

Electro-osmotic drainage of a weakly expansive soil slope using perforated tubular electrodes: proof-of-concept observations and a verified globally sampled numerical study

Yuanchao Lai

Sichuan Highway Planning, Survey, Design and Research Institute Co., Ltd.

Yuxuan Chen

457735683@qq.com

Sichuan Kangzang Road and Bridge Co., Ltd.

Ruhao Wang

Sichuan Kangzang Road and Bridge Co., Ltd.

Research Article

Keywords: electro-osmosis, expansive soil, slope drainage, tubular electrode, global sensitivity, intermittent voltage

Posted Date: October 27th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11324660/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Electro-osmotic drainage of a weakly expansive soil slope using perforated tubular electrodes: proof-of-concept observations and a verified globally sampled numerical study

Highlights

- Perforated tubular cathodes produced directional drainage in a slope model.
- A one-dimensional benchmark verified the total-flux formulation to within 0.12% L2 error.
- A 48-point global design identified drain conductance as the dominant discharge control.
- Intermittent voltage increased modelled drainage per unit energy but reduced total drainage.
- Physical observations remain qualitative and do not establish a field design optimum.

Abstract

Electro-osmosis can provide active drainage in water-sensitive fine soil, but the scarcity of repeatable slope tests makes numerical verification and uncertainty analysis essential. A laboratory slope fitted with perforated tubular cathodes provided qualitative evidence of directional water collection. Stepwise voltages of 8, 12, 20, 25, and 30 V produced currents of 0.202–1.034 A and drainage responses of 6–33 drops/min; the single sequential observations are treated as proof of concept rather than calibration data. A continuum model was formulated by superposing hydraulic and electro-osmotic Darcy fluxes and applying boundary conditions to their sum. A one-dimensional analytical benchmark gave relative L2 errors of 0.118% for cathodic flux and 0.103% for sealed-end pressure. In the two-dimensional model, fine-to-extra-fine mesh refinement changed 600-s cumulative drainage by –0.043%, 2-to-1-s time-step refinement changed it by 0.013%, and weak-form mass imbalance remained below 0.003% after 10 s. A 48-point Latin hypercube design spanning electro-osmotic coefficient, permeability, storage, electrical conductivity, and finite drain conductance produced a 600-s drainage range with 5th, median, and 95th percentiles of 1.92, 13.08, and 58.08 mL. Drain conductance dominated the ranking (Spearman $\rho = 0.902$; standardized $\beta = 0.823$). Smoothed intermittent operation at 20 and 25 V reduced total drainage but increased water removed per unit modelled energy at lower duty cycles. These results establish a verified comparative framework and identify the cathodic hydraulic boundary as the principal design uncertainty; they do not replace volumetric drainage, suction, temperature, and pH validation.

Keywords: electro-osmosis; expansive soil; slope drainage; tubular electrode; global sensitivity; intermittent voltage

1. Introduction

Expansive-soil slopes are governed by a coupled hydro-mechanical cycle rather than by rainfall intensity alone. Infiltration reduces matric suction and apparent cohesion, promotes swelling and fissure opening, and may generate positive pore-water pressure above low-permeability layers. Subsequent drying can restore suction but also creates shrinkage cracks that shorten later infiltration paths. Repetition of this cycle progressively changes fabric, hydraulic connectivity, and shear resistance (Morris et al., 1992; Ng and Shi, 1998; Albrecht and Benson, 2001; Lu and Likos, 2006; Tang et al., 2011; Chaduvula et al., 2017; Tu et al., 2022). These processes are especially relevant in humid western Sichuan, where weakly expansive road-cut and spoil slopes experience prolonged wetting. Recent tests on expansive soils confirm that strength varies strongly with suction and swelling state, so drainage must be evaluated as a means of controlling the soil-water state rather than simply removing visible runoff (Lan et al., 2022; Niu et al., 2024).

Conventional relief drains are passive and depend on a connected hydraulic gradient. They can intercept water in open fissures or permeable seams, but their response in an intact fine-grained matrix is limited by low hydraulic conductivity and by loss of drain contact during shrinkage. Electro-osmosis supplies an additional driving force that is not proportional to hydraulic conductivity. In a soil with predominantly negative surface charge, a direct-current field moves counter-ions in the diffuse double layer toward the cathode and transfers momentum to the pore fluid. The resulting flow is commonly from anode to cathode and can remain appreciable where Darcy flow is slow (Casagrande, 1949; Gray and Mitchell, 1967; Esrig, 1968; Asadi et al., 2013). This mechanism has supported ground improvement, consolidation, dewatering, and electrokinetic remediation, but its usefulness depends on providing a hydraulic outlet at the cathode rather than merely generating a pore-pressure gradient.

Classical electro-osmotic consolidation solutions relate generated pressure and discharge to voltage distribution, electrode spacing, hydraulic permeability, electro-osmotic permeability, and drainage conditions. Later models introduced nonlinear soil properties, large strain, surcharge preloading, multilayer profiles, nonuniform initial water content, and unsaturated transport (Wan and Mitchell, 1976; Deng and Zhou, 2016a, 2016b; Yuan and Hicks, 2016; Wu et al., 2017a, 2017b, 2017c; Shen et al., 2019; Zhou et al., 2019; Wang et al., 2021a, 2021b; Feng et al., 2022; Jiang et al., 2023; Zhao et al., 2024). A consistent result is that useful dewatering is controlled

by the complete water-flux boundary. If hydraulic and electro-osmotic fluxes are superposed in the domain but only the hydraulic component is constrained at a sealed boundary, the model introduces a spurious source or sink. Likewise, an ideal zero-pressure cathode can substantially overpredict drainage when pipe perforations, filter fabric, outlet elevation, or downstream resistance limit discharge.

Most experimental evidence nevertheless comes from one-dimensional soft-clay specimens, sludge, tailings, or dredged sediment. Slope application adds a free surface, gravity, spatially variable saturation, unequal electric paths, and several possible outlets. A perforated tubular cathode is attractive because it combines electrical forcing with distributed collection along an embedded length; in engineering terms it acts as both electrode and subhorizontal drain. Electro-osmosis combined with vertical drains and electrokinetic geosynthetics has shown the importance of this distributed hydraulic boundary (Shang, 1998; Burnotte et al., 2004; Fourie et al., 2007; Kalumba et al., 2009; Gan et al., 2022; Jayasiri et al., 2025). However, evidence for perforated tubular cathodes in expansive-soil slope geometry remains limited, and results obtained in confined consolidation cells cannot be transferred directly to a partially saturated slope. Shang (1998) investigated electroosmosis-enhanced preloading consolidation via vertical drains, highlighting the role of drainage provision in electro-osmotic treatment.

