. (2015) also distinguish between four main kinds of inventories:

- Event inventory: Data captured immediately after the landslide event (aerial images, field survey)
- Archive inventory: Collection from existing event databases and scientific literature
- Geomorphologic landslide inventories: Based on geomorphologic clues
- Comparison of multi-temporal aerial image series

According to the general purposes of modeling also the aims and scopes of potential users of landslide inventories should be clarified (Crawford 2014, Hübl et al. 2006). There is no best practice or standard methodology to develop such an inventory; much depends on the available documentations (Schwarz et al. 2014). It is unlikely that all pertinent data can be gathered for every documented landslide.
Most suitable data to run physical based models can be gained from special designed field surveys of selected events. Here, data from existing event databases were scanned for usefulness data to calibrate, verify and evaluate advanced models.
It should be noted that inventories usually aim on surveying a great number of landslides with the consequence of limited information on the single landslide event (e.g. national inventories: WLK-Ereignisportal (Naturgefahren.at, 2015), GEORIOS in Austria (Kociu et al. 2007), survey form of WLS for Swiss, (WSL 2005)). Field surveys (after events) usually do not consider model-requirements, if only for the fact that during the survey it is rarely known if - and if yes - which approaches will be used for simulation. This hinders the application and testing of landslide models on the base of these data sets. Thus, the focus was on detailed surveys, but these documents are rare, data hard to get and due to the different objectives of the surveys rather heterogeneous.
According to different processes, data for slope stability (starting zone modeling, thresholds…) and processes of transport/deposition should be separated (e.g. Kienholz et al. 2006).
Anyhow, obligatory data (key data) of landslides and optional data should be defined in issues of accuracy and process relevant information (Che et al. 2011). For the MUMOLADE – database, these minimal requirements are discussed within the presentation of the database standard attributes (chapter 4.3) presenting a best practice example. However, the quality of the data should be specified:

- By a defined qualitative (good, medium, low) assessment
- In a quantitative way (e.g. +/- distance)
- By citing the method of data compilation (e.g. field survey, aerial photo interpretation)
- Declaration of the data source (incl. period between event and data compilation)

Comments include supplemental meta-info on the data and/or links to further data which are not included (for any reasons) in the database.

Examples of inventories and databases considered while compiling the MUMOLADE database are:

- C3S-ISLS – inventory (Perzl et al. 2015)
- Event inventory Gasen/Haslau (Tilch et al. 2011, Andrecs et al. 2007), see chapter 5
- Event inventory Laternsertal event 1999 and 2005 (Andrecs et al. 2002, Markart et al. 2007), see chapter 5
- Kentucky Geological Survey Landslide Inventory (Crawford 2014)
- WLK-Ereignisprotal (Naturgefahren.at, 2015)
- Advisements on landslide databases (Guzzetti et al. 2012, Che et al. 2011, Mazengarb et al. 2010, Kienholz et al. 2006)

An urgent task is to clarify the property of the data as well as conditions and limitations of use. Thus, the holder of the data is identified and the rights of use are noted and classified as follows:

Property/ rights of use	Institution	Free	Limited	Conditions	Contract	Comments

- Free: without any limitations
- Limited: Use limited (e.g. within the MUMOLADE project, no commercial use)
- Conditions: e.g. citation (legal form)
- Contract: The institution has to be contacted to declare the using agreements (contract)
- Comments: E.g. contact address, responsible person etc.

4.2 Data base structure and management

It is assumed that a flexible database structure is required to fulfill the varying demands of simulation and to manage the inhomogeneous data sets in an efficient way.
Digital landslide databases should combine

- spatial data of the landslides (e.g. landslide polygons geometric data) and area information (e.g. DEM, geological map) and
- non spatial data referring to points (e.g. date, soil profiles >> info-points)

and take advantage of the current information technology available (Mazengarb et al. 2010).
In practice, usually the aim, available data and resources will dictate the choice of the landslide model. The scientific entry somewhat differ – it (also) means to choose the documented events according to the possibilities of analyzing a specific process respectively applying a specific model. Thus, the data structure should enable the search for datasets which may fulfill defined requirements best. Considering the different data sources and thus the different attributes, a main challenge is to generate standard attributes (Crawford 2014).
The data-management strategy, suggested within MUMOLADE considers available components of landslide inventories and modeling requirements. In order to keep the database effective, for several parameters minimal standards for “data – admission” are suggested. It is assumed, that data of landslides which do not achieve these minimal standards are unusable for the application within MUMOLADE and thus should not be part of the database. However for specific problems, the requirements on data might be significantly higher than the suggested minimal standards.

4.3 Suggestions for the standard attributes of the MUMOLADE database

It is a major decision within the management of databases: Which data should be added into the database and which not. On one hand, a wide event database is desirable anyway; on the other hand documented events need to satisfy specific qualitative requirements (in our case namely model requirements) to be useful. Hence, we defined attributes which make data sets valuable for modeling. As plenty of useless records impair the management and the use of the database, we also suggest minimal standards, which event documentations should fulfill. We willful defined these minimal standards on a rather low level, since model requirements vary considerable. Attributes which are essential in one approach might be dispensable applying another method.
Anyhow, the following attributes (overview) should be taken into account for event documentation:

Attribute (overview)	**Suggested min. requirement (Y/N)**
Location	Y
Date of event and survey	Y
Personal information	Y
Mechanism of mass movement (type) and transport	Y
Dimensions	N
Geometric information	Y
Material behavior	N
Settings	Y
Triggering	N
Direct measurements & on process relevant parameters	N
History & status	N
Damages	N

<u>Location (Table 1)</u>
The location of a landslide is usually defined through the geometry (landslide polygons). However, if this information is not available or in addition to the geometry to provide a quick overview (e.g. using google earth), so called info-points, situated in the middle of the scarp, are provided.
The landslide location is described in a standardized way (state, community, address, coordinates (coordinate system)) including information on accuracy. Thus, an overview of the spatial distribution (e.g. in relation to administrative units) of events can be gained. Precise information on the location enables to analyze landslides in a geologic and geomorphologic context along with other data like morphologic characteristics of the surface, material parameters (e.g. thickness of the loose material layer) vegetation or constructions (Crawford 2014) and to find correlations between the disposition for landslides and stand parameters.
To use location data in a suitable way, it is important to have information on the accuracy. In this context it is important to consider not only the quality of the method itself but the temporal aspect. With an increasing period between event and documentation (e.g. flight), the location of the primary scarp becomes insecure because of subsequent processes or remedial actions.

