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# Theoretical models for the solar absorptivity of a roadway embankment

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ABSTRACT

Building roadways through permafrost corridors is challenged by the presence of permafrost stratum, which is sensitive to the changes of the heat transfer balance at the ground surface. Due to the construction of the embankment, some reflected radiation from the nearby ground is trapped and absorbed by the side slope. This additional absorption of the embankment may be detrimental to the thermal stability of the permafrost stratum but has not been understood. Here we present two theoretical models to estimate the solar absorption of the embankment and we compare the prediction by the models against the experimental measurements. One is the solar trapping model and the other is the surface roughness model. The former is relatively complicate but it can estimate the macro-reflectivity/absorptivity of the embankment and of the side slope, respectively. The latter is relatively straightforward but can estimate the macro-reflectivity/absorptivity of the embankment only. It is found that the embankment absorbs more sunlight than the adjacent ground and that for a typical embankment, the macro-absorptivity of the embankment is 0.01–0.05 lower than its micro-absorptivity. This minimal difference suggests that the solar absorption of an embankment can be curtailed by raising the embankment's albedo, which can be done by flatting the side slope surface and painting the slope with high-reflectivity.

## 1. Introduction

Roadways in Arctic and sub-Arctic regions have been growing during last decades. Routing roadways in these regions is challenged by the presence of permafrost, which is sensitive to the changes of the heat transfer balance at the ground surface. The construction of the roadway modifies the pre-existing ground-surface conditions and consequently, negatively varies the heat convection, the vegetation coverage, and the solar absorption at the ground surface (Cheng et al., 2008; Lai et al., 2006; Ma et al., 2009).

On the aspect of solar absorption, previous studies have widely focused on the high-reflective paved surface (Bjella, 2013; Fulwider and Aitken, 1963; Reckard, 1985) and on the embankment-induced slope-facing thermal asymmetrical problem (Chou et al., 2008a; Chou et al., 2012; Ma et al., 2009). In the late 1950s, white surface have been used for the airfield, at Thule Air Base, Greenland to prevent the thawing of ice-rich subsoils that caused localized depressions at the airfield's runways. High albedo of the painted sections has been subjected to less thaw settlement and lower subsurface temperature (Reckard, 1985) but was not recommended for the factors of high cost, road slipperiness, and differential albedo after worn. Thank to this lesson, the Qinghai-Tibet Railway built in the early 2000s did not use high-reflective surface but laid the rail tracks upon an embankment, which is cooled by a serial of new technology in active ways (Arenson et al., 2006; Niu et al., 2006; Wu et al., 2008; Yu et al., 2004). However, this cooling-technology is costly and the embankments also have caused differential settlement along the embankment due to the slope-facing problem (Ma et al., 2009). A couple of models have been developed to calculate the differential solar absorption across the embankment (Chou et al., 2008a) and to estimate the temperature distribution in the roadbed (Chou et al., 2008b). The thermal asymmetrical problem may be remedied by increasing the side slope albedo and decreasing the side slope angle (Chen et al., 2006; Hu et al., 2006). In addition, the different solar absorption between the side slopes of an embankment varies with the embankment orientation (Wu et al., 2011). While both the embankment surface reflectivity and the embankment configuration greatly determine the solar absorption and thermal balance of an embankment, the reflectivity/absorptivity of an embankment and of its side slope is seldom known.

The absorptivity/reflectivity of a surface can be estimated in lab, in field, and in theory. In the laboratory, the reflectivity of a small homogeneous sample can be measured by using a spectrometer to measure the solar reflectance spectrum of the material and by integrating the spectral reflectance weighted with a typical solar spectrum. While the embankment surface is rough and heterogeneous, laboratory measurement techniques are not practical for many field applications.

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In field, a portable albedometer, which assembles two pyranometers back to back, can be centered and leveled over a certain height (usually 0.5 m) to measure the reflected radiation and the incident radiation simultaneously. The ratio of the reflected radiation to the incident radiation encompasses the reflectivity of the target and the reflectivity of the surroundings. To separate them, one technique is to estimate the reflectivity of the target by covering the target area with a pair of white and black solar-opaque masks and by measuring the incident and reflected radiation simultaneously (Qin et al., 2016c; Qin et al., 2016d). While this white-black controlled method is reasonable, it is available to measure the solar absorption of a small-scale embankment only, such as an embankment prototype (Qin et al., 2016a; Qin et al., 2016b). The real solar absorptivity/reflectivity of an embankment may be estimated in theory and validated by the experimental measurements.

The focus of this paper is to theoretically understand the solar absorptivity of the embankment surface. Two models that considering the radiative transfer at a rough surface are introduced to estimate the reflectivity of a real-scale embankment. The estimated reflectivity is compared against the albedo that is measured from an embankment prototype. Parameters influencing the reflectivity of an embankment are discussed with a focus on the difference between the micro- and macro-absorptivity of the embankment and on the factors influencing this difference.