Material and operating conditions further prevent a universal voltage criterion. Electro-osmotic efficiency varies with clay mineralogy, exchangeable ions, initial water content, degree of saturation, electrical conductivity, electrode contact, and drain capacity (Lockhart, 1983; Lockhart and Stickland, 1984; Reddy et al., 2006; Kaniraj and Yee, 2011; Ling et al., 2017; Harris et al., 2018; Yükses, 2022; Sutar and Rotte, 2024). During treatment, polarization, gas generation, pH fronts, Joule heating, and local desaturation change both current and water availability. Consequently, increasing voltage can raise power approximately with the square of voltage without producing a proportional increase in drainage. Interrupted, cyclic, or progressive energization may improve energy use, but reported benefits remain dependent on switching period and soil state (Rabie et al., 1994; Fourie and Jones, 2010; Iwata et al., 2013; Sun et al., 2019, 2022; Zhang and Hu, 2022; Sugiyama et al., 2023).

Electrokinetic reactions also move ions and fine particles. These processes are central to remediation and electroosmotic chemical stabilization (Probstein and Hicks, 1993; Chien et al., 2010; Ou et al., 2015; Sun et al., 2024), but they should not be inferred from drainage alone. A defensible slope study must distinguish hydraulic water removal from chemical cementation and must report pH, temperature, and electrode condition when chemical effects are claimed. The present work therefore treats the photographed cathodic outflow as hydraulic proof of concept and makes no chemical-stabilization claim.

Two methodological gaps are particularly important when physical slope testing is necessarily limited. First, many numerical studies report parametric trends without an analytical benchmark, explicit mass closure, or both; agreement between two meshes alone does not detect an incorrectly imposed coupled-flux boundary. Second, one-at-a-time studies obscure confounding among electro-osmotic permeability, intrinsic permeability, storage, bulk conductivity, and drain conductance. Global screening is therefore needed to determine which uncertain parameter most strongly controls the predicted response before additional calibration effort is assigned. Finite cathodic conductance and intermittent voltage also need to be assessed within the same verified formulation so that the drainage-energy trade-off is not confused with numerical error.

Against this background, the study addresses four questions: whether a staggered array of perforated cathodes can collect water directionally from a weakly expansive slope; whether the observed voltage-current-drainage sequence shows evidence of diminishing hydraulic return; whether a total-flux Darcy-electro-osmotic formulation satisfies analytical and conservation benchmarks; and which transport, storage, and outlet parameters control drainage under globally sampled uncertainty. The contributions are (i) a laboratory proof-of-concept geometry using perforated tubular cathodes, (ii) a boundary-consistent continuum formulation, (iii) analytical, spatial, temporal, and mass-balance verification, (iv) a 48-point Latin hypercube screening design, and (v) a comparison of continuous and smoothed intermittent operation. Because the physical observations comprise one sequential voltage sweep, the paper deliberately evaluates numerical robustness and conditional design trends rather than claiming a validated field optimum.

2. Materials and methods

2.1 Soil

The soil used to reconstruct the model condition was obtained from the G318 Heizhu (Chengdu boundary)–Duoying corridor in Yucheng District, Ya'an, western Sichuan, and is designated EO-YA-01 in this paper. The designation was assigned retrospectively because the archived model-box record did not contain a unique batch label. The untreated project soil was air-dried, gently disaggregated, and passed through a 2-mm sieve; distilled water was then mixed to a target gravimetric water content of 28.5%, and the wetted soil was sealed for 24 h before placement. This preparation protocol and initial state are the adopted reconstruction of the physical model, whereas the index properties in Table 1 are traceable to the project's untreated original-soil campaign. The distinction is retained because the archive does not provide a contemporaneous chain-of-custody record linking every characterization specimen to the soil placed in the model box.

The representative particle specific gravity was 2.69 from three pycnometer determinations. The original-soil campaign gave a liquid limit of 42%, plastic limit of 18%, plasticity index of 24%, and free-swell ratio of 45%, consistent with weak expansivity. X-ray diffraction showed a quartz-dominated framework with kaolinite and mica-type layered silicates and no pronounced montmorillonite peak. For model reconstruction, a dry density of 1.45 Mg/m³ was adopted. Together with $G_s = 2.69$ and $w = 28.5\%$, this gives a void ratio of 0.855, porosity of 0.461, and initial degree of saturation of 0.897. The baseline intrinsic permeability of $1.0 \times 10^{-15} \text{ m}^2$ corresponds to a water hydraulic conductivity of approximately $9.8 \times 10^{-9} \text{ m/s}$ at 20 °C. Bulk electrical conductivity was not measured independently on a trimmed specimen; the effective value 0.02194 S/m was inferred from the five model-scale voltage-current observations. Soil-index characterization used three replicate determinations where the archive retained parallel measurements, whereas the slope model and its voltage sweep were each performed once.

Property	Value used	Evidence basis
Source/designation	G318 Ya'an; EO-YA-01	Retrospective model-batch designation
Prepared fraction	<2 mm	Adopted model reconstruction
Initial water content	28.5%	Project-representative placement target
Dry density	1.45 Mg/m ³	Adopted compaction target
Particle specific gravity	2.69	Project test, n = 3
Void ratio / porosity	0.855 / 0.461	Derived from G_s and dry density
Initial degree of saturation	0.897	Derived from w , G_s , and e
Hydraulic conductivity	$9.8 \times 10^{-9} \text{ m/s}$	Baseline κ converted at 20 °C
Electrical conductivity	0.02194 S/m	Model-scale voltage-current fit
$w_L / w_P / IP$	42% / 18% / 24%	Project untreated original soil
Free-swell ratio	45%	Project untreated original soil

Table 1. Project-supported index properties and adopted initial-state parameters for the reconstructed model soil. Adopted and fitted quantities are distinguished from independently measured properties.

2.2 Slope model and electrode system

The physical model comprised a transparent acrylic box with nominal internal dimensions of 35 cm (width) × 40 cm (depth) × 40 cm (height), as confirmed from the supplied Rhino design file. A 10-cm retaining plate formed the front toe. The reconstructed longitudinal profile contained a 5-cm toe platform, a 25-cm horizontal slope run at 35°, and a 10-cm crest platform. The crest elevation was therefore approximately 27.5 cm above the box base, and the inclined face rose approximately 17.5 cm above the toe platform. Soil was placed in

nominal 5-cm lifts; each lift was statically tamped and lightly scarified before the next lift to approach the adopted dry density of 1.45 Mg/m³. No standing water or separately imposed phreatic surface was present before energization; the initial water condition was represented by the uniform 28.5% gravimetric water content reported in Section 2.1.