Table 1: Design with standardized and optional information on the location and example

Task	Content	Example
Nation *	National code	A
Fed. state/region	Name	Vorarlberg
Community *	Name	Laterns
Coord x *		-40235
Coord y *		236531
Coord. system *		MGI GK28
Accuracy *	High; medium; low*; estimation; unknown	Medium
Altitude (m a.s.l)		1355
Exposition (°)		200
Type of generation	Field (measured); GPS; DEM; orthophoto; remote sensing; else	field (measured), orthophoto,
Comments		

- * Suggested minimal requirements.
- The Info-point (start) located at the middle of the scarp (of the single landslide) is generally obligatory. Only if the start point of the process is unknown or for special requirements, the Info-point can be located at the end of the process (this might be the case for debris flow events).
- The nation is described by the national code (e.g. CH for Swiss).
- Accuracy high: cm -dm (e.g. laser scan, high resolution orthophoto), medium: At least 5 m, low: At least 50 m, estimation: Insecurity > 50 m or no clear identification possible. To consider: period between event and survey!
- The type generation describes the method, how the location of the point was determined. (e.g. in the field on the base of orthophotos).

<u>Date of event and survey (Table 2)</u>
For the simulation of the process the date (and time) is not relevant, but as soon as analyzes (also) aim on the estimation of the triggering conditions (e.g. thresholds - rain input during the event, preconditions) or for time depended analyzes (frequency of landslides, increase because of climate change etc.) it becomes relevant.
Usually the time of the first movement is stated. The date of survey gives advice on the quality of data since information “get lost” with an increasing space of time between event and documentation.

Table 2: Design with standardized and optional information on temporal information (date) of event and survey

Task	Content	Example
Year		1999
Month		7
Day		27
Accuracy *	High; medium; low*; estimation	low

- * Suggested minimal requirements.
- The table of date event and survey has the same structure.
- Date input in numbers (month).
- Accuracy high: Minutes, medium: Hours-day, low: Weeks, assignment to an event possible, estimation: No clear assignment to an event (period).

Personal information (Table 3)
Queries can support the interpretation of specific events. Personal information refers always to the responsible person(s) and institution(s) for data survey and interpretation. Information on the institution is necessary for the citation (source).

Table 3: Design with standardized and optional information on institution and responsible person (data compilation)

Task	**Content**	**Example**
Institution *	Name	BFW
Person	Name	Peter Andrecs
Email		peter.andrecs@bfw.gv.at
Address	National code, place, street; nr.	A, 1131 Vienna, Seckendorff-Gudent Weg 8
Phone		+43 1 87838 2215
Comments	E.g. further Persons with Info	Karl Hagen, Frank Perzl, BFW

- * Suggested minimal requirements.

Mechanism of mass movement (type) and transport (Table 4, Table 5)
The identification of the type of landslide and transport process is a basic task to facilitate proper hazard assessment. The documentation respectively the database should contain - in addition to the classified process-type - the description of type-relevant parameters (e.g. shape of the scare, visible bedrock, water outlets, levees) which led to the classification (see chapter 2). Besides, these data support the identification of the relevant physical mechanisms. At best, these data are documented for the scarp, transport- and deposition area separated. However, the table of transportation and deposition contain the same attributes, thus they can be documented together or separated.
In combination with gravity, slope angle is an important and easy to determine “first order prediction parameter”. However, Werlen (2004) found for rough DEMs (e.g. DEM 10) failures of slope-calculation at an average of 4-5° and on a small scale up to 20°. Hence, the type of generation (measurement in the field, on the base of DEM etc.) is reasonable.
It is obvious that some information of this attribute table is in parts redundant with the geometrical information. Due to possible different data sources (of crosschecking) and for reasons of data-management (search function) this information should be provided anyway.

Table 4: Design with standardized and optional information on landslide initiation zone

Task	**Content**	**Example**
Mass movement type *	Continuous; cont/spont; spontaneous; else; unclear	spontaneous
Classification	Rotational (R); translational (T); irregular (I); else; unclear	n. a.
Quality of assessment *	Certain; likely *; assumption	likely
Slope gradient (°)		35
Slope morphology	According to Rickli (2008)	8
Form of crack		n. a.
Form of scarp		n. a.
Surface of rupture		n. a.

Bedrock/ slide plane (%)		0
Crop out of spring	J/N	n. a.
Comments		

- * Suggested minimal requirements
- The occurrence of landslides depends strongly on the slope inclination. On the base of measured slope inclinations automatically, on the base of DEMs determined slope inclinations can be checked.
- The nomenclature, description and classification of the landslide types are according to chapter 2. Transient landslide types may be classified as e.g. R-I (rotational-irregular). If the landslide type is unclear, it should be assessed as else and commented.
- If it is assumed, that shallow landslides occur as secondary process collateral to continuous mass movement, they should be classified separate as continuous/spontaneous.
- The quality assessment of information is qualitative; however it should consider the method (field survey, aerial photo interpretation), the expertise of the institution/person and the date of survey (period to event – meanwhile ongoing erosion process or remedial actions?). Example: The description of the surface of rupture and slide plane (only) on the base of aerial photos is tricky and either shouldn't carried out or has to be rated as assumption.
- Slope morphology (classification according to Rickli et al. 2008)

1 2 3 4 5 6 7 8 9

- The form of the crack, scarp, rupture, the visibility of the bedrock and the crop out of springs characterize specific mass movement types (chapter 2).
- Comments e. g. description bedrock: Strike and fall, source…

Table 5: Design with standardized and optional information on landslide transport and deposition zone

Task	**Content**	**Example**
Transport type *	Falling; sliding; flowing; flowing granular; flowing viscous; else	flowing
Quality of assessment *	Certain; likely*; assumption	likely
Length (m)		
Slope morphology	According to Rickli (2008)	8
Cross section	Channel, convex, flat, concave	convex
Erosion	J/N	J
Deposition	1: Mainly in scarp, 2: Mainly close to scarp, 3: Mainly with distance to scarp, 4: Unclear	3
Speed of process		n. a.
Witnesses	J/N	n. a.
Comments	E.g. compare photos	

- * Suggested minimal requirements.
- Since the identification and separation of transport- and deposition zones is often not clearly possible, they can be assessed separated or together.
- The length refers to the flow path of the dominant process. Within this zone, transport relevant parameters as the morphology are described briefly, which led to the classification of the transport-type (according to chapter 2). Slow mass movement-types as lateral spreads are not

within the focus of the MUMOLADE project; however they can be considered under else and should be attributed with a specific comment.

