Deep-Seated Rock Slides: Understanding Processes and Assessing Impacts on Settlements and Infrastructure

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Abstract: This presentation provides an overview of the current state of knowledge and recent research on deep-seated rock slides, drawing from extensively investigated case studies in the Austrian Alps and the interaction with different types of critical infrastructure such as dam reservoirs, pressure pipes, highways and bridges.

Keywords: ***Deep-seated rock slides, Critical infrastructure.***

Introduction

Large-scale rock slides represent a common landslide phenomenon on mountainous slopes worldwide. These landslides can involve volumes of several cubic kilometers, thicknesses of hundreds of meters, and have the potential to destabilize entire valley slopes. Typically, such landslides develop in fractured rock masses of metamorphic, magmatic, or sedimentary origin. Although case studies have shown that temporary accelerations to several meters per day can happen, many deep-seated rock slides only move at rates of a few mm to cm per year. Rarely, abrupt failures can lead to long runouts and very high velocities, which can be extremely destructive. When active for extended periods, even slow-moving rock slides can have a major impact on engineering infrastructure and buildings. Based on case studies from the Austrian Alps, this presentation gives a summary of recent findings and current understanding of deep-seated rock slides. Slide geometry and kinematics, geomechanical processes governing initiation and basal shear zone development, and lithology and structural geology as predisposing factors are important subjects.

Structure and Geometry

Rock slides are characterised by shearing along one or more discrete shear zones, where most of the measured total displacement accumulates. In-situ investigations using drilling and exploratory drifts clearly demonstrate that slope deformations observed at the surface primarily reflect the cumulative displacements along decimetre- to metre-thick basal and internal shear zones (Strauhal et al., 2016). While internal deformations within the sliding mass can occur, they are typically minor. From a structural perspective, these shear zones are heterogeneous fault rocks composed of fault gouge and breccia (Strauhal et al., 2017). The material of these shear zones results from progressive cataclasis and fragmentation of the host rock during the sliding process, exhibiting mechanical and hydraulic properties characteristic of soil. Consequently, the slope stability and time-dependent deformation behaviour of deep-seated rock slides are predominantly governed by the hydro-mechanical coupled properties of the active shear zones.

The geometry and resulting kinematics of rock slides are strongly influenced by the lithological and structural characteristics of the rock mass. As a result, translational and rotational slides, as well as wedge-shaped breakout geometries of varying sizes, can develop (Zangerl et al., 2010). A common and frequently observed feature of rock slides is the fragmentation of the sliding mass into slabs. Slabs of varying sizes and movement activity can form at different times, remain active for certain periods, and subsequently stabilise. Their formation is often triggered by external factors, such as slope foot erosion. In cases where rock slides interact with a river, secondary slides may be initiated at the slope's foot. Portions of the mobilised rock mass are transported away by the river during flood events, which can, in turn, trigger new acceleration phases of the primary rock slide as stabilising material at the slope's foot is removed (Zangerl et al., 2015).

Interaction with Infrastructure

The interaction between critical infrastructure and existing slow-moving deep-seated rock slides involves both engineering geological and hydrogeological aspects. Insights from various case studies conducted over the past decades reveal that the underlying mechanisms and interactions are highly diverse. These mechanisms are often influenced by the specific geological, hydrological, and topographical conditions of a site and can be triggered or intensified by natural or anthropogenic factors.

A central challenge posed by rock slides is their complex internal geological structure, which includes active slabs of varying thickness, the spatial distribution and thickness of shear zones, and the heterogeneous geological composition at the slope's foot. This heterogeneity arises from the spatially and temporally variable interaction of the sliding mass with sedimentary processes in the surrounding, such as glacial, alluvial or rockfall processes. Over their long-term evolution, rock slides alter the geological subsoil at the slope's foot, creating a difficult subsoil with geological and hydrogeological properties that vary significantly across the area.

Slope movements can result in differential displacements both at the surface and underground, potentially causing damage to infrastructure. In some cases, such damage can substantially reduce the planned service life of the structures. Typical examples of such damage include overall deformations, cracks, or subsidence, which impair the functionality of the affected structures.

