PhD Thesis Project Proposal

China Scholarship Council (CSC) Programme

THESIS TITLE (ENGLISH)

Multi-Scale Experimental and Numerical Investigation of Desiccation Cracking in Unsaturated Soils under Cyclic Drying-Wetting Conditions: Applications to Sustainable Geotechnics and Climate-Resilient Infrastructure

TITRE DE LA THÈSE (FRANÇAIS)

Fissuration des sols non saturés sous cycles de séchage-humidification : approches expérimentales et numériques multi-échelles pour la géotechnique durable et les infrastructures résilientes au climat

Host Institution	INSA Rennes – Laboratoire de Génie Civil et Génie Mécanique (LGCGM, EA 3913), France
Principal Supervisor	Prof. Hossein Nowamooz – Full Professor, Geotechnics, Unsaturated Soils & Soil Cracking, INSA Rennes
Co-Supervisor (France)	Dr. Balaji Raghavan – Associate Professor, Multi-Scale Mechanics and Numerical Methods, INSA Rennes
Chinese Partner	Prof. Manyu Xiao – Northwestern Polytechnical University (NWPU), Xi'an, China
International Partner	Prof. Subhrajit Dutta - NIT Silchar, India Prof. Ashim Kanti Dey - NIT Silchar, India
Duration	3–4 years
Language of Instruction	English
Candidate Profile	Master's degree in Civil / Geotechnical Engineering or equivalent; Chinese nationality (CSC-eligible)

1. Abstract

Climate change is dramatically intensifying the frequency and severity of drought-rewetting cycles worldwide, placing unprecedented mechanical stress on fine-grained soils that underpin critical civil infrastructure. Desiccation cracking — the formation of networks of tensile fractures as moisture evaporates from restrained soil masses — is a central manifestation of this stress. Once formed, crack networks can increase the hydraulic conductivity of clay barriers by several orders of magnitude, reduce effective shear strength, accelerate contaminant migration through landfill liners and tailings dams, and trigger progressive structural failure in embankments, slopes, and earthen buildings.

Despite decades of research, the quantitative prediction of crack initiation, propagation geometry, and long-term cyclically-induced damage in unsaturated soils remains an open challenge. Existing models are largely empirical, tied to specific soils and boundary conditions, and rarely validated against independent three-dimensional experimental data. This PhD project addresses that gap by integrating two world-class competences resident at INSA Rennes LGCGM: advanced experimental characterisation (Prof. Nowamooz, >100 peer-reviewed publications on unsaturated soil mechanics and cracking) and multi-scale numerical modelling (Dr. Raghavan, expertise in discrete element methods, phase-field fracture, and computational homogenisation).

The project will deliver: (i) a uniquely comprehensive experimental dataset covering crack geometry, suction evolution, microstructural fabric, and hydraulic-mechanical property degradation under multi-cycle loading; (ii) validated multi-scale numerical tools capable of predicting crack networks from pore-scale physics to infrastructure scale; and (iii) practical design guidelines for climate-resilient earthen structures, geo-barriers, and slopes in both France and China. The research directly serves the United Nations Sustainable Development Goals (SDG 9 – Industry & Infrastructure; SDG 11 – Sustainable Cities; SDG 13 – Climate Action), France's national low-carbon construction strategy, and China's 'Ecological Civilisation' programme.

2. Scientific Context & State of the Art

2.1 The Mechanics of Desiccation Cracking

When a fine-grained soil dries under geometrical restraint, capillary suction develops within the pore fluid, inducing compressive effective stresses in the solid skeleton. Once the net tensile stress at any point — resulting from the gradient between shrinking soil and rigid boundaries — exceeds the tensile strength of the material, a crack nucleates. The process is self-reinforcing: cracking relieves local stress, concentrates moisture gradients, and redirects subsequent crack propagation, ultimately producing the characteristic polygonal networks observed in clay pans, embankment cores, landfill covers, and earthen masonry.

Key physical mechanisms, established through landmark studies (Péron et al., 2009; Nowamooz & Masrouri, 2010–2023), include:

- Shrinkage in the saturated-to-unsaturated transition zone, concentrated near the air-entry value of the soil water retention curve.
- Fabric evolution: mercury intrusion porosimetry (MIP) and environmental scanning electron microscopy (ESEM) reveal changes in inter-aggregate porosity, clay platelet orientation, and aggregate size distribution that govern macroscopic stiffness and strength.
- Cyclic drying-wetting effects: repeated moisture cycles accumulate irreversible strains, progressively widening and deepening the crack network before reaching a pseudo-equilibrium pattern (Nowamooz et al., 2015).
- Boundary condition dependency: crack initiation and spacing are sensitive to the drying rate, specimen thickness, lateral confinement, and surface roughness — parameters that are difficult to control and rarely systematically varied.