- Witnesses: Are there silent witnesses (e.g. levees, morphology). Videos etc. should be entered at task direct measurements.

<u>Dimensions (Table 6)</u>

The volume gives an impression of the dimension of the event. For landslides, it is usually determined at the scarp. However in some cases – e.g. if a debris flow with significant erosion develop from an initial landslide, the volume of the deposition might be more convincing. The methods and remarks to determine the volume are described within the task geometric information.

Table 6: Design with standardized and optional information on the dimension (volume) of the event

Task	**Content**	**Example**
Volume (m^3)		8200
Scarp/Deposition	S/D	S
Quality of assessment	H/M/L; assumption, unknown	L

- If information on scarp and deposition volume is available it is suggested to supply the greater value.
- High: Verified DEM 3D difference calculation, medium: 2D geometric information and reference measurements of depth, low: From sketches with measured reference values (l/b/d), assumption: Expert estimation without measurements.

<u>Geometric information (Table 7)</u>

Sound geometric information on landslides is valuable for the model calibration and evaluation. It is important that the scare and the transportation/deposition area are separated because they are attributed to different physical processes.

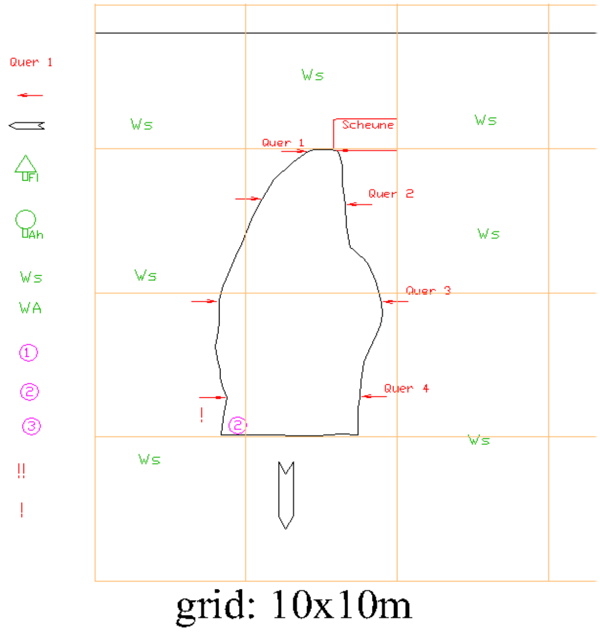
Geometric data support the identification of the process type, the assessment of triggering conditions, they display the process area (rage and spread) and are a valuable base to determine the volume. To enable the interpretation and assessment of geometric data and their quality, the survey method and the date of survey should be specified.

The estimations of size and volume are more or less imprecise, depending on the method:

I. Documentations in the field (sketches Figure 13): To ensure reasonably data, they should base at least on the measured length and width. For the volume the depth of the scarp and/or the deposits need to be estimated. Conventional photos support the interpretation of the situation.

II. Interpreted 2-D aerial images (Figure 13) offer high quality of information on the position and shape of the landslides and support the estimation of landslide volume and range. However, they should be taken as soon as possible after the event due to ongoing erosion processes or restoration measures as the removal of deposited material. The differentiation of scarp zone, transport zone and deposition zone only on the base aerial photos (without crosschecking in the field) is tricky and thus rather insecure. The determination of the range, especially of smaller landslides is fault prone because of vegetation. Further, aerial photos do not include explicit information on the depth of the scarp, erosion and thickness of deposition.

III. Maximum information can be gained from 3D laser-scans (terrestrial) and LiDAR (aerial) data, latter also if forests are covering the area. By difference calculations (Figure 14) of the surface before/after the event, the volume and zones of erosion and deposition can be determined theoretical precise. However, as with the areal pictures surface data need to be surveyed short after the event. The use of these methods is limited by their (high) costs and in the case of spontaneous landslides (often) by a gap of adequate information on the surface morphology (shortly) before the event.



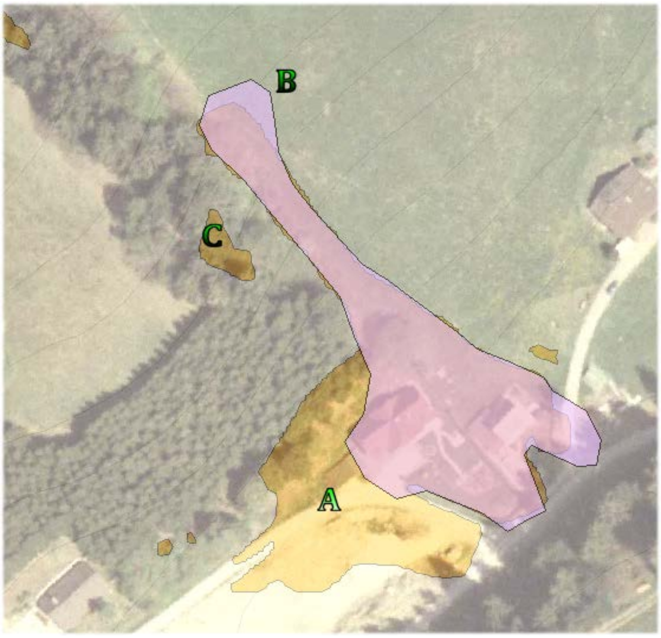


Figure 13: Examples; a: Digitized field sketch (scarp of a shallow landslide) with measured key-values (Laternsertal 1999); b: 2D data - compare of field survey (measured characteristics - draft on orthophoto – violet) and interpreted aerial photo (without field survey, brown): A - misinterpretation of process area (material deposition from clean-up operations - aerial photo), B - more exact identification of scarp (shape, location, aerial DB), C: not identified landslide-scarp by field survey (Gasen 2005), BFW, orthophoto BEV.

