Case Histories for the Investigation of Landslide Repair and Mitigation Measures in NW Germany

Annika Wohlers, Thomas Kreuzer, and Bodo Damm

Abstract

To understand the complex interactions between landslide risk, public and private risk awareness, including land use practices and repair and mitigation measures in a complete manner, case histories were developed and analyzed using the example of the highway network of the Lower Saxon Uplands, NW Germany. The case histories utilize datasets extracted from the German landslide database that includes information of historical and current landslide impacts, elements at risk as well as land use practices and provide an overview of spatio-temporal changes in the exposure and vulnerability to landslide hazards over the past 250 years. For the developed case histories the recorded landslide events were categorized and classified at representative sites, according to landslide types, processes, and damages as well as applied repair and mitigation measures. In a further step, data of recent landslides are compared with historical and modern mitigation measures and are correlated with concepts of risk management. As a result, it is possible to identify some complex interactions between landslide hazard, hazard awareness and damage impact. The case histories show that especially since the last 20 years public risk awareness rose due to an apparent increase in landslide frequency and magnitude at some sites. Before the 1990s landslide mitigation measures were mainly low cost prevention measures such as the removal of loose rock and vegetation, rock blasting, catch barriers, and temporal or perpetual traffic lane closure. Recently there is a shift towards the implementation of expensive mitigation measures in order to minimize landslide occurrence. Local decision makers increasingly invest in expensive long-term stabilization projects like soil anchoring, rock nailing, and steel-reinforced concrete walls.

Keywords

Structural landslide mitigation • Central Europe • Case histories

A. Wohlers (✉) · T. Kreuzer · B. Damm
Applied Physical Geography, University of Vechta,
Driverstraße 22, 49377 Vechta, Germany
e-mail: Annika.wohlers@uni-vechta.de

T. Kreuzer
e-mail: Thomas.kreuzer@uni-vechta.de

B. Damm
e-mail: Bodo.damm@uni-vechta.de

Introduction

Landslides occurring in the German Uplands, NW Germany are usually restricted to small areas with small to medium volumes involved. Nonetheless, the consequences of landslides impose a high risk to the public by disrupting essential infrastructure. Little is known about social and economic

impacts of landslides regarding infrastructures due to the complexity of the resulting economic losses (e.g., Klose et al. 2016; Zêzere et al. 2007).

Risk management describes four phases after a landslide event: response, recovery, mitigation and preparedness (Alexander 2002; Godschalk 1991). Mitigation is defined as application of measures in order to prevent an event or reduce its damage potential. Mitigation is related to structural (i.e., construction) and non-structural (i.e., planning, hazard mapping) measures and realization can impose a high financial burden for the involved communities, transportation offices and regional/federal construction authorities. As a consequence, preventive measures are realized in a sporadic way since public decision makers consider landslide risks acceptable, even though cost-benefit studies confirm the financial advantage of mitigation over post-disaster measures (Altay et al. 2013).

The presented study gives first insights into the development of repair and mitigation measures in Southern Lower Saxony, NW Germany. From historical data sets case histories at representative sites were created. Mitigation measures are used as indication of public risk awareness.

Study Area

The presented case histories are located in the Upper Weser area in Lower Saxony, NW Germany (Fig. 1). The region is characterized by a moderate population density of ~ 150 persons per km^2 (Destatis 2016). The transportation infrastructure is represented by a well-established federal highway system ("*Bundesstraße*"), which connects the regional urban centers (Kassel, Göttingen, Hannover) with the national highway A7 ("*Autobahn*"), one of the major transportation routes in Germany (Fig. 1).

The area is part of the Solling anticline between the Rhenish massif in the West and the Harz Mountains in the East. The bedrock formation of the Middle Lower Triassic consists of interbedded fine to medium-grained sandstone and fragile silt—and claystone with a thickness of 600–700 m. The bedrock is covered by a Quaternary layer of slope debris, which is susceptible to landslides in the case of high soil moisture content (Damm 2005). Due to river incisions up to 350 m of the Fulda, Werra and Weser rivers, a moderate relief was formed with elevations ranging between 50 and 500 m a.s.l.

