

Article

Effects of Road Alignment and Fill Height on Transverse Thermal Asymmetry in a G219 Rock-Filled Ventilated Embankment

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Abstract

Road alignment creates unequal shortwave-radiation inputs on opposite embankment slopes, whereas the way in which overlying fill height redistributes this contrast among embankment layers remains unclear. This study aimed to quantify how road-axis azimuth controls transverse heat input and how upper fill height redistributes this input among the upper fill, rock-filled target layer, and permafrost foundation of a representative G219 rock-filled ventilated embankment. A two-dimensional transient enthalpy-based heat-transfer model, incorporating a smoothed phase-change treatment and coupled convection–shortwave boundary conditions, was used to compare three azimuths (0°, 45°, and 90°), three upper fill heights (0.5, 1.5, and 3.5 m), and cold-year, reference-climate, and warm-year boundaries. Three counterfactual scenarios were used to separate the effects of target-layer equivalent thermal properties and exposed-surface optical conditions, while continuous simulations over 0°–165° verified the representativeness of the formal azimuths. The common-domain response at 45° reached 67.9–70.1% of that at 90°, indicating a continuous transition from near-symmetric to strong transverse heating input. Under the thermal–optical scenario at 90°, increasing fill height increased common-domain asymmetry by factors of 2.69–2.89; however, the target-layer response consistently peaked at 1.5 m, whereas the foundation-layer response decreased. The upper-fill-to-target-layer peak lag also increased with fill height. These patterns persisted across climate boundaries and prescribed thermal–optical–conductivity perturbations. Within the controlled scenarios, road alignment set the transverse heat input, whereas fill height regulated its within-profile transfer and layer-specific thermal response. The results support comparative thermal assessment of embankments with a similar upper-fill–rock-filled–target-layer–permafrost–foundation sequence, rather than design of an optimum fill height for a specific site.

Keywords: G219; rock-filled ventilated embankment; transverse thermal asymmetry; fill height; seasonal response lag



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1. Introduction

1.1. Background and Problem Statement

The thermal state of permafrost is a critical environmental condition governing the long-term performance of transportation infrastructure in cold regions. Climate warming is altering active-layer thickness and the position of the permafrost table, making embankments that are already close to a thermally stable limit more susceptible to engineering disturbance [1]. The spatial distribution of permafrost and changes in active-layer thickness across the Qinghai–Tibet Plateau show substantial regional variability, and the permafrost environment along transportation corridors is therefore highly sensitive [2]. Experience with highway construction on the Qinghai–Tibet Plateau also demonstrates that the compatibility between embankment structures and local climatic conditions directly affects the thermal stability of the underlying permafrost [3].

Embankment construction changes the cover condition, slope geometry, and radiative exchange of the natural ground, so the two sides of a cross-section no longer experience identical thermal boundary conditions. Differences in the albedo of pavement and slope surfaces in permafrost regions modify shortwave absorption and consequently affect the internal embankment temperature field [4]. Field experiments on the Qinghai–Tibet Plateau have shown that slope orientation can produce differences in near-surface temperature and moisture conditions [5]. Long-term observations and numerical analyses along the Qinghai–Tibet Highway further indicate that the heating contrast between sunny and shady slopes can induce an asymmetric talik beneath the embankment [6].

Because of their strong seasonal heat-dissipation capacity, rock-filled ventilated embankments have become a commonly used thermal-stability measure in permafrost regions. Thermal-response models for air-convection embankments show that cooling performance is jointly determined by the rock-fill skeleton, boundary conditions, and external climate [7]. Field monitoring in the Karakoram section of G219 indicates that a rock-filled ventilated layer can reduce heat transfer into the road structure, while the temperature lag at the bottom of the ventilated layer becomes more pronounced as the fill height increases [8]. Full-scale tests of ventilated embankments further demonstrate substantial spatial and seasonal variability in their internal thermal response [9].

Different types of air-cooled embankments exhibit distinct thermal stability and applicability in warm permafrost regions [10]. Long-term simulations under snow-drift conditions show that seasonal cover changes can weaken the local cooling capacity of rock-filled structures [11]. Studies of air-convection embankments in sub-Arctic regions have likewise shown that snow cover can modify airflow within the rock-fill layer and the embankment heat flux [12]. These findings indicate that the thermal process in ventilated embankments is controlled not only by the rock-fill material itself; radiative conditions at exposed surfaces and seasonal boundary forcing are also important.

In recent years, researchers have attempted to reduce solar-radiation absorption by regulating the albedo of engineering surfaces [13]. The development of wind-driven cooling devices has also shown that external cold-source utilization can broaden the available thermal-control approaches for permafrost embankments [14]. Field tests of solar-refrigerated embankments indicate that changing the external energy input alters both the cooling process and its seasonal behavior [15]. Although these studies provide a substantial basis for assessing embankment thermal stability in cold regions, how the transverse heating contrast generated by road alignment is redistributed among different fill heights and layers after entering the embankment still needs to be identified under common conditions.

1.2. Research Gaps

Studies of the sunny–shady slope effect and transverse embankment temperature differences have generally focused on a particular structural measure or a specific slope condition. Investigations of combined cooling measures under sunny–shady conditions have shown that structural configuration can regulate the asymmetric temperature field inside an embankment [16]. Numerical analyses of W-shaped rock-filled embankments have further examined structural thermal stability under asymmetric boundaries in warm permafrost regions [17]. Studies of L-shaped rock-filled structures have also considered cooling performance under different slope-heating conditions [18]. Field investigations and numerical analyses indicate that rock-filled embankments can exhibit pronounced transverse temperature differences under real environmental conditions [19]. Studies on the applicability of gentle-slope embankments likewise show that cross-sectional geometry changes the extent of thermal disturbance [20]. Nevertheless, few studies have, under a common cross-section, climate boundary, and evaluation location, related the difference in shortwave input caused by road alignment to the layer-by-layer transverse thermal responses of the upper fill, target layer, and foundation layer. Consequently, comparable controlled evidence is still lacking on how an external heating contrast generated by road alignment is converted into differentiated responses within an embankment cross-section.

Studies of fill height and structural dimensions have commonly used mean ground temperature, freeze–thaw interfaces, cooling extent, or overall stability as the primary metrics. A thermo-mechanical numerical study of rock-filled ventilated embankments in the G219 freeze–thaw region showed that fill heights of 0.5, 1.5, and 3.5 m alter the embankment temperature field and the settlement difference under sunny–shady conditions [21]. Recent work has further indicated that the structural scale and mutual thermal interference of block-stone embankments can modify the range of thermal response in permafrost embankments [22]. Numerical studies of rock-filled interlayers with longitudinal ventilation ducts have emphasized the influence of ventilation pathways on embankment cooling [23]. Experiments under rainfall infiltration have shown that changes in external boundaries can substantially modify the hydrothermal processes of the rock-filled layer and the underlying soil [24]. The influence of block-stone layers on heat transfer to the foundation has also been discussed numerically [25]. It is therefore necessary to compare the effect of fill height simultaneously at the domain, target-layer, foundation-layer, and seasonal-phase levels, in order to determine whether fill height changes only the overall magnitude of transverse thermal asymmetry or also shifts its primary receiving layer and transfer timescale within the cross-section.

Climate background and parameter choices also affect the assessment of rock-filled ventilated embankment thermal stability. Studies of snow cover and rock-filled embankment cooling mechanisms show that seasonal cover changes modify the structural thermal response [26]. The deterioration of rock-filled structures under climate warming further suggests that initial cooling performance cannot be taken as representative of long-term behavior [27]. Numerical studies of novel ventilated embankments show that structural cooling capacity is strongly constrained by the external thermal environment [28]. Engineering practice along the Alaska Highway in Canada demonstrates that coupled reflective and convective measures can improve the thermal environment of permafrost embankments [29]. Field observations of open ventilated spaces in high-altitude warm permafrost regions likewise show strong spatial and seasonal variability in ventilation cooling [30]. These studies indicate that climate and surface conditions alter the absolute thermal response of rock-filled embankments, and that results obtained under a single boundary condition are insufficient for mechanism identification. More importantly, comparisons of structural schemes often change target-layer thermal properties and exposed-surface

conditions simultaneously, making their relative contributions to transverse thermal asymmetry difficult to determine. A two-step counterfactual comparison under a common geometry and climate forcing is therefore needed, together with a test of whether the first two relationships persist across reasonable climate and parameter envelopes.

