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The influence of landuse on the stability of slopes with examples from the European Alps

Von Andreas Kellerer-Pirklbauer[1]
Mit 11 Abbildungen und 2 Tabellen

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Zusammenfassung: Der Einfluss der Landnutzung auf die Stabilität von Hangbereichen unter besonderer Berücksichtigung der Europäischen Alpen. – Instabile Hangbereiche stellen einerseits eine Bedrohung für Siedlungen dar, andererseits können aber auch Verkehrsinfrastrukturen und verschiedenste bauliche Strukturen, etwa zur Nutzung von natürlichen Resourcen (z.B. Dämme) oder für die Schiindustrie (z.B. Schipisten, Lifttrassen), von dieser Gefahr beeinflusst sein. Ausgelöste Massenbewegungen in Form von Rutschungen oder Muren können so große Schäden verursachen. Für gewöhnlich werden solche Ereignisse durch natürliche Prozesse, wie etwa Erdbeben, Fluten oder extreme Niederschlagsereignisse ausgelöst. In vielen Fällen aber erhöhen menschliche Aktivitäten, häufig in Form von falscher Landnutzung, das Auftreten von Massenbewegungen. Anthropogene Aktivitäten verursachen auf verschiedenen Wegen Hanginstabilitäten: Modifizierung von Geländebereichen (z. B. Pistenbau), Abholzung, die Errichtung von Straßen und Wegen, Siedlungserrichtung an Hängen, Dämme, Stauseen, etc. erfordern häufig die Umlagerung von beträchtlichen Erd- und Gesteinsmassen. Solche Prozesse haben einen großen Einfluss auf verschiedene Systeme am Hang (z.B. Hydrologie, Formenwelt) und konsequenter Weise kann das Potential für Massenbewegungen an Hangbereichen steigen. Diese können entweder während oder kurz nach der Umgestaltung des Terrains, oder aber auch viele Jahre nach der Bauausführung losgelöst werden. In dieser Arbeit kommt der menschliche Einfluss auf die Stabilität von Hangbereichen zur Diskussion. Zuerst werden die Faktoren und Systeme, welche die Hangstabilität beeinflussen, angesprochen. Als nächster Schritt werden hangdestabilisierende menschliche Aktivitäten and Landnutzung behandelt. Im letzten Unterkapitel werden Beispiele gegeben. Auf der einen Seite soll dabei aufgezeigt werden, welche katastrophale Auswirkungen Massenbewegungen haben können. Auf der anderen Seite werden darin aber auch typische kleinräumige Ereignisse in den Europäischen Alpen zur Diskussion gestellt.

Summary: Instable slopes pose serious threats to settlements and structures, which support transportation, natural resources, land management and tourism. Triggered mass movements do considerable damage to highways, railways, waterways and pipelines. Commonly such events occur with other major natural events such as earthquakes, floods and excessive precipitation events. But in many cases expanded development of unwise human activities can increase the incidence of landslide disasters. Human activities account in various ways for instabilities on slopes: Modified slopes (e,g, due to ski-run construction), deforestation, the construction of highways, hillside housing developments, dams, reservoirs, drainage and utility structures normally involve the movement of substantial amounts of soil or rock on slopes. Such activities influence various systems on the slope (e.g. hydrology, geomorphology) and as a consequence the hillslope is more prone towards failure. Failures may take place during or immediately following the construction process, but the effects of the human impact may also trigger a landslide many years after construction activities. In this paper the author discusses the influence of human activities on the stability of slopes. First the factors and systems influencing the stability of slopes are mentioned. Secondly the types of human activities and landuse, which may influence the stability of slopes, are described. The last chapters emphasize the situation in the European Alps by discussing examples of catastrophic and typical minor human-induced mass movement events.

1. Introduction

Mountainous environments are highly sensitive areas. An increasing intensity of human landuse on mountainous terrain has lead to an increase in natural hazards.

[1] MMag. Andreas Kellerer-Pirklbauer, Department of Geography and Regional Science, University of Graz, Heinrichstraße 36, 8010 Graz, Austria, e-mail: andreas.kellerer@uni-graz.at

Heuberger & Ives (1994) argue, that mountain environments are undergoing an ever intensified development which may create even more stress.

Because morphodynamical processes act more in steep than in flat terrain, slope instabilities and as a consequence landslides are very frequent in mountainous areas. Landslides are commonly natural events. Yet, human actions may reduce the stability of slopes and even trigger landslide events. In many cases landslides were caused because people have built structures near or on unstable slopes. Various types of human activities may favour and/or trigger mass movement processes. Also existing landslides may be influenced in their rate of speed.

The main area of interest in this study are the European Alps, a 1200 km long, 150 to 250 km wide and 220,000 km² large bended mountain range in the centre of Europe. While the Alps represent one of the most sensitive ecosystems in Europe, the pressure on them is far greater than on other environments. This is due to an aggressive development driven in the past, huge numbers of tourists as well as environmental damages. This change of landuse caused in the past even catastrophic slope failures. One well known example is the big landslide in the Vaiont Valley in Italy in 1963, in which more than 2500 people died. But many mass movement events happened in a much smaller scale and therefore it is important to consider smaller landslides in this study as well. Every year a countless number of minor landslides cause big damage on houses and sometimes even humans get killed.

Far reaching changes like intensive farming, excessive use of fertilisers, overgrazing, forest grazing and grass cutting have influenced agricultural land. Another area of concern is the use of alpine land for tourism, which increasingly is at odds with the aims of nature and landscape preservation. On the other hand the resultant change in the face of the landscape typically associated with the Alps has a negative impact on tourism, which is an economic factor. More areas of concern are uncontrolled urbanisation, intensified building activities and exploitation of nature in form of mining, quarries, engineering activities and others, which greatly enhance the chances of slope failure.

This study analyses the human-role in influencing slope instabilities and mass movement processes in terms of landslides. It should be emphasized here, that the study's aim is not to discuss surface erosion processes on slopes. The main questions to be answered in this study are: What are the factors and systems influencing the stability of slopes, how can various types of human activities interfere with the stability of slopes and what are the possible impacts of such events on the human environment?

2. Factors and systems influencing the stability of slopes

A movement on a slope occurs when the downslope component of the forces acting on the earth or rock mass exceeds the strength or shearing resistance of the material. The transition from a stationary hillside to an active slide implies that either the acting force or the soil or rock resistance has changed for some reason. Many types of mass movements occur very sudden and most of the time it is not just one cause for the instability and failure of a slope.

