Postprint: Toppling Deformation Evolution Mechanism and Failure Mode of Anti-dip Rock Slopes Based on Physical Model Tests

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Abstract

In the southwestern mountainous areas of China, where geological structures are complex, slope toppling failure has become a typical deformation mode that requires urgent attention in engineering construction and disaster prevention and control due to its suddenness and widespread occurrence. To deeply reveal its formation mechanism, the limestone sliding mass and shale sliding bed of the Guang' an Village landslide were selected as similar material prototypes to construct physical models of anti-dip limestone slope and anti-dip shale slope, respectively, and loading tests were conducted to simulate gravitational action during geological historical periods. Combined with digital photography, non-contact deformation measurement technology, and miniature pressure sensors, real-time images, displacement, and pressure data during the slope toppling deformation process were obtained. The experimental results completely reproduced the toppling of anti-dip rock strata and the process of slope instability. The results indicate that hard rock strata such as limestone are prone to brittle failure through toppling-fracturing, with slope instability dominated by shallow collapse; whereas soft rock strata such as shale tend to undergo long-term bending creep, ultimately leading to deep-seated sliding of the slope. With the continuous development of the toppling process, multi-level fracture surfaces gradually formed within the slope, dividing it into five zones with clear geological-mechanical implications. The study further proposed using the rock strata overturning angle as a parameter to describe the kinematic characteristics of the slope, and conducted a staged discussion of the toppling deformation process of rock masses in both unstable and stable regions. In anti-dip limestone slopes, the dominance of the rock strata displacement vector in the horizontal direction is a key characteristic of the rotational deformation around the slope toe after toppling-fracturing occurs; whereas in anti-dip shale slopes, the vertical displacement component gradually increases from the slope surface to within the slope, indicating that the rock strata exhibit bending-toppling characteristics.

During the loading process, the internal pressure of rock masses at the slope surface and the front edge of the slope crest exhibited a clear stepwise variation trend, highlighting the dynamic changes between tensile and compressive stresses. This experiment can serve as a typical case study for investigating the deformation and failure mechanisms of anti-dip rock slopes, and also provides important data support for stability assessment and risk prediction in geological engineering.

Full Text

Physical Model Study on the Evolution of Toppling Deformation Mechanism and Failure Modes in Anti-dip Rock Slopes

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Abstract

In the mountainous regions of southwestern China, complex geological structures have made slope toppling failures a critical deformation pattern requiring urgent attention in engineering construction and disaster prevention, due to their sudden onset and widespread occurrence. To elucidate the underlying formation mechanisms, this study selected the limestone sliding mass and shale sliding bed of the Guang' ancun landslide as prototype materials for similar material modeling, constructing physical models of both anti-dip limestone and anti-dip shale slopes. Loading tests were conducted to simulate gravitational effects during geological history.

Combined with digital photography, non-contact deformation measurement techniques, and micro pressure sensors, real-time images, displacement data, and pressure measurements were obtained throughout the slope toppling deformation process. The experimental results successfully reproduced the complete process of anti-dip rock layer toppling and slope instability. The results demonstrate that hard rock layers such as limestone are prone to brittle failure characterized by toppling-fracture, with slope instability dominated by shallow collapse. In contrast, soft rock layers like shale tend to undergo long-term bending creep, ultimately leading to deep-seated sliding of the slope mass.

As the toppling process continues to develop, multi-level fracture surfaces gradually form within the slope, dividing it into five distinct zones with clear geological-mechanical significance. The study further proposes the overturning angle of rock layers as a parameter to describe the kinematic characteristics of slope movement, presenting a staged discussion of the toppling deformation processes for both unstable and stable rock masses. In anti-dip limestone slopes, the dominance of horizontal displacement vectors is a key feature of the rotational deformation around the slope toe after toppling fracture occurs. In anti-dip shale slopes, the vertical displacement component gradually increases from the slope surface to the interior, indicating a bending-toppling characteristic of rock layers.

During loading, the internal pressure of rock masses at the slope surface and the front edge of the slope crest exhibits a distinct step-like variation trend, highlighting the dynamic transition between tensile and compressive stresses. This experimental study serves as a typical case for investigating the deformation and failure mechanisms of anti-dip rock slopes, providing important data support for stability assessment and risk prediction in geotechnical engineering.

Keywords: Anti-dip rock slopes; Physical model tests; Toppling deformation; Failure modes