1.3. Scope and Contributions

To address these three gaps, this study examines transverse heat-input identification, fill-height-dependent layer transfer, and counterfactual attribution of structural and boundary effects together with robustness checks. Road alignment is treated as the controlled source of the transverse shortwave-input difference, while the upper fill height is treated as the structural factor regulating the within-profile transfer pathway. The main contributions are as follows:

1. Under an identical cross-section, climate boundary, and evaluation location, continuous azimuth simulations from 0° to 165° are first used to establish the continuous response range from near symmetry to strong asymmetry. The 0° , 45° , and 90° cases are then selected as formal comparison conditions to examine layer-specific responses to shortwave-input differences in the upper fill, target layer, and foundation layer.
2. Upper fill height is analyzed jointly with the common-domain response, layer-specific paired left–right temperature differences, and daily peak lag. The results show that fill height does not simply increase or decrease the overall temperature difference; instead, it changes where transverse thermal asymmetry is primarily distributed within the cross-section and how long it takes to propagate.
3. A two-step counterfactual comparison of EF, RF-T, and RF-TO is used to separate the relative effects of target-layer equivalent thermal properties and exposed-surface shortwave boundaries on transverse thermal asymmetry. The repeatability of layer-specific response relationships is then tested across cold-year, reference-climate, and warm-year boundaries and within thermal–optical and thermal-conductivity parameter envelopes.

2. Materials and Methods

2.1. Research Question and Counterfactual Experiment Design

Using a representative climate boundary near Mazar in the Karakoram section of G219, we established a two-dimensional transient phase-change heat-transfer model to compare the combined effects of road-axis azimuth, overlying fill height, climate background, and structural scenario on transverse thermal asymmetry. The formal experiments considered azimuths of 0° , 45° , and 90° , overlying fill heights of 0.5, 1.5, and 3.5 m, and cold-year, reference-climate, and warm-year boundaries. Three scenario codes were used in the following analyses. EF denotes the conventional-fill counterfactual, RF-T denotes the target-layer equivalent-thermal-property control, and RF-TO denotes the thermal–optical scenario with reduced exposed-surface shortwave absorptivity. The evaluation focused on paired left–right temperature differences in the common domain and individual layers, the peak lag from the upper fill to the target layer, and the stability of response rankings. The complete workflow, including the controlled inputs, numerical model, layer-wise evaluation, counterfactual attribution, and robustness checks, is summarized in Figure 1.

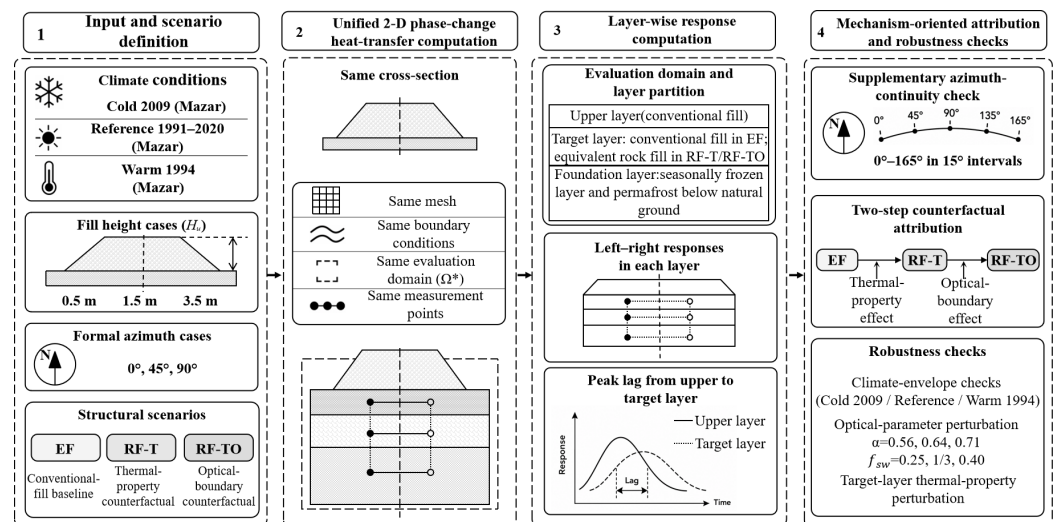


Figure 1. Overall methodological workflow.

2.2. Equivalent Representation, Cross-Sectional Geometry, and Counterfactual Scenarios

The computational domain was 50 m wide and 20 m deep. The road-top width was 8.5 m, and the side-slope ratio was 1.5H:1V. The representative layer sequence and the selected upper fill heights were informed by field monitoring of a rock-filled ventilated embankment on the Karakoram section of G219, where temperature and settlement observations were arranged for upper fill heights of 0.5, 1.5, and 3.5 m [8]. The present model retains this field-informed layered configuration but is used as a controlled numerical experiment rather than as a direct reconstruction of the monitored section. The pavement consisted of an asphalt surface course, a cement-stabilized aggregate base course, and a natural-gravel subbase, with original thicknesses of 0.06, 0.24, and 0.25 m, respectively. The pavement was represented by a 0.55 m equivalent layer based on series thermal resistance and areal heat capacity.

The 0–1.00 m interval above the natural ground surface was defined as the target layer. In the EF scenario, that layer was conventional fill; in the RF-T and RF-TO scenarios, it was assigned the equivalent thermal properties of the rock-filled ventilated structure. Conventional fill was placed above the target layer, and the overlying fill height was denoted by H_u and set to 0.5, 1.5, and 3.5 m. Accordingly, the total fill thickness from the natural ground surface to the bottom of the pavement structure was 1.5, 2.5, and 4.5 m, respectively.

The common cross-sectional geometry, layer configuration, paired evaluation points, and differences among the EF, RF-T, and RF-TO scenarios are shown in Figure 2. The material and phase-change parameters used in the simulations are listed in Table 1.

Table 1. Material and phase-change parameters used in the simulations.

Material	ρ (kg/m ³)	λ_f (W/(m K))	λ_t (W/(m K))	c_f (J/(kg K))	c_t (J/(kg K))	w	α_s
Pavement R–C equivalent layer	2100.9	1.475	1.475	921	921	0.0296	0.90
Conventional fill	2183	1.500	1.400	838	1020	0.12	0.72
Rock-filled ventilated equivalent layer	1850	1.940	1.940	1030	1030	0.03	0.72
Seasonally frozen layer	1870	2.200	1.690	856	1102	0.18	0.72
Permafrost layer	2025	2.120	1.360	1255	1703	0.22	0.72

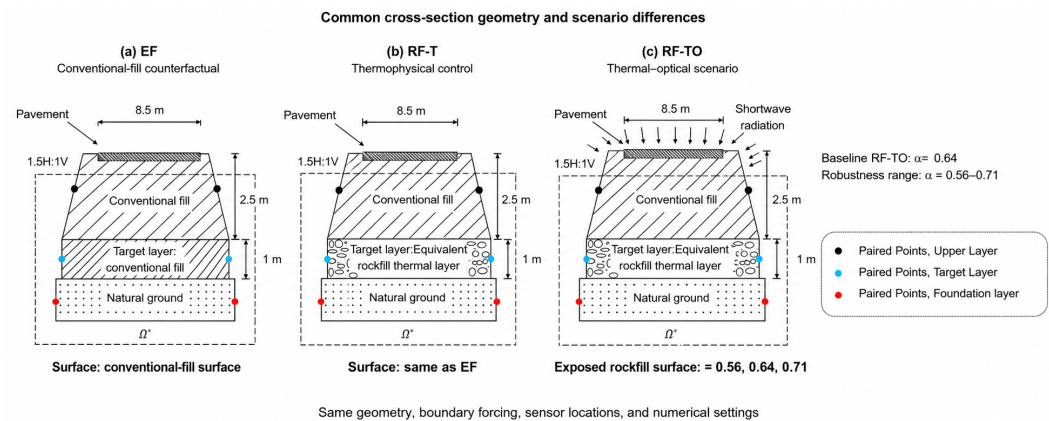


Figure 2. Cross-sectional comparison of the three scenarios.