The geologic predisposition to landslides is well known from previous studies in the area (e.g., Damm 2005; Klose et al. 2012). Hazard mapping indicates that 7% of federal highway length is exposed to landslides (Klose et al. 2016). Mitigation is documented since modern road construction and ranges from low-cost, (i.e., removal of material from

susceptible outcrop areas, rock blasting and road closure) to expensive measures (i.e., catch fences, mesh wiring and concrete injections).

Methods and Data

Landslide Database

The basis of the case histories developed in this study is a landslide database for Germany (Damm and Klose 2015). Most information within the database is gathered by means of archive studies from inventories of emergency agencies, state, press and web archives, company and department records as well as scientific and geotechnical literature. Furthermore, the database contains in addition to geoscientific, data from various sources, including field surveys, climatic records, and satellite imagery. The database stores information related to landslide characteristics, dimensions and dynamics as well as data concerning the relationship of landslides to soil and lithologic properties, geomorphometry and climatic conditions. Beyond that, it includes information about land use effects, damage impacts and economic losses. For the here studied area the database covers a time period of about 150–250 years (Damm and Klose 2015).

Case Histories to Study Mitigation Measures

In hazard assessment a key concept is to study historical data sets in order to analyze impacts and costs of landslides (Varnes and IAEG 1984; Glade 2001). Case histories are used to understand the interaction of landslide activity and land use practices including mitigation measures (Calcaterra et al. 2003; Klose et al. 2016). Although case histories are limited to a local area by design, they can be used in the area of the Upper Weser to differentiate landslide mitigation over time in order to identify local construction patterns. The main purpose is to understand the correlation of landslide activity, resulting vulnerability, concepts of mitigation as measures of public risk perception, and the resilience of infrastructures.

Case Histories

Site 1: Landslide Mitigation at Urban Infrastructures

The site is located at a federal highway within an urban area. The slope of 300 m length and 50–70 m height was formed as a river cut bank. The natural slope gradient varies between 30° and 50° . During road construction the slope was cut and

Fig. 1 Overview of the highway network in the Upper Weser area, NW Germany (sources Aster, OSM)

the material was used to create an embankment fill for the latter road (Damm 2005).

The first small to medium sized ($50\text{--}150\text{ m}^3$) landslides were registered during a phase of road construction in 1880–1882. First mitigation measures were realized (masonry gravity walls). Contemporary high financial relevance is linked with increased construction costs and mitigation during that time according to expert opinion (Klose et al. 2016). Subsequent landslides ($n \approx 30$) can be clustered in events in the 1920s ($n = 2$), 1936/1937 ($n = 5$), 1960s ($n = 3$), 1970–1975 ($n = 6$), 1999–2001 ($n = 7$). In these

small to medium sized events ($50\text{--}200\text{ m}^3$) upslope material collapsed due to sliding or falling (Damm 2005).

For long time mitigation measures were very simple and aimed at the removal of loose rock and vegetation from susceptible outcrop areas within the slope (1924, 1936, 1961/1962 and 1994). In 1937, 1994 and 2000 a wooden barrier was constructed to protect road traffic against rock-falls. In addition, in 1994 wire meshes were installed. In 2001 a comprehensive reconstruction of the slope was undertaken including rock blasting, concrete injections and a rear anchored concrete wall (Damm 2005).

Site 2: Rockfall Mitigation at a Rural Highway

The site is located at a federal highway between two small cities. The slope is situated in the federal state of Hesse and therefore in the responsibility of a different state office for transportation. Consequently, it is possible to compare mitigation measures in the federal states of Hesse and Lower Saxony. The 2.2 km long and 80–120 m high slope with an average natural gradient of 40° is formed as a river cut bank.