The array comprised six solid stainless-steel anodes and five perforated stainless-steel cathodes in three staggered slope-face levels. Four anodes occupied the lower level at transverse coordinates 2.5, 12.5, 22.5, and 32.5 cm. Three cathodes occupied the middle level at 7.5, 17.5, and 27.5 cm, while the upper level alternated two anodes at 2.5 and 22.5 cm with two cathodes at 12.5 and 32.5 cm. The within-level centre spacing and nominal vertical row spacing in the slope-face projection were both 10 cm. The lower and middle tubes were 30 cm long and the upper tubes were 25 cm long. All tubes had a 16-mm outside diameter; a nominal 1-mm wall thickness was used. The cathodes contained nominal 2-mm circular perforations at 10-mm staggered pitch and were wrapped in one layer of approximately 100 g/m² nonwoven permeable filter fabric. The wall thickness, perforation, and fabric values are reconstruction specifications because those consumables were not dimensioned in the archived CAD file.

Cathode inclination is defined relative to the horizontal: from the exposed slope-face outlet, the tube axis rose 20° toward the soil interior so that the inner end was higher than the outlet. The reconstructed lower, middle, and upper outlet elevations were approximately 10.3, 13.1, and 16.6 cm above the box base, respectively. Red leads connected the six unperforated anodes to the positive terminal; dark leads connected the five fabric-wrapped cathodes to the negative terminal. Electrodes of the same polarity were connected in parallel to the regulated direct-current supply, allowing each perforated cathode to act simultaneously as an electrode and a distributed drain. The laboratory setup and electrode arrangement are shown in Fig. 1.

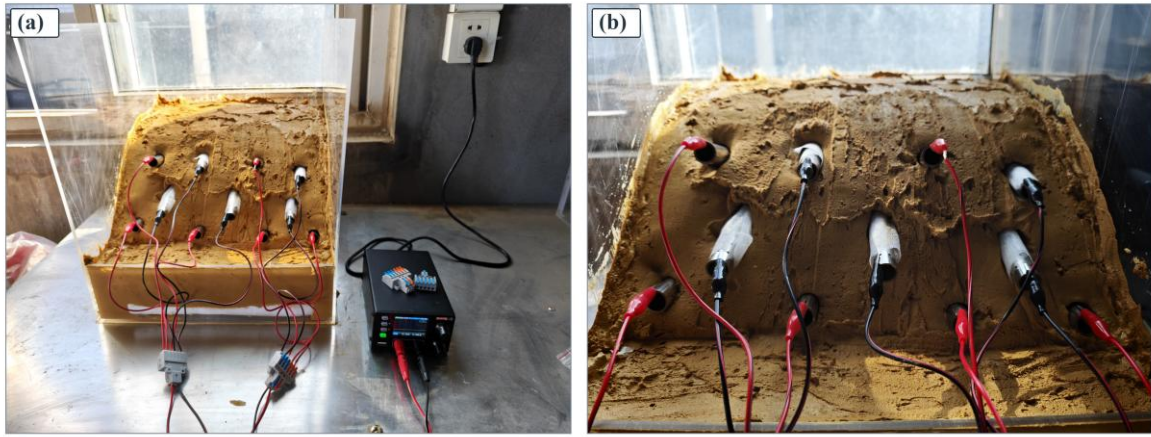


Fig. 1. Laboratory electro-osmotic slope model: (a) complete test system and regulated DC power supply; and (b) three-row electrode array and slope geometry before pronounced drainage. Red leads denote solid, unperforated anodes; dark leads denote perforated cathodes wrapped with permeable fabric.

2.3 Electrical loading and drainage observation

Applied voltages were increased stepwise to 8, 12, 20, 25, and 30 V. At each voltage, the real-time current and power indicated by the supply were photographed. The drop discharge from each monitored cathodic outlet was counted separately over one minute. The available record tabulates two individually monitored outlets, denoted Cathodes 1 and 2; total drainage is the sum of their separate counts. Apparent system resistance was calculated as V/I . The available records constitute one observation at each voltage and are treated as a preliminary response series rather than replicated inferential data. No error bars are reported.

The same slope model was energized sequentially in the increasing order 8, 12, 20, 25, and 30 V without a reset or moisture re-equilibration between steps. Current and power were read after the supply display became visually stable, followed by a 60-s outlet-drop count. The archive does not contain the exact stabilization interval, a logged ambient temperature, or a zero-voltage drainage control. The indoor test was conducted under normal room conditions, but no numerical temperature is assigned retrospectively. Mean drop volume was also not calibrated; therefore, the physical drainage observations remain in drops/min and are not converted to volumetric discharge. The recorded electrical and drainage responses are summarized in Table 2.

Voltage (V)	Current (A)	Power (W)	Resistance (Ω)	Cathode 1 (drops/min)	Cathode 2 (drops/min)	Total (drops/min)
8	0.202	1.616	39.6	2	4	6
12	0.35	4.2	34.3	3	8	11
20	0.645	12.9	31.0	11	17	28

Voltage (V)	Current (A)	Power (W)	Resistance (Ω)	Cathode 1 (drops/min)	Cathode 2 (drops/min)	Total (drops/min)
25	0.84	21.0	29.8	13	19	32
30	1.034	31.02	29.0	11	22	33

Table 2. Recorded electrical and drainage responses.

2.4 Data analysis

A least-squares linear fit was used only to summarize the voltage–current relation. Drainage response was examined descriptively because of the small sample size and absence of replicates. Drainage-to-power ratio was calculated in drops min⁻¹ W⁻¹ as an observational efficiency index; it is not a specific energy consumption and must be replaced by a volumetric, time-integrated metric in the final study.

2.5 Evidentiary scope of the experimental conditions

The existing experiment is a single sequential voltage sweep, not a replicated factorial or response-surface design. Voltage is the only recorded control factor, while initial state, elapsed treatment time, and progressive dewatering may covary with the loading sequence. The five observations are sufficient to demonstrate visible cathodic collection and to formulate hypotheses about voltage response; they are not sufficient to estimate experimental uncertainty, isolate electro-osmosis from gravity drainage, identify an optimum voltage, or validate the inclination and spacing cases. Section 6.2 therefore distinguishes the minimum confirmatory matrix from the conditions already completed.

