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Simulation of short-wave solar radiative transfer across a roadway embankment

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ABSTRACT

Permafrost under a roadway embankment is sensitive to temperature increments. Thermal stability of the underlying permafrost is mainly regulated by the solar absorption at the embankment surface. Multiple reflections between the embankment's side slope and its adjacent ground surface may increase the solar absorption of the embankment but have not been studied. Here we model the short-wave radiative transfer across an embankment and then compare the simulated reflectivity against the measured reflectivity of an embankment prototype at a clear weather. It is found that the solar absorption of the embankment is complexly and simultaneously influenced by the solar position, the embankment configuration, the sky clearness factors, and others. We do not exhaust these influences but focus on the absorptivity of the ground and of the side slope due to the solar trapping effect. It is found that the solar trapping effect increases the absorptivity of the side slope about 0–0.03 for a common embankment with a typical surface absorptivity of 0.80. This small difference implies that despite the solar trapping effect of the side slope, increasing the side slope reflectivity reduces the slope's solar absorption effectively.

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1. Introduction

Designing roadway 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. To minimize the thermal disturbance of the permafrost stratum, the roadway is usually laid upon an embankment [1–3]. The embankment, however, modifies the pre-existing ground-surface conditions and negatively varies the heat convection, the vegetation coverage, and the solar absorption [4–6]. To stabilize the permafrost in the roadbeds, roadway engineers have adopted a serial of passive cooling techniques to keep the embankment cool, including the uses of air convective embankment [7–9], thermosyphons [10–12], shading boards [13,14], high-reflective pavement surface [15–17], etc.

While these techniques effectively stabilize the permafrost in the roadbeds, differential solar absorption across the embankment surface is detrimental to the thermal stability of the embankment. Solar irradiance incident on the embankment surface is greatly different from that on the adjacent ground surface. In the northern hemisphere, the south-facing side slope is insolated for longer hours and exposed for greater solar irradiance than the

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north-facing one. Differential solar absorption between the two side slopes have caused distresses to the embankment, such as longitudinal cracks and differential settlements [18,19]. Differential solar absorption between two side slopes is not only influenced by the slope-facing problem, but also by a group of other complex factors including the side slope angle [18], the slope facing [20,21], and the day number of the year [22,23]. One countermeasure to remedying the differential solar absorption between the side slopes is to reduce the gradient of the side slopes [20]. Alternative mitigation strategy is to balance the solar absorption of the side slope of the embankment by increasing the reflectivity of the southern side slope [4,24].

Although the reflectivity is critical to the thermal balance at the embankment surface, the techniques of measuring the reflectivity of the embankment surface are insufficient. In theory, the reflectivity is the fraction of the incident radiation that is reflected by a surface. This theoretical concept is simple but in practice, the actual measurement of the surface reflectivity is complicate. Generally, the reflectivity of a surface can be measured in laboratory, by remote sensing, and in field. In laboratory, the spectral reflectance of a surface is measured by a spectrometer [25]; and integrating the spectral reflectance weighted with a typical solar irradiance spectrum yields the reflectivity. While the lab method is reliable to measure the reflectivity of a small sample in a scale of several centimeters, it cannot be adapted to measure the reflectivity of an embankment. The reflectivity of a bigger surface such as the albedo of a 1km^2 target area is inquired by remote sensing. Aircraft or satellite-based tools are applied to observe high-solution narrowband satellite information that includes the surface reflectivity globally [26]. The reflectivity of the target area is obtained by conversing the narrowband reflectance to the broadband reflectance [27–29].

In field, the reflectivity of a surface can be measured by centering and leveling a pyranometer or a pair pyranometer over a target surface to read the incident and reflected radiations simultaneously [30]. This surface must fill the field of view of the down-facing pyranometer. A surface with a 5×5 m^2 can fill 97% of the view field of a detector that is centered approximately 0.5 m above the surface [31,32]. For many field applications, preparing such a large surface is costly and even impractical. Recently, Akbari et al. [31] proposed a white-black control method that estimates the reflectivity of a diffusely reflective surface as small as 1 m square. This method had been extended to measure the reflectivity of a bent surface such as an embankment prototype [33], which is about 0.4–0.5 $\times$ 1 m^2. The procedure can be used to measure the reflectivity of an entire embankment prototype, but the solar absorptivity on the side slope of the embankment cannot be measured solely.

