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Thermosyphon-Regulated Foundations for Permafrost Infrastructure under Climate Change: A Quantitative Adaptation of the Canadian CSA S500:21 Framework to the Peruvian Andes

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Abstract

Global warming is accelerating permafrost degradation, threatening the stability of critical infrastructure in cold and high-mountain regions. Thermoregulated foundations using bidirectional thermosyphons, codified in Canada under standard CSA S500:21, provide a passive subsoil-cooling solution that requires no external energy supply. This article (i) synthesizes documented technical evidence on thermosyphon performance in North American infrastructure; (ii) details the modern heat-transfer, thermal-resistance and elastic-settlement formulations used in their design; (iii) builds a quantitative comparative matrix between the climatic and geotechnical conditions of Canada and the Peruvian Cordillera Blanca; and (iv) proposes a technology-adaptation protocol — tools, materials and construction procedures — feasible for the Peruvian high mountains. The literature review followed elements of the PRISMA 2020 protocol adapted to permafrost-engineering literature, restricting selection to verifiable sources with a DOI or an official technical standard. Results show that the technology is transferable to the tropical Andean context provided that working fluid, evaporator geometry and thermal insulation are adjusted to compensate for the lower air-freezing index and higher diurnal solar radiation characteristic of the Peruvian high mountains. The study concludes that the regulatory and field-validation gap in Peru can be closed through an instrumented pilot project, using the Canadian framework as a design baseline.

1. Introduction

Permafrost — ground that remains frozen for at least two consecutive years — underlies road, energy and telecommunications infrastructure across Arctic, subarctic and tropical high-mountain regions. Its documented degradation already affects up to 80% of buildings in some warm-permafrost Arctic cities and compromises roughly a third of road surfaces on the Qinghai–Tibet Plateau [1]. In Canada, the engineering response has been institutionalized through standard CSA S500:21, "Thermosyphon foundations for buildings in permafrost regions", which governs the design, installation, commissioning and monitoring of thermosyphon-regulated foundations, complemented by CSA S501:21, aimed at mitigation for existing foundations.

The closed-loop thermosyphon is a passive two-phase heat exchanger: during the cold season, the working fluid vaporizes in the buried section (evaporator), rises as vapor to the air-exposed condenser, releases heat to the environment and returns as liquid by gravity, extracting heat from the ground without external energy input. Long-term monitoring of embankments equipped with bidirectional thermosyphons on the Qinghai–Tibet Highway documents a net cooling effect with a seasonal duty cycle of approximately seven months per year [2].

Research gap and contribution. Despite the maturity of Canadian standards and Asian field evidence, the reviewed literature lacks a quantitative framework that explicitly translates CSA S500:21 design criteria to discontinuous, tropical high-mountain permafrost conditions — near-0°C ground temperatures, strong diurnal solar radiation and restricted logistical accessibility — as found in the Peruvian Cordillera Blanca [3]. The original contribution of this article is threefold: (1) it synthesizes the modern thermal and

geotechnical engineering formulations used in thermosyphon design; (2) it builds a quantitative comparative matrix, grounded in verifiable sources, between the climatic and regulatory conditions of Canada and those projected for Peru; and (3) it translates these findings into tools, materials and construction procedures suited to Peruvian logistics and market availability, bridging North American experience with the climate-adaptation needs of Andean infrastructure.

2. Materials and Methods

2.1 Literature review strategy

A structured search was conducted in Scopus, Web of Science and open-access databases (Copernicus, Nature Portfolio, MDPI, Wiley) using the terms "thermosyphon foundation", "permafrost engineering", "CSA S500", "Andean permafrost" and "rock glacier Peru", with no restriction on publication year but prioritizing 2013–2025 studies. Following elements of the PRISMA 2020 protocol adapted to technical engineering literature, the following criteria were applied: (a) inclusion — articles with quantitative field or laboratory data, currently valid official technical standards, and datasets with a verifiable DOI; (b) exclusion — references lacking a persistent identifier (DOI, ISBN or official standard code), non-verifiable conference abstracts, and non-peer-reviewed popular sources. Every reference cited in this article was individually verified prior to inclusion.