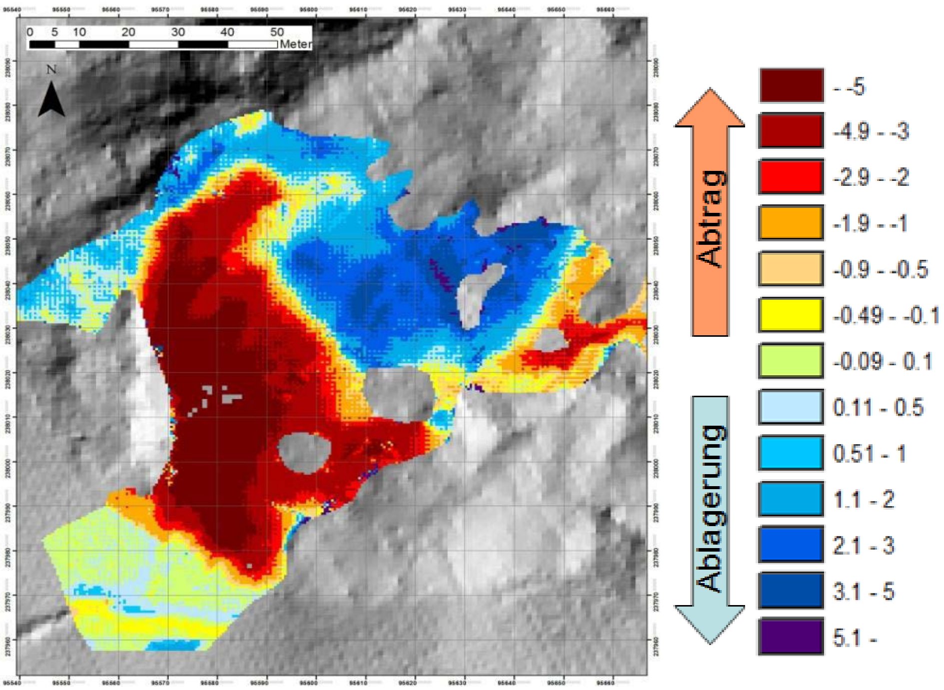


Figure 14: 3D data - vertical difference of altitudes (erosion and deposition) of the landslide Wattenbach/Eggerbach (Tyrol) in relation to the natural surface on the base of terrestrial laser-scans (Klebinder & Graf 2012)

The geometric data should be compared and crosschecked with the location data; deviations due to different methods or date of survey, should be corrected and commented.

Table 8: Design with standardized and optional information on landslide geometry (scarp, transport and deposition zone)

Task	**Content**	**Example**
Area information *	Sketch*, aerial photo, polygons*, laser scan; 3D difference calculation	sketch, polygon,
Coverage	S/T/D	S, D
Date	Year(s)	sketch 1999, polygon 2001
Accuracy *	H/M/L*/ unknown	M
Comments	E.g. specification what?	polygons form aerial photos

- * Suggested minimal requirements (either digital polygons from sketches of aerial photos from the event).
- 3D difference calculation on the base of high resolution DEM before and after the event.
- Coverage of the information: S – scarp, T – transport zone, D – deposition zone.
- Date of the (relevant) area information, e.g. date of flights aerial photos, laser scans.
- The assessment of the quality of the geometric information (H – high, medium – M, low – L) considers the limits of the method, the resolution and quality of the database and the time interval to the event. Thus sketches are usually quoted as low. Polygons based on aerial photos might be quoted from high to low (aerial photos resolution, clouds, shadowing, vegetation…). 3D calculation can be quoted by the plausibility of the results and (selected) spot tests in the field.

Material behavior (Table 9)

For the calibration, application and evaluation of advanced, physically based models, information on the properties of the loose material layer is necessary. To run these models, usually most of the model input parameters have to be derived from other information. There is a wide variety of information (usually surveyed for other aims and with partly overlapping information) which is potentially appropriate to parameterize the models.

Material parameters describe geologic and lithologic characteristics of the bedrock and the loose material layer (soil). For rainfall induced landslides, occurring primary in the loose material layer, bed rock characteristics are of indirect relevance as they influence the chemical and physical weathering (soil characteristics as material composition, thickness) and the subsurface flow (e.g. hydrological barrier – choice of finite or infinite model approach).

Lithologic parameters describe the behavior of the ground layer (e.g. Blume et al. 2010). They are the base to estimate forces of internal friction, cohesion (Coulomb – theory of failure in Fellin 2007) and pore water pressure as well as rheological /frictional parameters for the moving mass due to missing direct measurements in the field. Relevant parameters are (Askarinejad et al. 2012, Schwarz et al. 2012a, Kohl et al. 2002):

- Thickness of the layer (initiation), volume of the slide (transport, range)
- Specific weight, density
- Hydrological behavior (initiation) at different depths described by
  - Infiltration rate, pore volume
  - PF-curve (water retention curve)

- Internal friction (initiation) at different depths described by
    - Grain size distribution
    - Granular structure
    - Hydrological conditions
    - Roots (number and diameter)
- Internal friction (movement)
    - Grain size distribution
    - Water content

However, also other information like e.g. the genesis (glaciations) may help to parameterize models.
For the starting zone, information on the composition of the material in several depths (measured from the surface) is relevant for recreate slope processes as well as to determine triggering conditions and thresholds.
For transport- and deposition zones it allows inferences on the transport process and supports the calibration of the transport models (friction, rheology). Unfortunately, in practice there frequently is a gap on data about lithologic behavior, which hinders the successful application of physically based models.

Table 9: Design with standardized information on material behavior

Task	**Content**	**Example**
Bedrock	J/N	
Thickness loose mat. (m)	Shallow; moderate; medium; deep, very deep	very deep
Max grain diameter (dm)		18
Quality of assessment	Certain; likely; assumption	likely
Soil hydrology	N/F/L	L
Soil behavior	N/F/L	L
Roots	N/F/L	N
Comments		

- Information on bedrock additional to the standard information like generally geologic and lithologic maps (field survey, specific technical reports).
- Information on the thickness of the loose material layer additional to the standard information like lithologic maps (specific surveys technical reports, samples (e.g. soil profiles)…).
- Information on soil hydrology (e.g. moisture, pore pressure): L - laboratory methods (e.g. soil water – pF curves), F – measurements of moisture and/or pore pressure during or promptly after the event etc. in the field, N – no information.
- Information on soil behavior (e.g. density, grain size distribution): L - laboratory methods of samples (e.g. grading curves), F – methods in the field (field texture determination), N – no information.
- Are there information on roots to quantify vegetation effects (quantified root reinforcement e.g. with calculator, Schwarz et al. 2012b) or number and diameter according to different layers.
- Are there information helping to deduce these parameters (e.g. simple methods as the “field texture determination” or laboratory surveys of samples). However, the information on the depth (measured from the surface) is important.

Settings (Table 10)

Settings in the context of this paper describe the frame conditions regarding morphology of surface vegetation and land use (including constructions). The geological settings are described within the material behavior the meteorological settings within triggering.