To estimate the solar absorptivity of a real embankment, we simulate the short-wave radiative transfer across the embankment. Considering the solar trapping effect between the embankment side slope and it adjacent ground, we call the micro-absorptivity as the absorptivity of a flat surface that has a full sky view and we consider the macro-absorptivity as the ratio of the solar absorption of a surface to the incident radiation on it [34]. The simulated macro-reflectivity of an embankment is compared against the macro-reflectivity of an embankment prototype. Factors influencing the macro-absorptivity of the embankment encompass the sun position, the surface micro-reflectivity, the embankment configuration, the sky clearness factor, the embankment strike, and others. While these factors simultaneously influence the macro-reflectivity and -absorptivity of the embankment and of the side slope, this study does not exhaust the influences of these factors but focuses on the macro-absorptivity of an embankment with typical surface's micro-reflectivity.

2. Radiative transfer between the side slope and its adjacent ground

2.1. Sun position

The solar position determines whether a side slope of an embankment is shaded or sunlit. It varies with the solar declination angle, the solar zenith angle, the solar azimuth angle, and the solar hour angle. The solar declination angle [35], δ (rad), is

$$\delta = 0.409 \sin\left(2\pi \frac{N + 284}{365}\right) \tag{1}$$

where N is the number of the day with $N = 1$ for January 1.

The solar zenith angle, θ (rad), is determined from [36]

$$\cos\theta = \sin\delta\sin\phi + \cos\delta\cos\phi\cos\omega \tag{2}$$

where ϕ (rad) is the latitude of the observer on the earth surface; ω (rad) is the solar hour angle which is equal to $-\pi/2$ at sunrise, 0 at noon and $\pi/2$ at sunset. The time of sunrise and sunset can be derived as:

$$\cos\omega = \frac{\sin(-0.83^\circ) - \sin\delta\sin\phi}{\cos\phi\cos\delta} \tag{3}$$

where the sunset time is positive and the sunrise time is negative.

The solar azimuth angle, γ(rad), is given by

$$\sin\gamma = \cos\delta\sin\omega / \sin\theta \tag{4}$$

If $|\sin\gamma| > 1$ or if $|\sin\theta|$ is infinitesimal, the solar azimuth angle cannot be calculated properly. At this case, the solar azimuth angle has to be estimated by [37]:

$$\cos\gamma = \frac{\cos\theta\sin\phi - \sin\delta}{\sin\theta\cos\phi} \tag{5}$$

It is noted that when $\theta = 0$, the denominators in Eqs. (4) and (5) are zero. For computational convenience, this problem can be circumvented by using even time steps from the sunrise to the sunset.

Eqs. (1)-(5) determine whether a side slope of an embankment is sunlit or shaded. A typical embankment is schematically shown in Fig. 1. At a sunny weather, beam radiation creates a parallelogram shadow alongside the embankment. The shadow parallel to the embankment strike has a length of [38]

$$x_0 = h\tan\theta\cos(\gamma - \gamma_e) \tag{6}$$

where h (m) is the height of the embankment; and γ_e (rad) is the orientation of embankment, with 0 for the west-east orientation and $\pi/2$ for the north-south orientation. If $x_0 > h\cot(\eta)$, the south/

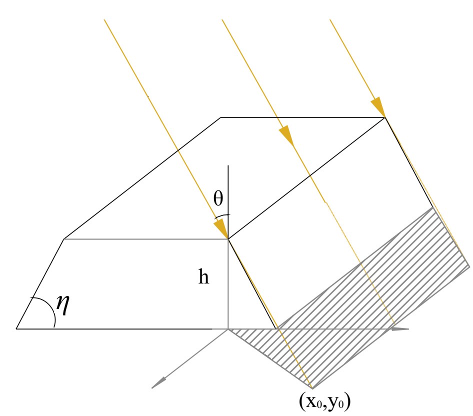

Fig. 1. Beam radiation creates a shadow alongside the embankment with a side slope angle η and a height of h.