3. Theoretical formulation

3.1 Continuum-scale coupled transport

At the scale of a representative elementary volume, hydraulic and electrical transport can be introduced as coupled linear flux–force relations. Retaining the two cross-effects gives:

$$q = -K_h \nabla H - k_{eo} \nabla V \quad (1)$$

$$J = -k_{sp} \nabla H - \sigma \nabla V \quad (2)$$

Here H is hydraulic potential, K_h is the hydraulic transport coefficient under the selected pressure- or head-based convention, k_{eo} is electro-osmotic permeability, k_{sp} represents streaming-current coupling, and σ is bulk electrical conductivity. Onsager reciprocity applies when fluxes and thermodynamic forces are written in properly conjugate normalized forms; the dimensional coefficients in Eqs. (1) and (2) should not be set

numerically equal without that normalization. Streaming current is assumed small compared with ohmic current in the present short-duration drainage model, so $k_{sp}\nabla H$ is neglected. This assumption can be checked experimentally using an open-circuit streaming-potential measurement.

3.2 Pore-scale origin of electro-osmotic flux

For low-Reynolds-number flow in the charged pore-water region, momentum balance contains the electrical body force $\rho_e E$. The local Stokes and Poisson equations are:

$$0 = -\nabla p + \mu \nabla^2 u + \rho_e E \quad (3)$$

$$\nabla^2 \psi = -\frac{\rho_e}{\varepsilon} \quad (4)$$

With a thin electrical double layer, no slip at the shear plane, $\psi = \zeta$ at the shear plane, and vanishing shear outside the double layer, integration gives the Helmholtz–Smoluchowski velocity. Pore connectivity, porosity, tortuosity, and saturation are collected in a dimensionless structure factor C_{eo} at continuum scale:

$$q_{eo} = k_{eo} E = -k_{eo} \nabla V \quad (5)$$

$$k_{eo} = C_{eo} \left(\frac{-\varepsilon \zeta}{\mu} \right) \quad (6)$$

Here V is electric potential, $E = -\nabla V$, ε is pore-fluid permittivity, ζ is zeta potential, and μ is dynamic viscosity. The units of k_{eo} are $m^2 V^{-1} s^{-1}$, so q_{eo} has units of $m s^{-1}$. Defining k_{eo} as nonnegative is convenient for the usual case $\zeta < 0$. The ideal capillary expression should not be used as a final soil parameter without calibration because ζ , surface conduction, pore geometry, ion concentration, and clay mineralogy evolve during treatment (Lockhart, 1983; Asadi et al., 2013; Harris et al., 2018; Martin et al., 2019).

3.3 Saturated electro-hydraulic mass balance

The total Darcy-scale pore-water flux is the sum of hydraulic and electro-osmotic contributions:

$$q = q_h + q_{eo} = -\frac{\kappa}{\mu} (\nabla p - \rho_w g) - k_{eo} \nabla V \quad (7)$$

$$S_p \frac{\partial p}{\partial t} + \alpha_B \frac{\partial \varepsilon_v}{\partial t} + \nabla \cdot q = Q_v \quad (8)$$

κ denotes intrinsic permeability, p pore-water pressure, ρ_w water density, g gravitational acceleration, S_p a pressure-form storage coefficient, α_B the Biot coefficient, ε_v volumetric strain, and Q_v a genuine volumetric source. For a rigid skeleton the strain term is omitted. Electro-osmosis transports existing water and is not itself water generation. If software input requires an equivalent domain term, $-\nabla \cdot q_{eo} = \nabla \cdot (k_{eo} \nabla V)$ can be moved to

the source side, but all hydraulic boundaries must still be interpreted using the total flux. Continuous and finite-capacity drainage boundaries materially change the consolidation solution (Ren and Wang, 2024).

3.4 Electric-current conservation

$$J = \sigma E = -\sigma \nabla V \quad (9)$$

$$\nabla \cdot J = 0 \quad (10)$$

The conductivity σ may depend on saturation, porosity, ion concentration, and temperature. Explicit ion transport, Joule heating, and electrode reactions may be neglected only when short duration and measured temperature/pH changes justify the assumption. Chemical-stabilization claims require Nernst–Planck transport and electrode reaction terms or direct chemical measurements (Zhang and Hu, 2022; Sugiyama et al., 2023; Sun et al., 2024).

3.5 Extension to unsaturated soil

Electro-osmotic dewatering can create an unsaturated zone. A defensible model therefore uses a measured soil-water retention curve, a saturation-dependent hydraulic coefficient $K(S_e)$, independently calibrated conductivity $\sigma(S_e)$, and an explicitly tested electro-osmotic relation $k_{eo}(S_e)$:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (11)$$

$$S_e = [1 + \alpha_{vg} |h_p|^{n_{vg}}]^{-m_{vg}} \quad (12)$$

$$\frac{\partial \theta}{\partial t} + \nabla \cdot [-K(S_e)(\nabla h_p + \nabla z) - k_{eo}(S_e) \nabla V] = Q_v \quad (13)$$

$$\nabla \cdot [\sigma(S_e) \nabla V] = 0 \quad (14)$$

θ_s and θ_r are saturated and residual volumetric water contents, h_p is pressure head, and α_{vg} , n_{vg} , and m_{vg} are water-retention parameters; the van Genuchten–Mualem closure is one established option for linking retention and hydraulic conductivity (Mualem, 1976; van Genuchten, 1980). Equation (13) assumes a rigid porous skeleton. The existing Notebook relation $k_{eo}/k_{eo,sat} = S_e^\beta$ is a sensitivity-analysis hypothesis, not a measured constitutive law. Saturation-dependent transport and effective-voltage loss have been shown to change electro-osmotic consolidation histories substantially (Zhou et al., 2019; Wang et al., 2021a, 2021b).

3.6 Mechanical coupling and slope-stability link

$$\nabla \cdot \sigma + \rho_b g = 0 \quad (15)$$

$$\sigma' = (\sigma - u_a I) + \chi(S_e)(u_a - u_w)I \quad (16)$$

σ is total stress, σ' effective stress, ρ_b bulk density, u_a pore-air pressure, u_w pore-water pressure, I the identity tensor, and χ a Bishop-type effective-stress parameter selected consistently with the soil model. Electro-osmotic drainage affects stability through changes in u_w or suction and resulting effective stress. A claim of improved factor of safety requires a coupled solid-mechanics calculation or transfer of transient pore pressure to a strength-reduction analysis; drainage alone is not sufficient evidence. The suction-to-strength mapping must be calibrated because apparent cohesion and friction response are soil- and suction-range dependent (Fredlund et al., 1978; Alonso et al., 1990; Lu and Likos, 2006; Lan et al., 2022; Niu et al., 2024). Transient seepage can also change the location and mechanism of the critical slip surface (Ng and Shi, 1998; Huang and Jia, 2009).