It is generally known, that high resolution DEM's are the base of numeric simulations especially for transport processes. Information on vegetation and land use are usually not directly needed to calibrate physical models but may help to determine needed model input parameters (as e.g. root forces or roughness of the surface). Constructions may influence the start- and transport process and they may affect damages significant.

However, this data is often offered from third party institutions. Hence the rights of use (conditions) need to be clarified!

Table 10: Design with standardized information on settings in the landslide area

Task	Content	Example
DEM resolution (m) *		1
Date		2004, 2011
Land use	Forest; open land, settlements, waste land	forest
Constructions	Buildings; infrastructure; protective structures; else, 0	
Comments		shed 9 m above

- * Suggested (minimal) DEM resolution 1 m.
- DEM resolution best available with date of compilation, further DEM's (with lower resolution might be mentioned in the comments).
- Land use type: Source and resolution (according to CORINE land cover classification: forest, open land settlements and wasteland).
- Information on constructions as buildings, infrastructure (roads, railway, pipelines…) and protective measures (slope drainages, dams…), description and sources in comments.

Triggering (Table 11)

Natural triggers are:

1. Earthquakes (not discussed in this project),
2. Erosion of the slope toe caused e.g. by flood events.
3. Heavy rain events
4. Snowmelt

The MUMOLADE project deals hydrologic driven landslides, thus the focus is on 3 and 4. However, these triggering factors reinforce each other.

Precipitation data are the base of threshold estimations (starting conditions). Precipitation affects relevant parameters of the loose material layer as the internal friction angle, cohesion or water pore pressure. In the case of shallow landslides, event precipitation but also the preconditions, determining the moisture of the soil at the beginning of the precipitation event, are relevant. Information on precipitation is provided by rain gauges (in dependence of distance, interpolation of neighbor stations – may not be sufficient in case of convective precipitation) and/or weather radar data (best if calibrated with gauging stations, e.g. INCA_CE, Meirold-Mautner 2010).

However, not only the direct precipitation need to be considered but also the subsurface flow (water input from above situated areas e.g. according to the tank model / soil water index calculation, TRIGRS, Baum et al. 2008, Figure 15) by the combination of data according to morphology and topology, material behavior and precipitation.

Figure 15: “Slope explosion”, and subsequent earth flow with significant contribution of subsurface flow, the crop out of the spring changed during the event and caused (a further) landslide; Gasen 2005, (Andrecs et al. 2007)

Table 11: Design with standardized information on settings in the landslide area

Task	Content	Example
Trigger	Earthquake, erosion of slope toe, heavy rain, snowmelt, else, unknown	heavy rain, snowmelt
Comments		
Precipitation data	0, gauge, radar, snow-height, water equivalent, else	gauge
Comments	to precipitation (data)	point

- Further triggering factors as anthropogenic causes (e.g. additional load, concussions) should be mentioned for the process understanding.
- The type of precipitation data should be clarified (point (gauge) or area-data (polygons, raster)) within the comments.

<u>Direct measurements and information on process relevant parameters (Table 12)</u>
Direct measured values of relevant parameters in the field as e.g. in Ruedlingen (CH, full size field test, Askarinejad et al. 2012) are very rare. As it is usually unknown where and when a landslide event will occur, measuring instruments cannot be installed. However, there are sporadic “artificial induced” landslides (in the field e.g. triggered by sprinkling) where several parameters were measured (e.g. internal friction, moistness and pore pressure). Slightly more often data from (channel) debris flows (hydrographs, velocities, forces, e.g. Illgraben, Walter & McArdell 2015, Graf et al. 2009) or Moscardo torrent (Italy, Franzi et al. 2013) are measured. However, this data needs to be reviewed carefully since measurements are difficult and potentially fault-prone. Such data is usually neither free for use nor commercially available. With the rapid spread of digital cameras and Smartphone’s, video-documentations of events increase, these may support the understanding of the process.

Table 12: Design with standardized information on direct measurements

Task	**Content**	**Example**
Scarp	J/N	N
Transport/deposition	J/N	N
Semi-measured documents	J/N	N
Comments	Description of measurements and videos	

- Direct measurements according to the initiation zone can be internal friction, pore pressure or moisture (compare Askarinejad et al. 2012).
- Direct measurements of the transport zone can be velocity and pressure/forces.
- Semi-measured documents are videos or recalculated values of forces and velocities.

History & status (Table 13)
The status of the landslide (active, inactive, sanified), provided in several inventories, is primarily in the interest of (practical) hazard management (steering measures). For the simulation of spontaneous landslides the status is not relevant.
Information on historic movements/landslides supports the estimation of landslide frequency (e.g. in the course of risk assessment). Further it may indicate deep seated mass movements. However, this information might be available in rather different ways, hindering standardization.

Table 13: Design with standardized information on history and status

Task	**Content**	**Example**
Status of landslide	Active, inactive, sanified, else	n. a.
History	J/N	N
Comments		

Damages (Table 14)
Actually, information on damages, caused by events, is not necessary for modeling the process but may be helpful in order to evaluate the model results. Additionally damages may be used to determine the socio-economic impact of certain events or processes. Thus, information on damages is often the core of documentations and projects.
Model results will be used often as base of risk assessment (magnitude) and to classify actual events (e.g. observed damages / potential damages). Furthermore, damaged constructions may offer a source to recalculate forces etc.

Table 14: Design with standardized information on direct measurements

Task	**Content**	**Example**
Persons	Casualties, injured (J/N), no info	N
Buildings	Destroyed, damaged, (J/N), no info	N
Infrastructure	Main road (Rm), side roads (Rs), railway (Ry), supply lines Sl, else	N
Costs(€)		n. a.
Comments		

- If there are no casualties, injured persons or damaged buildings this should be specified (N).
- The description of damage should include also a monetary assessment of direct (costs of reconstruction…) and (separated) optionally also of indirect costs (closed roads etc.) to improve the comparability of different events and their effects.
- Other damage (farm animal, wasted agricultural areas etc.) and nature and degree (e.g. number of casualties) can be specified within the comments.

5. Data - examples

For purposes of modeling, two landslides in the community of Laterns (Vorarlberg/Austria) from 1999 (5, 7) and one from the community of Gasen (Styria/Austria) from 2005 were chosen and provided as examples within the “best practice data base”.