Causes of failure may be divided in two groups: The first group includes all forces which act directly on the slope and are called "external"-causes. These forces lead to an increase of shear stress but do not influence the shear strength conditions of the slope. The second group comprises all such processes and forces, which reduce the shear strength conditions of the slope material, on which the forces from the first group act on. These causes therefore are called "internal"-causes. Internal-causes act predominantly as triggering factors (Bunza & al. 1976). Furthermore the acting forces on a slope may act permanently or episodically, the occurrence of mass movements depends on the latent instability of a slope or the motion sensitivity of the material and the water content, and the water absorbing capacity of the slope material is an important influencing slope stability factor (Örok 1986, Egli 1991).

Changes in the (natural) field of forces lead to the occurrence of mass movements. This indicates that the analysis of a possible increase of the shear stress and/or decrease of the shear strength of the material is the clue for the understanding of stability conditions of slopes. As a consequence it is necessary to determine the factors, which are influencing shear stress and shear strength conditions (Tab. 1). Thereby the role of human activities on the slope's shear stress and shear strength conditions must be identified.

Tab. 1: Factors contributing to (A) an increase of shear stress ("external factors") and (B) an decrease of the material strength ("internal factors") – (after Bunza et al. 1976, Singhroy et al. 2000).

(A) Factors increasing shear stress ("external factors")
● Removal of lateral and underlying support (erosion, previous slides, road cuts, mining and quarries) ● Increase of load (weight of rain/snow, fills, vegetation) ● Increase of lateral pressures (hydraulic pressures, roots, crystallisation, swelling of clay) ● Transitory stresses (earthquakes, vibrations of road traffic, machinery, blasting) ● Regional tilting (tectonic movements).
(B) Factors decreasing material strength ("internal factors")
● Decrease of material strength (weathering, change in state of consistency) ● Changes in intergranular forces (pore water pressure, solution) ● Changes in structure (decrease strength in failure plane, fracturing due to unloading)

The factors mentioned in table 1 may influence a number of systems. These systems are: hydrological system, geological system, geomorphological system, pedological or soil system (e.g.: condition of soil, soil type) and the vegetation system. But because of the interference of different systems with each other, it is never just one system influencing the stability of a slope. A change in the soil structure for example will eventually change the runoff and infiltration rate of precipitation. Or a change in the vegetation cover influences morphodynamical processes on the surface of the slope.

Considering just these possibilities of interactions and dependencies it is understandable that various types of human activities may easily disturb the natural equilibrium of a slope.

3. Types of human activities and landuse influencing the slope stability

Various types of human activities trigger mass movements. Construction activities of hillside housing developments, highways, dams, reservoirs and drainage as well as and utility structures normally involve the movement of huge amounts of rock and regolith. But also undercutting of slopes alter the natural land surface. These topographical changes influence the force system of the slope and may trigger landslides.

In extreme cases, mass movements take place during or immediately following the construction process, but the effects of construction can be very subtle in many circumstances. One typical example: the placement of fill material for a road across a hillside may not, through its own weight, cause the slope to fail, but may interfere with the hydrological system. A change in the morphology and the soil conditions of the hillside may alter the water flow and drainage through the soil, regolith and rock. In this way the weight of the material is perhaps increased or the water pressure is changed in the pores of the soil and regolith or in rock joints. Both consequences can trigger slope failures months or years after the completion of construction (Bolt & al. 1975).

In recent years much attention has been paid to the environmental sustainability of human developments, but there are still various types of human activities and landuse, which have a strong influence on slope stability. The following chapters discuss the most important types of anthropogenic activities, which are considered to enhance greatly the chances of slope failures.

3.1 Agriculture

The impact of agriculture on land, especially in terms of accelerated erosion, is a well known problem. In some areas in the world these higher rates of erosion have influenced the land surface since thousands of years. To describe and understand the impact of agricultural landuse on the stability of slopes it is helpful to study areas where this kind of human impact is relatively recent, as for example in New Zealand.

Barrow (1991) studied areas in New Zealand and the Pacific islands. Steep slopes in this region seem to have been particularly vulnerable to mass movements. One example from Otago, a dry wind swept area in the south of New Zealand, shows that a great disruption of vegetation since the first European settlements (~1850) caused landslides and gullying. Much was caused by the introduction of grazing animals like the red deer and above all by livestock as well as by deforestation for fuel and timber. Before the arrival of man New Zealand had no native grazing mammals, so vegetation was not adapted to survive the pressure placed on it. This is a good example of relatively recent changes on the landscape, but how is the situation in the European Alps?

Studies from Moser (1980) in the provinces of Carinthia and East Tyrol revealed, that more than 90 percent of slope movements in these areas take place in meadows, pastures or arable farmland. This percentage is probably similar in other parts of the European Alps. Intensive farming, excessive use of fertilisers, heavy machinery, overgrazing, forest grazing and grass cutting has influenced agricultural land since many decades or even centuries. All these activities led to changes as: compacting of soil and regolith due to heavy machinery, erosion of soil material (especially humus) due to the change of the vegetation cover and destruction of the closed vegetation cover due to the hoofs of cows, sheep and goats and due to overgrazing. The impact of hoofs may cause the formation of small, slope parallel terraces that may cover whole mountain slopes. The common name for these structures in the Eastern Alps is "Viehgangeln". Especially the destruction of the closed vegetation cover increases the rate of surface erosion and may lead to (mostly minor) slope failures, in terms of slumps or slides. These terraces – for example – act frequently as trigger areas for small landslides during or after heavy precipitation events.

3.2 Forestry

The acceleration of erosion and resulting sediment supply to streams as a result of logging has been documented in many studies. But studies about the influence of forestry on the stability of hillsides are not as frequent. Where soils are steep and shallow and the cut trees do not have the ability to resprout, the soil strength previously provided by tree roots is reduced and the initiation of landslides following logging is enhanced (Gray 1970, ODF 1998).

It is important to notice that different tree species behave different after logging. This means, that species which have roots that do not die after the tree is cut down (e.g. redwood trees and hardwood trees) still help to stabilise slopes (CFPC 1999). Recent studies indicate that the number and size of landslides in logging areas do not increase significantly over a hundred year time period. According to the results from the Oregon Department of Forestry (ODF 1998), there is some increase over natural rates in landslides in logging areas during the first ten years after logging but found fewer in the next 90 years. Thus the influence of logging activities on landslides also depends on the timescale. Therefore it can be stated that because of logging activities, the probability of landslides occurrence is higher just after the trees are being cut down, but the probability at such sites is decreasing at least after ten years.