3.7 Boundary conditions and observable quantities

$$n \cdot (q_h + q_{eo}) = 0 \quad (17)$$

$$-n \cdot q = C_d(p - p_{out}) \quad (18)$$

$$Q_{out}(t) = - \int_{\Gamma_c} n \cdot q d\Gamma \quad (19)$$

Equation (17) is the sealed-boundary condition and must include electro-osmotic flux. Equation (18) is a Robin condition for a perforated cathode with finite drainage conductance C_d ; $p = p_{out}$ is recovered as the large-conductance limit. The measured cumulative discharge is the time integral of Eq. (19). Electrical conditions are $V = V_0$ on anodes, $V = 0$ on cathodes, and $n \cdot J = 0$ on insulating boundaries. These conditions close the problem and provide directly measurable calibration targets (Shang, 1998; Ren and Wang, 2024).

4. COMSOL Multiphysics implementation

A transient two-dimensional equivalent model was implemented in COMSOL Multiphysics 6.4. The rectangular slope-face domain was 0.35 m wide and 0.28 m high; the latter is the approximate vertical rise obtained from the measured 0.40-m model depth and 35° slope angle. Six anodes and five cathodes were represented by circular openings in the staggered arrangement inferred from the test photographs. An equivalent electrode radius of 0.008 m was assumed pending direct measurement. Embedded lengths of 0.30 and 0.25 m were used to convert the two-dimensional boundary fluxes to discharge for the lower/middle and upper rows, respectively.

The electric-potential equation and pressure-form total-flux equation were both implemented using coefficient-form PDE interfaces. Constant potentials $V = V_0$ and $V = 0$ were prescribed at the anodes and cathodes, respectively, and the external box boundaries were electrically insulating. A drained condition $p = 0$ was prescribed at the perforated cathodes. All other hydraulic boundaries, including the unperforated anodes, were closed to total hydraulic plus electro-osmotic flux. The baseline parameters were intrinsic permeability $\kappa = 1.0 \times 10^{-15} \text{ m}^2$, electro-osmotic coefficient $k_{eo} = 5.0 \times 10^{-9} \text{ m}^2/(\text{V s})$, water viscosity $\mu = 1.0 \times 10^{-3} \text{ Pa s}$, and pressure-form storage coefficient $S_p = 1.0 \times 10^{-7} \text{ Pa}^{-1}$. Only bulk electrical conductivity was fitted to the present experiment: a through-origin least-squares fit to all five voltage–current observations gave $\sigma = 0.02194 \text{ S/m}$.

1. Time integration: 0–600 s with results stored every 10 s.
2. Voltage cases: 8, 12, 20, 25, and 30 V, independently initialized.
3. Material sensitivity at 20 V: $k_{eo} = 2.5, 5.0$, and $7.5 \times 10^{-9} \text{ m}^2/(\text{V s})$, crossed with $\kappa = 0.5, 1.0$, and $2.0 \times 10^{-15} \text{ m}^2$.
4. Storage sensitivity at 20 V: $S_p = 0.5, 1.0$, and $2.0 \times 10^{-7} \text{ Pa}^{-1}$.
5. Cathodic outlet sensitivity at 20 V: total-flux drain conductance $C_d = 10^{-12}, 10^{-11}$, and $10^{-10} \text{ m}/(\text{Pa s})$, compared with the ideal $p = 0$ outlet.
6. Mesh independence: normal, fine, and extra-fine meshes with 6370, 7479, and 11932 triangular elements.
7. Electrode arrangement: horizontal and vertical row spacings of 6, 8, and 10 cm, with electrode number, radius, polarity, and domain dimensions held constant and each array recentered in the domain.
8. Outputs: current, maximum electric-field magnitude, total and individual cathodic discharge, pressure, and total water flux.

The pressure field is a provisional storage response rather than a validated suction prediction. The model assumes constant saturated-type properties and an ideal, zero-pressure cathodic outlet. A submission-level model must therefore include finite drain conductance, measured initial suction/water content, and calibration of k_{eo} and S_p against volumetric drainage and pore-pressure histories.

The numerical conditions form a diagnostic hierarchy rather than a single optimization design. The 2D model screens voltage, transport coefficients, storage, drain conductance, spacing, and mesh; only the k_{eo} – κ study is crossed factorially, while the remaining groups vary one factor at a time. The 3D model then checks the inferred tube geometry. Because spacing also changes boundary distance and the 30° case changes effective embedded length, these comparisons identify sensitivity but cannot isolate causal main effects or define an optimum.

Electrode configuration and three-dimensional drainage require controlled geometry and independent validation (Zhang et al., 2017; Sutar and Rotte, 2024).

4.1 Three-dimensional cathode-inclination cases

A geometry-matched three-dimensional slope prism was constructed to resolve the embedded tubular lengths and inclinations that cannot be represented in the two-dimensional circular-boundary model. The model box was 0.40 m deep and 0.35 m wide. Its longitudinal profile comprised a 0.05-m toe platform at the 0.10-m retaining-plate elevation, a 0.25-m horizontal slope run inclined at 35°, and a 0.10-m flat crest platform; the resulting crest elevation was approximately 0.275 m. Six solid anodes and five tubular cathodes were represented as cylinders of assumed 0.008-m radius. Lower and middle cathodes were 0.30 m long and upper cathodes were 0.25 m long. From each exposed slope-face outlet, the cathode axis was directed upward toward the soil interior at 10°, 20°, or 30° relative to the horizontal; the measured 20° arrangement was the baseline. With the inferred row coordinates and specified lengths, all 20° cathodes remained inside the 10-cm-crest geometry with the upper tube retaining approximately 2.3 cm of vertical soil cover at its inner end. At 30°, the middle and upper tubes locally intersected the flat crest; this case was therefore retained only as a geometric-limit scenario.

The 3D outputs were total cathodic drainage rate, cumulative drainage, current, electrical energy over 600 s, and pressure-derived suction. Automatic mesh sizes 6, 5, and 4 gave 32426, 90636, and 293399 tetrahedral elements in the 20° case. Relative to the baseline cumulative discharge, the coarse and fine results differed by -6.80% and +1.92%, respectively. The baseline mesh was therefore retained for the factorial cases as a documented compromise between accuracy and computational cost. Independent voltage cases of 0, 8, 12, 20, 25, and 30 V were solved from the same initialized state.