The density, frozen and thawed thermal conductivities, and specific heat capacities of the conventional fill, seasonally frozen layer, and permafrost layer were adopted from Wang et al. [21] and converted to SI units where necessary. The rock-filled ventilated equivalent layer used the thermal properties of natural gravel reported in [21], consistent with the equivalent-property representation adopted in this study. The pavement R–C equivalent properties were calculated from the asphalt, cement-stabilized aggregate base, and natural-gravel subbase parameters reported in [21] by preserving series thermal resistance and areal heat capacity. The baseline surface absorptivity values of 0.90 for pavement and 0.72 for exposed fill/ground were also adopted from [21]. The gravimetric water contents were prescribed phase-change inputs for the present controlled simulations and were not calibrated against a specific G219 monitoring section. Table 2 presents the counterfactual experimental settings defined for this study, rather than a compilation of externally observed material data. The material assignments and the baseline exposed-surface shortwave absorptivity of 0.72 in EF and RF-T refer to the parameters listed in Table 1, which were adopted from Wang et al. [21]. The value of 0.64 in RF-TO was prescribed as a counterfactual optical-boundary setting to isolate the additional conditional effect of reduced surface absorption. This value was not intended to represent a unique site-specific surface condition; rather, it served as the reference optical perturbation in the controlled comparison. Its influence on the principal response rankings was further examined by varying surface absorptivity from 0.56 to 0.71 in the robustness analysis described in Section 4.5.

Table 2. Common and differentiated settings of the EF, RF-T, and RF-TO scenarios.

Setting	EF	RF-T	RF-TO
Target-layer material	Conventional fill	Rock-filled ventilated equivalent layer	Rock-filled ventilated equivalent layer
Internal target-layer thermal properties	Conventional-fill parameters	Equivalent rock-fill parameters	Equivalent rock-fill parameters
Exposed-surface shortwave absorptivity	0.72	0.72	0.64

The transverse coordinates of paired measurement points on the two sides were fixed. The upper points were located 0.25 m below the bottom of the pavement structure, the target-layer points were located at the middle of the target layer, and the foundation-layer points were located 0.50 m below the natural ground surface. The upper points moved upward as the fill height increased, whereas the elevations of the target-layer and foundation-layer points remained fixed. The common evaluation domain, Ω^* , included the

embankment fill and the zone extending 5 m below the natural ground surface and was symmetric about the road centerline.

The rock-filled ventilated layer was represented at the layer scale using prescribed equivalent thermal properties. This representation does not explicitly resolve pore-air circulation within rock voids, local moisture migration, or individual block geometry. Accordingly, the EF–RF–T–RF–TO comparisons quantify the conditional effects of the prescribed equivalent thermal properties and exposed-surface absorptivity under a common geometry and climate forcing, rather than the complete physical ventilation process of a field embankment.

2.3. Governing Equations and Phase-Change Treatment

A two-dimensional Cartesian finite-volume enthalpy formulation was used to describe transient heat transfer under freezing and thawing conditions. Heat exchange between adjacent control volumes was calculated using harmonic-mean thermal conductivities at material interfaces. The governing equation is:

$$\frac{\partial H}{\partial t} = \frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda \frac{\partial T}{\partial y} \right). \quad (1)$$

where T is temperature, H is volumetric enthalpy, λ is thermal conductivity, and t is time.

The volumetric enthalpy consists of sensible heat and latent heat of phase change:

$$H(T) = \rho \int_{T_0}^T c(\xi) d\xi + \rho w L f_l(T). \quad (2)$$

where ρ is material density, c is specific heat capacity, w is gravimetric water content, L is the latent heat of phase change of water, and f_l is the liquid fraction.

The liquid fraction varied smoothly from -0.5°C to 0.5°C :

$$f_l(T) = \begin{cases} 0, & T \leq -\Delta T, \\ \frac{1}{2} \left[1 + \frac{T}{\Delta T} + \frac{1}{\pi} \sin \left(\frac{\pi T}{\Delta T} \right) \right], & -\Delta T < T < \Delta T, \\ 1, & T \geq \Delta T. \end{cases} \quad (3)$$

where $\Delta T = 0.5^\circ\text{C}$. The thermal conductivity and specific heat capacity in the frozen and thawed states were continuously interpolated according to the liquid fraction, avoiding the simplification of the phase-change process as a fixed-temperature plateau.

For each material, the thermal conductivity was evaluated as

$$\lambda(T) = \lambda_f [1 - f_l(T)] + \lambda_t f_l(T).$$

The apparent specific heat capacity used in the enthalpy–temperature relation was evaluated as

$$c_{\text{app}}(T) = c_f [1 - f_l(T)] + c_t f_l(T) + w L \frac{df_l(T)}{dT}.$$

Thus, sensible heat and latent heat were represented continuously across the phase-change interval. A monotonic volumetric-enthalpy lookup table was constructed for each material, and the updated temperature was obtained by inverse interpolation from the updated enthalpy after each time step.

A coupled convection–shortwave boundary condition was applied to all exposed surfaces:

$$q = h_c (T_a - T_s) + \alpha f_{\text{sw}} I_s. \quad (4)$$

where q is the surface heat flux directed into the computational domain, with $q > 0$ denoting heat input into the embankment; h_c is the convective heat-transfer coefficient; T_a and T_s are the air and surface temperatures, respectively; α is the surface shortwave absorptivity; f_{sw} is the effective shortwave correction factor, set to $1/3$; and I_s is the incident shortwave radiation on the slope after accounting for road alignment, slope orientation, solar position, direct radiation, diffuse radiation, and ground reflection.

The convective heat-transfer coefficient was calculated as $h_c = 5.7 + 4u$ [21], where u is the interpolated 2 m wind speed in m s^{-1} , and h_c is expressed in $\text{W m}^{-2} \text{K}^{-1}$. For each month, the prescribed daily global horizontal irradiation was distributed over the day according to solar-elevation weights, so that the time-step radiation summed to the prescribed daily total. The diffuse fraction was estimated using the Erbs correlation [31], and the direct, diffuse-sky, and ground-reflected components were projected separately onto each slope according to solar position, road-axis azimuth, slope orientation, and ground albedo. The ground albedo was fixed at 0.20. The formal simulations used an effective shortwave fraction of $1/3$; additional robustness checks used values of 0.25 and 0.40.

The enthalpy solver was independently benchmarked against a one-dimensional Stefan phase-change problem to verify the phase-change heat-transfer calculation. The results are presented in Section 4.1.

Numerical Implementation and Stability Control

All simulations were executed using custom Python 3.10 code. Numerical-array operations were performed with NumPy 1.26.4, whereas post-processing and figure generation were conducted using the Python standard library and Matplotlib 3.8.4. The finite-volume enthalpy balance was advanced using an explicit forward-Euler time update. Therefore, no nonlinear iteration was performed within an individual time step. Before each simulation, the stability condition was checked using the maximum thermal diffusivity across all materials, requiring the sum of the two directional Fourier numbers to satisfy $Fo_x + Fo_y \leq 0.50$. The formal simulations used a uniform grid with $\Delta x = \Delta y = 0.50$ m and a time step of 1.5 h. The refinement check used $\Delta x = \Delta y = 0.25$ m and a time step of 0.375 h. Temperatures at the prescribed evaluation points were sampled by bilinear interpolation at fixed physical coordinates, rather than by nearest grid-cell values. The mesh configuration, grid-time-step sensitivity analysis, and numerical acceptance criteria are summarized in Figure 3.

