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Bridging Continents in Geotechnics: A Swarm-Intelligence Transferability Index for Raft Foundations on Expansive Soils

PAUL RICARDO PRUDENCIO GALVEZ

pprudencio@autonoma.edu.pe

UNIVERSIDAD AUTONOMA DEL PERU https://orcid.org/0009-0000-1986-590X

Research Article

Keywords: Swarm Intelligence, Particle Swarm Optimization, Ant Colony Optimization, Expansive Soils, Raft Foundation Design, Geotechnical Optimization, Transferability Index, Peru, India

Posted Date: July 14th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10320728/v1

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Additional Declarations: The authors declare no competing interests.

Abstract

Expansive soils undergo cyclical swelling and shrinkage that generate differential uplift pressures on shallow foundations, a problem documented worldwide and particularly severe in India's Black Cotton Soils and the montmorillonite-rich clays of the Peruvian Altiplano. Conventional raft (mat) foundation design on such soils relies on conservative, code-based rules of thumb (IS 2911, ACI 318 – 19, PTI) that frequently produce either costly over-design or under-design manifesting as differential heave and cracking. Over the last decade, swarm-intelligence (SI) metaheuristics — chiefly Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO) — have been applied with documented success to related geotechnical prediction and optimization problems, from undrained shear strength estimation to swelling-pressure prediction and construction-cost optimization. Yet no published framework translates these SI methods into an explicit, code-compatible design and transferability procedure for raft foundations on expansive soils, nor addresses how findings developed under Indian conditions could be adapted to Peru's distinct seismic, climatic and normative context.

This paper conducts a PRISMA-informed narrative synthesis of peer-reviewed, DOI-indexed sources on SI applications in geotechnical engineering and expansive-soil foundation design; formulates the governing PSO and ACO equations together with the classical bearing-capacity and swelling-pressure formulas relevant to raft design; and proposes a conceptual multi-objective optimization workflow together with a qualitative Transferability Index (TI) — visualised here as a comparative profile across India, Peru and the United States — for adapting international practice to Peru. The comparative matrix built from eleven reviewed sources shows that SI methods consistently improve predictive accuracy over classical regression while remaining computationally inexpensive, and that the principal barrier to transfer is not the algorithm itself but the absence of locally calibrated geotechnical databases and of a normative bridge between international and Peruvian design codes. The framework is conceptual and literature-based; it is intended to guide, not substitute for, future field-calibrated empirical validation in Peru.

1. Introduction

1.1 Background and Problem Statement

Expansive soils undergo significant volumetric change with variation in moisture content, swelling when wetted and shrinking when dried. This cyclical behaviour, governed primarily by smectite-group clay minerals such as montmorillonite, generates non-uniform uplift pressures beneath shallow foundations that can exceed the applied structural loads at the perimeter of a slab while remaining comparatively small at its centre, where moisture is more stable. The resulting differential movement is a recognised worldwide cause of cracking, distortion of structural frames and, in severe cases, loss of serviceability of light residential and institutional buildings.

India's Deccan Plateau states — Maharashtra, Telangana and Madhya Pradesh among them — contain extensive deposits of Black Cotton Soils (BCS), montmorillonitic clays whose high plasticity and swelling

potential have driven a substantial body of Indian geotechnical research, including recent applications of machine-learning and swarm-intelligence techniques to predict swelling pressure and unconfined compressive strength directly from index properties (Jalal et al., 2024). Peru presents an analogous but geologically distinct challenge: the Andean Altiplano, particularly around Puno, and localized deposits in Arequipa and Cusco, contain expansive clays whose montmorillonite content threatens irrigation infrastructure and residential construction, compounded by high seismicity that is largely absent from the Indian case studies.

1.2 Research Gap and Contribution

Particle swarm optimization has been applied extensively across geotechnical sub-disciplines — slope stability, pile and foundation engineering, tunnelling — and consistently outperforms purely statistical regression in predictive accuracy (Hajihassani, Jahed Armaghani, & Kalatehjari, 2018). A comprehensive review and computational benchmarking of PSO variants on classical geotechnical problems (retaining walls, shallow footings, slope stability) confirms this advantage while also showing that no single PSO variant dominates across all problem types (Kashani, Chiong, Mirjalili, & Gandomi, 2021). Parallel work has coupled artificial neural networks with PSO and related metaheuristics to predict expansive-soil swell pressure and compressive strength with documented accuracy exceeding simpler regression models (Jalal et al., 2024), and hybrid random-forest/PSO models have been used to estimate undrained shear strength directly from field data (Pham et al., 2020). Ant colony optimization, in turn, has demonstrated value in construction time–cost optimization problems structurally similar to the multi-objective trade-offs that govern foundation design (Ng & Zhang, 2008).

