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Increasing the southern side-slope albedo remedies thermal asymmetry of cold-region roadway embankments

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ABSTRACT

Roadways in permafrost regions usually need embankments to disperse the traffic loadings to the underlying layer. Most roadway embankments have differential solar absorption across the embankment due to the slope-facing problem, which can cause longitudinal cracking along the roadway. This problem may be remedied by increasing the albedo of the sun-facing side slope because the solar absorption of the slope is the product of solar radiation and absorptivity (absorptivity = 1-albedo). This study fabricated eight embankment models with differential surface albedo on the one side slope. The albedo of the models was measured on June 22, 2015, by a proposed method for measuring the albedo of bent surfaces. It is found that raising the albedo of the side slope of the embankment can increase the embankment's albedo about 0 to 0.2. Therefore for the cold-region roadway embankments in the Northern Hemisphere, painting the southern side slope with highly reflective, non-white pigments can cool the roadbed and remedy the thermal asymmetry across the embankment.

1. Introduction

Roadways in cold regions usually need embankments to disperse the traffic loadings to the underlying layer. The embankment modifies the pre-existing ground surface and the ground-surface thermal balance, negatively varying the heat convection, the vegetation coverage, and the solar absorption (Zhang et al., 2008). During a clean daytime, at the low solar angle, the embankment creates shade at the northern side while the southern side slope is sunlit; at the high solar angle, the irradiance incident on the southern side slope is stronger than that on the northern side. This different incident irradiance on the side slopes causes differential solar absorption across the embankment, leading to thermal asymmetrical problem (Chen et al., 2006; Chou et al., 2008a, 2008b). The problem has further caused structural damages of the roadways, such as the development of longitudinal cracking and of side-slope collapse.

Countermeasures to this problem have been well documented (Cheng et al., 2008; Lai et al., 2009; Ma et al., 2009; Qin and Zhang, 2013). One solution is to embed thermosyphons along the roadway side slope to extract the deep soil's heat out to the local atmosphere. The technique, however, is expensive and may lead to traffic safety issue (Wagner, 2014). Another is to pave a crushed rock layer on the southern side slope to promote air convective cooling, counteracting the additional heat gain of the sun-facing side slope. But the use of this layer promotes differential settlement across the embankment (Lai et al., 2006; Qin and Zhang, 2010; Qin et al., 2010). Installing shading boards above the southern side slope may be another alternative to balance the solar absorption on both side slopes (Feng et al., 2006; Qin et al., 2015; Yu et al., 2007, 2008), but the boards are susceptible to wind damages. As the solar absorption is the product of solar radiation and absorptivity (absorptivity = 1-albedo), increasing the albedo of the sun-facing side slope may directly balance the solar absorption of both side slopes and cool the embankment. Knowledge of the albedo of the side slope, of the embankment, and of the embankment with differential side-slope albedo remains scare. Whether raising the albedo of the sun-facing side slope can remedy the thermal asymmetry of a cold-region roadway embankment remains unknown.

This study measured the albedo of the embankment with differential side-slope albedo. Different pigments were painted on one side slope of the embankment, with an albedo from about 0.05 to 0.80. The albedo of these embankments was measured, respectively, to conclude if raising the side-slope albedo effectively increases the embankment albedo and potentially balance the solar absorption of the side slopes. The influence of the side slope facing on the embankment albedo was characterized and discussed. We presented a group of high-reflective, non-white pigments, which can be candidate for painting the side slope with high reflectivity (reflectivity and albedo is used interchangeably through this paper).

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2. Theory

2.1. The concept of albedo

Albedo, or reflectivity, is the percentage of solar radiation reflected by a surface. It is quantified as the proportion of solar irradiance of all wavelengths reflected by a body or surface to the amount incident upon it. Let irradiance I denote incident power per unit surface and let $i(\lambda)$ represent incident power per unit surface area per unit wavelength λ. Considering a surface (flat or curved) that has a spectral reflectance $r(\lambda)$, the albedo (ρ), or reflectivity, of the surface

$$\rho = \frac{\int_{\lambda_0}^{\lambda_1} i(\lambda) r(\lambda) d\lambda}{\int_{\lambda_0}^{\lambda_1} i(\lambda) d\lambda} \quad (1)$$

where $\lambda_0 = 250$ nm and $\lambda_1 = 2.5$ μm are usually considered.