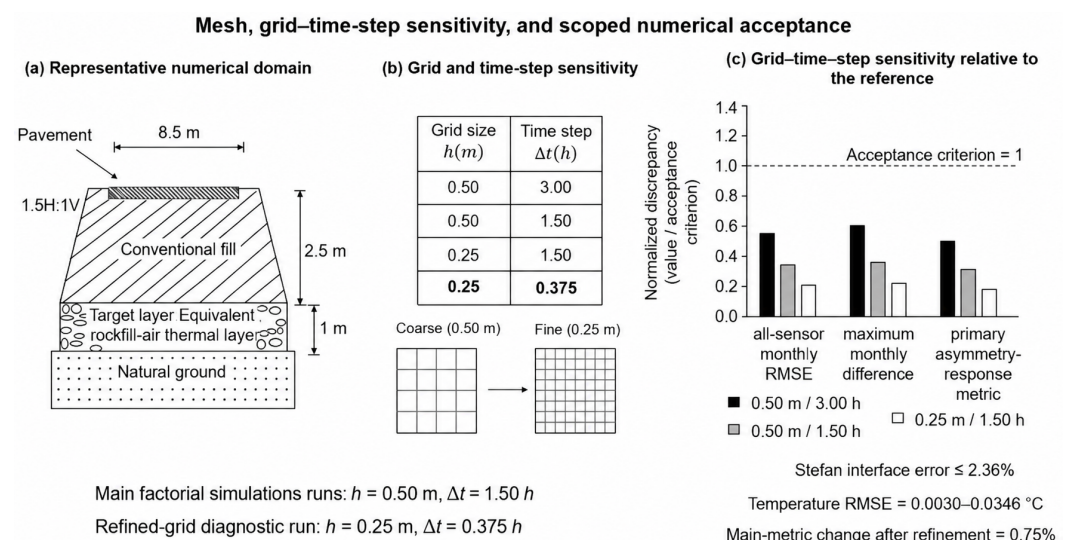


Figure 3. Grid, time-step, and acceptance checks.

2.4. Initial and Boundary Conditions

The same prescribed initial temperature field was used for all structural scenarios and climate boundaries. Because the analysis was driven by periodically repeated annual forcing, this field was specified only to initiate numerical spin-up rather than to reproduce a measured temperature profile. These values were not taken from a site-specific borehole-temperature record and were not used for parameter calibration. They were prescribed as a numerically convenient warm near-surface to subzero deep-ground profile solely to initiate the periodic solution. Their influence was removed through multi-year spin-up, and all reported results were extracted only after the periodic-stability criteria described in Section 2.6 had been satisfied. Temperatures of 6.5, 0, -0.8 , and -1.0 °C were assigned at depths of 0, 2, 5, and 20 m below the original ground surface, respectively, to establish a warm near-surface and subzero subsurface initial profile; linear interpolation was applied between these depths. The embankment fill above the natural ground surface and the equivalent pavement layer were initialized at 9.0 °C. All formal results were extracted from the final annual cycle only after periodic stability had been reached and were therefore not interpreted as responses to the prescribed initial field.

Zero-heat-flux conditions were imposed at the lateral and bottom boundaries. All exposed pavement, slope, and ground faces were assigned the coupled convection-shortwave boundary condition. Monthly minimum, maximum, and mean air temperatures, 2 m wind speed, and daily surface shortwave radiation were interpolated periodically between adjacent monthly midpoints to obtain a continuous annual forcing. A sub-daily air-temperature series was reconstructed from the interpolated monthly minimum, maximum, and mean temperatures using an asymmetric harmonic diurnal function with an afternoon maximum. Wind speed was used to calculate the convective heat-transfer coefficient, whereas daily shortwave radiation was resolved into slope-specific time-step inputs as described in Section 2.3. Longwave-radiation exchange was not included because no internally consistent longwave-radiation series was used in the present controlled input package.

2.5. Climate–Alignment–Fill-Height Experiment Design

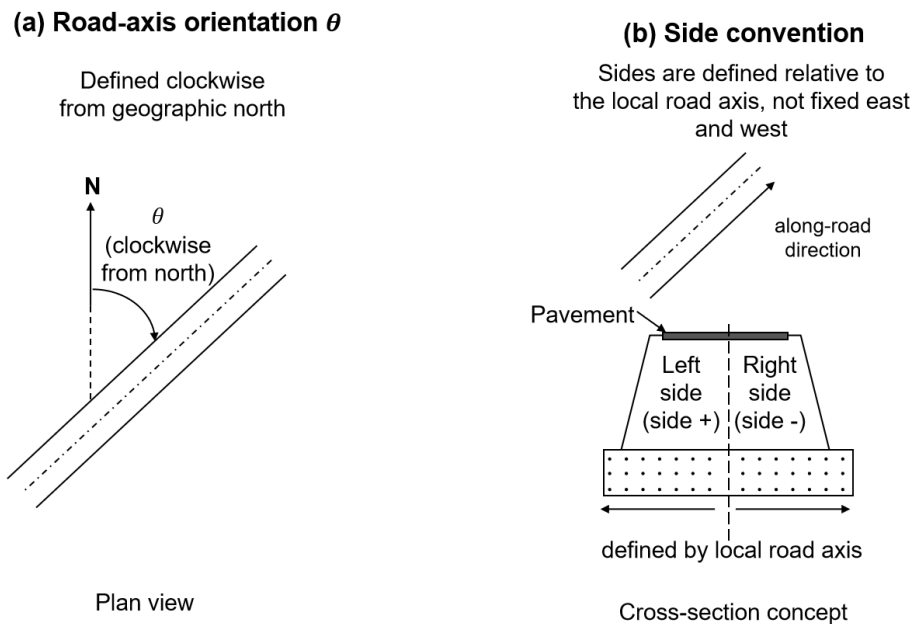
The road-axis azimuth was defined clockwise from geographic north. Throughout this study, “left” and “right” refer to the two sides of the cross-section when viewed along the direction of increasing road-axis azimuth, as defined in Figure 4. These labels are therefore local to the road axis and do not represent fixed east–west directions. At the 90° azimuth used for the mechanism-oriented analyses, the left slope is north-facing and the right slope is south-facing; consequently, the right slope receives the larger annual shortwave input. The road-axis definition and the cross-sectional side convention are illustrated in Figure 4. The formal cases were 0°, 45°, and 90°, representing near-symmetric, intermediate, and relatively strong transverse shortwave-input differences, respectively. The overlying fill heights were 0.5, 1.5, and 3.5 m. The climate boundaries were the 2009 cold year, the 1991–2020 reference climate, and the 1994 warm year. The three structural scenarios, three climate boundaries, three fill heights, and three azimuths produced 81 formal cases.

Except for azimuth, fill height, climate boundary, and structural scenario, the initial field, computational domain, equivalent pavement layer, boundary conditions, phase-change interval, evaluation domain, and measurement locations were identical. To test whether the three formal azimuths were representative of the continuous directional response, 12 additional azimuths from 0° to 165° at 15° intervals were simulated under RF-TO.

The supplementary azimuth-continuity check was performed for each of the three climate boundaries and each of the three upper-fill heights, resulting in 108 RF-TO directional simulations. The 0°, 45°, and 90° cases embedded in this sweep were used to verify that the

formal comparison cases sampled the near-symmetric, transitional, and maximum-response parts of the continuous directional curve.

Road-axis definition, side convention



At $\theta = 90^\circ$: left slope = north-facing; right slope = south-facing.

The right (south-facing) slope receives the larger annual shortwave input.

Figure 4. Road-axis definition and side convention.

2.6. Thermal-Asymmetry Metrics, Numerical Verification, and Acceptance Criteria

The monthly area-weighted mirror temperature difference in the common evaluation domain was defined as:

$$A_{\Omega^*}(m) = \frac{1}{|\Omega^*|} \int_{\Omega^*} |T(x, y, m) - T(-x, y, m)| d\Omega. \quad (5)$$

where m denotes the month, and $A_{\Omega^*}^{\max}$ is the maximum over the 12 months of the year. This metric represents the overall intensity of transverse thermal asymmetry across the entire embankment–shallow-foundation system.