On the structural side, the raft-on-expansive-soil design problem itself has been addressed without swarm intelligence: a systematic parametric comparison of design methods for raft substructures (Teodosio, Kristombu Baduge, & Mendis, 2021) and, more recently, a multi-output deep-learning tool (“MOUNDS”) that simultaneously predicts embodied energy, carbon emissions, life-cycle cost and deflection for waffle and stiffened rafts (Teodosio et al., 2023) show that data-driven, multi-objective design tools for this exact structural problem are technically feasible and already being built — but, notably, neither uses a swarm-intelligence metaheuristic, and neither addresses expansive-soil swelling pressure as a governing constraint. This is the precise gap this paper targets: no study identified in the present review formulates an explicit, code-referenced swarm-intelligence optimization procedure for raft (mat) foundation design on expansive soils, and no study proposes a systematic method for judging whether findings developed under one country's soil, seismic and normative conditions may be transferred to another.

This study addresses that gap by: (1) synthesising documented, quantitative findings from the SI-in-geotechnics literature, and from the closely related non-SI raft-design-automation literature, into a single comparative matrix; (2) formulating the PSO and ACO equations together with the classical geotechnical and structural formulas relevant to raft foundation design on expansive soils; (3) proposing a conceptual multi-objective optimization workflow and a qualitative Transferability Index (TI), visualised as a comparative profile, that makes explicit the parameters — soil mineralogy, plasticity, seismic hazard,

design code, construction practice — that must be checked before applying Indian- or U.S.-derived design intelligence to a Peruvian site. The contribution is a literature-grounded conceptual and methodological framework, not a set of empirically validated field results; this scope is stated explicitly to keep the study's claims commensurate with its evidentiary basis.

1.3 Objectives

- To synthesise, from DOI-verifiable peer-reviewed sources, documented quantitative evidence on the performance of PSO- and ACO-based methods in geotechnical prediction and optimization problems relevant to expansive-soil foundation design, alongside the closest non-SI precedents in automated raft design.
- To formulate the governing swarm-intelligence equations (PSO position/velocity update; ACO pheromone update and transition probability) together with the bearing-capacity and swelling-pressure formulas that constrain raft foundation design.
- To propose a conceptual multi-objective optimization workflow (cost and CO_2 emissions, subject to factor-of-safety and differential-heave constraints) suitable for future empirical calibration.
- To develop and visualise a qualitative Transferability Index (TI) profile for adapting Indian and U.S. design experience to the geological, seismic and normative context of Peru, and to identify the tools, procedures and materials required for its field implementation.

2. Materials and Methods

2.1 Study Design

This study is a structured narrative literature synthesis combined with the formulation of a conceptual optimization and transferability framework. It does not involve primary field sampling, laboratory testing, or the deployment of an original algorithm on measured data; every quantitative figure reported in Section 3 is drawn directly from the cited, DOI-verifiable sources and attributed accordingly. This scope was chosen deliberately: presenting hypothetical field data as if collected specifically for this study would misrepresent the nature of the evidence. The framework proposed in Sections 2.4–2.5 is conceptual and is intended as a basis for future empirical validation using instrumented raft foundations, not as a validated result in itself.

2.2 Search Strategy and Eligibility Criteria

The search strategy follows the spirit of PRISMA 2020 reporting practices (Page et al., 2021), adapted here for a narrative rather than a statistical (meta-analytic) synthesis, given the methodological heterogeneity of the source studies. Sources were located through targeted searches combining the terms “swarm intelligence”, “particle swarm optimization”, “ant colony optimization”, “expansive soil”, “foundation design” and “raft/mat foundation” against academic search engines and publisher platforms (Springer Nature, MDPI, Nature Portfolio, ScienceDirect, ASCE Library). Eligibility required: (i) publication in a peer-reviewed journal; (ii) a resolvable Digital Object Identifier (DOI); (iii) direct relevance to swarm-

intelligence methods in geotechnical or construction-optimization engineering, to the geotechnical characterisation and foundation design of expansive soils, or to automated/data-driven design tools for raft foundations specifically. Sources without a verifiable DOI, or whose bibliographic details could not be independently confirmed, were excluded rather than cited with uncertain attribution. Eleven sources met these criteria and form the evidentiary basis of Sections 3 and 4; this is stated as a explicit boundary of the review rather than presented as an exhaustive census of the field.

