Landslides and cascading effects on Madeira Island

Erdrutsche und Kaskadeneffekte auf der Insel Madeira

Hieu T. Nguyen[1], Tómas M. Fernández-Steeger[1], Thomas Wiatr[2], Rafig Azzam[1]

[1] Department of Engineering Geology and Hydrogeology, RWTH Aachen University, Aachen, Germany
[2] Institute of Neotectonics and Natural Hazards, RWTH Aachen University, Aachen, Germany

Abstract

Heavy rainfall on February 20, 2010 triggered numerous shallow rapid landslides across Madeira Island. Most failures started as debris slides or avalanches at high elevations and transformed into debris flows which rushed downslope into populated coastal areas. The exceptional storm event induced multiple landslide types which show the relations of a cascading effect between preceding landslide processes and triggered successive landslide processes. Cascading effects taken place as large-scale shallow landslides were subsequently channelized into debris flows, which in turn transformed into linked-chains of debris flows by the remobilization of older deposits. The cascading effect continued as channelized debris flows abruptly or transitionally diluted into abrasive hyperconcentrated flows, triggering further slope failures by removal of the lateral support of adjacent slopes. At abrupt changes to low flow velocities and low water-to-sediment ratios, hyperconcentrated flows formed temporary closures, causing inundation and redirected flows. A secondary cascading effect took placed as those flows caused further closures with repeated effects for adjacent areas. Especially in Ribeira Brava and Funchal City, the severity of the landslides impacts resulted from the combination of debris slides, debris avalanches, debris flows, hyperconcentrated flows and flooding.

Keywords: Cascading effects, landslides, hyperconcentrated flows, Madeira

Zusammenfassung

Am 20 Februar 2010 lösten itensive Niederschläge zahlreiche Erdruschte auf der Insel Madeira aus. Hangmuren in den Hoch- und Gebirgsstufen der Insel wandelten sich in Talmuren um, welche hangabwärts in besiedelte Küstengebiete vorstießen. Die qualitative Prozessanalyse der Rutschungen zeigen, dass ein Kaskadeneffekt zwischen vorangehenden und nachfolgend ausgelösten Erdrutschen, Hangmuren und Talmuren stattfindet. Nach erster Transformation oberflächlicher Erdrutschen hin zu Hangmuren entwicklen diese sich zu mehrere aufeinanderfolgende Talmuren durch die Mobilisierung vorangegangenden Ablagerungen. Die Verlagerungsprozesse zeigen einen graduellen oder abtrupte Tranformation zwischen Murgang, murartigen Feststofftransport, fluviatiler Feststofftransport und Hochwasser auf, deren abrasiver Charakter sukzessiv zu Hangunterschneidungen und letztlich weitere Rutschungen führte. Bei abrupten Änderungen zu geringere Fließgeschwindigkeiten bildeten sich Murköpfe aus, wodurch das Umland überschwemmt und der Oberflächenabfluss umgeleitet wird. Kaskadierend finden in angrenzenden Bereichen weiter Verklausungen mit wiederholten Auswirkungen statt. Insbesondere in Ribeira Brava und Funchal richtete das schwere Schäden an.

Schlüsselwort: Kaskadeneffekte, Rutschungen, Muren, Madeira

1 Introduction

Madeira is a mountainous island, located in the eastern subtropical area of the North Atlantic Ocean. The entire island is characterized by canyons in a volcanic landscape of high mountain ridges with ravines and steep deep valleys which trend radially from the central part of the island toward the coast. The coastline consists of rocky cliffs interrupted by river deltas, shingly beaches and a large theatre open towards the south in the central part of the island. Due to its orography, the mountains act as an effective barrier between the north and south side of the island, giving both completely different climatic characteristics and different exposures to erosive agents.

Natural disasters by landslides and floods are frequent events on Madeira Island; they are usually of single spatial occurrence and interminable to record over time. Relevant rain-induced hazards are floods, landslides, debris flows and tsunamis caused by coastal rock slides (Rodrigues & Ayala-Carcedo, 2003). During recent years a systematic survey and mapping of these processes has been carried out.