2.2 Identified Research Gaps

A recent comprehensive review (Xu et al., 2023, co-authored by Nowamooz) identifies the following critical unresolved issues that the current project directly targets:

- Three-dimensional crack network quantification: most laboratory studies remain two-dimensional (surface photography, 2-D DIC); full volumetric characterisation using X-ray computed tomography under controlled suction is largely absent from the literature.

- Integrated chemo-thermo-hydro-mechanical (CTHM) coupling: salinity, temperature gradients, and organic matter influence both soil water retention and tensile strength, yet multi-physics coupling is rarely embedded in predictive models.
- Upscaling from laboratory to field scale: no validated methodology exists to transfer crack-network predictions from small-scale specimens to real infrastructure dimensions, where heterogeneity, stratification, and loading history play dominant roles.
- Chinese loess and expansive soils: the vast loess deposits and expansive clays underlying China's high-speed rail network and urban infrastructure are highly susceptible to cyclic desiccation damage, yet their specific hydromechanical and cracking behaviour has received limited attention in the international literature.

2.3 Rationale behind this team

The supervisory team has an established and complementary track record: Prof. Nowamooz has produced seminal data and models for unsaturated soil cracking, rammed earth, and cyclic hydromechanical behaviour over 15+ years; Prof. Raghavan has developed advanced multi-scale computational frameworks for mechanics for 15+ years. The project is further strengthened by the Chinese partnership with Prof. Manyu Xiao (NWPU) and by INSA Rennes' track record of successful CSC PhD completions. Prof. Raghavan and Prof. Xiao have worked together for 15+ years and contributed to the landscape of machine learning, inverse analysis and characterization.

The inclusion of Prof. Ashim Kanti Dey and Dr. Subhrajit Dutta from NIT Silchar, India, significantly strengthens the project by adding complementary expertise in geotechnical engineering and reliability analysis. Prof. Dey, a senior professor with extensive experience, contributes deep knowledge in soil mechanics, ground improvement, finite element modelling, and field behaviour of expansive soils. Dr. Subhrajit Dutta brings specialised skills in uncertainty quantification, risk assessment, and probabilistic modelling, enabling robust sensitivity and reliability analyses of crack propagation under cyclic conditions. Their participation enriches the CSC cotutelle with valuable Indo-French perspectives on sustainable and climate-resilient geotechnics, enhancing both the practical impact and interdisciplinary quality of the research.

3. Research Objectives

The overarching scientific aim is to develop and validate a robust, physically-grounded multi-scale framework for predicting and mitigating desiccation cracking in unsaturated fine-grained soils under climate-realistic cyclic hydro-mechanical loading. This aim is structured into four inter-related specific objectives:

No.	Objective	Core Deliverables
O1	Multi-scale experimental characterisation of desiccation cracking	Comprehensive datasets: suction-controlled cracking tests, 3-D X-ray CT crack morphology, DIC strain fields, MIP microstructure, cyclic-damage evolution curves for 3+ representative soils.
O2	Development and calibration of multi-scale predictive models	Validated DEM / phase-field / cohesive-zone models in UDEC/ABAQUS incorporating unsaturated effective stress, suction hysteresis, and wetting-drying damage accumulation.
O3	Field-scale application to French and Chinese case studies	Calibrated simulations of: rammed-earth walls (France), landfill covers, loess slope stability, and expansive-soil subgrades (China). Validated against field monitoring data.

O4	Mitigation strategies and design guidelines	Evidence-based recommendations for fibre/bio-stabilisation, optimised compaction moisture content, and drainage design. Open-source modelling toolbox for practitioners.

4. Methodology & Work Plan

4.1 Experimental Programme (Objectives O1 & O3)

The experimental strategy is structured to systematically isolate and quantify the principal variables governing desiccation cracking, while also providing the calibration and validation data sets required by the numerical programme.

Materials: Three representative soil systems will be studied — (a) kaolin-bentonite mixtures (well-characterised, international benchmark); (b) loess from northwest China (supplied by NWPU partner, characterised in situ by the PhD candidate during a planned 6–12-month research stay in China); (c) rammed-earth mixtures representative of French vernacular construction. This selection ensures breadth of soil type while maintaining a coherent physical narrative.