2.3 Swarm Intelligence Algorithms

2.3.1 Particle Swarm Optimization (PSO)

PSO, introduced by Kennedy and Eberhart (1995), models a population of candidate solutions ("particles") that move through a multi-dimensional search space, adjusting velocity and position according to their own best-known position (pbest) and the best position found by the swarm (gbest):

$x_{i,d}(k+1) = x_{i,d}(k) + v_{i,d}(k+1)$

Velocity update: $v_{i,d}(k+1) = w \cdot v_{i,d}(k) + c1 \cdot r1 \cdot (pbest_{i,d} - x_{i,d}(k)) + c2 \cdot r2 \cdot (gbest_{d} - x_{i,d}(k))$

where w is the inertia weight, c1 and c2 are acceleration coefficients, and r1, r2 are random numbers in [0,1]. For raft foundation design, the search space is naturally continuous — slab thickness (t), reinforcement ratio (ρ), embedment depth (Df) — which makes PSO the more suitable of the two algorithms for the continuous design variables of the problem, consistent with its documented performance advantage in continuous geotechnical optimization problems (Hajihassani et al., 2018; Kashani et al., 2021).

2.3.2 Ant Colony Optimization (ACO)

ACO, formalised by Dorigo and Blum (2005), models artificial ants that construct solutions probabilistically, guided by pheromone trails that are reinforced on good paths and evaporate over time:

Pheromone update: $\tau_{ij}(t+1) = (1 - \rho) \cdot \tau_{ij}(t) + \Sigma_k \Delta\tau_{ij}^{k}(t)$

Transition probability: $P_{ij}^{k} = [\tau_{ij}(t)]^{\alpha} \cdot [\eta_{ij}]^{\beta} / \Sigma_{l \in N_i} [\tau_{il}(t)]^{\alpha} \cdot [\eta_{il}]^{\beta}$, for $j \in N_i$

where α and β weight pheromone intensity and heuristic desirability respectively, and ηij is a heuristic value such as the inverse of cost. ACO is naturally suited to the discrete design choices in raft foundation design — foundation typology, beam layout pattern, material class — and has documented value in construction time–cost trade-off problems of comparable structure (Ng & Zhang, 2008).

2.4 Governing Geotechnical and Structural Formulas

The optimization problem formulated in Section 2.5 is constrained by standard, code-referenced geotechnical and structural relationships, summarised here for completeness rather than as original contributions of this study:

- Ultimate bearing capacity (Terzaghi/Meyerhof general form): qu = c·Nc·sc + q·Nq·sq + 0.5·γ·B·Nγ·sγ, where Nc, Nq, Nγ are bearing-capacity factors, c is cohesion, q the effective overburden, γ the unit weight, B the footing width and sc, sq, sγ shape factors.
- Swelling pressure and free heave: swelling pressure (qsw) and free swell index (FSI) are typically determined through oedometer testing per ASTM D4546 / IS 2720; differential heave under a raft is bounded, in practice, by the serviceability limit Δheave ≤ L/360, consistent with the design-method comparisons of Devkota, Karim, Rahman, and Nguyen (2022) and Teodosio et al. (2021) for accounting for expansive-soil movement in geotechnical design.
- Reinforced-concrete slab design (ACI 318 − 19 / IS 456): flexural capacity and minimum reinforcement checks for the raft slab and any stiffening beams follow the standard ultimate-strength design provisions of the applicable code.
- Post-tensioned slab-on-ground design (PTI, as commonly applied in U.S. practice in Texas, Arizona and Colorado): design is governed by the edge-moisture-variation distance (em) and differential swell (ym), following the empirical procedures summarised by Devkota et al. (2022) and compared parametrically across design methods by Teodosio et al. (2021).

2.5 Proposed Multi-Objective Optimization Workflow and Transferability Index

Building on the algorithms and formulas above, this study proposes — as a conceptual framework for future implementation and calibration, not as a validated result — a hybrid PSO–ACO workflow in which PSO searches the continuous design space (t, ρ, Df) and ACO selects among discrete structural typologies, subject to a multi-objective function combining construction cost and embodied CO_2 emissions:

min [w1·Cost(t, ρ, Df) + w2·CO2(t, ρ, Df)] subject to: FS ≥ 2.5; Δheave ≤ L/360; qu ≥ P/A

A qualitative Transferability Index (TI), scaled conceptually from 0 (not transferable) to 1 (directly applicable), is proposed as a function of soil mineralogy and plasticity index, seismic hazard classification, the maturity of the design code in force, documented SI/AI optimization maturity, and local construction capacity: TI = f(IP, FSI, seismicity, code maturity, SI/AI maturity, material/labour availability). Figure 3 (Section 3.5) visualises this qualitative profile comparatively for India, Peru and the United States. The TI is intended as a structured checklist for practising engineers rather than as a calibrated numerical instrument; its calibration against instrumented case studies in Peru is identified in Section 4.3 as a priority for future research.