A huge proportion of the European Alps, about 40%, is still covered with forest. In some regions even up to 70 to 80 per cent of the area consists of forests. But the European Alps are a region of commercial forestry, where intensive commercial forestry has also altered the natural geomorphical system in many places due to the construction of forest roads. Furthermore clearcuts increase the probability of slope failure. The web of forest roads on many forested slopes interrupt the surface and subsurface water flow, concentrating water as runoff in the ditches and culverts. Unless drainage is carefully controlled, saturated roadbeds and culvert outlets often become source and trigger areas of mass movements. Clearcuts and thinned forest canopy expose remaining trees to wind stress increasing the potential of blow down, which in turn exposes bare soil and encourages saturation failures.

Because of the rapid growth and minor demands on soil and other environmental factors, spruce trees (*Picea abies*) are dominating the forests, even though they are causing soil degradation (increase of the acidity of the soil). The roots of this species die after the tree is cut down and thus the stability of the slope will decrease. As a consequence, the probability of slope failures are enhanced after clear cuttings.

While modern forest management practices have increased the frequency and size of road culverts and timber harvest using cable suspension systems has reduced the effects of soil compaction, the large magnitude storms with heavy rainfalls often trigger geomorphic responses from older management features, especially when the event exceeds the 50 year return interval. As a result, the anticipated benefits of modern forest practices are sometimes obscured by disturbances initiated as a result of the lack of maintenance to remaining road and culvert systems or older management practices (Rosenfeld 1998).

3.3 Mining

Landslides triggered due to mining activities are relatively frequent. Many of these failures cause loss of human life. The British Association for Immediate Care (Basics 2000) published a list of major mining incidents of the 20th century with human losses. Of this long list at least 12 major incidents were caused due to human-induced mass movements. The incidents are listed in table 2.

Tab. 2: Human-induced mass movement events at mining sites with major human losses in the 20th century (after the British Association for Immediate Care – BASICS 2000).

Country	Location	Type of mass movement	Incident	Date
Austria	Lassing	Land subsidence (Mudslide)	Lift cable snaps: 10 dead	17.07.1998
Bolivia	Tipuani Mountains	Mudslide	~50 Gold miners killed	11.02.1998
China	Yunnan Province	2 Landslides	227 Gold miners killed	June, 1996
Colombia	Northern Colombia	Landslide	Emerald mine: 17 dead	16.06.1979
Great Brit.	Aberfan, Wales	Landslide	144 people killed	21.10.1966
Philippines	Diat and Diwata	Landslide	150 Gold miners killed	Oct. 1985
South Africa	Orkney	Falling rock	Vaals Reef Goldmine	19.12.1973
South Africa	Randfontein	Rush of mud	Randfontein Gold Mine	20.05.1977
South Africa	Johannesburg	Rockfalls	10 Gold miners killed	Feb. 1992
South Africa	Free state province	Mudslide	22 Diamond miners killed	27.11.1996
South Africa	Welkom	Rockfall	12 Gold miners killed	15.12.1965
USA	Frank, Alberta	Rockslide	70 people killed	29.04.1903

Two well known examples of mass movement events triggered by mining activities listed in table 2 are the rock slide from the Turtle Mountain, Alberta in 1903 and the landslide from Aberfan, Wales in 1966.

The town of Frank in the southwest corner of Alberta, Canada is dominated by the Turtle Mountain, which consists of massive beds of limestone lying on much weaker shales and sandstone. Coal was mined in coal beds in the shale and sandstone layers. Due to this mining, on the 29th of April, 1903 a limestone rockslide developed in the joint planes and quickly reached high velocities, falling a vertical distance of almost 1,000 m to flow 4,000 m across the valley, thereby killing 70 people (Bolt & al. 1975).

Aberfan is a small town in Wales, situated in a coal mining area of the Welsh mountains. In this coal mining region, heaps of excavated debris from the coal mine were being piled on a hillside above the town. The spoil heaps or tips had been there for more than 20 years on top of the local Brithdir Sandstone, a highly porous rock layer. The sandstone contains many springs and several of the tips were placed above these springs. This had led to destabilization of some of the tips in 1944 and 1963 with the result of minor landslides. But at 9:15 a.m. on the 21st October 1966 on one of the seven artificial tips a huge slope failure occurred. About 160,000 m^3 of coal mining waste slumped abruptly on the valley sides and flowed downhill at high speed. The front part of the debris became liquefied and moved as a series of viscous surges down slope. Approximately 120,000 m^3 of debris were deposited on the lower slopes of the mountain and about 40,000 m^3 came to rest in the urban area of Aberfan (Fig. 1). The landslide destroyed part of the town and killed 144 people (Alexander 1993) .

The tip consisted of mine waste debris in different grain sizes. High annual rainfalls, the disturbance of the natural drainage system, unstable slopes and the presence of fine grained so called “tailings” caused the failure in Aberfan (Bolt & al. 1975, Waltham

Fig. 1: Photograph to show the extent of the 1966 Aberfan landslide (Johnes & McLean 1999).

1978). In the case of Aberfan it was not a natural slope which failed, but a human built hill which suffered slope failure.

3.4 Construction activities

Construction activities generally cause a change of the natural topography of an area. These changes of the geomorphology may consequently influence also other systems, mainly the hydrological system. Artificial changes in the geometry of a natural slope and as a consequence the stress conditions are caused either by further weight on the top of a slope (by a house, earth and debris material or a dam), or by undercutting of a slope (due to hillside housing developments or the building of a road). Three different types of construction activities may be considered as destabilisation causes and are discussed here: hillside housing developments, construction of transportation infrastructure and hydraulic engineering activities.

Hillside housing developments: The construction and occupation of houses at the top of a sloping area can cause changes in the groundwater conditions through: the use of cesspools instead of appropriate sewage or drainage collection systems, by watering of gardens, improper water supply, improper drainage collection systems and through changes in natural runoff and drainage patterns of the hillside because of the presence of paved streets and roofs (Rosenfeld 1998).

But also changes of stress and strain conditions on a hillside (e.g. pore pressure changes) due to uncontrolled urbanisation or intensified building increase the incidence of landslides.

Recent development in large metropolitan areas intrudes upon unstable terrain. This has thrown many urban communities into disarray, providing grim examples of the extreme disruption caused by ground failures. In Los Angeles, California for example, failures of hillsides on which houses have been constructed and occupied has not been uncommon. In many cases, these failures, although difficult to investigate, most probably are due to changes in the amount of water present in the normally arid hillsides (Bolt & al. 1975). Because of its significance the well known example from Portugese Bend near Los Angeles is discussed in the next paragraph.