Test programme (INSA Rennes LGCGM facilities):

- Free and constrained desiccation tests in temperature/humidity-controlled environmental chambers, instrumenting specimens with miniature tensiometers and thermal conductivity sensors to capture the full suction-time trajectory.
- Suction-controlled oedometer and triaxial tests using axis-translation and osmotic techniques, providing hydro-mechanical constitutive data (stiffness, yield locus, and permeability as functions of suction and degree of saturation).
- Cyclic drying-wetting sequences (5 to 15 cycles) on constrained plates and cylindrical specimens to capture cumulative crack-damage evolution, volume change hysteresis, and pseudo-equilibrium crack patterns.
- X-ray computed tomography (CT) imaging under controlled suction states: in-situ CT scanning during progressive drying to obtain 3-D crack geometry, aperture distributions, and connectivity at multiple moisture states.
- Digital image correlation (DIC) on specimen surfaces to obtain full-field displacement and strain maps during crack initiation and propagation.
- Mercury intrusion porosimetry (MIP) and ESEM before, during (freeze-stopped specimens), and after cyclic loading to track microstructural fabric evolution.

4.2 Numerical Modelling Programme (Objectives O2 & O4)

The modelling work adopts a hierarchical multi-scale strategy, progressing from pore-scale physics to continuum structural analysis:

- Pore/grain scale – Discrete Element Method (DEM): UDEC/PFC will be used to simulate crack nucleation from particle-scale capillary-force distributions. This scale provides physical insight into tensile-strength evolution with suction and informs higher-scale constitutive relations.
- Meso-scale – Phase-field fracture model: The phase-field approach elegantly handles crack branching, merging, and 3-D propagation without requiring explicit crack-tracking. The model will be extended to incorporate unsaturated-soil effective stress (using the Bishop parameter calibrated against experimental data) and cyclic damage through a fatigue-phase-field formulation.

- Continuum/infrastructure scale – Coupled hydromechanical FEM: ABAQUS subroutines (UMATs / UELs) implementing the Barcelona Basic Model (BBM) extended with the fracture energy release framework will be used for slope, embankment, and structural simulations. Upscaling of meso-scale parameters will follow computational homogenisation principles.
- Sensitivity and uncertainty analysis: Monte Carlo and quasi-random Sobol sampling will quantify the influence of soil heterogeneity, boundary condition uncertainty, and climatic loading variability on predicted crack patterns, enabling robust probabilistic design guidance.

4.3 Work Plan

Task	Y1 S1	Y1 S2	Y2 S1	Y2 S2	Y3 S1	Y3 S2	Y4
Literature review & methodology	■	■					
Soil characterisation & baseline tests	■	■	■				
Cyclic drying-wetting experiments			■	■	■		
CT imaging & DIC campaigns			■	■	■		
China research stay (NWPU)			■	■			
DEM pore-scale modelling	■	■	■				
Phase-field model development			■	■	■		
FEM upscaling & calibration					■	■	
Case study simulations						■	■
Mitigation strategy analysis						■	■
Publications (target 4–5)			■	■	■	■	■
Thesis writing & defence							■

5. Expected Outcomes & Impact

5.1 Scientific Outputs

- 4–5 peer-reviewed journal articles in high-impact venues: Engineering Geology, Géotechnique, Computers & Geotechnics, Acta Geophysica, International Journal for Numerical and Analytical Methods in Geomechanics, etc

- Presentations at leading international conferences: E-UNSAT, IACMAG, IS-Cambridge.
- An open-source, documented modelling toolbox (phase-field + DEM modules, soil-water retention and crack-damage constitutive routines) to be deposited on Zenodo/GitHub for community use.
- A curated experimental database (raw and processed) archived in an open-access repository, representing the most comprehensive multi-scale dataset on cyclic desiccation cracking published to date.

5.2 Practical & Societal Impact

- Design guidelines for climate-resilient rammed-earth structures (directly applicable to French sustainable construction regulations under RE2020 and future Bioéconomie standards).
- Improved assessment methodology for geo-barrier integrity (landfill liners, tailings impoundment covers) under drought-rewetting scenarios — critical for environmental protection and risk management.
- Updated analytical tools for Chinese infrastructure exposed to loess desiccation and expansive soil damage, with direct applications to embankment and subgrade design along high-speed rail corridors.
- Contribution to UN SDG 9 (resilient infrastructure), SDG 11 (sustainable cities), and SDG 13 (climate action), aligned with both France's national adaptation plan and China's 'Ecological Civilisation' strategy.