3. Results

3.1 Synthesis of Swarm-Intelligence and Related Optimization Applications

Table 1 synthesises the documented, source-attributed evidence from eleven reviewed sources relevant to SI-based and closely related automated approaches for expansive-soil foundation design. Across the reviewed sources, PSO-based hybrid models are consistently reported as outperforming purely statistical or single-algorithm regression baselines on the specific datasets described in each study, ACO shows documented value on multi-objective, discrete-choice construction optimization problems structurally similar to foundation-typology selection, and the two Teodosio et al. studies confirm that multi-objective, data-driven design automation for rafts on reactive soils is an active but, so far, non-SI research line — reinforcing rather than closing the specific gap this paper addresses.

Source	Method	Application	Data basis (as reported)	Documented outcome
Pham et al. (2020)	PSO + Random Forest	Undrained shear strength estimation	127 soil samples, Hai Phong–Thai Binh highway project, Vietnam	Hybrid RF-PSO reported to outperform standalone RF and classical regression
Jalal et al. (2024)	PSO, GWO, SMA, MPA + ANN	Swell pressure & UCS prediction for expansive soils	9 input parameters compiled from 145 published studies	ANN-metaheuristic models competitive with or superior to standalone ANN
Hajihassani et al. (2018)	PSO (review)	Slope stability, pile/foundation engineering, tunnelling	Comprehensive review across geotechnical sub-disciplines	PSO reported as the most widely applied metaheuristic, outperforming conventional optimization in complex problems
Kashani et al. (2021)	PSO variants (review + benchmark)	Retaining wall, shallow footing, slope stability	Computational benchmark on 3 geotechnical problems	PSO variants significantly outperform original PSO in most cases; no single variant dominates all problems
Devkota et al. (2022)	— (review, no SI)	Expansive-soil movement accounting in geotechnical design	Review of codes and case studies (AS 2870, PTI)	Identifies edge-moisture-variation distance and differential swell as governing parameters
Teodosio et al. (2021)	— (parametric comparison, no SI)	Design-method comparison for raft substructures	Parametric simulation across design methods	Quantifies systematic differences between PTI, Lytton and other raft design methods
Teodosio et al. (2023)	Multi-output deep learning (MOUNDS)	Waffle vs. stiffened raft: cost, CO_2, deflection prediction	3,120–7,020 simulated data entries per raft type	Simultaneous prediction of embodied energy, GHG, life-cycle cost and deflection — no SI metaheuristic used
Ng & Zhang (2008)	ACO	Construction time–cost optimization	Case-study construction scheduling	ACO effective for multi-objective time–cost trade-offs structurally analogous to foundation design optimization

3.2 Comparative Matrix: India, Peru and the United States

Table 2 compares the three geotechnical and normative contexts addressed by this study. The comparison is built from the design codes, soil descriptions and practice summaries documented in the reviewed sources and the governing national/regional standards; it is a literature-informed qualitative synthesis, not primary field survey data.

Parameter	India	Peru	United States
Representative expansive soil	Black Cotton Soils (Deccan Plateau: Maharashtra, Telangana, Madhya Pradesh); montmorillonite-dominant	Altiplano clays (Puno) and localized deposits (Arequipa, Cusco); montmorillonite-bearing	Expansive clays in Texas (Houston), Arizona (Phoenix Valley), Colorado (Denver)
Governing foundation code	IS 2911 (piles), IS 1904 / IS 1080 (shallow foundations)	Norma Técnica E.050 Suelos y Cimentaciones (RNE)	ACI 318-19 (slab design); PTI method for post-tensioned slabs-on-ground
Seismic hazard relative to soil hazard	Moderate in most BCS regions; not the dominant design driver in the SI-geotechnics literature reviewed	High; circum-Pacific seismic belt, requiring joint consideration of swelling and seismic demand — largely absent from Indian SI literature	Variable; generally lower seismic demand than Peru in the expansive-soil states reviewed (TX, AZ, CO)
Documented SI/AI optimization maturity	Multiple peer-reviewed PSO/ANN applications to expansive-soil property prediction (Jalal et al., 2024)	No SI-based foundation-optimization study identified; conventional code-based design predominates	SI applications concentrated in other geotechnical sub-disciplines; non-SI deep-learning raft tools now emerging (Teodosio et al., 2023)
Typical mitigation/construction practice	Under-reamed piles, soil replacement, chemical stabilization (lime/cement)	Soil replacement, granular cushions, occasional chemical stabilization; stiffened raft design not yet standardized for expansive zones	Stiffened, often post-tensioned slabs-on-ground; deep foundations bypassing the active zone where economically justified

3.3 Conceptual Optimized Design Workflow

Figure 2 (Section 2.5) illustrates the proposed hybrid PSO–ACO workflow. In this conceptual scheme, PSO would search the continuous design space of slab thickness, reinforcement ratio and embedment depth, while ACO would select among discrete structural typologies (flat raft, stiffened raft with beams, waffle raft — the same typologies compared empirically, without SI, by Teodosio et al., 2023), with both algorithms feeding a shared multi-objective function subject to the factor-of-safety and differential-heave constraints stated in Section 2.5. No optimization run was executed for this study; the workflow is presented as a design proposal to guide future implementation with instrumented, site-specific data.