A well studied and described landslide, which was triggered due to various types of construction activities, is the landslide at Portuguese Bend. In 1956 this slow moving landslide was triggered due to housing developments and the construction of road infrastructure. The majority of houses constructed on the endangered hillside employed cesspools rather than a sewer system, so that the wastewater discharged from these houses went straight into the ground in the potential slip zone. The construction of houses and streets disrupted the natural drainage of the area and once slide movement occurred, the breaking of water pipes and drainage pipes gave rise to an increase in the ground water supply.

In addition to this, a highway was built on the endangered slope between 1955 and 1956. This road construction increased the stress on the slope and in August 1956 the mass movement was triggered. In the first 18 years the mass had moved a maximum distance of about 70 m. It was estimated, that about US$ 10,000,000 worth of property damage was caused by the moving mass (Bolt & al. 1975).

This example from Portuguese Bend shows clearly, that a landslide was favoured by hillside housing developments, but triggered due to the construction of transportation infrastructure.

Construction of transportation infrastructure: According to Barrow (1991) there has been considerable increase in transport and communications development across uplands. New highways for example have been built recently in the Himalayans, the

Andes and through the Alps. If constructing transportation infrastructure in mountainous area, it is generally necessary to increase the angle of the slopes on at least one edge of the new route in order to get a plain surface. To get this plain surface either further load and therefore stress is put on the top of a slope due to embankment material, or the slope angle will get steeper by artificial undercutting and removal of material. This reduces the strength of the slope. In both cases the probability of slope failure increases.

Studies from Moser (1980) in southern Austria revealed, that about 30 per cent of all slope movements occur on artificial or at least human modified banks of transportation infrastructure.

Hydraulic engineering activities: When a dam is built across a valley and water impounded behind the dam to form a reservoir, slope failures along the valley sides can develop. Such failures are caused by the saturation of the adjacent rock material (changes of pore pressure, weakening of the material at the base of the hillside) or by the erosive action of waves at the toe of the slopes if they are not protected. Material can be removed in this way in minor amounts but also even a whole mountainside may become unstable (see chapter 4.4.). Furthermore the possibility of soil or rock failures at earth dams itself should be mentioned here.

3.5 Tourism

Nowadays the most important landuse type in the European Alps is tourism. Huge areas within the mountain range are excessively used for tourism.

Tourists have lots of demands: stay somewhere, eat something and do something. Hence tourists need infrastructure such as: hotels, restaurants and shops, transportation infrastructures to travel to and from places, hiking trails, ski-lifts, ski-runs, swimming pools, golf courses and much more. This list indicates the huge variety of possibilities of how tourism and tourist activities directly and indirectly may influence the slope stability. All the mentioned demands cause a huge amount of stress on land; but because of the topographical constraints very often infrastructure has to be constructed on sloping land.

But not just valleys are influenced by tourism, also the mountain environment is under constant stress. In summer thousands of people use chair lifts and funiculars to reach subalpine and alpine regions, where uncounted hiking boots have great negative impact on this fragile environment. Because many people also leave the so-called "beaten tracks", closed vegetation cover may get destroyed, which alters the hydrological system and besides higher erosion rates slope failures may occur. In winter the impact of tourism is even worse. Among a variety of concerns there is also specific interest in the environmental suitability of skiing related infrastructure and skiing activities. The building and maintaining of skiing infrastructure and skiing activities cause huge stresses on the environment. Sharp edges of skis harm the underlying vegetation cover during times of little snow. Heavy machinery, which is used to prepare the slopes for skiing, has tremendous impacts on soil and vegetation.

Due to expansion of ski-areas in the recent past, large portions of forest was destroyed and changed into areas with ski-runs and ski-lifts (Kellerer-Pirklbauer 2001). In many cases it was necessary to change the natural topography. Therefore caterpillars destroyed and changed the shape of hillsides and whole mountainsides. The protecting vegetation and soil cover was harmed or removed. Such impacts alter the stability of slopes and as a consequence slope failures along ski-runs are quite common. This type of slope failures occur especially in spring during the melting period when the water table is high or after heavy rainfall.

Since many ski-areas are already saturated with a dense net of ski-lifts and ski-runs, there is hardly any space left for new projects. The current trend concentrates on the improvement of existing facilities and on the integration of adjacent areas to one complex to increase the potential and the attractiveness of an area or region. With respect to this, several activities may take place concerning specific issues: Increase of transport capacity by densifying the net of ski-lifts and replacing old ski-lifts by more powerful lifts, extending the existing area of ski-runs for the safety and convenience on a ski-run and production of artificial snow to achieve a sufficient snow cover. To produce artificial snow it is necessary to build water reservoirs, dams, water pipelines. All these activities influence the topography again and thus may further reduce the stability of slopes.

4. Examples of human-induced events and their causes from the European Alps

As already pointed out, human-induced slope failures of different sizes are common in the European Alps. Especially in spring and summer many small slides and debris flows cause destruction and due to their minor importance they are – if at all – only mentioned in local newspapers. Yet, because of the high frequency of such mass movement events it is important also to discuss human-induced minor events. Therefore the author is going to discuss two areas in the European Alps, where different types of minor mass movements occurred: the Holzaepfel Valley and the Hauser Kaibling ski-area (Fig. 2).

Unlike minor landslides big catastrophic mass movement events are generally entirely naturally triggered. Many of the big landslides occurred either in the late Pleistocene or in the early Holocene. Because of glacial erosion during the Pleistocene, many slopes became over-steepened. After the glaciers retreated the support of many over-steepened