The total number of reported landslides is considerably less than at the first site ($n = 9$), probably linked to an incomplete landslide record. Under the consideration that most data are extracted from newspaper articles, it can be assumed that newspaper coverage focused on events in urban areas. Clusters can be found in the 1890s/1900s ($n = 3$), 1960s ($n = 1$), 1980s ($n = 3$) and 2010s ($n = 2$). In all events small to medium sized volumes were involved in landslides and rockfalls (Landslide Database of Germany).

The mitigation measures are similar to those of site 1. Apart from drywall construction in 1907 to stabilize the slope, mitigation focused on removal of loose material. In the 1960s a gravity wall was constructed for slope stabilization. In 1983/1984 the slope was comprehensively reconstructed implementing the use of rock nailing, new gravity walls, wooden barriers, catch fences and wire meshes. A cascade system was installed to prevent gully erosion. In 2015/2016 the mitigation was modernized. While the gravity walls and wooden barriers are still intact, catch fences with a system of dynamic brakes and anchored wire meshes are installed. Gullies are reshaped to control erosion (Landslide Database of Germany).

Site 3: Landslide/Rockfall Mitigation at an Important Infrastructural Junction

The third site represents a 550 m long and 70 m high slope formed as a river cut bank which is situated at an important infrastructural junction. The importance of the site for the city is emphasized by occurrence of a federal highway in the vicinity of a river port and a railway line. Even though the port is no longer in use, and the railway only seldom for heavy load transportation, the site is still of some infrastructural importance for the Upper Weser area since it represents the alternative route to the national highway in case of full closure.

The importance is reflected by the early road construction in the 1770s with first documented landslides during that time ($n = 4$). The number of subsequent landslides (in total $n \approx 30$) can be clustered in events in the 1880s ($n = 2$), 1900s ($n = 2$), 1925–1930s ($n = 3$), 1950–1960s ($n = 8$), 1970–1980s ($n = 2$), 2000s ($n = 4$) and 2010s ($n = 3$).

Early mitigation measures focused on slope stabilization on both sides of the road (slope cut and roadbed) by constructing gravity walls (1770s, 1930s). Aside from drywall construction, sliding and falling material in general was removed from the road for a long time (until the 1950s). Some of the small to medium scale (50–150 m³) events are related to construction works.

With the broadening of the highway from 1962–1975 the slope was reshaped and mitigation measures were installed. To decrease the slope gradient 7000–8000 m³ material was removed. A concrete barrier with retention space, wire meshes and a drainage system was realized. The concrete barrier was shortly replaced by a wooden barrier. In 1986 the wire meshes were renewed. In 2015/2016 new mitigation measures were installed including concrete injections, anchored wire meshes covered with geofabrics and shotcrete (Landslide Database of Germany).

Development of Mitigation Measures in the Upper Weser Area

The reported case histories show that for the last 150 years clusters of landslide events can be found in many decades, especially since the 1950s (Fig. 2). An apparent increase in the landslide events must be reflected under the consideration of a general worldwide increase of event reports in the last century linked to a more complete documentation in recent years (cf. Raška et al. 2014; Taylor et al. 2015). However, clusters of landslides can be found in the 1770s, 1880s, 1900s, 1930s, 1950s and 1970s. For the last four decades (since the 1980s) the number of landslides is

Fig. 2 10-year clusters of the landslide events in the Upper Weser area in combination with total precipitation since 1880. Arrows indicate phases of increased construction/mitigation (sources DWD, Landslide Database of Germany)

Fig. 3 Development of mitigation measures in southern Lower Saxony, NW Germany. **a** Rockslide event (02/1937) in the Upper Weser area. The drywall in the front stabilizes slope with no protection against rockfalls/slides. **b** Removal of loose rock and vegetation in the Upper Weser area in 1936. **c** Combination of steel buttress/wooden

planks as a barrier against rockfall. Construction in the Harz Mountains, NW Germany. **d** Rockfall mitigation in the Upper Weser area. The barrier wall in the left and wooden barrier in the right foreground are constructed in 1983, rock drapey and catch fence constructed in 2015 (photos retrieved from Landslide Database of Germany)

constant. The peaks of landslides events can be explained by construction phases on one side (i.e., 1770s, 1880s and 1930s), and high precipitation phases on the other in the 1960s and 1970s (Fig. 2, Damm and Klose 2015).