4.2 Exploratory strength-reduction scenario

Slope stability was evaluated separately with the Geomechanics Module strength-reduction formulation. A 10× prototype extrapolation of the laboratory profile was used: 4.0-m base length, a 0.5-m toe platform, a 2.5-m horizontal slope run at 35°, a 1.0-m crest platform, a 1.0-m retaining-plate elevation, and a 1.751-m slope rise. The initial total-stress parameters were $c' = 13.7$ kPa and $\phi' = 10.9^\circ$, taken from the project archive at approximately 31.1% water content. Elastic parameters $E = 20$ MPa, $\nu = 0.35$, and bulk density 2000 kg/m³ were assumed. Mean 600-s suction from each 3D case was transferred through the following apparent-cohesion expression:

$$c_{app} = c' + (u_a - u_w)\tan\phi_b \quad (20)$$

A provisional suction friction angle $\phi_b = 10^\circ$ was assumed, giving apparent cohesion values of 18.350, 17.770, and 17.308 kPa for the 10° , 20° , and 30° cases. Cohesion and $\tan \phi$ were reduced by a common continuation factor. The continuation sequence ended by local constitutive nonconvergence before the 0.20-m displacement threshold was reached; accordingly, the last converged continuation value is reported, not a formally bracketed collapse factor. This one-way transfer neglects deformation-dependent flow, wetting collapse, and measured suction–strength nonlinearity; it is intentionally reported as a scenario rather than a validated factor of safety (Fredlund et al., 1978; Huang and Jia, 2009).

4.3 Numerical verification and global parameter design

The implementation was verified independently of the slope observations. A 0.10-m one-dimensional domain was subjected to a linear 20-V electric field, a drained cathode at $x = L$, and zero total flux at $x = 0$. With constant coefficients, the pressure equation reduces to diffusion after subtracting its steady linear solution. The resulting cosine-series solution, with eigenvalues $\lambda_n = (n + 1/2)\pi/L$, was evaluated using 5000 terms and compared with three COMSOL meshes from 5 to 600 s. The incompatible $t = 0$ field was excluded from the error norm. Two-dimensional verification then crossed normal, fine, and extra-fine meshes with strict BDF maximum steps of 10, 5, 2, and 1 s at the central finite-drain case.

Mass closure was evaluated in the weak form. The domain storage rate $\int_{\Omega} (S_p \partial p / \partial t) d\Omega$ was compared with the finite-drain boundary flux integrated directly from $C_d(p_{out} - p)$, rather than by reintegrating strong-form solution gradients over every boundary. This distinction is required because the finite-element method enforces the prescribed boundary flux weakly.

Global screening used a deterministic 48-point Latin hypercube design at 20 V and 600 s. The ranges were $\kappa_{eo} = 2.5\text{--}7.5 \times 10^{-9} \text{ m}^2/(\text{V s})$, $\kappa = 0.5\text{--}2.0 \times 10^{-15} \text{ m}^2$, $S_p = 0.5\text{--}2.0 \times 10^{-7} \text{ Pa}^{-1}$, $\sigma = 0.0165\text{--}0.0275 \text{ S/m}$, and $C_d = 10^{-12}\text{--}10^{-10} \text{ m}/(\text{Pa s})$. κ , S_p , and C_d were sampled logarithmically. The ranges are epistemic screening bounds, not fitted probability distributions. Parameter influence was reported using Spearman rank correlation and standardized main-effect regression with six-fold cross-validation; the sample size was not used to claim higher-order Sobol indices.

4.4 Smoothed intermittent-voltage cases

Operational cases compared nominal voltages of 20 and 25 V at duty cycles of 1.00, 0.75, 0.50, and 0.25. The period was 300 s and total treatment time was 3600 s. To avoid the nonphysical solver singularity caused by an

instantaneous square-wave boundary, each transition was represented by a periodic hyperbolic-tangent waveform with a 15–20-s transition interval. Results were stored every 15 s. Energy was integrated from the actual voltage and current histories; the isolated $t = 0$ current initialization value was replaced by the median post-initial I/V conductance. The comparison therefore concerns a smoothed power-control strategy, not an ideal switch.

5. Results

5.1 Electrical response

Current increased from 0.202 A at 8 V to 1.034 A at 30 V. A linear descriptive fit gave $I = 0.0378V - 0.1033$ with $R^2 = 0.9998$. Apparent resistance decreased from 39.6 to 29.0 Ω over the voltage sequence. This change may reflect improved electrode contact, redistribution of pore water and ions, temperature, or the sequential nature of the loading. It should not yet be interpreted as an intrinsic nonlinear conductivity without repeated time-resolved measurements (Burnotte et al., 2004; Zhang and Hu, 2022; Sugiyama et al., 2023). The measured voltage–current relationship is shown in Fig. 3.

5.2 Cathodic drainage

Visible water discharge occurred at the perforated cathodes. The total count increased from 6 drops/min at 8 V to 28 drops/min at 20 V, but increased by only 5 drops/min between 20 and 30 V. The response at Cathode 2 increased monotonically from 4 to 22 drops/min. Cathode 1 reached 13 drops/min at 25 V and then decreased to 11 drops/min at 30 V. The unequal outlet responses indicate spatial heterogeneity in electric-field paths, local water supply, permeability, electrode contact, or outlet resistance. This heterogeneity is a useful target for the spatial COMSOL model. Visual evidence of cathodic drainage is presented in Fig. 2, and the individual and total outlet counts are plotted in Fig. 3.

