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Parallel retreat of rock slopes underlain by alternation of strata

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ABSTRACT

Characteristic landscapes (e.g., cuesta, cliff and overhang of caprock, or stepped terrain) formed by differential erosion can be found in areas composed of variable geology exhibiting different resistances to weathering. Parallel retreat of slopes, defined as recession of slopes without changes in their topography, is sometimes observed on slopes composed of multiple strata. However, the conditions needed for such parallel retreat have not yet been sufficiently clarified. In this study, we elucidated the conditions for parallel retreat of rock slopes composed of alternating layers using a geometric method. In addition, to evaluate whether various rock slopes fulfilled the conditions for parallel retreat, we analyzed topographic data obtained from periodic measurement of rock slopes in the Aka-kuzure landslide, central Japan. Our geometric analysis of the two-dimensional slopes indicates that dip angle, slope gradient, and erosion rate are the factors that determine parallel retreat conditions. However, dip angle does not significantly affect parallel retreat conditions in the case of steep back slopes (slope gradient > 40°). In contrast, dip angle is an important factor when we consider the parallel retreat conditions in dip slopes and gentler back slopes (slope gradient < 40°). Geology in the Aka-kuzure landslide is complex because of faulting, folding, and toppling, but spatial distribution of the erosion rate measured by airborne LiDAR scanning and terrestrial laser scanning (TLS) roughly fulfills parallel retreat conditions. The Aka-kuzure landslide is characterized by repetition of steep sandstone cliffs and gentle shale slopes that form a stepped topography. The inherent resistance of sandstone to weathering is greater than that of shale. However, the vertical erosion rate within the sandstone was higher than that within the shale, due to direct relationship between slope gradient and vertical erosion rate in the Aka-kuzure landslide.

1. Introduction

Knowledge of the spatial distribution of weathering and erosion rates is essential in predicting landscape development and sediment disasters. Therefore, numerous investigations have been conducted on weathering and erosion processes in various geological and environmental settings (e.g., Coleman, 1981; Maybeck, 1987; Alexandrowicz, 1989; Turkington and Paradise, 2005). Resistance against physical, chemical, and biological weathering is different not only between geologic units (e.g., Dibb et al., 1983; Pentecost, 1991; Hettema et al, 1998; Mutlutürk et al., 2004) but also within the same geological unit due to inhomogeneous joint density and the chemical composition of different rock types (Nicholas and Dixon, 1986; Schmidt, 1989). Characteristic landscapes (e.g., cuesta, cliff and overhang of caprock, or stepped terrain) formed by differential erosion can be found in areas comprising multiple strata with different weathering resistances (e.g., Moon and Selby, 1983; Nicholas and Dixon, 1986; Schmidt, 1989; Matsuoka, 1995; Suzuki, 2002). However, many of these studies have been conducted in regions with a simple coherent formation, and relatively few have focused on complex geology such as disrupted formations and deformation.

Parallel retreat of slopes, defined as the recession of slopes without changes in the slope surface topography, is a typical type of landform development throughout the world (e.g., Kirk, 1977; Obanawa and Matsukura, 2008). In cases in which the slopes are not completely flat, the direction of the parallel retreat can be determined by the travel direction of knick lines. Parallel retreat progresses not only in the vertical direction but also sometimes horizontally and at right angles to the slope surface (e.g., Kirk, 1977; Obanawa and Matsukura, 2008). Regardless, the erosion rate along the parallel-retreat direction should be spatially constant. However, few studies have considered the dip angle of the strata, which we believe is an important factor controlling the direction of the parallel retreat. In regions with high tectonic activity, geological strata may be inclined, and the dip angle can affect sediment supply processes (Chigira and Kiho, 1994; Lin et al., 2004; Nishii and Matsuoka, 2010; Tsou et al., 2011). Thus, an exploration of the relationship between parallel slope retreat and dip angle is needed to clarify the landform development of rock slopes in tectonically active regions.

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Topographic factors such as slope gradient and slope aspect are also important in terms of controlling weathering and erosion rates (Bradley, 1963; Alexandrowicz, 1989; Pentecost, 1991; Hall, 1993, 2004). Erosion rates vary over time when the topographic factors associated with landform development change, so clarifying the interactions between weathering and landform development is essential to adequately understand weathering processes (Alexandrowicz, 1989; Phillips, 2005).

The purpose of this study was to explain the conditions for parallel retreat of rock slopes comprising alternating layers using a geometric model. In the model, dip angle of the strata, which is sometimes a key factor controlling the rate of slope retreat and the slope gradient (Nicholas and Dixon, 1986; Suzuki, 2002), was considered as one parameter defining the conditions for parallel retreat. Furthermore, to evaluate whether our geometric model could be applied to the short-term erosion rate of rock slopes with complicated geological settings, we analyzed topographic data obtained from the periodic measurement of rock slopes in the Aka-kuzure landslide, central Japan, by airborne light detection and ranging (LiDAR) scanning and ground terrestrial laser scanning (TLS). The Aka-kuzure landslide, similar to rocky slopes in many other regions (Selby, 1982; Moon and Selby, 1983; Matsuoka, 1995), consists of alternating strata with stepped terrain. The geology of this landslide, located in a humid and tectonically active region where this type of study has rarely been conducted, features alternating sandstone and shale affected by faulting, folding, and toppling (Kano and Matsushima, 1988). Because this landslide continuously produces large sediment volumes after its initial failure (12.2×10^4 m^3 year^{-1} according to Chigira and Kiho, 1994), its topographic changes can be detected in a short time period. We also discuss the relationship between topography and the erosion rate that satisfies parallel retreat conditions. In this study, we focus on small-scale slope retreat of alternating layers in which hillslope sediment movement such as rockfall and surface erosion plays an important role in landscape development (Phillips, 2005). We do not consider fluvial processes, which commonly play an important role in landscape development on the scale of an entire hillslope or catchment.