2.2 Modern civil-engineering formulations used in design

The thermal and structural sizing of a thermosyphon-regulated foundation relies on four fundamental relationships from classical thermal and geotechnical engineering, widely adopted in normative practice (CSA S500:21):

(1) Thermosyphon heat-transfer rate (energy balance for continuous flow):

$$Q = \dot{m} \cdot cp \cdot (Tout - Tin)$$

where Q is the heat-extraction rate (W); $\dot{m}$, the mass flow rate of the working fluid (kg/s); cp, its specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$); and Tout, Tin, the fluid temperatures at the condenser outlet and evaporator inlet (K), respectively.

(2) Soil temperature profile with depth (quasi-steady-state solution of the thermal diffusion equation):

$$Ts(h) = T0 - (T0 - Tp) \cdot exp[- h / \sqrt{(\alpha \cdot t)}]$$

where Ts is the soil temperature at depth h (°C); T0, the mean annual surface temperature (°C); Tp, the permafrost temperature at the depth of zero annual amplitude (°C); α, the soil's thermal diffusivity (m^2/s); and t, time (s).

(3) Elastic settlement of a foundation on frozen soil (elasticity theory for saturated media):

$S = [\, q \cdot B \cdot (1 - v^2) / Es \,] \cdot Is$

where S is settlement (m); q, the foundation's contact pressure (kPa); B, its width (m); v, the frozen soil's Poisson's ratio; Es, its elastic modulus (kPa); and Is, the depth-to-width influence factor.

(4) Thermal efficiency of the thermosyphon system:

$\eta = Q / [\, A \cdot (Tsoil - Tair) \,]$

where A is the evaporator's heat-exchange area (m²); Tsoil, the soil temperature at the foundation base (°C); and Tair, the average ambient air temperature during the thaw period (°C). These four relationships form the analytical core used in the Results section to interpret the relative performance of Canada and Peru.

2.3 Construction of the comparative matrix

An eight-variable technical matrix — climatic, geothermal, regulatory and constructional — was built comparing the Yukon/Northwest Territories region (Canada) with the Cordillera Blanca (Peru, > 4,800 m a.s.l.). Each cell was populated exclusively with data documented in the verified sources listed in the References, avoiding unsupported estimates; where no direct Peruvian measurement exists, the cell is explicitly marked as "projected" and the analogous data used for extrapolation is referenced.

3. Results

3.1 Quantitative Canada–Peru comparative matrix

Table 1
summarizes the documented differences between the Canadian context and the projected conditions for the Cordillera Blanca.

Variable	Canada (Yukon / NWT)	Peru (Cordillera Blanca, projected)	Source
Average annual air temperature (°C)	−8 to − 12°C (Yukon / NWT)	−2 to − 5°C (> 4,800 m a.s.l., Cordillera Blanca)	Yoshikawa et al. (2020); CSA S500:21
Permafrost temperature at 10–15 m	−1 to − 9°C	−2.5 to − 5°C (projected)	Yoshikawa et al. (2020)
Permafrost type	Continuous to discontinuous, road embankments	Discontinuous, high-mountain, rock glaciers	Medina et al. (2025)
Thermosyphon cooling effect (field record)	Net soil-temperature reduction documented in embankments with bidirectional TPCT, duty cycle ~ 7 months/yr	Projected duty cycle 5–7 months/yr due to lower diurnal AFI	Song, Jin & Zhang (2013)
Solar radiation / thaw control	Low–moderate (snow albedo)	Critical (intense high-altitude radiation, requires reinforced insulation)	Zhou et al. (2022); PISCOt v1.2 (Huerta et al., 2023)
Regulatory framework	CSA S500:21 and CSA S501:21 (national standards)	No permafrost-specific standard (general E.050 applies)	CSA Group (2021a, 2021b)
Recommended thermal insulation	XPS, placed above the evaporator	Reinforced XPS (greater thickness due to diurnal radiation)	Zhou et al. (2022)
Infrastructure impact of thaw (global context)	Documented damage in up to 80% of buildings in some Arctic warm-permafrost cities	No national quantification; analogous risk from rock-glacier degradation	Hjort et al. (2022)

Table 1. *Comparative matrix of technical variables for thermosyphon-regulated foundations: Canada vs. Peru. Own elaboration based on the cited sources.*

3.2 Documented thermal performance

Long-term monitoring of embankments with closed-loop bidirectional thermosyphons on the Qinghai–Tibet Highway (2004–2011) confirms that the device behaves as a thermal semiconductor: it extracts heat only during the cold season, with a duty cycle of approximately seven months per year, and does not transfer energy in reverse during summer, thereby preserving a colder thermal regime than conventional embankments [2]. This "thermal diode" behavior is the physical basis of Eq. (1) and supports extrapolating the technology to climates with a lower air-freezing index, such as the Peruvian altiplano, provided that condenser and insulation design compensate for the shorter available cooling window.

