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Theory and procedure for measuring the albedo of a roadway embankment

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The construction of roadway embankments in permafrost regions modifies the pre-existing ground surface, possibly increasing the solar absorption of the embankment. Measuring the albedo of the embankments is crucial to understand the degree of the construction-induced thermal disturbance and to cool the permafrost in the roadbed. While there are existing standards for measuring the albedo of a curved surface, these standards cannot be adpated to the albedo of an embankment. This study develops a theoretical model for measuring the albedo of a roadway embankment. The albedo of an embankment prototype is estimated by successively covering a target surface with a white mask, a black mask, and the embankment prototype and recording the diffuse reflections and the global horizontal radiation accordingly. The albedo of a typical embankment is about 0.05 to 0.08 lower than a flat surface that has the same surface material as the embankment, suggesting that an embankment absorbs more sunlight than its adjacent ground surface and its pre-existing ground surface. The embankment-albedo measuring procedure is compared with the ASTM E1918-06, with a focus on minimizing the errors of the measurements.

1. Introduction

Roadways in permafrost regions are usually built upon embankments, which are constructed to disperse the traffic loadings and to prevent the thawing damage of the underlying layer (Esch, 1978, 1983, 1996a; Ma et al., 2009; Qin and Zhang, 2010; Qin et al., 2010; Vinson, 1993). The embankment buries the pre-existing ground surface and modifies the ground surface thermal balance, negatively varying the heat convection, the vegetation coverage, and the solar absorption (Cheng et al., 2008; Esch, 1996b; Qin and Zhang, 2013; Vinson, 1993).

The roadbed can be cooled by enhancing the air convection in the embankment; by reducing the solar absorption at the embankment surface; and the combinations of these approaches (Cheng et al., 2008; Esch, 1996b; Lai et al., 2006, 2009; Reckard, 1985; Vinson et al., 1996). Techniques to enhancing the embankment convective heat loss includes the air convective embankment (Cheng et al., 2007; Goering, 2003; Goering and Kumar, 1996); heat drains (Beaulac and Dore, 2006); air ducts embankment (Coulombe et al., 2012; Dong et al., 2010; Lepage and Dore, 2010; Qin and Zhang, 2013); thermosyphons (Haynes and Zarling, 1988; Lai et al., 2009; Wagner, 2014). The solar absorption of the embankment can be reduced by using light-colored or white-colored pavement surfaces (Berg and Esch, 1983; Jørgensen, 2008; Lepage and Dore, 2010; M-Lepage et al., 2012a); by installing of shading boards and sunsheds on the side slopes (Feng et al., 2006; M-Lepage et al., 2012b; Qin et al., 2015b); by facing the embankment side slopes with high-reflectivity paints (Qin et al., 2015a, 2016).

Among these techniques, reducing the solar absorption of the embankment is the most direct approach to cool the roadbed because the temperature of the earth subsurface is driven by the solar radiation. While there are some investigations of the solar absorption of the embankment (Chen et al., 2006; Chou et al., 2010; Hu et al., 2002), knowledge of the solar absorption of an embankment is scanty. Measuring the absorptivity (absorptivity = 1-albedo) of an embankment is crucial to quantify the construction-induced thermal disturbance and to develop engineered solutions to keep the embankment cooler. With a curved surface, some diffuse reflections leaving adjacent ground surfaces is intercepted by the embankment side slopes rather than by the sky. This solar trapping effect is the subject of multiple reflections, increasing the solar absorption of the embankment. The methods to measuring the solar absorption of an embankment, however, have not been developed. An existing standard such as ASTM C 1459 (2014) is designed to measure the albedo of a flat surface with 5 cm^2. Due to this small surface, it is difficult to adapt this method to the albedo of an embankment. ASTM E1918-06 (2015), designed to measure the albedo of roof tile, is capable to measure the albedo of a curved surface with an area of 1 m^2(Akbari et al., 2008). Nevertheless, the roughness of roof tiles is greatly smaller than that of an embankment so that the ASTM E1918-06 cannot be adapted to measure the albedo of an embankment.

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Nomenclature

English symbols

F	the view factor from the lower pyranometer to the target
I	global horizontal solar radiation (GHSR)
I_b	diffuse reflections when the black mask is on the target surface
I_t	diffuse reflections when the embankment prototype is on the target surface
I_w	diffuse reflections when the white mask is on the target surface
I_{hb}	the GHSR when the black mask is on the target
I_{ht}	the GHSR when the embankment prototype is on the target
I_{hw}	the GHSR when the white mask is on the target

Greek symbols

λ	wavelength
r	spectral reflectance
ρ_b	the albedo of the black mask
ρ_p	the albedo of the paint on the embankment surface
ρ_t	the albedo of the embankment
ρ_w	the albedo of the white mask
ρ_{1918}	the embankment's albedo estimated by the ASTM E1918-06

This study develops a theoretical model to measure the albedo of an embankment prototype. The procedures for measuring a curved surface like an embankment are provided in detail. We measured the albedo of an embankment prototype and of a flat plate that had the same material as the embankment, to conclude the solar absorptive difference between an embankment and its pre-existing ground surface. To avoid the slope-facing problem effect on the analysis of the embankment albedo, the experiment was conducted on a cloudy day. This albedo-measurement approach is compared to the existing standard ASTM E1918-06, with a focus to minimizing measurement errors.