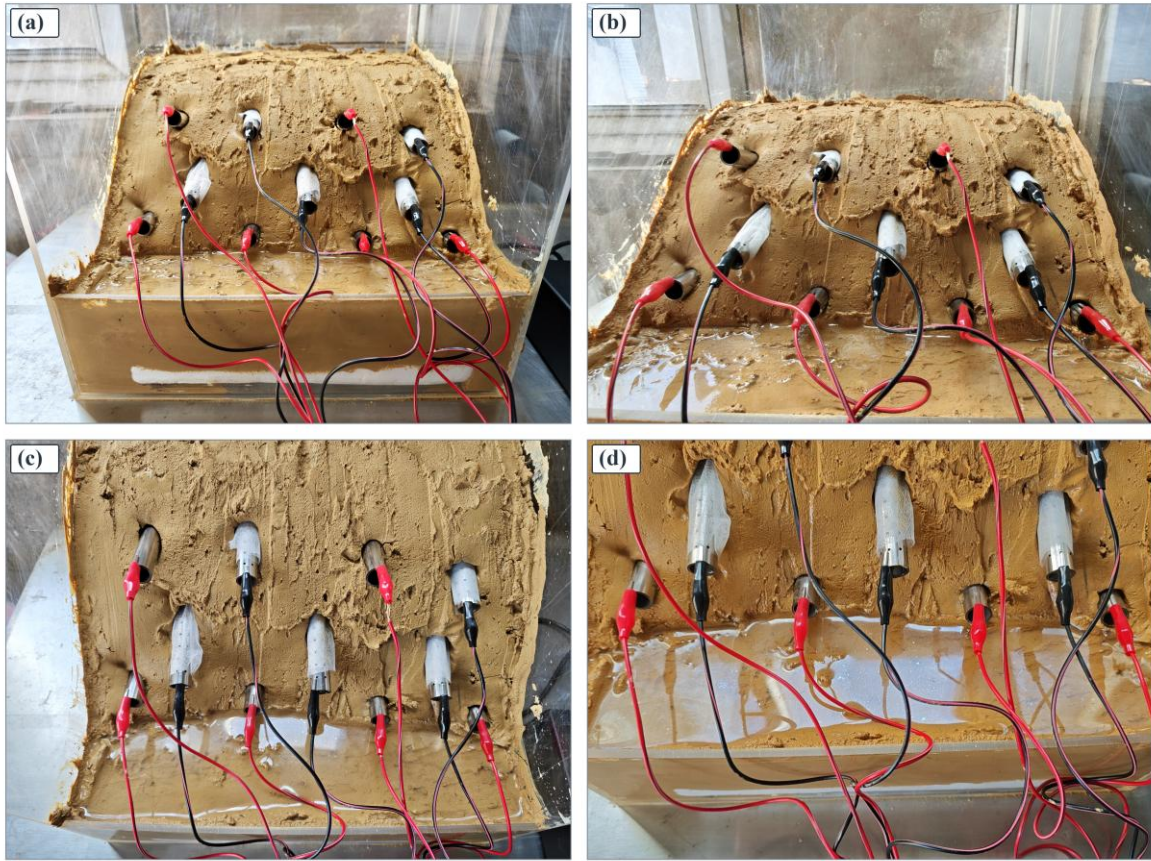


Fig. 2. Visual drainage observations during electro-osmotic treatment: (a,b) cathodic outlets and localized water discharge; and (c,d) water accumulated on the toe platform beneath the treated slope. The photographs document collection and ponding during treatment but do not, without a 0-V control and water mass balance, establish that all ponded water originated solely from electro-osmosis.

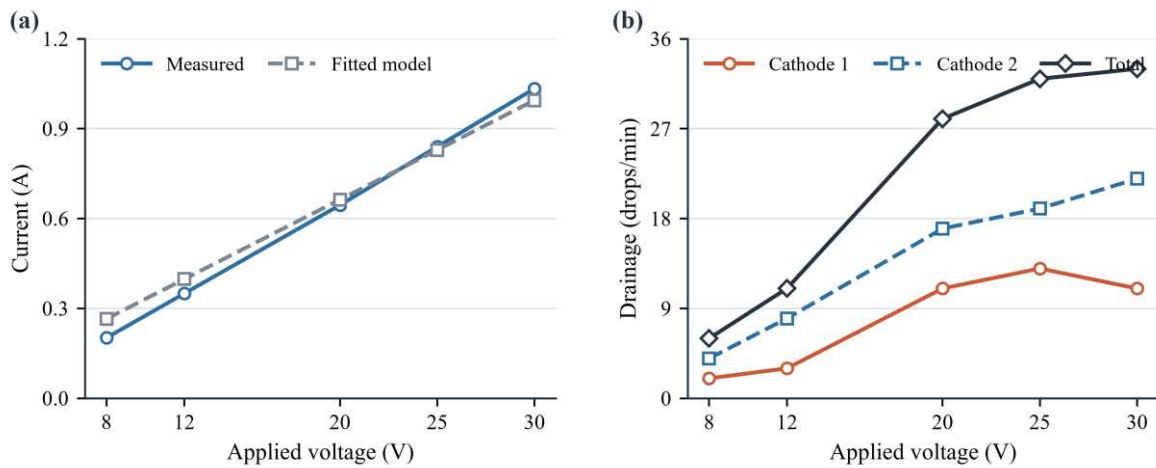


Fig. 3. Recorded voltage-current and cathodic drainage responses. Cathode 1 and Cathode 2 are individual outlet counts and Total is their sum. Points are single observations; error bars are unavailable.

5.3 Electrical demand and model–experiment comparison

Power increased by a factor of 19.2 between 8 and 30 V, whereas the drainage count increased by a factor of 5.5. The simple drainage-to-power ratio consequently fell from 3.71 to 1.06 drops $\text{min}^{-1} \text{W}^{-1}$. Because drop volume and treatment history were not measured, this ratio cannot be reported as engineering energy consumption. It nevertheless supports a testable hypothesis: voltages above approximately 20–25 V may yield limited additional drainage under the present geometry, while increasing electrical demand and the likelihood of electrochemical or thermal side effects. Normalizing each drainage series by its own maximum further shows that the experiment approached a plateau above 20–25 V, whereas the provisional constant-property model remained nearly linear. The shape mismatch provides a direct target for hydraulic calibration and moisture-dependent constitutive laws. Comparable studies likewise show that energy assessment must use cumulative water removal and time-resolved power rather than nominal voltage alone (Fourie and Jones, 2010; Sun et al., 2019). Figure 4 compares the apparent system resistance and the normalized experimental and numerical drainage responses.

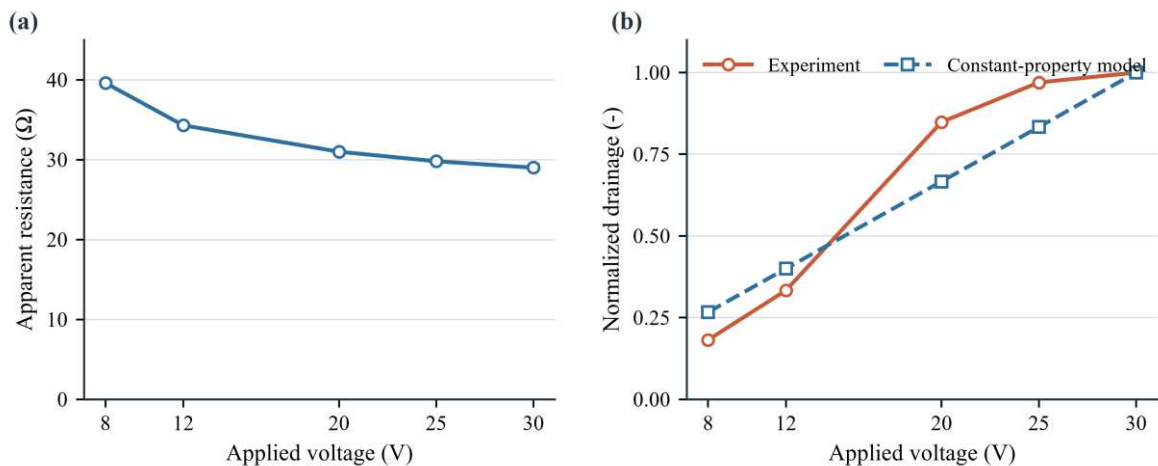


Fig. 4. Electrical and drainage comparison: (a) measured apparent system resistance; and (b) normalized experimental total drainage and predicted 600-s cumulative drainage. Each drainage series is normalized by its own maximum because the historical drop counts are not volumetric.