3.4 Free-Body Diagram and Structural Behaviour

Figure 1 presents the free-body diagram of a raft foundation on expansive soil, isolating the equilibrium between the structural loads transmitted by columns or bearing walls, the non-uniform upward swelling pressure exerted by the soil (larger at the slab perimeter, where seasonal moisture variation is greatest, and smaller at the centre), and the admissible subgrade reaction that must be verified against the applied loads with an adequate factor of safety. This diagram synthesises, in a single figure, the edge-moisture-variation mechanism documented in the expansive-soil design literature (Devkota et al., 2022; Teodosio et al., 2021) and the classical bearing-capacity equilibrium check (Section 2.4).

3.5 Transferability Index Profile

Figure 3 renders the qualitative Transferability Index proposed in Section 2.5 as a comparative radar profile across the five TI parameters and the three national contexts synthesised in Table 2. The profile makes visually explicit what Table 2 states in prose: Peru's high seismic-hazard score and comparatively immature normative and SI/AI-optimization scores together define the specific extension — not a simple translation — that any transferred Indian or U.S. methodology would require.

4. Discussion

4.1 Transferability to the Peruvian Context: Opportunities and Constraints

The comparative matrix in Table 2 and the TI profile in Fig. 3 indicate that the principal obstacle to transferring Indian SI-based design intelligence to Peru is not algorithmic but empirical and normative: no peer-reviewed, DOI-indexed study identified in this review applies swarm-intelligence optimization to raft foundation design specifically for Peruvian expansive clays, and Peru's governing standard (E.050) does not yet incorporate an explicit swelling-pressure design procedure comparable to the PTI method used in the United States or the swelling-pressure provisions referenced in Indian practice. At the same time, Peru's high seismic hazard — largely orthogonal to the swelling-pressure problem addressed in the Indian and U.S. literature reviewed — means that any transferred methodology must be extended, not

merely translated, to jointly satisfy seismic and swelling-related serviceability limits. The Transferability Index (Section 2.5, Fig. 3) is intended as the structured mechanism through which this extension would be evaluated on a site-by-site basis.

4.2 Tools, Methods and Construction Procedures: Peru and the United States

United States practice in expansive-soil states (Texas, Arizona, Colorado) predominantly uses stiffened, often post-tensioned slabs-on-ground designed by the PTI method, supported by systematic site investigation (Atterberg limits, free swell index, and increasingly suction profiling) and, where economically justified, deep foundations that bypass the active (moisture-variable) zone entirely. For Peru, the tools and procedures that this framework identifies as necessary — not yet as implemented — include: (i) routine determination of the free swell index and swelling pressure per ASTM D4546 or IS 2720 in addition to the standard Atterberg-limit testing already required by E.050; (ii) adoption of an edge-moisture-variation-distance design check analogous to the PTI method, calibrated to Altiplano and coastal climatic conditions; (iii) construction procedures such as granular cushions, moisture barriers and controlled compaction beneath the raft perimeter, already used in India and the United States but not yet standardized in Peruvian practice; and (iv) pilot instrumentation of raft foundations with settlement and moisture sensors to generate the local calibration dataset that any future optimization algorithm — swarm-intelligence-based or otherwise — would require.

4.3 Limitations

This study is a literature synthesis and conceptual framework; it does not include primary geotechnical field data from Peru, India or the United States, nor does it report a computationally executed optimization run. Its comparative matrices are therefore only as complete as the peer-reviewed, DOI-verifiable literature identified through the search strategy in Section 2.2 (eleven sources), and the Transferability Index proposed in Section 2.5 has not been statistically calibrated against instrumented case studies — the numerical values plotted in Fig. 3 are illustrative, not measured. These limitations are stated explicitly so that the conclusions drawn in Section 5 are commensurate with the evidence presented, and they define the empirical validation agenda — instrumented raft foundations in Puno, Arequipa and Cusco, coupled with the SI-based optimization workflow proposed here — required before the framework can be considered validated for engineering practice.