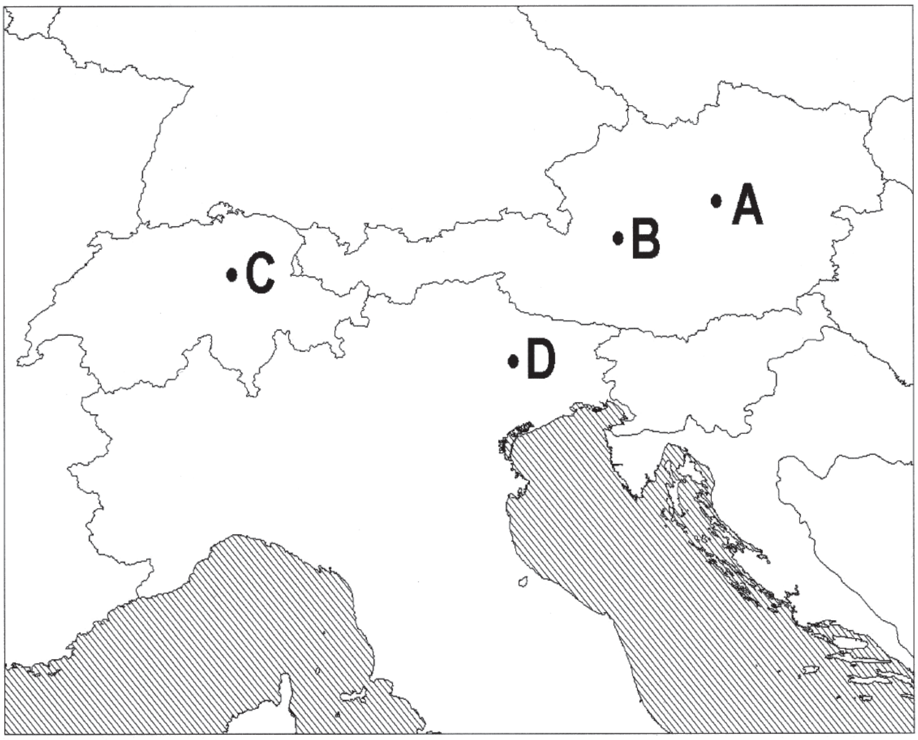

Fig. 2: Locations of the 4 human-induced mass movement events mentioned in chapter 4: A=Holzaepfel Valley, B=Hauser Kaibling ski-area, C=Elm, D=Vaiont.

mountain slopes vanished as well. As a consequence, tremendous landslides occurred – some of them already in the Pleistocene, some of them later in the Holocene. The largest landslides of Europe happened at Flims near the Rhine source in eastern Switzerland, where debris piled up several hundred metres where once a wide valley existed. The huge amount of about 12 km^3 of rocks and debris were moved (Louis & Fischer 1979). Since the slide happened in prehistoric times, there is no human evidence left. More examples of prehistoric huge natural-induced landslides in the Eastern Alps happened at Mount Tschirgant, at the Fernpass and some in the Ötz Valley N and S of Tumpen, particularly at Koefels (Tollmann 1995).

Yet, sometimes human actions reduce the stability of even whole mountainsides and millions of cubic metres of material rushes down valleys. One example is from the year 1618, where 2430 people died when the southern Swiss town of Pleurs was buried by a massive rockfall from the slopes of Monte Conto. Indiscriminate quarrying into the mountain slopes

Fig. 3: Debris filled valley bottom of the Holzaepfel Valley around 1950. Note the partly buried buildings and the almost unvegetated steep slopes with debris cones in the background (by courtesy of WLV, Vienna, Austria).

triggered this rockfall (Waltham 1978). Two more examples, which are described below, are the rockfall in Elm in 1881 and the Vaiont dam landslide in 1963 (Fig. 2).

4.1 Instable slopes and debris flows: Holzaepfel Valley

The Holzaepfel Valley is a small alpine valley, close to the village of Wildalpen in the north of the Austrian province of Styria. The valley is known for the huge amounts of debris, which are covering the valley floor. Once this valley floor was used for agricultural purposes, but due to intensive and unwise logging activities in the whole catchment during the 19th and 20th century, the closed vegetation cover got destroyed. No reforestation was undertaken, thus many slopes, especially slopes with huge amounts of glacial till and debris material, lost their stability. Most of the mass movement events – mainly in form of debris flows – rushed down the valley after the last big clear-cuts in the first half of the 20th century. Another factor for destabilisation of slopes and triggering of mass-movements was a change of the precipitation regime of the area in the 20th century. Heavy rainfalls occurred more often and therefore more potential for triggering slope failures was available (Strasser 1998).

Transported material from higher areas of the drainage catchment covered the agricultural land at the valley bottom with a thick layer of debris. Figure 3 shows the situation at the valley floor and the neighbouring hillside around 1950. Debris from the adjacent slopes and the side valley deposited on the valley floor, thereby destroying a farmhouse and the agricultural land around it. Clearly visible in the same figure are the almost unvegetated steep slopes behind the buildings. Today, a broad braided river is covering the whole width of the valley floor in some sections. No agricultural use of the valley floor is possible and most adjacent slopes are again covered with mature forest (Fig. 4). Yet, many slopes with till material depots, especially in the valley bottoms of small side

Fig. 4: The situation of the Holzaepfel Valley in 1998. The whole valley floor is covered with debris. The adjacent slopes are covered with mature mixed forest. (by courtesy of Herwig Proske, Joanneum Research, Graz, Austria).

valleys, are unstable and must therefore be considered as potential area of release for further landslide events.

The Holzaepfel Valley is a good example of long-term effects of human activities on slopes. Human actions reduced the stability of slopes and thus the threshold to trigger mass movement events was lowered. Even today many till material depots in side valleys are unstable and due to the more frequent occurring heavy-rainfalls the instability problem is getting even worse and more debris flows may occur in the future.

4.2 Landslides at ski-runs: Hauser Kaibling ski-area

The Hauser Kaibling ski-area is a typical major ski-area in the Austrian Alps, situated in the northwest of the province of Styria, close to the village of Haus im Ennstal. During the last few decades many ski-lifts and ski-runs were constructed or modernised and today vast areas of the northern mountainside of the Hauser Kaibling are used for skiing purposes. These landuse changes influenced the stability condition of many slopes in the whole ski-area. Generally, the topography of areas of ski-runs but also ski-lifts may either be natural (no artificial change of the topography) or human-modified (Mayer 1990). In the Hauser Kaibling area most ski-run areas are of the second type.

The main reason for destabilisation at the study area are changes of the natural topography due to digging off and relocating of slope material during the construction of ski-lift and ski-run infrastructure. But also the building of supply-roads for the skiing infrastructure caused slope instabilities. Further reasons for altered stress conditions on slopes are changes in the hydrological system (altered groundwater flow, higher surface runoff), in the pedological system (destruction of soil structure due to heavy machinery) and the vegetation system (destruction of forest and closed vegetation cover) (Kellerer-Pirklbauer 2001).

Fig. 5: A shallow translational slide on the upslope edge of a human-modified ski-run in the Hauser Kaibling ski-area. Note the ~20 cm long field book for scale in the centre. The white arrows indicate the area of release. The underlying bedrock material (schist) is visible. The black error indicates the landslide deposits (Kellerer-Pirklbauer 2001).