2. Theory

2.1. The albedo of a material

Albedo, or solar reflectance, is quantified as the proportion of solar radiation 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 incident solar radiation intensity I

$$I = \int_{\lambda_0}^{\lambda_1} i(\lambda) d\lambda, \tag{1}$$

and the albedo (ρ), or reflectivity, of the surface

$$\rho = \frac{1}{I}\int_{\lambda_0}^{\lambda_1} i(\lambda) r(\lambda) d\lambda, \tag{2}$$

where $\lambda_0 = 280$ nm and $\lambda_1 = 2500$ nm are usually considered.

According to Eq. (2), the albedo of a surface depends on the incident solar spectral irradiance $i(\lambda)$ and the spectral reflectance $r(\lambda)$. If a flat surface is homogeneous, $r(\lambda)$ is the spectral reflectance of a small sample of the surface. The albedo of this flat surface can be estimated by assuming an incident solar spectral irradiance $i(\lambda)$. However, if a surface is curved or heterogeneous, the spectral reflectance of the surface is immeasurable and the albedo of this curved surface cannot be estimated by using Eq. (2).

2.2. Theory for measuring the albedo of an embankment prototype

The embankment is a curved surface consisting of two side slopes and an upper surface. The embankment in field is so large that it is uneconomical to set a pyranometer some meters above the embankment to measure the diffuse reflections of the embankment. However, we can fabricate an embankment prototype in lab and measure the albedo of the prototype. The albedo of this prototype can represent the embankment in field because the wavelength of the sunlight is several orders of magnitude lower than the size of the embankment prototype so that the diffraction radiation at the curved surface can be neglected.

Placing an embankment prototype on a target area and then centering and leveling an albedometer (an instrument that assembles two pyranometers back to back with the lower one reading the diffuse reflection I_t(W/m^2) and the upper one measuring the global horizontal solar radiation (GHSR) I_{ht} (W/m^2), one gets

$$I_t = [\rho_t F + \rho_s(1-F)]I_{\mathrm{ht}} \tag{3}$$

where F is the view factor from the lower pyranometer to the target area; ρ_s is the weighted albedo of the surroundings; ρ_t is the albedo of the embankment prototype.

In Eq. (3), both ρ_t and ρ_s are unknown so we cannot find ρ_t unless one another equation is introduced. This additional equation can be found by covering the target area with a mask that has a known albedo. Usually, a white solar-opaque mask and a black solar-opaque mask are used while measuring the GHSR and the diffuse reflections, respectively. The solar reflectance obeys:

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

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

where ρ_w and ρ_b are the albedo of the white and black masks, respectively. I_w (W/m^2) and I_{hw} (W/m^2) are the diffuse reflections and the GHSR when the white mask is used; I_b(W/m^2) and I_{hb}(W/m^2), when the black mask is used. Once ρ_w and ρ_b are known, one can find ρ_t as:

$$\rho_t = \frac{\left(\frac{I_t}{I_{ht}} - \frac{I_b}{I_{hb}}\right)\rho_w - \left(\frac{I_t}{I_{ht}} - \frac{I_w}{I_{hw}}\right)\rho_b}{\left(\frac{I_w}{I_{hw}} - \frac{I_b}{I_{hb}}\right)} \tag{6}$$

where the albedo of the target surface ρ_t is independent to the view factor F and to the albedo of the surrounding ρ_s.

According to Eq. (6), the albedo of the surroundings does not influence the albedo of the target area. This means that the objects around the embankment prototype would not affect the albedo measurement of the prototype. This is true only if the incident solar spectrum $i(\lambda)$ varies negligibly during a specific measurement cycle. This is because in Eqs. (3)–(5), ρ_s is assumed as a constant during the replacements of the white mask, black mask, and embankment prototype. According to Eq. (2), this assumption satisfies only if the incident solar spectrum $i(\lambda)$ varies negligibly during a specific measurement cycle. In this study, if the maximum difference among I_{hw}, I_{hb}, and I_{ht} is greater than 10 W/m^2 for a cloudy day and 20 W/m^2 for a sunny day, the measurement must be redone. The other assumption in Eqs. (4)–(5) is that the albedo of the white and black masks is a constant for each. According to Eq. (2), this assumption means that the spectral reflectance $r(\lambda)$ must be a scale regardless of the solar irradiance wavelength λ. This means that the white and black mask must be selected such that their spectral reflectance is a constant for each regardless of the irradiance wavelength; i.e., ($r(\lambda) = r$).