5.1 Event Laternser Valley 1999 (Perzl et al. 2015, Markart et al. 2007, Andrecs et al. 2002)

In May 1999 several landslides occurred in the Laternser Valley (Austria, Vorarlberg). A survey, conducted by BFW, was aiming on a complete documentation of shallow landslides in this area to provide an overview and to determine parameters which are relevant for landslide initiation from a statistical viewpoint. Documents and resources were limited, e.g. there were no aerial photos taken directly after the event but only sketches of the landslides in maps. However, for selected landslides, laboratory analyses of important soil physical characteristics (particle size, porosity, bulk and particle density, organic matter and saturated water conductivity) were carried out. After another landslide event in the area in 2005, further landslides were documented. Comparative analyses of documentations and aerial photos (time series) were carried out and landslide areas were digitized.

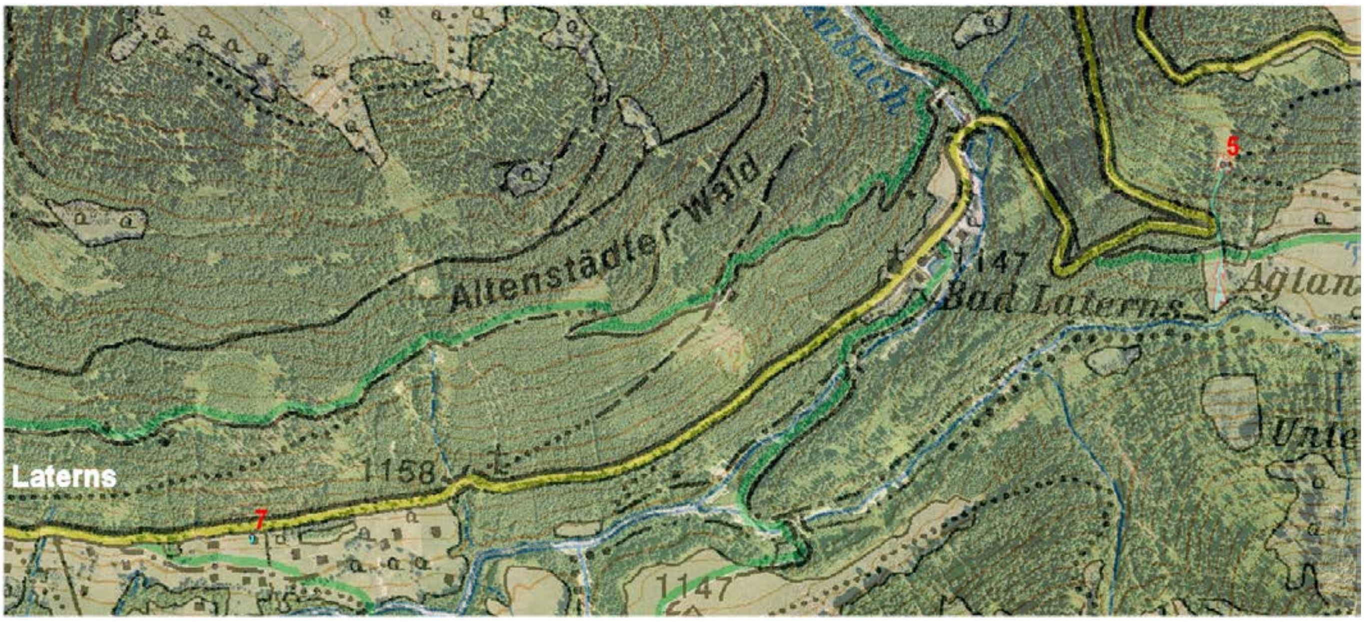


Figure 16: Position of the landslide event examples Laterns (1999), ÖK 1:500.000, orthophoto BEV

5.2 Event communities of Gasen & Haslau 2005 (Tilch et al. 2011, Andrecs et al. 2007)

In August 2005 in the communities of Gasen and Haslau (ca. 60 km²) more than 770 gravitational mass movements took place over a period of several days caused by a period of high initial soil moisture and several days of continuous, rather moderate precipitation. Infrastructure (electric power lines, drinking water supply lines) buildings (residential housing and commercial buildings) and roads were badly damaged. Many buildings had to be evacuated and a number of people were cut off from the outside world for days. The event caused considerable property damage and there were two fatalities. From parts of the area, aerial photos were taken directly after the event. Several area-wide documents with landslide relevant information were compiled. However, since the aim was registering the landslides as complete as possible and testing area-wide approaches to determine landslide deposition and process area, detailed survey of landslides were not undertaken.

Figure 17: Example - an earth flow/soil flow destroyed an house and caused two fatalities, Gasen 2005, Photo BFW Hagen, compare also Figure 13

6. Conclusions

According to the inhomogeneous data, which is available in various inventories and case studies and the rather diverse requirements of different model approaches, the data-management within MUMOLADE aims at high flexibility. The vital demand to search for documented events according to data requirements of specific models is met by a data information system based on defined attributes of mass movement indication and transportation. Each attribute as e.g. location or material behavior is discussed according to the expected contend, the methods of generation and the assessment of data quality. Further, a real case example illustrates the discussed issues. To keep the database slender and valuable, minimal standards are suggested, which event documentations should fulfill.

The data base might be seen as a pre-GIS data base, which keeps the efforts for data management as low as possible. Besides, it offers the possibility to build up GIS-projects for specific needs in any GIS-software (e.g. ESRI, GRASS) easy.

It is a fact that well documented landslide events which “perfectly” match the needs of model application, calibration and validation are rare. The presented report also should give an impulse to improve the event documentation regarding model testing and subsequently to make the required data available for potential users.

7. Summary

This report aims on the development of a database-design (“best practice”) for hydrologic driven landslides, which meet the specific needs of testing and evaluating advanced numeric simulation models. In a first step, the various landslide types and transport processes are described and defined to avoid misunderstandings; customary classifications are discussed. Furthermore a brief general overview of methods and model approaches to determine landslide susceptibility and the mass transport processes is provided.
Landslide inventories and case studies, which are the main data sources, usually don’t aim on testing model approaches. The expectable information content of these sources is briefly discussed and considered in the database design. Attributes, according to landslide relevant parameters are defined and described with respect to the inherent information. It is noted, that the assessment of the data quality is important to interpret data inaccuracy and its impact on model results. Based on the suggested attributes, a simple approach for a targeted search for suitable datasets according to the requirements of specific model approaches is introduced.
Selected event documentations of landslide events in Austria are enclosed.