Corresponding to the event clusters, construction and mitigation phases can be identified in the 1770s, 1880s (both construction), 1930s, 1960s, 1980s and 2010s (mitigation combined with road extension). Clusters of landslide events are followed by an intensified period of mitigation (Fig. 2).

The mitigation phases in the Upper Weser area can be differentiated by distinct measures. In the road construction phase in the 1770s and 1880s mitigation focused on slope

stabilization by constructing dry walls (Fig. 3a). Protection against rockfall was not achieved, falling material had to be removed during road closure. The construction of higher dry walls was intensified at the beginning of the 20th century and especially in the 1930s. After a period of high landslide activity, engineered mitigation was planned at some sites but not realized. Instead, loose material from cover beds and vegetation was removed by clearing and rock blasting (Fig. 3b).

Engineered mitigation was executed in the 1960s. Slope stabilization was realized by constructing concrete walls and piles. Protection against rockfall was achieved by building

wires meshes and barriers in a combination of steel buttress and wooden planks (Fig. 3c).

In the 1980s the use of wire meshes and rock drapery increased. In addition to the 1960s, they were nailed to the ground. Rockfalls were mitigated by installing catch fences. Furthermore, drainage systems were realized to improve slope stability.

Comprehensive mitigation measures have been installed since the turn of the millennium to stabilize sediment layers with concrete injections and anchor them deep in the ground. Dynamic catch fences are not only designed to protect against rockfalls but against falling trees likewise (Fig. 3d). In modern mitigation measures esthetic and ecologic aspects are considered as well (cf. Popescu and Sasahara 2009). Geofabrics and colored shotcrete are used to maintain the impression of a natural slope.

Discussion

The increase in mitigation efforts and resultant costs in the study area (Southern Lower Saxony and Northern Hesse) is linked with increased risk awareness. The risk management in the Upper Weser area follows a cycle of event with a short-term response in terms of material removal from the affected site, recovery, which means the reinstatement of the infrastructure, and mitigation measures. Finally, a period of awareness/preparation should follow (Crozier and Glade 2005; Alexander 2002) to maintain high sensibility to the risk. That includes investments into existing mitigation measures. Instead, public awareness to landslide vulnerability decreases and subsequently mitigation measures are neglected which may result in a decrease of structural integrity. As a consequence, landslide events cannot be prevented and instead dysfunctional mitigation measures become more damaging than before (i.e., loose wire meshes and wooden planks from barriers).

With a new phase of landslide events the risk management cycle starts from the beginning. Public risk awareness raises and new mitigation measures are installed. An increase in mitigation effort and costs is intensified by technical standards. Introduced in the 1960 s technical standards are created to define slope stability and calculate modes of failure (cf. Eurocode 2014). With the technical development the standards for slope stability increased and consequently mitigation measures become outdated and must be reconstructed.

The trend of installing cost intensive and maybe oversized mitigation measures is enhanced by producers of relevant systems. Technical warranties of 50 years and more are common, even though construction engineers argue that these numbers are hardly realistic. Decision makers in transportation offices and involved communities might be under the impression that measures with extended warranties

are highly efficient long-term solutions to landslide hazards. Mitigation concepts from the 1980s show, that this argument is only valid, if regular maintenance is applied.

Conclusions

The paper presents preliminary results of the study of repair and mitigation measures in the Upper Weser area, NW Germany. Several phases of increased landslide activity are followed with a small delay by a period of intense mitigation construction. Linked to risk awareness, after a series of landslide events, awareness raises together with public need for mitigation. In a phase of functional mitigation, only a few and small volume landslides occur. As a result, risk awareness decreases and aged mitigation measures lose their integrity. In a next phase of high landslide activity mitigation is inefficient and infrastructure is vulnerable again.

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