2.2. The albedo of an embankment

The embankment is a bent surface consisting of two side slopes and an upper surface, as a schematic show in Fig. 1. The sunlight incident on the sunlit side slope, the shade side slope, and the upper surface are different because their tilt angles are different. Only the reflection from the upper surface can completely escape to the sky. Due to the bent embankment, the reflection from the side slopes is partially intercepted by the adjacent ground surface, and vice versa. The portion of the reflection from the side slope to the sky is the sky view factor of the slope, which is

$$\psi_{slope \to sky} = (1 + cos\theta)/2 \quad (2)$$

where θ is the angle of the side slope. The reflection between the side slope and the adjacent ground surface is the subject of multiple reflections. However, if only the first order of reflection is considered, the contribution of the side slope albedo to the entire embankment albedo, ρ_e, obeys

$$\rho_e = \frac{\psi_{slope \to sky} A_{slope} I_{slope}}{A_e I_g} \rho_{slope} + C \quad (3)$$

where A_{slope} and A_e are the project area of the side slope and of the embankment; C is a constant representing the contributions of the upper-surface albedo and of the other side slope albedo to the embankment albedo; I_g = the global horizontal solar radiation; and I_{slope} is the incident solar radiation on the side slope.

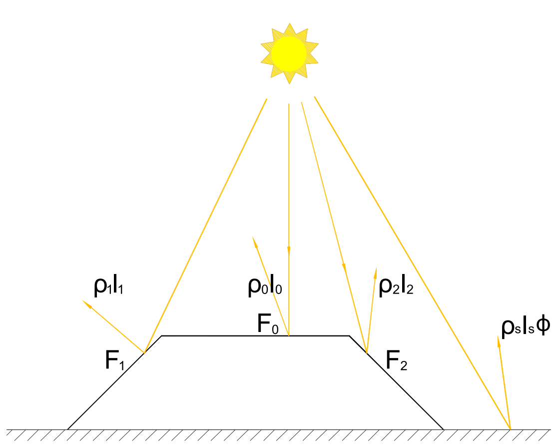

Fig. 1. A schematic show on the view factor, incident radiation, reflection of an embankment section. $F_{i(i\,=\,0,1,2)}$ = view factor; I = incident radiation; ρ = albedo; ϕ = sky view factor of the adjacent ground surface.

Directly measuring ρ_e of an embankment is uneconomical and seems impossible because a real roadway embankment is too large to set a pyranometer some meters above the embankment to measure the solar reflectance of the embankment. However, we can fabricate a mesoscale embankment in lab and measure the albedo of the embankment. The albedo of this mesoscale embankment can represent reflectivity of the embankment in field because the wavelength of the sunlight is several orders of magnitude smaller than the size of the embankment model so that the diffraction radiation at the bent surface can be neglected.

To measure the albedo of an embankment model, we can respectively cover the project area of the model with a solar-opaque white mask and a solar-opaque black mask, and the embankment model. At the same time, we record the arriving horizontal global solar radiation and the diffuse reflection from the ground, by centering one pyranometer up-facing to the sky and the other down-facing pyranometer to the project area. Supposing the view factor from the project area to the down-facing pyranometer is F, one has the following:

$$I_w = [\rho_w F + \rho_s (1-F)] I_{hw} \quad (4)$$

$$I_b = [\rho_b F + \rho_s (1-F)] I_{hb} \quad (5)$$

$$I_e = [\rho_e F + \rho_s (1-F)] I_{he} \quad (6)$$

where I_w, I_b, and I_e are the diffuse reflection reading from the down-facing pyranometer when the white mask, black mask, and embankment model are used; correspondingly, I_{hw}, I_{hb}, and I_{he} are the global horizontal solar irradiance recording from the up-facing pyranometer. ρ_s is the weighted albedo of the material surrounding the project area, and ρ_e is the albedo of the embankment model. If the spectral reflectance of the white mask and black mask are constant with respective to the incident sunlight wavelength ($r(\lambda) = $ r), ρ_w and ρ_b are constant according to Eq. (1). Once ρ_w and ρ_b are known, one can find ρ_e as

$$\rho_e = \frac{\left(\frac{I_e}{I_{he}} - \frac{I_b}{I_{hb}}\right)\rho_w - \left(\frac{I_e}{I_{he}} - \frac{I_w}{I_{hw}}\right)\rho_b}{\left(\frac{I_w}{I_{hw}} - \frac{I_b}{I_{hb}}\right)} \quad (7)$$

3. Experiments

We selected two solar-opaque masks with relatively constant spectral reflectance as the white and black masks. Their spectral reflectance was measured by a Spectrophotometer Lambda 750 and shown in Fig. 2. Their albedo was $\rho_w = 0.692$ and $\rho_b = 0.048$ according to ASTM-E903-

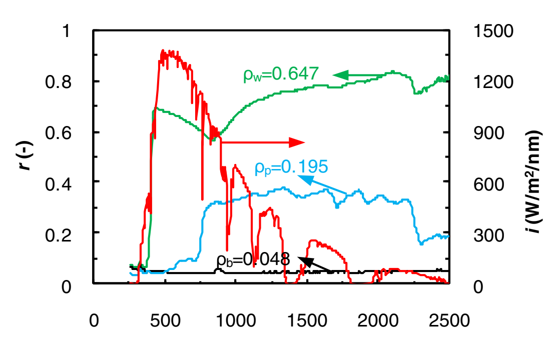

Fig. 2. The spectral reflectance of the white mask, the black mask, and the embankment model's surface.