Hence morphodynamical processes in terms of small landslides are typical on the edges of human-modified ski-runs. A few minor slope failures, for example, occurred in spring 2000, when soil material was saturated from meltwater. Two examples are described below:

The first example is shown in figure 5. This figure shows a translational landslide, which occurred on the upslope edge of a human-modified ski-run. Because of removal of rock material and artificial steepening of the natural slope during construction activities in summer 1999, the slope's shear strength was decreased. Until spring 2000 the modified slope was stable but due to an increased water pore pressure in the snow-melting period, shear stress exceeded eventually shear strength and a translational shallow landslide occurred (Kellerer-Pirklbauer 2001). In this case the landslide itself was not human-induced, but human actions favoured the event.

The second example is shown in figure 6: In this case a short but broad slump or rotational landslide occurred on the topographical lower margin of a human-modified ski-run. This ground failure was mainly caused due to high water pore pressure from meltwater. Because the artificial margin of the ski-run was just about 2 m higher than the natural margin and the gentle slope below the ski-run, the probably slow moving mass stopped already at the bottom of the short ski-run slope.

Similar examples of mass movements in a ski-area are discussed by Mayer (1990), who studied the ecological impacts of ski-runs in the Gasteiner Valley in Salzburg, Austria.

4.3 The rockfall in Elm

In 1881 a big human-induced rockfall happened near Glarus in eastern Switzerland. A large part of the Tschingelwand rock wall (also called Plattenberg) crashed down over 500 meters to the valley floor, where the mass changed its type of movement into a huge rock avalanche before stopping its movement near the village centre of Elm. Astonishingly the rockfall was almost entirely the work of man (Waltham 1978).

Order of events: A large quarry had been cut into the slate of the mountain, forming a big gash with a length of almost 200 m and a depth of about 70 m. The overhanging upper wall of the quarry was not supported and as a consequence by 1876 the sagging and creeping movement of the mountain was made apparent by the opening of great curved

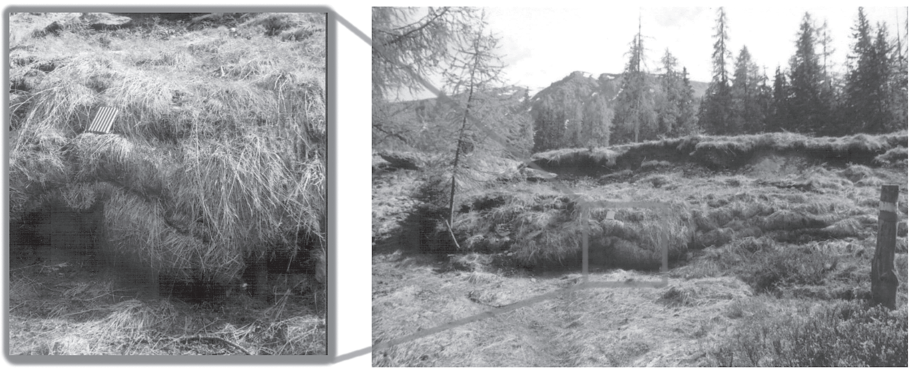

Fig. 6: A rotational landslide on the topographical lower margin of a human-modified ski-run in the Hauser Kaibling ski-area. Field book for scale (20×12cm). The landslide mainly consists of fine material. Remarkable is the roll-in structure of the head of the moved mass (Kellerer-Pirklbauer 2001).

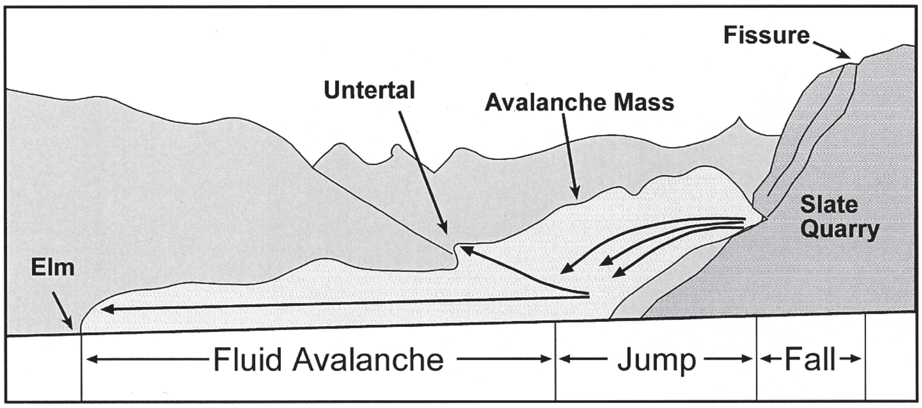

Fig. 7: Schematic cross-section of the rockfall in Elm (based on ABBOT 1996).

fissures higher up the mountain slope. In 1881 the fissures were still growing and at one place absorbed already a small stream. By 8th September 1881, the main fissure was over 30 m wide and creep rate and creaking noise from the rockwall were such that quarry work was suspended.

At 5:15 p.m. on the 11th September a small landslide occurred above the quarry. People in the village of Elm below the mountain wall watched in awe, fear and amazement. Seventeen minutes later another small slide was released and about 20 people were killed. And then, for about four minutes, the mountain was still. Until 5:36 p.m., when the whole mass of unstable slate above the quarry broke away. It crashed on to the quarry floor and then almost took off out into the valley like a great waterspout. The rockfall turned into a huge rock avalanche or high-velocity flow with accompanying high winds. Over 11 million m^3 of rubble crashed to the valley floor, bounced about 120 m up the opposite wall, turned and in less than a minute rushed down the valley around 1.5 km before coming to a sudden stop (Fig. 7). Fortunately the rock avalanche missed the centre of Elm, but 116 people lay dead under the debris. Furthermore 90 ha of arable land, 22 residential houses, barns, buildings and machinery from the quarry and the quarry itself with half a million slate tables was destroyed (HEIM 1932, WALTHAM 1978, BOLT & al. 1975). Within a few decades the destroyed land was recultivated, because the landslide deposits were easily breakable and hence the surface of the landslide was smoothed (HEIM 1932). Today, the debris cone on the food of the Plattenberg is the main visible witness of this devastating event (Fig. 8).

Of great interest is the spectacular take-off of the rock mass from the quarry floor. It is quite feasible that the Elm rockfall could have ridden down the valley on a cushion of trapped air. This theory seems to be confirmed because it managed to override some patches of vegetation almost without disturbing them. But there is also strong evidence that the debris flowed as it was fluidised by air and dust inside it. Further information about the order of events and the behaviour of the moving mass is to be found in WALTHAM (1978), ABELE 1974 and especially in HEIM (1932).