On 20 February 2010, an exceptionally storm event took place after a prolonged rainy season on Madeira Island (Fragoso et al., 2012). Strong south-westerly winds brought torrential rain, impinging on the islands geography. Encountering already wet antecedent ground conditions, a large total amount of high intensity rain triggered primarily shallow rapid landslides during this storm event. As heavy rainfall began across southern Madeira, low infiltration rates of rainwater lead to a rapid surface runoff and stream flows that rose quickly in response to the rainfall. Intense flooding followed the heavy rainfall, primarily along the drainage basins belonging to the southern flank of the island. Severe water flows swept woody debris and sediments, including material from landslides, downslope in the river valleys. The debris clogged channels which created temporary closures (Figure 1). This caused widespread deposition of mud and debris, and floodwaters inundated the surrounding areas. Inundation was especially severe in the city centers of Funchal and Ribeira Brava. It was estimated that as a result of this large number of landslides, a volume of at least 250000 m³ of solid material was deposited in the Funchal urban areas (SRES, 2010).

As the storm event of 20 February 2010 triggered numerous landslides, the high numbers of events allow the characterization and interaction of different landslide processes.

Fig. 1: A debris flow blocked a channel with huge boulders and entrained cars.

Abb. 1: Von einem Murgang durch große Blöcke und mitgerissene Fahrzeuge blockierte Kanal.

2 Landslide characterization

During the storm event, most of the triggered landslides were rockfalls, debris slides, debris avalanches, hyperconcentrated flows, debris flows or complex debris slide-flows which were open-slope or channelized (Nguyen et al., 2013). Usually initiating at places where shallow soils overlie bedrock, most of them were observed on gentle to moderate slopes of intensely weathered volcanic bedrock in areas above the timberline. The slides and avalanches were characterized by unconsolidated rocks and soils that moved downslope along a shallow failure plane. The vast majority of the slides and avalanches have the following common features: On open-slopes, landslides formed vegetation-less depressions in the head zone and if present, irregular hummocky deposits in the accumulation zone. They also left a cover of debris, including boulder size rocks on straight landslide traces between the head and accumulation zone. The boulders were sourced from either the exposed and weathered bedrock, or locally incised shallow bedrock gullies. Beneath the timberline, slides and avalanches were characterized by shallow niches leaving long narrow tracks through denuded vegetation (Figure 2).

For channelized landslides, most of them started as debris slides or avalanches and quickly transformed to debris flows as their deposits of loose materials comprising wood, rocks and boulders moved downslope along gullies or channels. They share in the head zone the same characteristics like slides or avalanches but along their traces were long stretches of bare, unstable channel banks that have been scoured into the ground by liquefied landslides of unconsolidated, saturated debris. It is assumed that after an initial failure, the related landslide volumes have been directly liquefied into debris flows being in terms complex debris slide-flows (Figure 2).

Fig. 2: Example of open-slope and channelized debris slides in the high mountainous areas.

Abb. 2: Beispiel für Erdrutsche in den Hochlagen.

Coarse-grained debris flows were also common as they evolved from single slope failures, coalescence of superficial debris slides or in stream channels when the slide material or prior deposits incorporated a lot of water and gained momentum. The material comprising the debris flows ranged from clay to boulders with a large amount of organic material such as timber. The debris flows have been recognized by poorly sorted lateral levees or rarely, by an intact fan of a debris flow fronts, body and tail.

Hyperconcentrated flows are high-discharge flows of low water-to-sediment ratios in which turbulence is not the only sediment-support mechanism. They showed a multiple phase stream flow behavior where coarser sediment, fines and water travelled at different velocities. Observed hyperconcentrated flow deposits were generally homogeneous, matrix-supported with weak sorting characteristics by exhibiting bimodal clast fabrics.

In addition to the described landslides, single or clustered rockfalls occurred along roads next to steep slopes. They were characteristically of small volume and scattered all over the island.

3 Cascading Effects

In contrast to the hazard of a singly occurring landslide event, the exceptional storm event triggered multiple landslide types which required an analysis of the relations between the different hazard types. Kappes et al. (2012) pointed out that for dealing with relations between different hazard types neither a uniform conceptual approach nor a generally used terminology is applied. To this, the process.