This study has identified numerous mechanisms by which rock slides impact infrastructure. One particularly significant example is the progressive narrowing of valley cross-sections due to slope movements, which can lead to deformation and cracking of dams (Barla, 2018). Further, rock slides or their individual slabs may be reactivated or accelerated during the initial filling of a large reservoir. The geometry of the slide and the geological composition play a critical role in determining the deformation behavior (Zangerl et al., 2010; Zangerl et al., 2024).

Slope movements in areas with discrete active shear zones can cause long-term deformation of pressure and water supply tunnels, potentially compromising the structural integrity and functionality of these underground structures. Additionally, the compression and deformation of alluvial sediments, combined with their interaction with the sliding mass, can create a heterogeneous hydrogeological environment near dams. This may lead to challenging pore water pressure conditions and seepage issues beneath the dam (Leobacher, 2009).

Active rock slides or their individual slabs can also cause sections of highways to slip, posing significant risks to traffic safety and, in some cases, necessitating the complete closure of affected highway stretches. Slope movements can severely impact the stability of bridge foundations, compromise safety and reducing the planned service life of the infrastructure. Furthermore, rockfall processes originating from highly active slabs at the foot of the slope can damage bridge carriageways, potentially restrict their use or render them unusable.

In general, predicting the behavior of inactive rock slides is challenging, particularly when they are reactivated or accelerated by extreme meteorological events or erosion at the slope's foot due to flooding. In this context, a case study is presented in which a flood event reactivated and accelerated existing rock slides, causing damage to highways, bridge structures, and pressure pipes of a hydroelectric power plant.

Conclusion

Rock slide impacts are diverse, requiring detailed investigation of geometry, depth, activity, and rock structure. In alpine regions, many slides are inactive or low activity, making complete avoidance during planning difficult. Therefore, thorough investigations, monitoring, and, where needed, targeted technical measures are essential to protect infrastructure. Climate change exacerbates risks by increasing extreme precipitation, floods, glacier retreat, and permafrost thaw, potentially reactivating existing slides. This study underscores the importance of reliable analyses to minimize construction and operational issues and safeguard infrastructure service life.

References

Barla, G. (2018). Numerical modeling of deep-seated landslides interacting with man-made structures. Journal of Rock Mechanics and Geotechnical Engineering, 10 (6), 1020–1036. https://doi.org/10.1016/j.jrmge.2018.08.006

Leobacher, A. (2009). Errichtung von zusätzlichen Entspannungsbrunnen beim Erddamm Durlassboden. Österreichische Wasser- und Abfallwirtschaft, 61 (9–10), 144. https://doi.org/10.1007/s00506-009-0121-5

Strauhal, T., Zangerl, C., Fellin, W., Holzmann, M., Engl, D. A., Brandner, R., Tropper, P., and Tessadri, R. (2017). Structure, mineralogy and geomechanical properties of shear zones of deep-seated rockslides in metamorphic rocks (Tyrol, Austria). Rock Mechanics and Rock Engineering, 50 (2), 419–438. https://doi.org/10.1007/s00603-016-1113-y

Strauhal, T., Loew, S., Holzmann, M., and Zangerl, C. (2016). Detailed hydrogeological analysis of a deep-seated rockslide at the Gepatsch reservoir (Klasgarten, Austria). Hydrogeology Journal, 24(2), 349–371. https://doi.org/10.1007/s10040-015-1341-3

Zangerl, C., Lechner, H., and Strauss, A. (2024). Influence of rock slide geometry on stability behavior during reservoir impounding. Applied Sciences, 14 (11), 4631. https://doi.org/10.3390/app14114631

Zangerl, C., Chwatal, W., and Kirschner, H. (2015). Formation processes, geomechanical characterisation and buttressing effects at the toe of deep-seated rock slides in foliated metamorphic rock. Geomorphology, 243, 51–64. https://doi.org/10.1016/j.geomorph.2015.03.030

Zangerl, C., Eberhardt, E., and Perzlmaier, S. (2010). Kinematic behaviour and velocity characteristics of a complex deep-seated crystalline rockslide system in relation to its interaction with a dam reservoir. Engineering Geology, 112 (1–4), 53–67. https://doi.org/10.1016/j.enggeo.2010.01.001