Causes of failure: Because of improper mining activities at the slate quarry this huge rockfall occurred. Naturally the Tschingelwand rock wall seemed to be stable. Especially because the dipping of the slate layers, which can be considered as penetrative discontinuities, was towards the mountain and not from the mountain out to the surface (HEIM 1932). The geological situation favoured a stable rock wall. Therefore the whole slope failure was caused due to unwise and improper human actions.

Fig. 8: The forest and meadow covered debris cone on the foot of the Plattenberg of the 1881 rockfall in Elm, Switzerland (Swissfot).

4.4 The Vaiont dam landslide

The most destructive human-induced mass movement in the European Alps occurred on October 9th, 1963, at the Vaiont Dam in northern Italy. This largest dam disaster in the world was a case of ignorance and inattention to geology.

Location and background: Vaiont is located in the south-eastern part of the Dolomite region of the Italian Alps, near Belluno and about 100 km north of Venice (Fig. 9). The dam was built as a part of the on-going, post-war development of Italy in order to provide power for the rapidly expanding north Italian cities of Milan, Turin and Modena. The dam was built in 1959–1960. The completed doubly curved arch dam was 265.5 m tall, one of the world's highest dams. An elongate reservoir formed behind the dam.

The dam was built across the Vaiont Valley, a deep and narrow gorge. The geological setting of the valley was well researched and fully understood. The generalised geological structure is of a syncline cut by the Vaiont valley (Fig. 10). The syncline is based in Middle Jurassic (Dogger) limestone, overlain with successive layers of upper Jurassic (Malm) limestone with clay and Cretaceous limestones (Jaegar 1980 and Petley 1999). The more recent study from Semenza and Chirotti (2000) shows a slightly different generalised geological structure.

Order of events before the landslide: The following paragraphs are based on studies by Petley (1999), Mueller (1964) and Longwell & al. (1969). Already during the construction of the dam the chief engineer was concerned about the stability of the left or southern bank of the dam. A number of reports were compiled on this during 1958 and 1959, which identified a possible ancient slide on the right or northern bank (Fig. 9). Whilst there was a big discussion of the stability of the valley walls about the inclined synclinal form of the strata and the possibility of old slides in this area, it was concluded

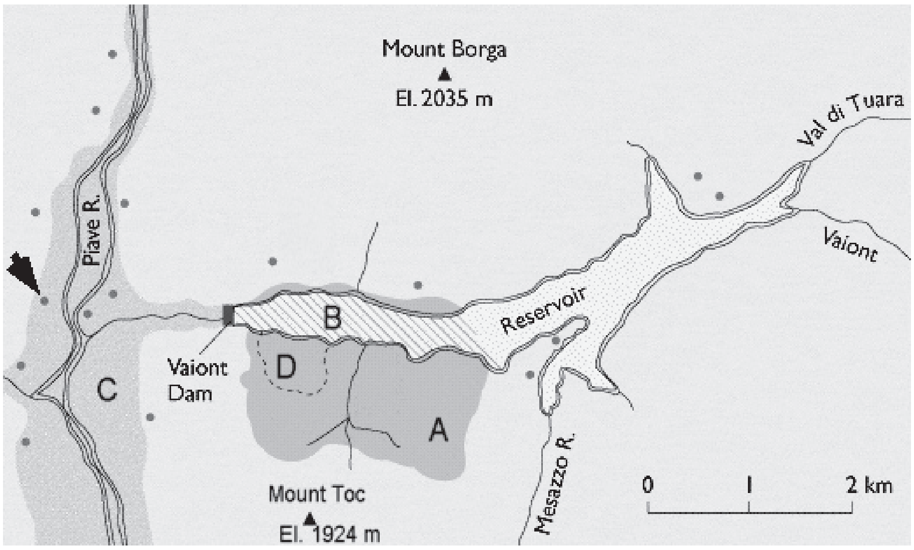

Fig. 9: Map showing the location of the Vaiont dam and reservoir and extent of the Vaiont Dam Disaster – October 9th, 1963. (A) Limit of 1963 landslide; (B) Area filled by 1963 landslide; (C) Limit of flood, downstream from landslide; (D) Limit of 1960 landslide; Arrow indicates the location of Longarone (Bromhead 2000).

that deep seated landslides were extremely unlikely as: (1) areas of weakness were not identified in the three test borings, (2) it was assumed that any shear plane would have a "chairlike" form that would exert a "braking effect" and (3) seismic analyses had suggested that the banks consisted of very firm in-situ rock with a high modulus of elasticity. Smaller slides in the looser surface layers were considered to be likely, although volumes and velocities of movement were expected to be low.

Filling was initiated in February 1960 before the final completion of the dam, which occurred in September 1960. By March 1960 the level of the reservoir had reached 130 m above the level of the river, when the first small detachment occurred. Continued filling of the reservoir occurred whilst monitoring of the movements on the slopes was undertaken. In October 1960, when the depth of the reservoir had reached 170 metres, a rapid increase in the rate of displacement to approximately 3.5 cm per day was observed. At the same time a huge joint of 2 km length opened up, defining an area about 1.7 km long and 1 km wide, indicating that a very large landslide had been mobilised. On 4th November 1960, with the depth of the reservoir at 180 m, a large mass movement occurred when 700,000 m^3 of material slid into the lake in about ten minutes (Fig. 9). As a result the level of the reservoir was gently dropped back to 135 m. At this point movement reduced to close to 1 mm per day. At least at that stage it was realised by the engineers of the dam that the large mass of the left bank was inherently unstable.

Thus it was decided that an attempt could be made to gain control of the sliding mass by varying the level of water in the reservoir whilst controlling the joint water thrust within the rock mass with the help of drainage tunnels. It was realised that this could lead to the blockage of that section of the reservoir by the landslide mass. However, the volume of water after a big landslide event in the unblocked upstream section would still be sufficient to allow the generation of electricity. Hence a bypass tunnel was constructed on the opposite (right) bank of the moving mass such as if the reservoir was divided into two sections the level of the lake could still be controlled.