Permafrost records from the southern Peruvian Andes show ground temperatures between − 2.5°C and − 5°C above 5,000 m a.s.l., with strong sensitivity to ENSO phase [3], while the national rock-glacier inventory identifies 2,338 units between 4,416 and 5,783 m a.s.l. that may host ice-rich permafrost [4]. These values, compared with the − 1°C to − 9°C range reported for Canada, indicate a smaller available thermal gradient in Peru, which — per Eq. (2) — requires evaporators with larger contact area or a greater number of units per foundation point to achieve an equivalent freezing radius.

3.3 Thermal insulation and solar radiation

Studies of L-shaped thermosyphons with extruded-polystyrene (XPS) insulation boards show that the combination of evaporator inclination and insulation thickness significantly improves embankment cooling efficiency [5]. In the Peruvian context, the high-resolution PISCOt v1.2 climate dataset confirms that diurnal solar radiation and thermal variability in the Peruvian highlands are substantially greater than in the Canadian Arctic [6], so condenser and insulation design must be reinforced — greater XPS thickness and condenser shielding from direct radiation — to prevent reversal of the thermal cycle during daytime.

3.4 Construction procedures: North America vs. Peru

Canadian/U.S. method: drilling with large-capacity equipment (15–20 m depth, 250–300 mm hole diameter), borehole stabilization with drilling mud, carbon-steel or stainless-steel tubes, sand-bentonite thermal backfill, and installation of thermistor strings along the borehole depth per the monitoring requirements of CSA S500:21.

Proposed procedure for Peru: (1) site characterization via thermistor boreholes and mapping of active rock glaciers; (2) drilling with portable rotary or pneumatic percussion equipment, adapted to the limited accessibility of the high mountains (> 4,800 m a.s.l.), avoiding heavy machinery; (3) modular thermosyphon installation, with threaded joints to avoid high-altitude welding; (4) thermal backfill using a silica-sand and activated-bentonite mixture, pumped with portable equipment; (5) condenser protection via solar deflectors and high-albedo coatings, oriented to minimize diurnal heat gain; and (6) low-power remote monitoring with satellite or radio transmission, reducing the need for periodic visits to hard-to-reach sites.

4. Discussion

Results indicate that the CSA S500:21 technical framework is, in principle, transferable to tropical high-mountain infrastructure, since the physical relationships governing design — Equations (1) to (4) — are general and latitude-independent. However, direct transfer without adjustment would lead to system under-sizing, since (a) the smaller thermal gradient available in Andean permafrost reduces the cooling driving force described by Eq. (1); and (b) the higher diurnal solar radiation documented by the PISCOt v1.2 dataset [6] increases the risk of thermal-cycle reversal, a phenomenon of little relevance in the Canadian Arctic due to low solar angle and snow albedo.

Asian evidence on L-shaped, reinforced-insulation thermosyphons [5] suggests a concrete adaptation pathway: increase the evaporator's exchange surface and reinforce condenser insulation, rather than modify the working fluid, which can remain within already-validated international standards.

Limitations. This study is desk-based and relies on literature with a verifiable identifier; no field instrumentation was conducted in Peru, so the "projected" values in Table 1 should be interpreted as first-order estimates, subject to validation through an instrumented pilot project. The comparative matrix is limited to eight variables for reasons of length and source verifiability; future studies should expand it to include cost and service-life data once field-validated.

5. Conclusions

1. The Canadian CSA S500:21 technical framework provides a physically transferable design basis for tropical high-mountain permafrost infrastructure, since Equations (1)–(4) governing thermosyphon performance are latitude-independent.
2. The quantitative comparative matrix shows that Andean permafrost has a smaller thermal gradient and greater diurnal solar loading than Canadian Arctic permafrost, requiring evaporators with larger contact area and reinforced condenser insulation.
3. The construction procedure proposed for Peru — portable drilling, modular installation, local thermal backfill and low-power remote monitoring — is compatible with the accessibility and material-availability constraints of the Andean high mountains.
4. An instrumented pilot project in the Cordillera Blanca, with at least two years of thermal monitoring, is recommended to validate the projected values in Table 1 and lay the groundwork for a future Peruvian technical standard equivalent to CSA S500:21.