Paired left–right measurement points were assigned to the upper fill, target layer, and zone below the natural ground surface. The monthly paired temperature difference for the l th layer was defined as:

$$D_l(m) = |T_{R,l}(m) - T_{L,l}(m)|. \quad (6)$$

Its annual peak was denoted by $D_l^{\max}$. This metric was used to identify whether thermal asymmetry was concentrated primarily in the upper fill, target layer, or natural foundation.

The seasonal response lag from the upper fill to the target layer was calculated from the days of the daily mean-temperature peaks:

$$\tau = d_{\text{peak,target}} - d_{\text{peak,upper}}. \quad (7)$$

When the peaks crossed the year boundary, the lag was converted according to the cyclic calendar and constrained to -182 to 182 d. It was used to characterize the seasonal heat-transfer timescale from the upper fill to the target layer.

Because the external forcing was constructed from monthly meteorological data, τ is interpreted as a seasonal-phase lag resolved on the simulation calendar rather than an event-scale response to observed daily weather fluctuations.

The main experiments used a 0.50 m grid and a 1.5 h time step and simulated at least six annual cycles. Periodic stability was considered achieved only when two consecutive annual cycles satisfied all three criteria: $\text{RMSE} \leq 0.10\text{ }^{\circ}\text{C}$, a maximum absolute difference of $\max|\Delta T| \leq 0.50\text{ }^{\circ}\text{C}$ for the complete temperature series at the prescribed evaluation points, and a relative change of $\leq 1\%$ in the primary common-domain asymmetry metric. Results were extracted from the final converged annual cycle.

Left/right are defined while viewing along the direction of increasing road-axis azimuth. They are local cross-sectional labels, not fixed east–west directions.

3. Study Area and Input Processing

3.1. Representative Location and Public Meteorological Data

Monthly meteorological inputs were obtained from the NASA Prediction Of World-wide Energy Resources (POWER) point-data service for the representative Mazar location (36.5790° N , 77.0035° E) [32]. The input package contained monthly minimum, maximum, and mean 2 m air temperatures, 2 m wind speed, and all-sky surface shortwave downward irradiation. The 2009 and 1994 files retained the monthly records of the selected cold and warm reference years, respectively, whereas the reference-climate file contained monthly means over 1991–2020. All three files were checked for complete January-to-December coverage, non-negative wind speed and shortwave radiation, and $T_{\min} \leq T_{\text{mean}} \leq T_{\max}$ before simulation. Air temperature and wind speed were used to define the convective forcing, whereas the shortwave-radiation series was converted to slope-specific time-step inputs using the solar-geometry procedure described in Section 2.3. Different azimuth cases used identical meteorological forcing and differed only in the slope-solar incidence geometry. The G219 setting, regional permafrost background, and representative Mazar location are shown in Figure 5.

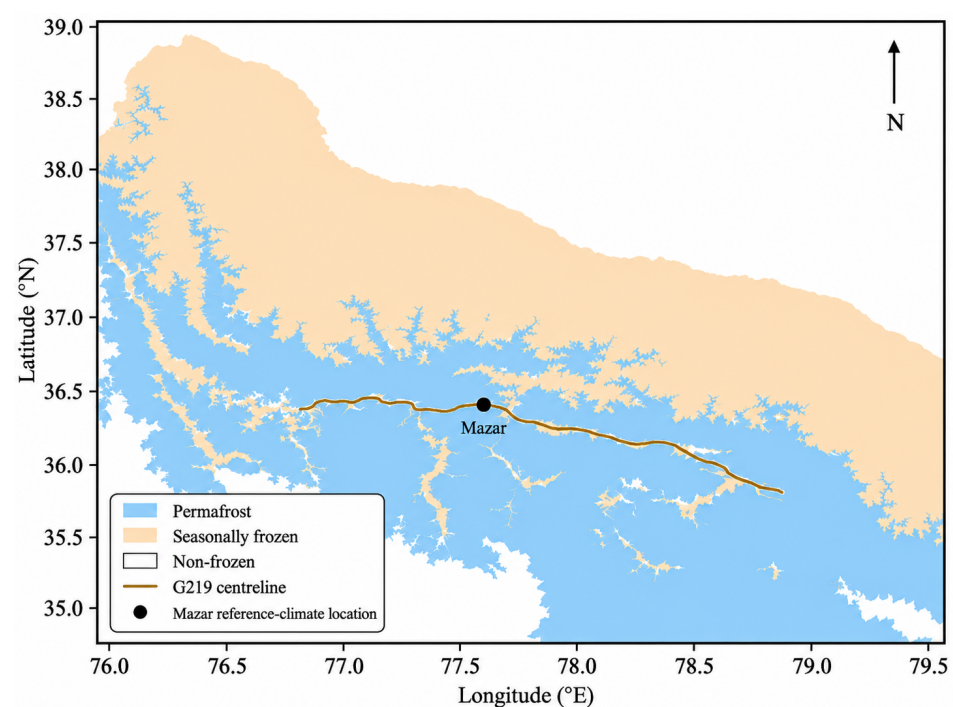


Figure 5. G219 study area, permafrost background, and the representative Mazar climate location.

3.2. Construction of Cold-Year, Reference-Climature, and Warm-Year Boundaries

Based on the 10th and 90th percentiles of annual mean 2 m air temperature over 1991–2020, 2009 and 1994 were selected as actual climate years close to the cold and warm ends, respectively. The reference climate was constructed from the mean value for each calendar month over the same period.

The annual mean air temperatures of the three climate backgrounds were -6.261 , -5.745 , and -5.264 °C, representing the relatively cold end of the interannual distribution, the climate-average state, and the relatively warm end, respectively. The three boundaries were combined with the same cross-section and material-parameter set to determine whether the layer-specific thermal responses induced by road alignment and fill height occurred only under a particular climate year. The monthly air-temperature, wind-speed, and shortwave-radiation inputs for the three climate boundaries are compared in Figure 6.

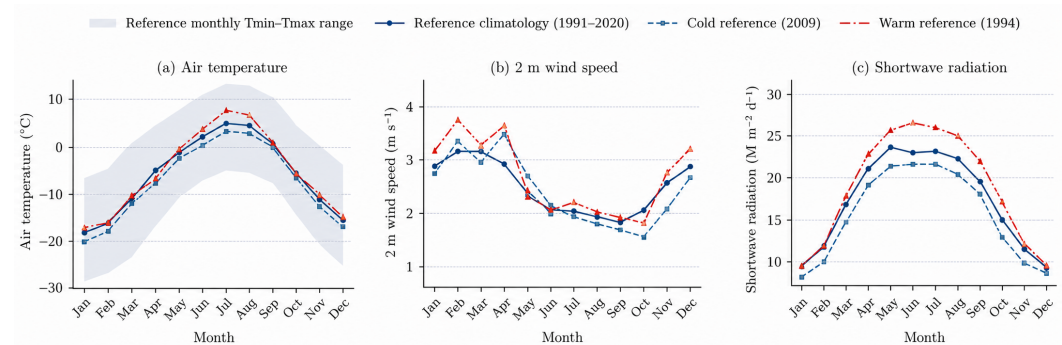


Figure 6. Air temperature, wind speed, and shortwave radiation under the three climate boundaries.

4. Results and Discussion

4.1. Numerical Verification, Periodic Convergence, and Near-Symmetric Control

The enthalpy solver was independently benchmarked using a one-dimensional semi-infinite Stefan melting problem. To approximate the sharp-interface assumption of the analytical solution, the half-width of the phase-change smoothing interval was set to 0.05 °C for the benchmark, whereas the formal cross-sectional simulations retained a value of 0.5 °C. On the benchmark grid with $\Delta x = 0.02$ m, the maximum relative errors of the phase-change interface at days 5, 15, and 30 were 2.36%, and the temperature RMSEs in the melting zone and near the phase-change interface were 0.0030 – 0.0315 °C and 0.0224 – 0.0346 °C, respectively. At day 30, the interface relative error was 0.40% and decreased further to 0.018% on the refined grid with $\Delta x = 0.01$ m. The benchmark errors confirm correct numerical reproduction of the analytical solution; this verification concerns model implementation rather than calibration against G219 field temperatures. Accordingly, the results reported below are interpreted as controlled comparative responses under a representative G219-type layered configuration, rather than as site-specific temperature predictions or direct design values for an individual embankment section.