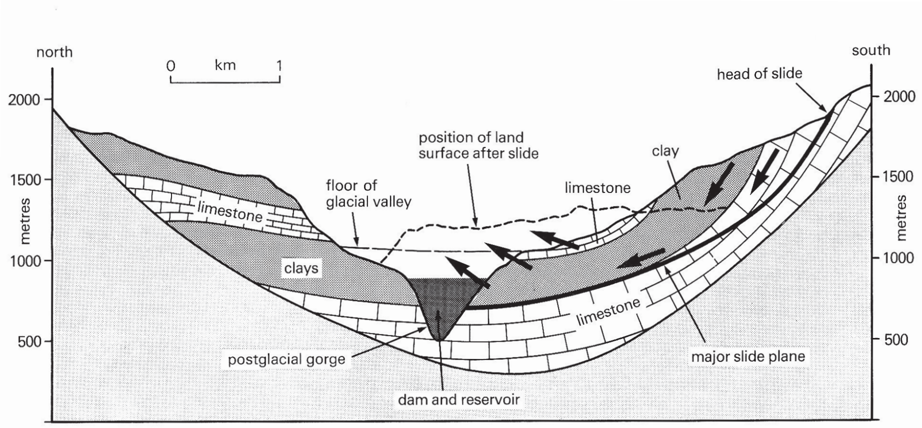

Fig. 10: Schematic N-S cross-section of the Vaiont valley and the Vaiont dam landslide (Kiersch 1964).

It was assumed that by elevating the level of the reservoir in a careful manner movement of the large landslide mass could be initiated. Altering the level of the lake could control the rate of movement. It was realised that if a final sudden movement might occur, and as long as the movement did not exceed a rate that would lead to the filling of the reservoir by the landslide in ten minutes or less, over-topping of the dam would be avoided.

However, between November 1960 and October 1963 the rate of movement was primarily influenced by the water level of the reservoir which was gradually increased over this period. In late September 1963, the water level was slowly dropped to bring the rates of creep back under control. By October 9th 1963 a depth of 235 m was reached. Excessive precipitation in early October caused the weight of the hillside to increase as the ground became water saturated. The water level of the reservoir also caused the ground-water table to be high, which also saturated some of the rock in the mountainside and decreased its strength. Velocities of movement continued to slowly increase, and by October 9th maximum rates of 20 to 80 cm per day were recorded. The engineers attempted to lower the level of the lake. Even though the lake floodgates were opened, the lake level continued to rise. This indicated that the water in the reservoir was being displaced by the slow creep of the impending landslide.

Catastrophic failure: At 10:38 p.m. on October 9th, 1963 catastrophic failure of the 1.8 km long and 1.6 km wide landslide occurred. This tremendous mass on the northern slope of Monte Toc, consisting of an estimated 240 million m^3 or 0,24 km^3 (Longwell & al. 1969), slid approximately 500 m northwards at up to 30 m per sec. This movement was setting even seismic waves that were recorded throughout much of Europe.

Within about 1 minute, debris had filled the reservoir and had piled up to more than 150 m higher than the water surface. The mass completely blocked the gorge to a depth of up to 400 m (Fig. 11). At the time the reservoir contained 115 million m^3 of water. Air compressed by the rapidly flowing debris, water and rock masses moved up the opposite wall of the reservoir where it destroyed the village of Casso, 260 m above the former lake level, before spilling over the dam by approximately 100 m. The water, estimated to have had a volume of about 30 million m^3, then rushed down to Val Serpentine, where it almost completely destroyed the large village of Longarone (Fig. 9). The smaller rural villages of Pirago, Villanova, Rivalta and Fae were totally destroyed . In total about 2500 lives were lost. All of this occurred in about seven minutes. The disaster came too fast to allow the slightest chance of escape. Remarkably the dam remained

Fig. 11: The Vaiont landslide: Note the rock mass in the centre of the valley, the area of release (covered partly in snow) and the transition zone to the left and the residual lake at the left bottom corner of the photo. View of the landslide from upstream to West (Bromhead 2000).

almost unbroken by the flood and and is still standing today (Petley 1999, Longwell & al. 1969 and Erisman & Abele 2001).

The disaster probably would have been far less serious, if the reservoir had not been present. But the sudden filling with rock material displaced a huge volume of water, which caused this catastrophic event.

Causes of failure: Since the catastrophic landslide, a huge range of work has been undertaken on the causes of the failure. Initially there was a large amount of speculation about the location of the sliding surface, but more recent studies have confirmed that it was located in thin (5–15 cm) clay layers in the limestone. It is claimed by some that as such it represents a reactivation of an old landslide (Hendron & Patten 1985 and Pasuto & Soldati 1990), whilst others claim that it was a first-time movement (Skempton 1966 and Petley 1996). It is likely that increasing the level of the reservoir drove up pore pressures in the clay layers, reducing the effective normal strength and hence the shear resistance. The chair-like form of the shear surface created resistance to movement. Dropping the level of the reservoir caused hydraulic pressures that increased the stresses as water in the jointed limestone tried to drain. It has been estimated that the total thrust from this effect was 2–4 million tonnes (Mueller 1964). Failure occurred in a brittle manner, causing catastrophic loss of strength. The speed of movement is probably the result of frictional heating of the pore water in the clay layers (Voight & Faust 1982 and 1992).

It can be concluded that two conditions had contributed greatly to the movement: (1) an unfavourable geologic situation (general instability) and (2) the presence of the reservoir (trigger effect). Summing up, both natural conditions and human activity were involved in this tragic event.

5. Discussion and conclusion

The relationship between mass movements and landuse show that mass movements are not confined to a particular landuse type. There is also no relationship between a particular mass movement type and a particular landuse type. These facts indirectly point out that natural conditions of a slope prior to human interference play an important role. If a slope, because of its natural conditions, is little or not at all landslide-prone, human actions has to be very crucial to cause a landslide (e.g. Elm). On the other hand, if a slope is prone to be unstable, disturbance of the stability conditions of the slope due to even minor human actions could lead to slope failure (e.g. Hauser Kaibling).

The paper clearly shows, that many landuse practices have the potential to reduce the stability of slopes and trigger mass movement events. Examples from different mountainous areas of the earth indicated, that especially agriculture, forestry, mining, construction activities and tourism have a huge impact of slope stability conditions.

Examples from minor human-induced mass movement events described typical landuse situations in the European Alps in the past and at present. The first example described the impact of unwise logging activities in a small catchment, which caused unstable conditions of slope sediments. Hence, numerous landslide events buried the once fertile valley floor. The second example stressed the impact of the construction of human-modified ski-runs on slope instabilities.

Catastrophic human-induced mass movements are rare, but if they occur big damage is caused. Two such events in the European Alps, the Vaiont dam landslide in Italy and the rock fall in Elm in Switzerland, showed what could happen in the worst case to human life and human properties.

Summarizing, this work demonstrated what may happen if humans do not consider natural force conditions of slopes and what has to be considered, in order to minimise the amount of human-induced mass movements.

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