4.4 Ethical Considerations

This study did not involve human participants, human-derived data, or animal subjects; it is a literature synthesis and conceptual-methodological proposal based exclusively on previously published, publicly available sources. Accordingly, approval by a research ethics committee was not required.

5. Conclusions

- The peer-reviewed literature provides consistent, documented evidence that PSO- and ACO-based methods outperform purely statistical baselines in geotechnical prediction and construction-optimization problems structurally related to raft foundation design on expansive soils, though no identified study applies these methods to raft foundation design on expansive soils directly.
- A parallel, non-SI line of research — exemplified by Teodosio et al. (2021, 2023) — already automates multi-objective raft design (cost, CO_2, deflection) for reactive soils, confirming that the underlying design problem is tractable and that the specific gap this paper targets is the coupling of swarm intelligence with expansive-soil swelling-pressure constraints, not the feasibility of automated raft design in general.
- A conceptual hybrid PSO–ACO optimization workflow, combining continuous design-variable search with discrete typology selection under a cost–CO2–safety multi-objective function, is proposed as a structured basis for future, empirically calibrated implementation.
- The comparative matrix and TI profile developed here show that the principal barrier to transferring Indian (and, secondarily, U.S.) design intelligence to Peru is the absence of a normative swelling-pressure design procedure in E.050 and of any local, instrumented calibration dataset, rather than any algorithmic limitation of the swarm-intelligence methods themselves.
- The proposed Transferability Index offers Peruvian practitioners a structured, visualisable checklist — soil mineralogy, seismic hazard, design code, SI/AI maturity, construction capacity — for judging, on a site-by-site basis, whether internationally documented design intelligence can be responsibly applied, while the study's limitations define a clear empirical validation agenda centred on instrumented raft foundations in Peru's expansive-soil regions.