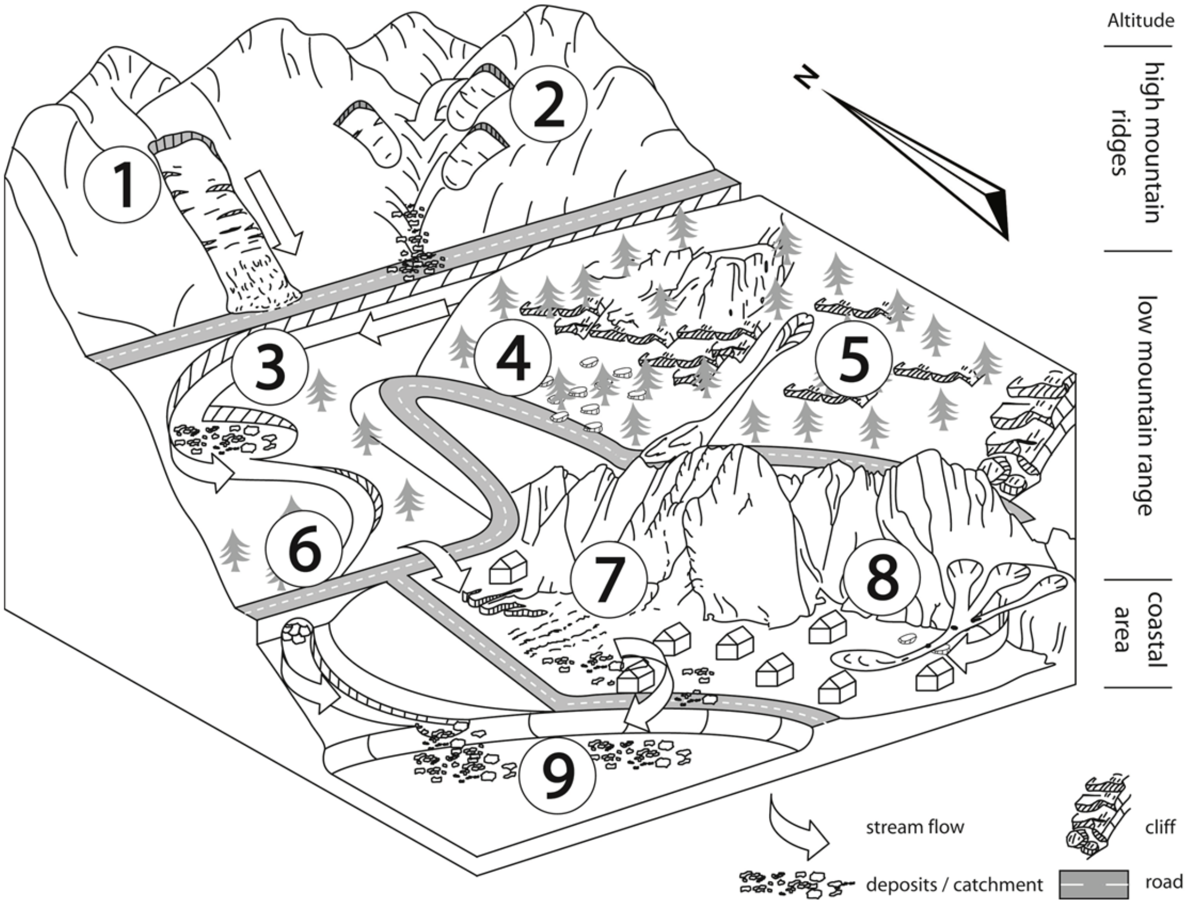

Fig. 3: A Sketch of the three susceptible areas zoned by altitude. At the high mountain ridges, heavy rainfall triggered (1) open-slope or (2) channelized debris slides which transformed quickly into (3) debris flows, following downslope the drainage basin. In the lower mountain range, the occurrence of (4) rockfalls were noticeable and (5) the shape of debris slides changed to shallow niches with long narrow tracks through denuded vegetation. Closer to the coastal areas, (6) debris flows formed temporary closures, causing local inundation and (7) redirected flows which left the drainage channels and entered the road system. At the distal end, (8) huge volumes from the coalescences of landslide material were deposited (9) in the urban areas.

Abb. 3: Skizzierte Einteilung der rutschungsanfälligen Bereiche. In den Hochlagen lösten schwere Regenfälle (1) Erdrutsche aus, welche oftmals in (2) Rinnen kanalisiert wurden und sich schnell in (3) Murgänge umwandelten. In den Mittellagen treten neben (4) Steinschlägen vor allem (5) Hangmuren auf. Im städtischen Gebiet erfolgten durch Verklausung oder durch (6) Murgänge blockierte Gewässerengstellen lokalen Ausuferungen bzw. (7) Überschwemmungen des tiefer gelegenen Straßennetzes. (8) Die von zahlreichen Erdrutschen stammenden Erd- und Gesteinsmassen wurden (9) im städtischen Gebiet abgelagert.

for triggering of one hazard by another, leading to a subsequent hazard event is referred as a cascade effect. In close terms, a cascade effect deals with the interconnection between a preceding process and a triggered successive process. However, it also implies an interaction, indicating a mutual influence between two or more processes. These have usually unexpected effects and pose threats that are not captured by means of separate single-hazard analyses (Kappes et al. 2012).