Across the most unfavorable case, the refined-grid checks for the three fill heights, and the enlarged-domain test, the core response rankings of the common domain, target layer, and foundation layer did not reverse. Under the 0° near-symmetric control, the common-domain metric was only 0.000247 – 0.000543 °C, indicating that the transverse differences discussed below mainly originated from the heating-boundary contrast caused by road alignment rather than from left–right discretization error. Under the reference climate, 90° azimuth, and RF-TO scenario, the fine-grid check preserved all four response rankings: the common-domain response increased with fill height, the target-layer response peaked at 1.5 m, the foundation-layer response decreased with fill height, and the peak lag generally

increased. The corresponding main-grid and fine-grid values were close, indicating that the reported redistribution pattern was not caused by the adopted discretization.

Enlarging the computational domain from $50\text{ m} \times 20\text{ m}$ to $70\text{ m} \times 30\text{ m}$ changed the common-domain, target-layer, and foundation-layer peak responses by no more than 0.79%, 0.70%, and 1.75%, respectively, without reversing the main rankings.

4.2. Control of Transverse Thermal-Asymmetry Input by Road Alignment

Figure 7 compares the annual cumulative and monthly shortwave inputs on the two slopes under the three formal road-axis azimuths. To verify that road azimuth first changes the external shortwave boundary, rather than merely producing a difference in the temperature field, paired comparisons were made using the same meteorological forcing, solar geometry, and time step as in the formal experiments. At 0° , the differences between the two sides were less than 1 MJ/m^2 , indicating near symmetry. At 45° , the differences for the cold year, reference climate, and warm year were 1.43 , 1.72 , and $2.10 \times 10^3\text{ MJ/m}^2$, respectively; at 90° , they increased to 2.06 , 2.52 , and $3.06 \times 10^3\text{ MJ/m}^2$. Thus, 0° , 45° , and 90° formed a controlled sequence from near-symmetric to strong transverse shortwave input, which was then traced through the common cross-section to the individual layers.

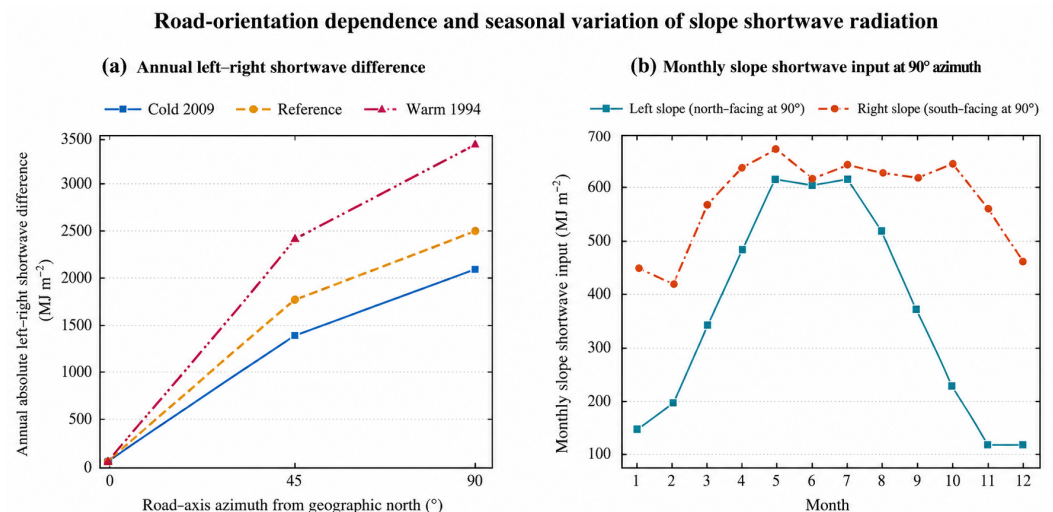


Figure 7. Annual cumulative incident shortwave radiation on the two slopes under the three climate boundaries and different road-axis azimuths.

To avoid judging the directional effect from only the three discrete values of 0° , 45° , and 90° , 12 road-axis azimuths were additionally simulated at 15° intervals over 0° – 165° . Only the road azimuth was changed among these cases; the climate boundary, fill height, cross-sectional structure, and numerical settings were kept identical.

Under all three climate backgrounds and all three fill heights, the peak thermal asymmetry in the common domain increased continuously as the azimuth increased from 0° to 90° and reached its maximum at 90° . The response at 0° was only 0.000 – $0.001\text{ }^\circ\text{C}$, indicating nearly symmetric heating of the two sides of the cross-section, whereas the response at 90° was 0.142 – $0.649\text{ }^\circ\text{C}$. The response at 75° already reached 97.1–98.3% of the corresponding 90° peak. Strong thermal asymmetry therefore did not arise accidentally from a single discrete azimuth; instead, it formed a continuous high-response interval around 90° .

As the road azimuth increased beyond 90° toward 165° , peak thermal asymmetry gradually declined and showed an approximately mirror-symmetric distribution relative to the 0° – 90° interval. These results indicate that the formal cases of 0° , 45° , and 90° represent near-symmetric, transitional, and maximum-heating-asymmetry states, respectively, and are representative azimuths for the subsequent comparison of fill height and layer responses.

Accordingly, 90° was used for the mechanism-oriented analysis, but this choice represents only the maximum directional response under the equivalent thermal–optical boundary used here and should not be extrapolated as an engineering route-selection threshold.

The continuous azimuthal distribution shown in Figure 8 further confirms that the selected formal cases capture the major directional-response regimes. The peak thermal asymmetry exhibits a smooth increase from the near-symmetric state at low azimuth angles toward the maximum response around 90°, followed by a gradual decrease toward 165°. This continuous pattern demonstrates that the selected azimuths are not isolated cases but representative points along the directional response curve.

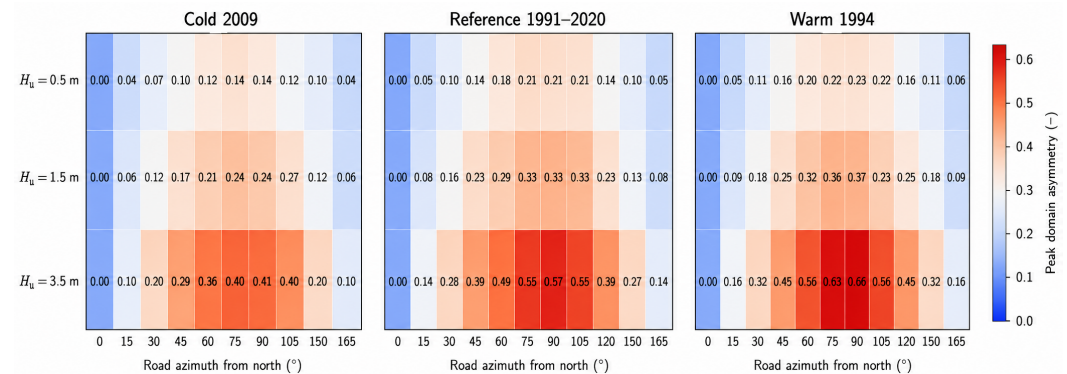


Figure 8. Peak thermal asymmetry in the RF-TO common evaluation domain over the continuous road-azimuth range of 0°–165°.

4.3. Vertical Redistribution and Seasonal Phase Lag Induced by Fill Height

Under the RF-TO scenario at 90°, increasing fill height did not cause transverse thermal asymmetry to increase or decrease synchronously across all layers; instead, it changed the location of the response within the cross-section. In the cold year, reference climate, and warm year, the peak common-domain thermal asymmetry increased from 0.142, 0.210, and 0.230 °C to 0.410, 0.566, and 0.649 °C, respectively, corresponding to factors of 2.89, 2.69, and 2.83. By contrast, the target-layer response reached its maximum at a fill height of 1.5 m under all three climate backgrounds, whereas the foundation-layer response continuously weakened as fill height increased. The three layer-dependent response patterns are compared directly in Figure 9.