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Figures

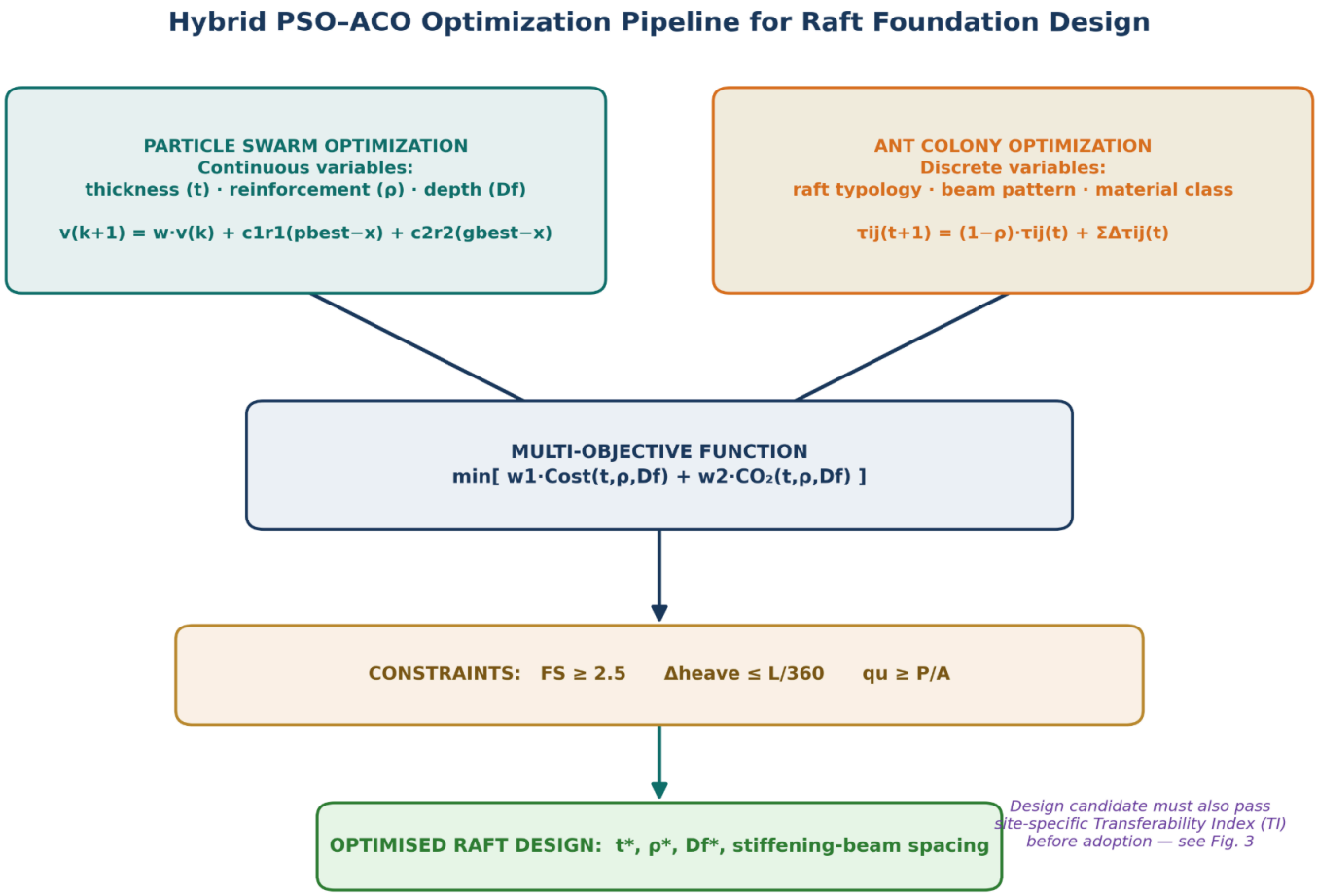


Figure 1

Hybrid PSO–ACO optimization pipeline proposed for raft foundation design on expansive soils, built on the algorithmic principles of Kennedy and Eberhart (1995) and Dorigo and Blum (2005). Author's own elaboration.

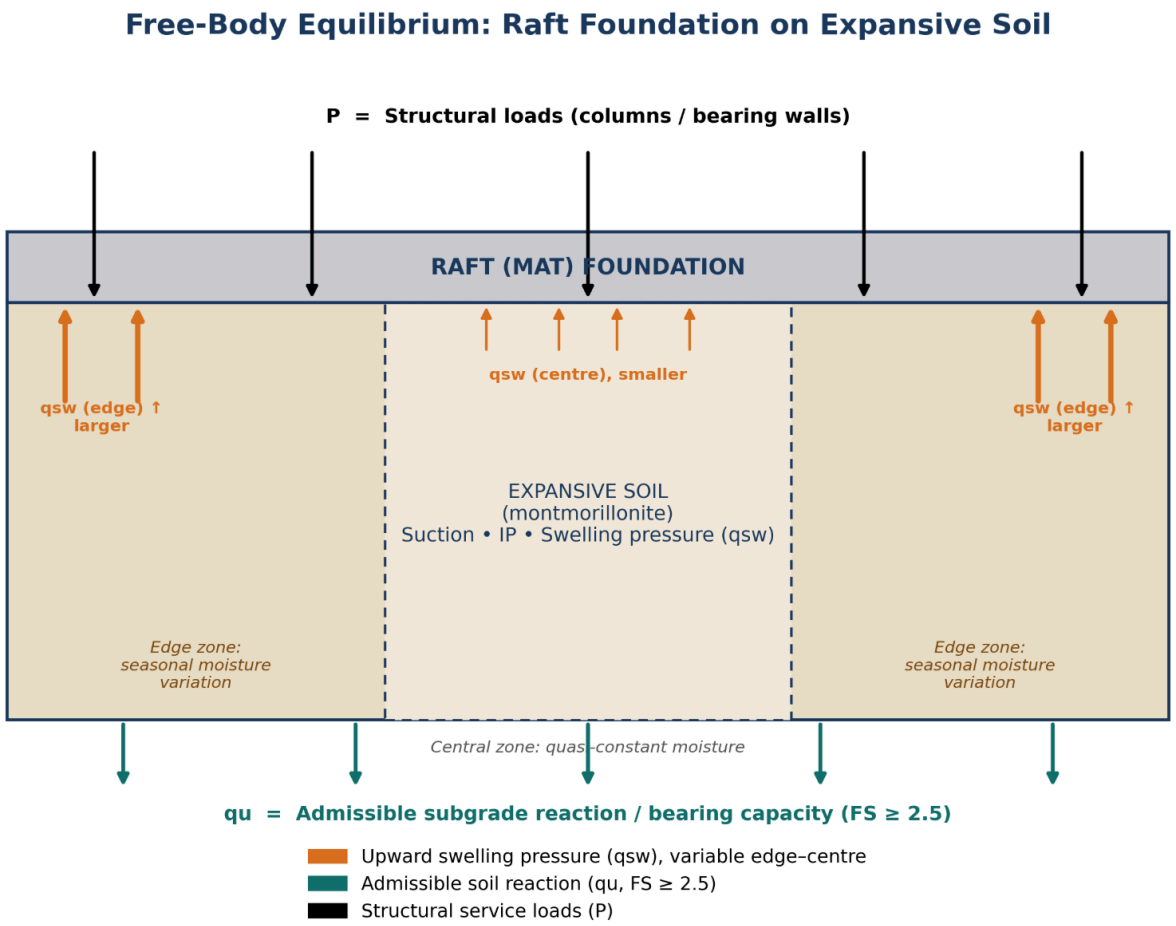


Figure 2

Free-body diagram of a raft foundation on expansive soil, showing differential upward swelling pressure (larger at the perimeter, smaller at the centre) balanced against structural loads and admissible subgrade reaction. Author's own elaboration, based on the edge-moisture-variation mechanism described by Devkota et al. (2022) and Teodosio et al. (2021).