8. References

Andrecs P., Markart G., Lang E., Hagen K., Kohl B., Bauer W. (2002): Untersuchungen der Rutschungsprozesse vom Mai 1999 im Laternsertal (Vorarlberg). In: Beiträge zur Wildbachforschung, BFW-Berichte 127, pp 55-87

Andrecs, P., Hagen, K., Lang, E., Stary, U., Gartner, K., Herzberger, E., Riedel, F. & Haiden, T. (2007): Dokumentation und Analyse der Schadensereignisse 2005 in den Gemeinden Gasen und Haslau (Steiermark). BFW-Dokumentation; Schriftenreihe des Bundesforschungs- und Ausbildungszentrums für Wald, Naturgefahren und Landschaft,Wien, Nr. 6, p 75

Askarinejad A., Casini F., Bischof P., Beck A., Springman S.M., (2012): Rainfall induced instabilities in a silty sand slope: a case history in northern Switzerland, ETH-Zürich, p 19

Baillifard F., Jaboyedoff M., Sartori M. (2003): Rockfall hazard mapping along a mountainous road in Switzerland using a GIS-based parameter rating approach, Natural Hazards and Earth System Sciences (2003) 3, pp 431–438

Baum R. L., Savage W. Z. Godt J. W. (2008): TRIGRS—A Fortran Program for Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Analysis, Version 2.0 , USGS open-File Report 2008–1159, p 75

Bell R. (2007): Lokale und regionale Gefahren- und Risikoanalyse gravitativer Massenbewegungen an der Schwäbischen Alb. PhD diss., Mathematisch-Naturwissenschaftlichen Fakultät. Rheinische Friedrich-Wilhelms-Universität, Bonn, p 270

Blume H.P., Brümmer G.W., Horn R., Kandeler E., Kögel-Knabner i., Kretzschmar R., Stahr K., Wilke B.M. (2010): Scheffer/ Schachtschnabl: Lehrbuch der Bodenkunde, Springer, p 550
Carrara, A., Cardinali, M., Detti, R., Guzzetti, F., Pasqui, V., Reichenbach, P. (2006): GIS techniques and statistical models in evaluating landslide hazard. Earth Surf. Process. Landforms, 16: pp 427–445

Carson, M.A. & Kirkby ,M.J. (1972): Hillslope Form and Process. Cambridge Geographical Studies No. 3, Cambridge University Press, p 1

Che V.B., Kervyn M., Ernst G.G.J., Trefois P., Ayonghe S., Jacobs P., Van Ranst E., Suth C.E. (2011): Systematic documentation of landslides in Limbe area (Mt Cameroon Volcano, SW Sameroon): geometry, controlling, and triggering factors, Nat. Hazards 59, pp 47-74

Cervi F., Berti M., Borgatti L., Ronchetti F., Manenti F., Corsini A. (2010): Comparing predictive capability of statistical and deterministical methods for landslide susceptibility mapping: a case study in the northern Apennines (Reggio Emilia Province, Italy), in Landsides (2010), Springer, pp 433-444

Cóussot P. (2003): FAN Agenda, Forstliche Arbeitsgruppe Naturgefahren, Glarus, Schweiz

Crawford M. (2014): Kentucky Geological Survey Landslide Inventory: From Design to Application, University of Kentucky, Lexington, p 18

Cruden, D.M. and Varnes, D.J., (1996). Landslide types and processes, in Landslides, Investigation and Mitigation. Special Report 247, Transportation Research Board, Washington, pp 36-75

Fellin W. (2007): Bodenmechanik und Grundbau Übungsunterlagen Institut für Geotechnik und Tunnelbau, Uni Innsbruck, p 142

Franzi L., Arattano M., Arai M., Katz o. (2013) Overview: Documentation and monitoring of landslides and debris flows for mathematical modeling and design of mitigation measures – outcomes of the EGU 2011, NH session, in Nat Hazards Earth Syst. Sci 13, pp 2013-2016

Frometta G., Capparelli G., Rigon R., Versace P. (2014): Physically based landslide susceptibility models with different degree of complexity: calibration and verification, in iEMSs, 7th Int. congress on Env. Modelling and Software, proceedings, San Diego, USA, p 8

Girty G.H. (2009): Chapter 8, Landslides in Perilous Earth: Understanding Processes Behind Natural Disasters Department of Geological Sciences, San Diego State University, p 8

Graf C., Badoux A., McArdell B.W. (2009): Alarmsystem Illgraben – Erfahrungen während der Pilotbetriebsphase, in Wasser Energie Luft» – 101. Jahrgang, 2009, Heft 2, CH-5401 Baden, pp 101-107

Guzetti F. (2006): Landslide hazard and risk assessment, PhD diss. Rheinische Friedrich-Wilhelmsuniv. Bonn, p 373

Guzetti F., Mondini A.C., Cardinali M., Fiorucci F., Santangelo M., Chang K.-T. (2012): Landslide inventory maps: New tools for an old problem. Earth Science Rieviews 112 (2012), pp 42-66

Heim A. (1932): Bergsturz und Menschenleben - Fretz und Wasmuth, Zurich, p 218

Hübl J., Kienholz H., Loipersberger A. (2006): DOMODIS – Dokumentation alpiner Naturereignisse [Documentation of Mountain Disasters], Interpraevent, p 40
Hübl, J., Sitter, F., Totschnig, R., Schneider, A., Krawtschuk, A, (2009): Historische Ereignisse – Band 4: Zusammenstellung und Analyse dokumentierter Ereignisse in Österreich bis 2009, IAN Report 111, Band 4, Institut für Alpine Naturgefahren, Universität für Bodenkultur-Wien (unpublished), p 79

Keusen H.R., Bollinger D., Rovina H., Wildberger A., Wyss R. (2004): Gefahreneinstufung Rutschungen i.w.S – Permanente Rutschungen, spontane Rutschungen und Hangmuren. AG Geologie und Naturgefahren, Schweizerische Fachgruppe für Ingenieurgeologie, BAFU, p 44

Kienholz H., Perret S., Schmid S. (2006): Dokumentation von Naturereignissen. Feldanleitungen. Alpensignale 4. Plattform Naturgefahren der Alpenkonvention (PLANAT), Innsbruck, Bern, p 65

Klebinder K., Graf A. (2012): Monitoring Massenbewegung Wattenbach/Eggerbach Vögelsberg, Gemeinde Wattens, Endbericht, p 20

Kociu B., Kautz H., Tilch N., Grösel K., Heger H., Reischer J. (2007): Massenbewegungen in Österreich, in Jahrbuch der Geologischen Bundesanstalt, Band 147, pp 215-220