Impact of Upper Fill Height on Peak Asymmetry at 90° Azimuth (RF-TO)

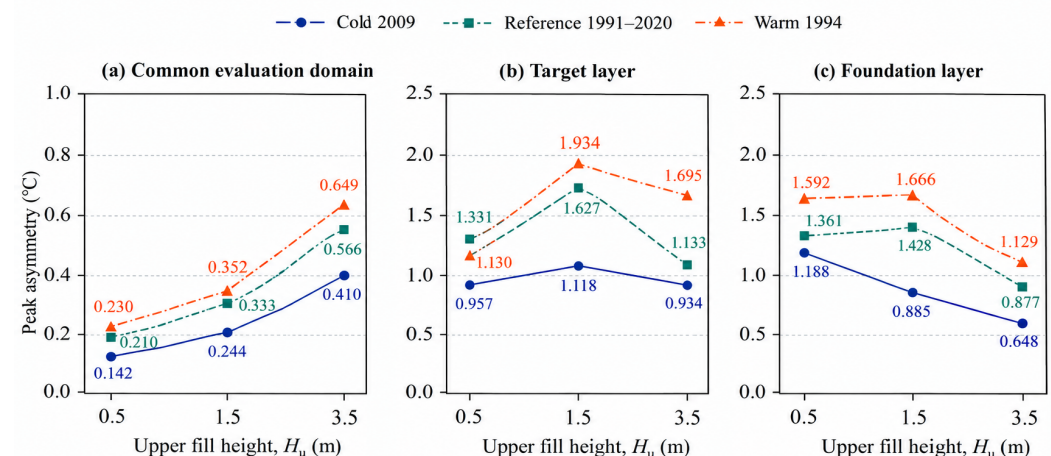


Figure 9. Effects of overlying fill height on peak thermal asymmetry in the common domain, target layer, and foundation layer at a 90° azimuth.

As shown in Figure 9, the horizontal dotted lines are included only as background grid lines to facilitate comparison among different response magnitudes. They do not indicate physical thresholds or acceptance criteria. The comparison focuses on the relative variation of peak thermal asymmetry with increasing upper-fill height under different climate boundaries.

The upper-fill response showed no consistent monotonic trend and is therefore not treated as a primary result. The increase in common-domain asymmetry did not imply a synchronous increase at deeper layers: higher fill was associated with a broader domain-scale response, whereas the target-layer response concentrated at 1.5 m and the foundation-layer response weakened. The EF–RF–T–RF–TO comparison was then used to examine this differentiation.

The 1.5 m result denotes a response-concentration location under the present cross-section and boundary conditions, not an optimum engineering fill height.

This redistribution can be interpreted as a competition between the lateral extent of the asymmetric thermal field and its vertical transmission path. With a small upper-fill height, the slope-boundary contrast can reach the target and foundation layers through a relatively short path, but it occupies a limited fill volume. With a large upper-fill height, the asymmetric response extends through a larger upper-fill domain, while the longer vertical path attenuates and delays its transfer toward the foundation. At the intermediate height, the target layer remains sufficiently coupled to the surface-induced contrast while the overlying fill is thick enough to sustain a pronounced lateral thermal difference. This interpretation is limited to the present equivalent conduction–phase-change representation.

Increasing fill height also prolonged the transfer time of the seasonal thermal signal from the upper fill to the target layer. Under all three climate boundaries, the peak lag on both sides increased with fill height, indicating that fill height changed not only the spatial distribution of transverse thermal asymmetry but also its seasonal transfer time. The specific lag values are shown in Figure 10.

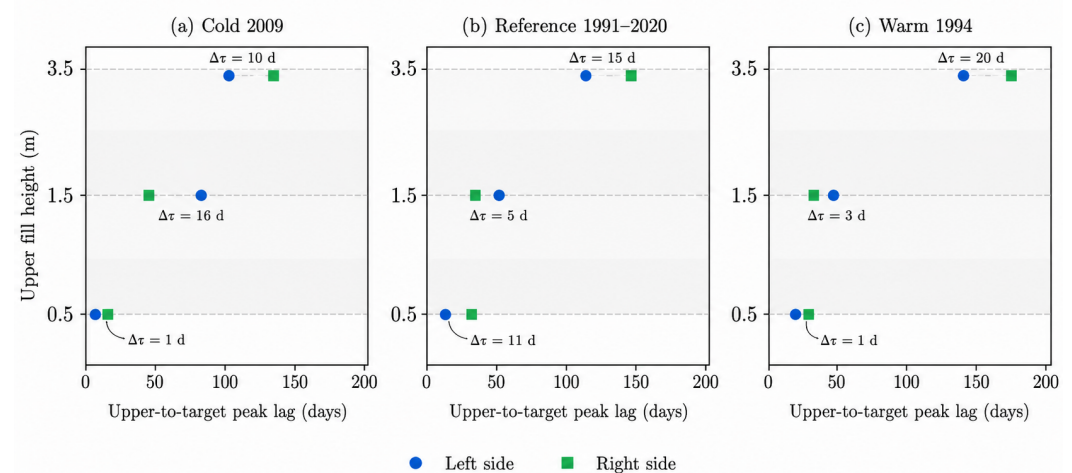


Figure 10. Daily temperature peak lag from the upper fill to the target layer under RF–TO at a 90° azimuth.

4.4. Two-Step Counterfactual Attribution of Target-Layer Thermal Properties and Exposed Optical Conditions

4.4.1. Effect of Target-Layer Thermal-Property Changes

To identify the effect of target-layer thermal-property changes, RF–T was compared with EF while the cross-sectional geometry, exposed-surface shortwave condition, climate boundary, and measurement locations were kept identical. The difference between the two scenarios therefore represents only the relative response change caused by replacing

conventional fill with the equivalent thermal properties of the rock-filled layer in the target layer.

Under the 90° configuration, the RF-T-EF difference in the target-layer response ranged from -0.809 to $+0.055$ °C, with the largest magnitude occurring under the warm-year boundary at $H_u = 1.5$ m. The corresponding foundation-layer response ranged from -0.198 to $+0.219$ °C and showed no consistent sign. The response increment was strongest in the target layer, whereas its direction in the foundation layer was not consistent. Thus, equivalent-property replacement did not impose a uniform cross-sectional cooling effect.

4.4.2. Additional Effect of Exposed Optical Conditions

RF-TO differed from RF-T only by reducing exposed-surface shortwave absorptivity from 0.72 to 0.64, thereby isolating the conditional optical-boundary increment.

For the 90° combinations, the RF-TO–RF-T differences in the target and foundation layers ranged from -0.118 to $+0.054$ °C and from -0.247 to $+0.031$ °C, respectively, with no consistent sign. The optical-boundary increment also had no consistent sign, indicating that its local effect depended on fill height and climate condition.

The sign changes should be interpreted in relation to the asymmetry metric rather than as direct evidence of uniform warming or cooling. Because the reported quantity is the peak difference between paired left and right responses, a material-property or optical-boundary change may alter the two sides by different magnitudes and at different seasonal phases. Consequently, a reduction in absolute heat input does not necessarily produce a negative increment in peak thermal asymmetry. The conditional sign changes therefore reflect the interaction among climate boundary, fill height, and layer-specific thermal storage and phase-change behavior. The three layer-dependent response patterns are compared directly in Figure 9.

Figure 11 summarizes the two-step counterfactual attribution and clarifies the different contributions of target-layer thermal properties and exposed-surface optical conditions. The RF-T-EF comparison isolates the effect of replacing conventional fill with equivalent rock-filled thermal properties, whereas the RF-TO–RF-T comparison identifies the additional conditional contribution from reduced surface shortwave absorptivity. The results indicate that both mechanisms influence transverse thermal asymmetry in a layer-dependent manner rather than producing a uniform response across the embankment profile.