Based on the investigation to characterize landslides on natural terrain in Madeira Island, and to determine the statistical correlations between the number of landslides and the natural factors contributing to their initiation (Nguyen et al., 2013), a qualitative analysis of individual chain processes had been applied. It was possible to identify chains of hazardous events and to conceptually assign different concurrent hazards in a spatial relationship.

4 Discussion

The study area can be divided roughly into three regions of landslide occurrence (Figure 3). From top to bottom and from inland to littoral, the first region is the central high mountain ridges above the timberline where stream development and erosion have formed high north-south elongated ridges with long slopes and steep V-shaped drainage channels. The gradient of many of these channels increases sharply from the main channel to the ridge. The headwall region is covered with only a shallow soil mantle of precarious stability, and exposed bedrock is present. The second region is a forest belt at low mountain range with altitudes between 800 m and 1200 m, which is bounded by the high mountain ridges further upslope. The slopes flank perennial stream channels in deep valleys, which link the higher central region to the coast. The third region extends from the littoral zone up to an altitude of 800 m. With the exception of the shingly coastal strip of Funchal City, the coastline is made up of high steep sea cliffs. With gentle slopes beginning at the coast, areas beyond 300 m elevation quickly change into high and steep slopes similar to the rest of the island. The confluence of the perennial stream channels forms the main rivers of the island, running downslope in natural riverbeds until they enter canals in urban areas closer to the coast. These three regions are linked by one drainage system which originates in the first region and ends in the third region. As a result, discharge of the large volumes of rainfall in the high mountain ridges area increased sharply at lower mountain range and peaked during the storm event up to 663 $m^3\ s^{-1}$ in the coastal areas (SRES, 2010).

Beginning in the headwall region, a cascading effect took placed as large-scale shallow landslides were subsequently channelized in intermittent gully channels. Coalescence further downslope frequently caused the landslides to transform into debris flows because of a substantial increase in water content. Either by the confluence with further debris flows or by the high influx of water, the cascading effect continued due to the remobilization of older fluvial or landslide deposits down to the bedrock. It caused linked-chains of debris flows, which received an increased sediment supply through subsequent remobilization of prior landslide deposits. Following downslope the drainage basins, the debris flows joined torrential stream flows. Due to the abundant sediment supply and high magnitude of surface runoff, channelized debris flows developed into hyperconcentrated flows by dilution with water or less concentrated flows.

In the second region, heavy rainfall triggered landslides at the valley flanks with similar transformation process into debris flows like in the headwall region. Usually originating from single slope failures, debris flows along gullies were observed as they transported loose material such as woody debris, rocks and boulders downslope to the perennial stream channels. With the concurrence of floods, debris flows transformed into hyperconcentrated flows merging with those originating from the higher central areas. Further cascading effects too placed as abrasive stream flow eroded river margins with the subsequent removal of lateral support of adjacent slopes, causing rectilinear low to moderate slope failures.

In urban areas the original riverbeds have been channelized in artificial canals, often additionally narrowed by bridges or elbows. Due to the flow properties of hyperconcentrated flows, a downstream segregation of coarser grain sizes in highly concentrated debris flows took place. In several cases, the canals were filled with landslide material which subsequently formed temporary closures, causing local inundation in surrounding areas. If deprived of a direct drainage route the flows were redirected into the road systems causing the following cascading effect. They showed complex flow architectures with an abrupt or gradational transition between debris flows, hyperconcentrated flows or normal stream flows. Their deposits buried houses and streets, and at abrupt changes to low flow velocities and low water-to-sediment ratios, further closures were caused by debris flows with repeated effects for adjacent areas.

5 Conclusion

The severity of the landslides impacts resulted from the combination of debris slides, debris avalanches, hyperconcentrated flows, debris flows and flooding. Due to the general identification of possible relations of a cascading effect between a preceding landslide process and a triggered successive landslide process, it was possible to determine the spatial location of these interactions. Furthermore, a secondary cascading effect took placed as spreading spatial reach of hyperconcentrated flows caused severe damage.

These flows began in artificial canals, spread to adjacent urban areas and then to more distant urban areas causing devastation. Areas which were considered to be safe were vulnerable to the impact of the hyperconcentrated flows due to unexpected flow and stream patterns. Because of that protection measures in these areas were insufficient or non-existent. At the distal end of the main rivers, boulder accumulation in-filled harbor basins and jetties and covered the level plain regions within urban areas.

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