Kohl B., Markart G., Bauer W. (2002): Abflussmenge und Sedimentfracht unterschiedlich genutzter Boden-/ Vegetationskomplexe bei Starkregen im Sölktal/Steiermark, in BFW-Berichte 127, Wien, pp 5-30

Krummenacher B., Tobler D. (2009): Anwendung des Risikokonzepts Prozess: Spontane Rutschung / Hangmuren in Risikokonzept für Naturgefahren –PLANAT Leitfaden

Losey S. (2013): SilvaProtect-CH: Prozessmodellierung – Appendix; http://www.bafu.admin.ch/naturgefahren/01920/01964/index.html?lang=de (state: 29.4.2014)

Lotter M., Haberler A. (2013): Geogene Naturgefahren - gravitative Massenbewegungen und ihre Ursachen, Berichte Geol. B.-A., 100, p 17

Markart G., Perzl F., Kohl B., Luzian R., Kleemayr K., Ess B., Mayerl J. (2007): 22. Und 23 August 2005 – Analyse von Hochwasser- und Rutschungsereignissen in ausgewählten Gemeinden Vorarlbergs, BFW Dokumentation; Schriftenreihe des Bundesforschungs- und Ausbildungszentrums für Wald, Naturgefahren und Landschaft, Wien 2007, Nr. 5, p 48

Mazengarb C., Flentje P., Miner A.S., Oscuchowski M. (2010): Designing a Landslide Database: lessons learnt from Australian Examples. Geologically Active, Proceedings of the 11th IAEG Congress of the International Association of Engineering Geology and the Environment, Auckland, New Zealand, p 7

Meirold-Mautner I., Wang Y., Kann, A., Bica B., Gruber C., Pistotnik G., Radanovics S. (2010): Integrated nowcasting system for the Central European Area : INCA-CE, Data and Mobility, Advances in Soft Computing, Volume 81, 107-114

Naturgefahren.at (State 20.5.2015): Das Ereignisportal des digitalen Wildbach- und Lawinenkatasters des Forsttechnischen Dienstes für Wildbach- und Lawinenverbauung, http://www.naturgefahren.at/karten/chronik/ereignisdoku/Ereignisportal.html; state 20.4.2015)

ÖREK (2015): Risikomanagement für gravitative Naturgefahren in der Raumplanung, Materalienband, Geschäftsstelle der Österr. Raumordnungskonferenz, Wien, p 285

Perzl F., Rössel M., Zieher T. (2015 unpublished): Landslide Data Acqusition and Geodatabase Management Description of the Landslide Inventory, ACRP – C3S-ISLS projectdraft, BFW, p 53

Potter P.E. (2007): Exploring the Geology of the Cincinnati/ Northern Kentucky Region, Second revised edition, Kentucky Geological Survey, Lexingtion, p 128

Rickli C., Kamm S., Bucher H. (2008): Projektbericht Ereignisanalyse Hochwasser 2005, Teilprojekt Flachgründige Rutschungen, WSL/BAFU, p 114

Schwarz M., Cohen D., Or D. (2012a): Spatial characterization of root reinforcement and stand scale: Theory and case study, Geomorphology 171-172, pp 190-200

Schwarz M., Thormann J.J., Zürcher K., Feller K. (2012b): Quantifying root reinforcement in protection forests: Implications for slope stability and forest management, 12th Congress INTERPRAEVENT 2012 – Grenoble / France, Conference Proceedings, pp 791-802

Schwarz M., Matti J., Dorren L., Hunziker G., Loup B., Hagen K., Mazzorana B., Rickli C., Bebi P., Wohlwend S., Huwiler A., Vacchiano G. (2014): Best Practice Methods for Shallow Landslide Hazard Assessment – A Review of the Alpine Region, in Wildbach und Lawinenverbau, Heft Nr. 174, pp 222 – 231

Soeters R. & Van Westen C.J. (1996): Slope instability recognition, analysis and zonation. In A.K. Turner & R.L. Schuster (eds), Landslides − Investigation and Mitigation: Washington, D.C.: National Academy Press, Board Special Report 247

Thiebes B. (2012): Landslide Analysis and Early warning Systems, Local and Regional Case Study in the Swabian Aib, Germany, Springer, Heidelberg, p 260

Tilch N., Hagen K., Proske H. Pistotnik G., Schwarz L., Aust G., Fromm R., Herzberger E., Klebinder K., Perzl F., Bauer C., Kronberger B., Kleb U., Granica K., Haiden T. (2011): Modelling of Landslide Susceptibility and affected Areas – Process-specific Validation of Databases, Methods and Results for the Communities of Gasen and Haslau, (AdaptSlide – Endreport), http://bfw.ac.at/rz/bfwcms.web?dok=8935, p 305

USGS Geology.com (state 22.5.2015): Anatomy of a Landside, http://geology.com/usgs/landslides/

USGS (2004): Landslide Types and Processes, fact sheet; http://pubs.usgs.gov/fs/2004/3072/pdf/fs2004-3072.pdf, p 4

Van Asch Th. W. J., Malet J.-P., Van Beek L.P.H., Amitrano D. (2008): Techniques, advances, problems and issues in numerical modeling of landslide hazard; http://arxiv.org/ftp/arxiv/papers/0709/0709.2642.pdf, p 32

Varnes D.J. (1978) Slope movement types and processes, in Transportation Researsch Board Special Report Nr. 176, Washington DC, pp 11-33

Walter F., McArdell B. (2015): What is the velocity profile of debris flows, EGU 2015 NH3.9, Vienna

Werlen S. (2004): Hangmuren, Einflußfaktoren von Lockergesteinsrutschungen, Diplomarbeit, Uni Bern, p 117
WP/WLI (1993): Multilingual Landslide Glossary. The International Geotechnical Societies. UNESCO Working Party on Word Landslide Inventory. Bi Tech Publishers Ltd. Richmond, Canada, p 32

WSL (2005): Datenbank flachgründige Rutschungen und Hangmuren – Aufnahmeformular Rutschungen, http://www.wsl.ch/fe/gebirgshydrologie/wildbaeche/projekte/Hanmurendatenbank/form_1.jpg?hires

Zizioli D., Meisina C., Valentino R., Montrasio L. (2013): Comparison between different approaches to modeling shallow landslide susceptibility: a case history in Oltrepo Pavese, Northern Italy, in Nat. Hazards Earth Syst. Sci 13, pp 559-573