## 2. Theory

### 2.1. The micro- and macro-reflectivity of a surface

Reflectivity of a surface is the fraction of incident solar radiation that is reflected at an interface. It is an integral of the incident solar irradiance spectrum over the reflective spectrum, which is the plot of the reflectance as a function of wavelength. Let $i(\lambda)$ represent incident power per unit surface area per unit wavelength $\lambda$. The albedo of a flat homogeneous surface, denoted as micro-reflectivity, is

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

where $\lambda_0 = 250$ nm and $\lambda_1 = 2500$ nm are usually considered.

In the following, we denote micro-absorptivity as the absorptivity that is the integral of the solar absorptive spectrum weighted with the incident solar spectrum. We denote macro-absorptivity as the absorptivity that is the ratio of the total absorption of a surface (flat or curved) to the incident solar sunlight on it. The micro-reflectivity and -absorptivity are denoted as lower case letters $r$ and $a$, respectively. The macro-reflectivity and -absorptivity are denoted as upper case letters $R$ and $A$, respectively.

### 2.2. The solar trapping model

The embankment side slope absorbs some reflected radiations that leave from the adjacent ground (Fig. 1). This process is the multiple reflections, which decrease exponentially with the reflection iterations. If only the first cycle of multiple reflections is considered and the subsequent reflections are neglected, the additional absorption of the side slope is

$$A_s' = I_g r_g F_{g\to s}(1-r_s) \tag{2}$$

where $I_g$ is the solar irradiance incident on the ground; the subscripts $s$ and $g$ stand for the side slope and the ground, respectively; $F_{g\to s}$ is the view factor from the adjacent ground to the side slope, which is

$$F_{g\to s} = 0.5(1-\cos\eta) \tag{3}$$

where $\eta$ is the side slope angle.

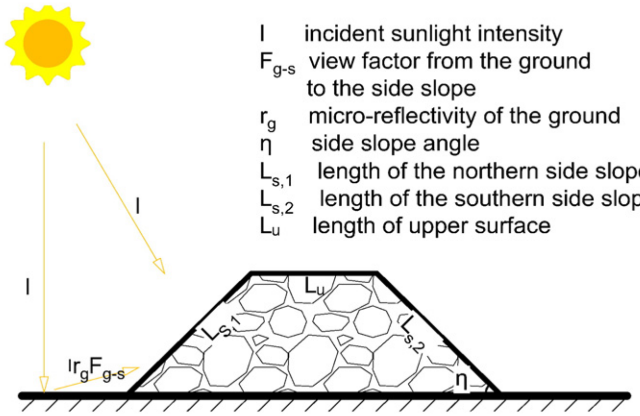

**Fig. 1.** A schematic show for the additional reflected radiation on the side slope.

Due to the additional reflected from the adjacent ground, the macro-absorptivity of the side slope is

$$A_s = \frac{I_s(1-r_s) + I_g r_g F_{g\to s}(1-r_s)}{I_s} \tag{4}$$

where $I_s$ is the solar irradiance incident on the side slope.

Correspondingly, the macro-reflectivity of the side slope is

$$R_s = 1-A_s \tag{5}$$

In practice, the macro-reflectivity and -absorptivity of an entire embankment is also of concern. The macro-absorptivity of the embankment is the weighted absorptivity of the embankment upper surface and of its two side slopes.

$$A_e = \frac{A_{s,1}I_{s,1}L_{s,1} + A_u I_u L_u + A_{s,2}I_{s,2}L_{s,2}}{I_{s,1}L_{s,1} + I_u L_u + I_{s,2}L_{s,2}} \tag{6}$$

where the subscript $u$ stands for the upper surface of an embankment; the subscript "*1*" stands for the northern side slope; and the subscript "*2*", the southern side slope.

Correspondingly, the macro-reflectivity of the embankment is

$$R_e = 1-A_e \tag{7}$$

In Eqs. (1)–(6), the solar radiation incident on the ground and on the side slope remains unknown. At the ground near the side slope, there may be some shadow near the sunrise and sunset but the shadow at other time is negligible. Ignoring the shadow effect, one gets the solar incident on the ground as

$$I_g = I_0 \cos\theta \tag{8}$$

where $I_0$ is the daily zenith solar radiation; $\theta$ is the sun zenith angle (Appendix A).

The solar radiation incident on the side slope is relatively complicate because the side slope may be shaded or sunlit. The solar radiation incident on the slope is divided into diffuse radiation ($I_d$) and beam radiation ($I_b$). The solar radiation on the slope is

$$I_s = I_b(\sin\theta\sin\eta\cos(\psi-\gamma_s) + \cos\theta\cos\eta) + F_{s\to sky}I_d \tag{9}$$

where $\gamma_s$ is the solar azimuth angle (Appendix A); $F_{s\to sky}$ is the sky view factor of the side slope, $F_{s\to sky} = 0.5(1+\cos(\eta))$

$$F_{s\to sky} = 0.5(1+\cos\eta) \tag{10}$$