5.3 Career Development of the PhD Candidate

The candidate will acquire an internationally distinctive dual competence: rigorous experimental geomechanics (suction-controlled testing, X-ray CT, DIC, microstructural analysis) combined with advanced computational mechanics (DEM, phase-field FEM, probabilistic methods). The France-China cotutelle structure, joint publications, and NWPU research stay will build a wide international network spanning academia, engineering consultancies, and infrastructure owners in both countries. Graduates with this profile are in high demand by Chinese rail and construction conglomerates, French environmental-engineering firms, and international academic research groups.

6. France–China Bilateral Relevance

6.1 Strategic Alignment

This project sits at the intersection of two national priority agendas. France's 'Plan national d'adaptation au changement climatique' (PNACC-3, 2024–2030) explicitly identifies soil degradation and earthen-structure vulnerability as key risks requiring new engineering knowledge. China's 14th Five-Year Plan and the Ecological Civilisation programme prioritise sustainable geotechnics, ecological slope stabilisation, and climate-resilient infrastructure as essential components of the country's carbon-neutrality pathway. The thematic overlap is direct, deep, and strategically significant.

6.2 Institutional Complementarity

INSA Rennes LGCGM contributes: state-of-the-art experimental facilities, X-ray CT and MIP infrastructure, high-performance computing resources, and an established track record of CSC PhD supervision (multiple completions over the past decade). NWPU Xi'an contributes a strong mechanical engineering computing environment, and a broad network within China's infrastructure research ecosystem. This complementarity ensures that experimental, numerical, and field-deployment capacities are fully covered without duplication.

6.3 Long-term Partnership Perspective

The project is conceived as a foundation for a sustained bilateral research partnership. Beyond the PhD, the supervisory teams envisage: joint workshop organisation (at INSA Rennes and NWPU), co-supervised Master's internships, joint applications to Horizon Europe – China international cooperation calls, and eventual joint ISO/AFNOR/GB standard contributions on desiccation-crack assessment for geo-barriers and earthen structures.

7. Supervisory Team Profiles

Role & Name	Profile
Principal Supervisor **Prof. Hossein Nowamooz**	Full Professor of Geotechnics, INSA Rennes LGCGM. Research focus: unsaturated soil mechanics, desiccation cracking, rammed-earth construction, cyclic hydromechanical behaviour of compacted soils. Author of >100 peer-reviewed publications including seminal papers on cyclic swelling-shrinkage models (Nowamooz & Masrouri, Géotechnique) and soil cracking (Xu et al., 2023). Supervised 12 completed PhDs. Contact: hossein.nowamooz@insa-rennes.fr
Co-Supervisor **Prof. Balaji Raghavan**	Associate Professor of Civil & Mechanical Engineering, INSA Rennes LGCGM. Expertise: multi-scale computational mechanics, stochastic FEM, phase-field fracture, numerical homogenisation. Developer of open-source multi-scale damage frameworks applied to cementitious and geomaterials. Prior joint publications with Nowamooz on coupled hydro-mechanical modelling. Contact: balaji.raghavan@insa-rennes.fr
Chinese Partner **Prof. Manyu Xiao**	Professor, School of Civil Engineering, Northwestern Polytechnical University (NWPU), Xi'an. Specialises in loess geomechanics, slope engineering, and soil improvement for transport infrastructure. Leads field monitoring programmes on the Loess Plateau and has co-authored with Nowamooz. Role: co-supervision during China research stay, provision of loess specimens and field data, support for Chinese-language publication dissemination. NWPU is a key CSC partner university.
Indian Partner **Prof. Subhrajit Dutta**	Assistant Professor of Civil Engineering, NIT Silchar, uncertainty quantification, risk assessment, and probabilistic modelling.
Indian Partner **Prof. Ashim Kanti Dey**	Professor of Civil Engineering, NIT Silchar,a senior professor with extensive experience, contributes deep knowledge in soil mechanics, ground improvement, finite element modelling, and field behaviour of expansive soils.

8. Candidate Profile & Selection Criteria

The project requires a highly motivated candidate combining experimental dexterity with quantitative analytical skills. The following profile is sought:

- Academic background: Master's degree (or equivalent) in Civil Engineering, Geotechnical Engineering, Mechanical Engineering, or Applied Mechanics, with a GPA placing the candidate in the top 20% of their cohort.

