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Gravitational deformation mechanisms of slate slopes revealed by model tests and discrete element analysis

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ABSTRACT

This study investigated the factors influencing the gravitational deformation of slate slopes prior to sliding failure, including the slope angle, foliation angle, and material deterioration. To simulate these phenomena, physical model tests were performed in the laboratory under simplified environmental conditions. Subsequently, the discrete element method was employed in simulations to elucidate the deformation behavior exhibited by slate slopes under the long-term influence of gravity and material deterioration. The physical model tests revealed two types of gravitational deformation of slate slopes. The first type is flexural toppling, which was observed in obsequent slopes with high-angle foliation. The second type is fold extrusion near the slope toe; this was exhibited by consequent slopes with low-angle foliation and is attributable to gravitation and deterioration caused by wetness. The results of the physical model test were used to verify the results of the discrete element simulation. The simulated deforming patterns were in strong agreement with the actual deformation at various slope angles. Regarding the factors influencing slope deformation, the simulation showed that the fold in consequent slopes became sharper and the folding area increased as the foliation angle increased; moreover, the folding area rose as the slope angle increased. In obsequent slopes, higher slope and foliation angles induced more substantial flexural toppling deformation.

1. Introduction

Slate is a fine-grained, foliated metamorphic rock derived from an original shale-type sedimentary rock that was subjected to low-grade metamorphism. In Taiwan, slate is distributed mainly in the central mountain range (Fig. 1) and formed between the Miocene and Eocene epochs. Slate easily splits into thin, flat, parallel planes called slaty cleavage, and the ease with which this rock splits along the direction of the slaty cleavage weakens its resistance to erosion and weathering. In dry conditions, slate slopes exhibit a hard texture and high strength, for which they are considered more stable than shale and interbedded sandstone slopes. However, slate exhibits strong foliation, and the long-term influence of gravity, groundwater, rainwater infiltration, and weathering can weaken the form, resulting in deeply weathered deformations and colluvium. The geological structure of slate slopes can be severely compromised by changes in material strength, the degree of weathering, and permeability; consequently, slate slopes can become prone to failure and, therefore, a threat to the safety of residents and road users in the vicinity.

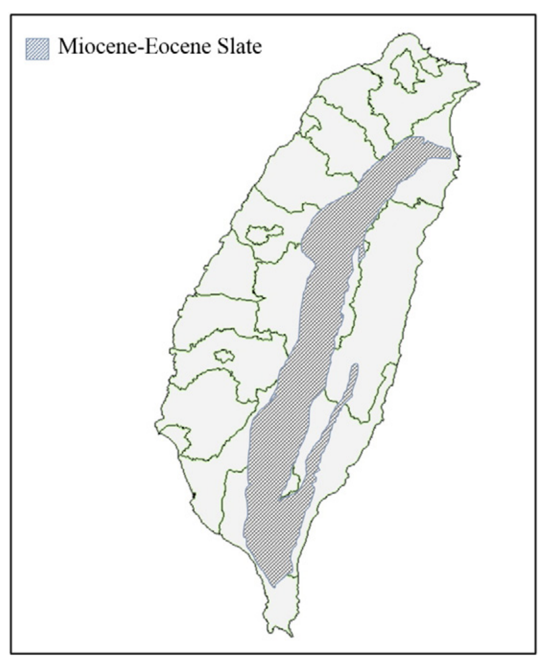

Fig. 1. The distribution of slate in Taiwan.

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Numerous previous studies have investigated the deformation of slate slopes. Nemcok (1972) observed that the deformation of metamorphic rock slopes is characterized by a tendency towards heterogeneity and strong foliation. Under the force of gravity, foliation often forms buckling folds, which extend to the toe of the slope, with the strata near the surface becoming folded. The characteristics of plasticity are more pronounced when creeping behavior penetrates deeper, and because the rock is inhomogeneous, most of the discontinuous deformation is created along the shear plane near the surface. In 1978, Radbruch-Hall (1978) classified creep as a type of landslide that moves slowly downward or outward. When no continuous fracture planes are present, slopes in regions of metamorphic rock often exhibit toppling and creep because of gravity. Deep rock deformation is associated with foliation. Chigira (1992) and Chigira and Kiho (1994) investigated the influence of foliation on the deformation of rock under the force of gravity and four types of mass rock creep structure were proposed. However, most of these research results are speculative and based solely on evidence from outcrops. The depth of slate deformation is nearly impossible to confirm, differing according to the inclination of foliation and resulting in varying degrees of failure. Few studies have addressed this topic.

To investigate mechanisms associated with the deformation of slate slopes prior to sliding failure, Broili (1967) discovered that large-scale deformation or creep can lead to catastrophic landslides.

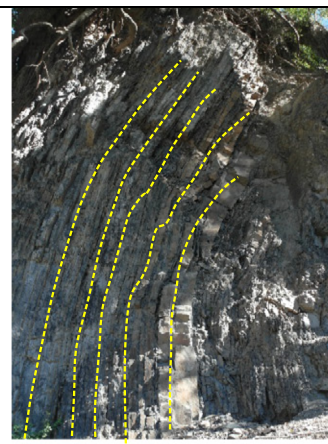
Foliation angle	Phenomena of gravitational deformation
(a) 75° ~90° in obsequent slope	
(b) 75° ~90° in consequent slope	
(c) 60° ~75° in consequent slope	

Fig. 2. Gravitational deformation of slate slope.