Declarations

Ethics statement

This study relies exclusively on published technical literature, publicly available standards and open datasets; it does not involve human or animal experimentation and therefore did not require institutional ethics committee approval.

Conflicts of interest

The author declares no conflicts of interest.

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This work received no specific external funding; it was developed as part of the author's research activities at the Faculty of Civil Engineering, Universidad Autónoma del Perú.

Author contribution

P.R.P.G. conceived the study, conducted the literature review, developed the comparative matrix and figures, and wrote the manuscript in its entirety.

Data availability

The values in Table 1 and their traceability to original sources are available from the author upon reasonable request.

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Figures

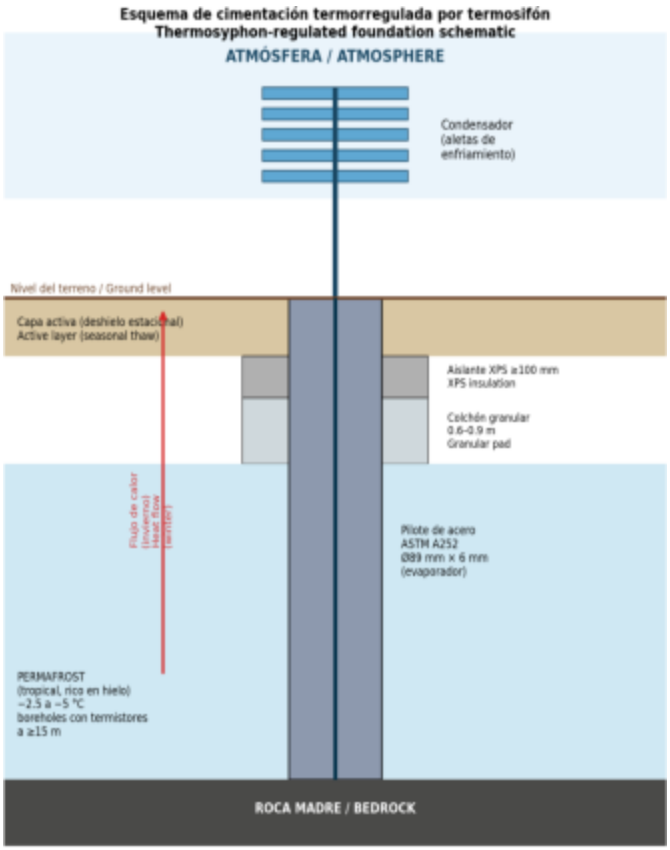


Figure 1

Schematic of a thermosyphon-regulated foundation adapted to high-Andean mountain permafrost. Author's own elaboration, Paul Ricardo Prudencio Gálvez (2025), based on the typology described in CSA S500:21.

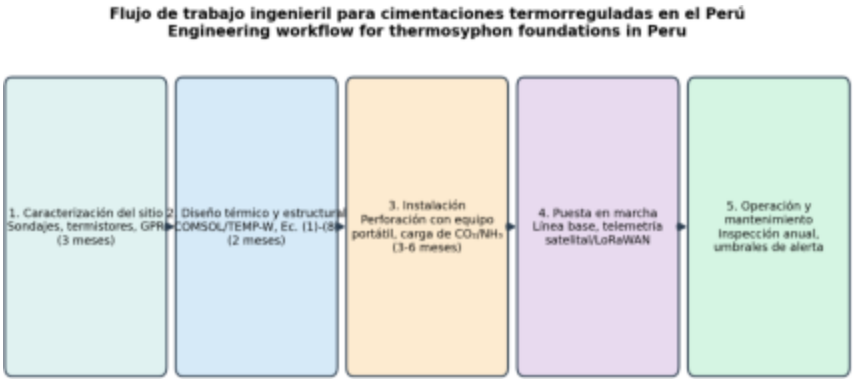


Figure 2

Proposed five-phase engineering workflow for implementing thermosyphon-regulated foundations in Peru. Author's own elaboration, Paul Ricardo Prudencio Gálvez (2025).