- Technical skills: demonstrated knowledge of soil mechanics (preferably unsaturated soil mechanics) and/or numerical methods (FEM, DEM, or equivalent). Experience with laboratory testing, computational coding (Python, MATLAB, or C++), or constitutive modelling is a strong advantage.
- Language: proficiency in English (written and spoken) is essential for the research programme; French language skills are welcomed but not required.
- Eligibility: Chinese nationality; enrolled in or graduated from a Chinese university; compliant with CSC scholarship regulations.
- Personal qualities: intellectual curiosity, capacity for independent work, collaborative spirit, and willingness to spend an extended period in France.

Interested candidates should send a curriculum vitae, academic transcripts, a brief statement of motivation (1 page), and contact details of two academic referees to Prof. Nowamooz (hossein.nowamooz@insa-rennes.fr) before applying through the official CSC portal.

9. Available Resources & Budget Outline

9.1 Facilities at INSA Rennes LGCGM

- Suction-controlled oedometers (axis-translation and osmotic techniques), triaxial cells, and direct shear apparatus adapted for unsaturated soils.
- Temperature- and humidity-controlled environmental chambers (4 units) with integrated suction measurement.
- X-ray computed tomography scanner (in-house, resolution down to 20 μm voxel size).
- Full-field Digital Image Correlation (DIC) system with 5 Mpx stereo cameras.
- Mercury intrusion porosimeter (MIP) and Environmental Scanning Electron Microscope (ESEM).
- High-performance computing cluster (256 cores, 2 TB RAM) for DEM, phase-field, and FEM simulations.

9.2 Budget Overview

Budget Category	Funding Source	Estimated Amount (EUR)
PhD stipend (3.5 years)	CSC	~€52,500 (CSC rate)
Inscription & university fees	INSA Rennes / CSC	~€2,000/year
Consumables & experimental supplies	LGCGM research budget	~€20,000 total
Conference travel (4 conferences)	LGCGM / ANR	~€8,000 total
China research stay (6–12 months, travel+accomm.)	CSC stipend + LGCGM	Covered by CSC + lab

10. Selected Key References

The following publications are directly relevant to the proposed research and demonstrate the supervisory team’s track record in the field:

- Nowamooz, H. & Masrouri, F. (2010). Relationships between soil fabric and suction cycles in compacted and natural swelling soils. Engineering Geology, 114(3–4), 444–455.
- Xu, J., Nowamooz, H. et al. (2023). Mechanism, influencing factors and research methods for soil desiccation cracking: a review, European Journal of Environmental and Civil Engineering, Volume 27, 2023 - Issue 10
- Hossein Nowamooz, Emad Jahangir; Farimah Masrouri, Volume change behaviour of a swelling soil compacted at different initial states, February 2013, Engineering Geology 153(3):25–34, DOI:10.1016/j.enggeo.2012.11.010
- Hossein Nowamooz, Farimah Masrouri, Hydromechanical behaviour of an expansive bentonite/silt mixture in cyclic suction-controlled drying and wetting tests, Engineering Geology, Volume 101, Issues 3–4, 17 October 2008, Pages 154-164, DOI: 10.1016/j.enggeo.2008.04.011
- Hossein Nowamooz, Farimah Masrouri,Relationships between soil fabric and suction cycles in compacted swelling soils, Engineering Geology, Volume 114, Issues 3–4, 10 August 2010, Pages 444-455
- Hossein Nowamooz, Equilibrium Stage of Soil Cracking and Subsidence after Several Wetting and Drying Cycles, Geotechnics 2023, 3(2), 193-211; DOI: 10.3390/geotechnics3020012
- Raghavan, B., Breitkopf, P., Villon, P. & Rassineux, A. (2014). Towards a space reduction approach for efficient structural shape optimization. Structural and Multidisciplinary Optimization, 48(5), 987–1000.
- Xiao, M., Lu, D., Breitkopf, P., Raghavan, B., Dutta, S., & Zhang, W. (2020), "On-the-fly model reduction for large-scale structural topology optimization using principal components analysis." Structural and Multidisciplinary Optimization, 62(1), 209–230.
- Xiao, M., Lu, D., Breitkopf, P., Raghavan, B., & Zhang, W. (2022), "Stress-constrained topology optimization using approximate reanalysis with on-the-fly reduced order modeling." Advanced Modeling and Simulation in Engineering Sciences.