2. Conditions for parallel retreat at alternating layers

To improve our understanding of parallel retreat, we discuss here the conditions for parallel retreat on a two-dimensional (2-D) slope comprising alternating layers. In the case of inclined strata, lithology along the horizontal (except in the direction of strike) and vertical directions from a certain point is spatially variable (Fig. 1). Therefore, the spatial distribution of horizontal and vertical erosion rates is not simply comparable to that of the lithology. In this paper, we discuss conditions for parallel retreat along dip direction (Fig. 1), because a single lithology along this direction enables us to derive simple conditions for parallel retreat. Knick lines of slopes comprising multiple lithologies usually exist along the boundary where lithology changes (e.g., Selby, 1982; Suzuki, 2002). If knick lines continue to be located on the boundary, the direction of parallel retreat should be consistent with the dip direction. Therefore, we believe that a discussion of parallel retreat in the dip direction is helpful in terms of understanding the retreat of slopes comprising multiple lithologies.

One of the key conditions for the parallel retreat of alternating strata is that the erosion rate in the dip direction is constant among strata:

$$E_{\mathrm{d}(i)} = const \tag{1}$$

in which $E_{\mathrm{d}(i)}$ is the erosion rate of the ith stratum along the dip direction ($\mathrm{m\ yr}^{-1}$; Fig. 2). $E_{\mathrm{d}(i)}$ can be expressed by

$$E_{\mathrm{d}(i)} = \frac{V_i}{D_i} \tag{2}$$

in which V_i is the cross-sectional area of the eroded rock in the ith stratum per year ($\mathrm{m}^2\ \mathrm{yr}^{-1}$), and D_i is the width of the ith stratum (m). In addition, V_i can be expressed as

$$V_i = A_i E_{\mathrm{v}(i)} = a_i D_i E_{\mathrm{v}(i)} \tag{3}$$

in which $E_{\mathrm{v}(i)}$ is the erosion rate along the vertical direction for the ith stratum ($\mathrm{m\ yr}^{-1}$), A_i is the vertically projected area of the exposed part of the ith geology (m), and a_i indicates the ratio of A_i to D_i. By using slope gradient θ_i and dip angle ϕ, a_i for back slopes is

$$a_i = \frac{\cos\theta_i}{\sin(\theta_i + \phi)} \tag{4}$$

and a_i for dip slopes ($\theta \neq \phi$) is

$$a_i = \frac{\cos\theta}{|\sin(\theta_i - \phi)|}. \tag{5}$$

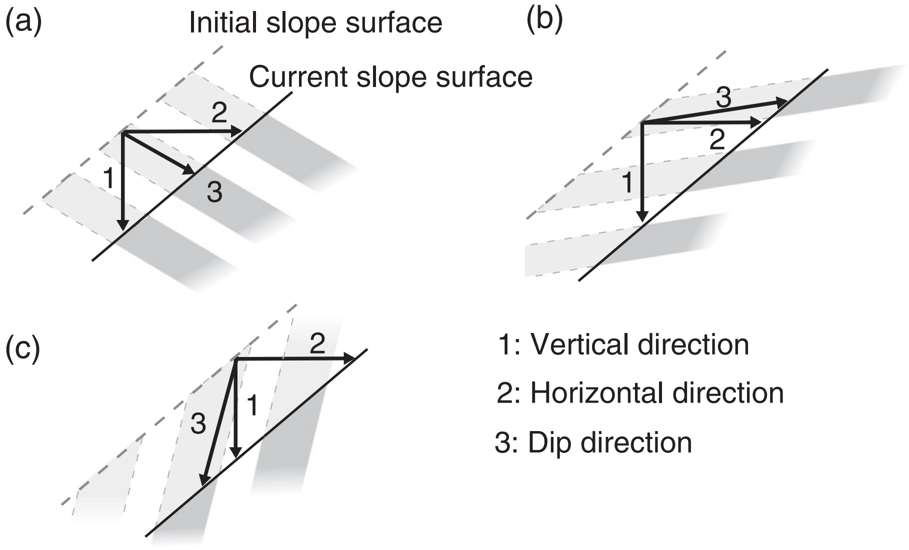

Fig. 1. Vertical, horizontal, and dip directions of a slope with inclined alternating strata: (a) back slope, (b) dip slope with a dip angle below the slope gradient, and (c) dip slope with a dip angle that exceeds the slope gradient. In each case, the geology is spatially variable along the vertical and horizontal directions whereas it is constant along the dip direction.