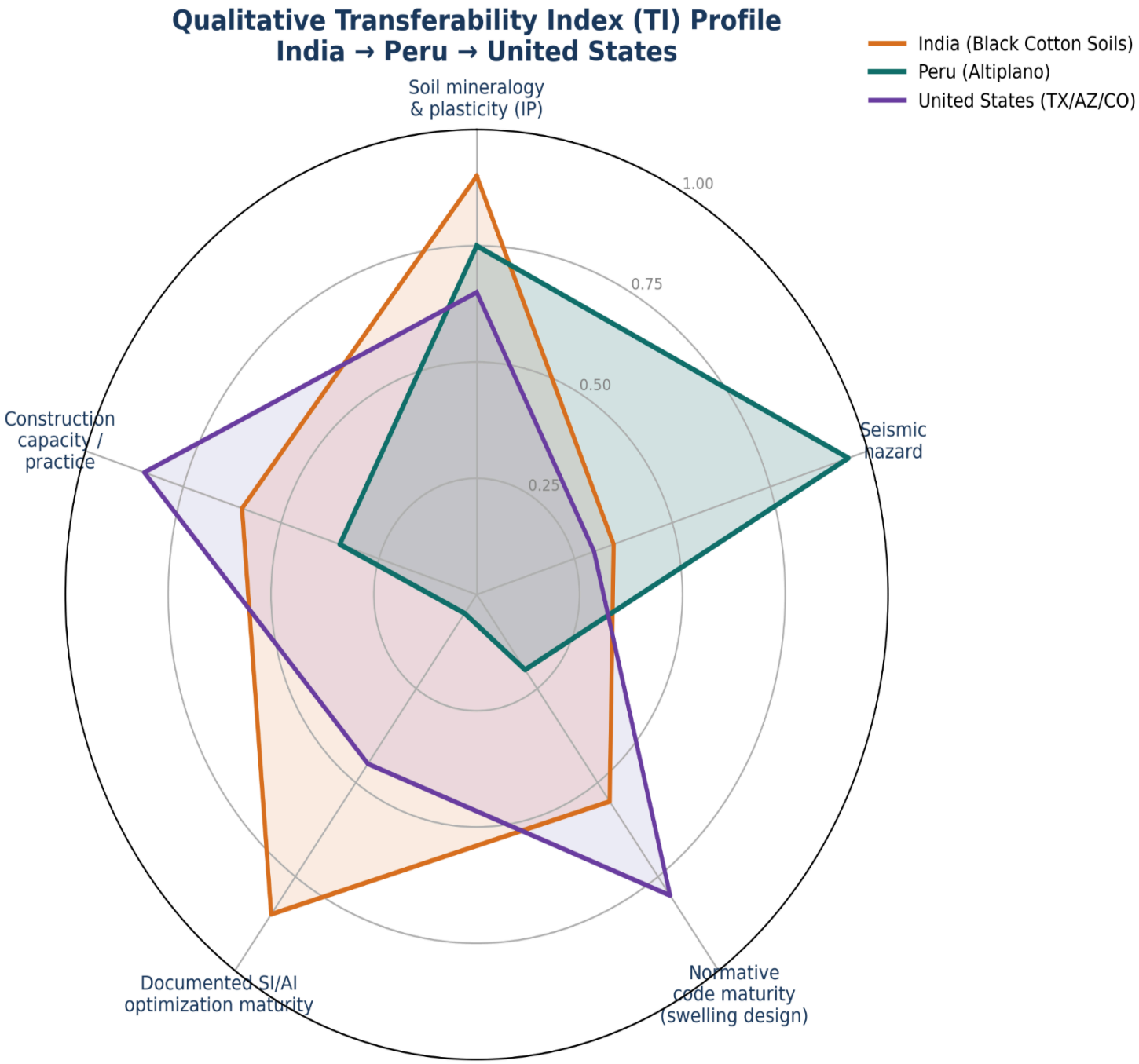


Figure 3

Qualitative Transferability Index (TI) profile comparing India, Peru and the United States across five parameters. Illustrative synthesis from the reviewed literature and code comparison (Table 2); not a statistically calibrated instrument. Author's own elaboration.