4.5. Robustness of Response Rankings Across Climate and Selected Thermal–Optical–Conductivity Perturbations

Under the reference climate, 90° azimuth, and RF-TO scenario, targeted perturbations were applied to surface shortwave absorptivity (0.56, 0.64, and 0.71), effective shortwave fraction (0.25, 1/3, and 0.40), and target-layer thermal conductivity (0.8×, 1.0×, and 1.2× the baseline value). Table 3 summarizes the resulting common-domain asymmetry, the location and magnitude of the maximum target-layer response, the foundation-layer response change from 0.5 m to 3.5 m, and the left/right seasonal peak lags. Although the absolute response magnitude changed, all perturbations preserved four common features: increasing common-domain asymmetry with fill height, a target-layer maximum at 1.5 m, decreasing foundation-layer response with fill height, and longer upper-fill-to-target-layer peak lags at greater fill heights.

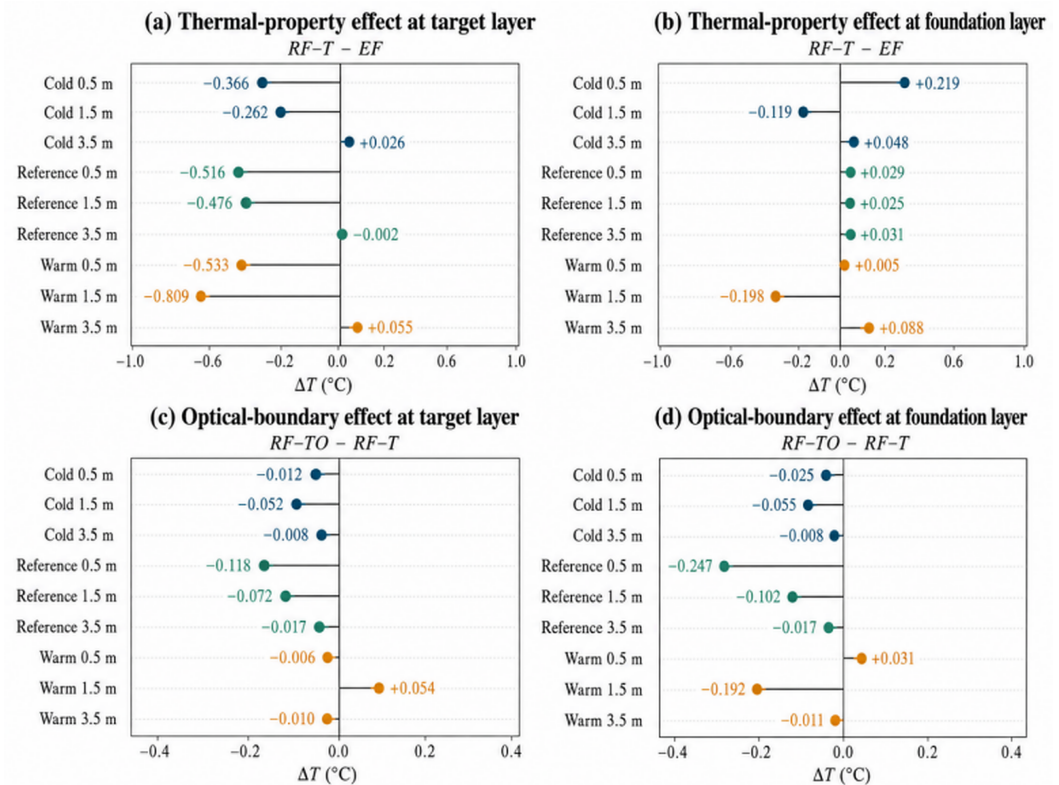


Figure 11. Two-step counterfactual attribution of the effects of target-layer equivalent thermal properties and exposed-surface shortwave conditions on peak thermal asymmetry at a 90° azimuth.

Table 3. Key response characteristics under RF-TO parameter perturbations for the reference climate and 90° azimuth.

Perturbation Condition	Peak Common-Domain Thermal Asymmetry: $H_{\mu} = 0.5/1.5/3.5$ m ($^{\circ}C$)	Maximum Target-Layer Response ($^{\circ}C$)	Foundation-Layer Response, 0.5 m $\rightarrow$ 3.5 m ($^{\circ}C$)	Peak Lag, Left/Right Sides, 0.5 m $\rightarrow$ 3.5 m (d)
$\alpha = 0.56$	0.187/0.307/0.542	1.747 (1.5 m)	1.578 $\rightarrow$ 0.860	9/12 $\rightarrow$ 123/138
$\alpha = 0.71$	0.230/0.358/0.588	1.890 (1.5 m)	2.068 $\rightarrow$ 0.891	9/20 $\rightarrow$ 124/140
Effective shortwave fraction = 0.25	0.136/0.230/0.379	1.057 (1.5 m)	1.140 $\rightarrow$ 0.596	13/12 $\rightarrow$ 119/129
Effective shortwave fraction = 0.40	0.238/0.404/0.655	2.129 (1.5 m)	2.193 $\rightarrow$ 1.130	17/18 $\rightarrow$ 148/156
Target-layer thermal conductivity = 0.8×	0.199/0.314/0.551	1.780 (1.5 m)	1.783 $\rightarrow$ 0.841	11/12 $\rightarrow$ 127/142
Target-layer thermal conductivity = 1.0×	0.210/0.333/0.566	1.827 (1.5 m)	1.851 $\rightarrow$ 0.877	9/20 $\rightarrow$ 124/139
Target-layer thermal conductivity = 1.2×	0.218/0.346/0.577	1.863 (1.5 m)	1.853 $\rightarrow$ 0.901	18/20 $\rightarrow$ 121/138

5. Conclusions

This study used a representative cross-section of a G219 rock-filled ventilated embankment to examine the combined effects of road alignment, upper fill height, and climate background under an equivalent thermal-optical representation. Under the controlled scenarios considered here, road alignment determined the intensity of the transverse heating input. In RF-TO, increasing the azimuth from 0° to 90° continuously strengthened the peak common-domain thermal asymmetry across all climate–fill-height combinations; the response at 45° was 67.9–70.1% of the corresponding response at 90°. Thus, 0°, 45°, and 90° represent near-symmetric, intermediate, and relatively strong transverse heating contrasts, respectively, and provide a stable comparison basis for identifying fill-height effects.

The effect of fill height was not a simple amplification or attenuation of the temperature difference; it changed where transverse thermal asymmetry was distributed within the cross-section. When the upper fill increased from 0.5 to 3.5 m, the common-domain response under the cold-year, reference-climate, and warm-year boundaries increased by factors of 2.89, 2.69, and 2.83, respectively. The target-layer response reached its maximum at a 1.5 m fill height under all three climate backgrounds, whereas the foundation-layer response continuously decreased with increasing fill height. Higher fill therefore expanded the domain-scale range of asymmetric response but did not necessarily enhance its local transfer toward the foundation.

Fill height also prolonged the seasonal transfer from the upper fill to the target layer. The EF–RF–T–RF–TO comparison showed that equivalent target-layer properties and exposed optical conditions produced conditional, layer-dependent response increments rather than uniform effects. Across the three climate boundaries and the prescribed thermal–optical–conductivity perturbations, the rankings of increasing domain-scale response, target-layer concentration near 1.5 m, decreasing foundation-layer response, and increasing peak lag were preserved. These findings provide a controlled basis for thermal-response comparison in similar layered embankments but do not represent direct predictions of pore-air flow, settlement, optimum fill height, or corridor treatment requirements.

Because the present study is based on an equivalent thermal–optical numerical representation, future work should combine laboratory testing and multi-season field monitoring to verify the predicted layer-dependent redistribution of transverse thermal asymmetry. Measurements of slope-specific shortwave radiation, temperatures in the upper fill, target layer, and foundation, and seasonal pore-air conditions would enable direct evaluation of the equivalent-property assumptions and the predicted peak-lag behavior.

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