5.4 Numerical electrical and hydraulic fields

The fitted constant-conductivity model reproduced the overall voltage–current scale. Predicted currents at 8, 12, 20, 25, and 30 V were 0.265, 0.398, 0.663, 0.829, and 0.995 A, respectively, compared with measured values of 0.202, 0.350, 0.645, 0.840, and 1.034 A. The resulting RMSE and MAE were 0.041 and 0.036 A. At 30 V, the maximum electric-field magnitude was approximately $1.19 \times 10^3 \text{ V/m}$. Field concentration occurred around the electrode boundaries, and the computed total water flux converged toward the drained cathodes. The strong

negative pressure predicted near sealed anodes at 600 s should not be interpreted quantitatively until storage and unsaturated retention parameters are measured. The computed electric-potential and pore-pressure fields are shown in Fig. 5.

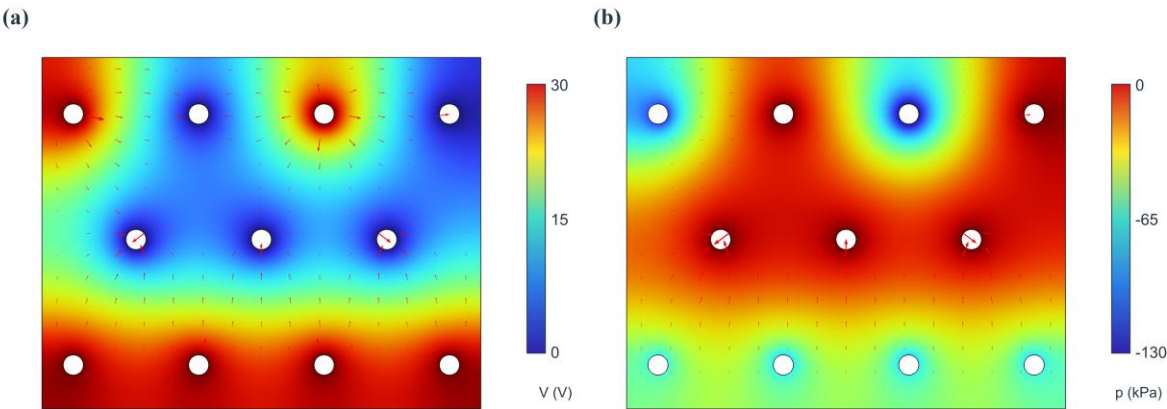


Fig. 5. Computed fields at 30 V and 600 s: (a) electric potential with electric-field vectors; and (b) provisional pore-pressure field with total water-flux vectors. The ideal drained-cathode condition is $p = 0$.

5.5 Voltage cases and material sensitivity

At the provisional baseline parameters, the predicted total cathodic drainage rate at 60 s increased from 3.73 mL/min at 8 V to 14.00 mL/min at 30 V. The corresponding cumulative drainage over 600 s increased from 28.64 to 107.39 mL. Because k_{eo} , κ , and S_p were not fitted to volumetric drainage, these values are used only for comparison among numerical cases. In particular, the nearly proportional numerical voltage response does not reproduce the measured high-voltage plateau. This discrepancy indicates that constant properties and an ideal outlet omit controlling processes such as moisture-dependent k_{eo} and σ , finite drain resistance, electrode polarization, and progressive local depletion. The time-dependent drainage rates and cumulative drainage for the voltage cases are shown in Fig. 6.

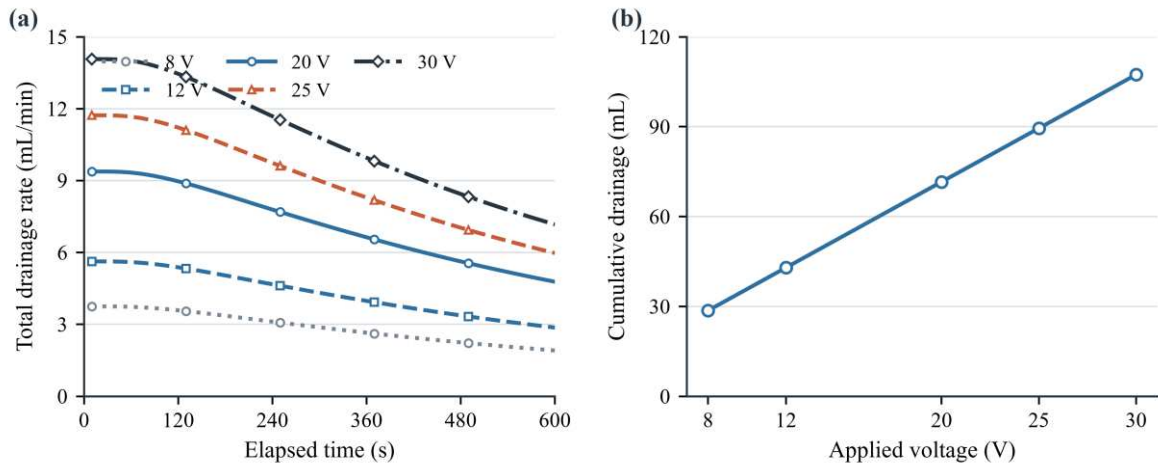


Fig. 6. Provisional numerical voltage cases: (a) time-dependent total cathodic drainage rate; and (b) cumulative cathodic drainage over 600 s.

At 20 V, increasing k_{eo} from 2.5×10^{-9} to $7.5 \times 10^{-9} \text{ m}^2/(\text{V s})$ increased predicted cumulative drainage by an almost exact factor of three at each permeability because the present equations are linear in k_{eo} . For $k_{eo} = 5.0 \times 10^{-9} \text{ m}^2/(\text{V s})$, increasing κ from 0.5×10^{-15} to $2.0 \times 10^{-15} \text{ m}^2$ reduced cumulative cathodic drainage from 84.89 to 52.05 mL. Higher hydraulic permeability allowed a larger compensating Darcy flux and more rapid pressure redistribution under the sealed-domain assumptions. This result is model-specific and must not be generalized before the hydraulic boundary and initial state are validated. Figure 7 summarizes the sensitivity of cumulative drainage to the electro-osmotic coefficient and intrinsic permeability.

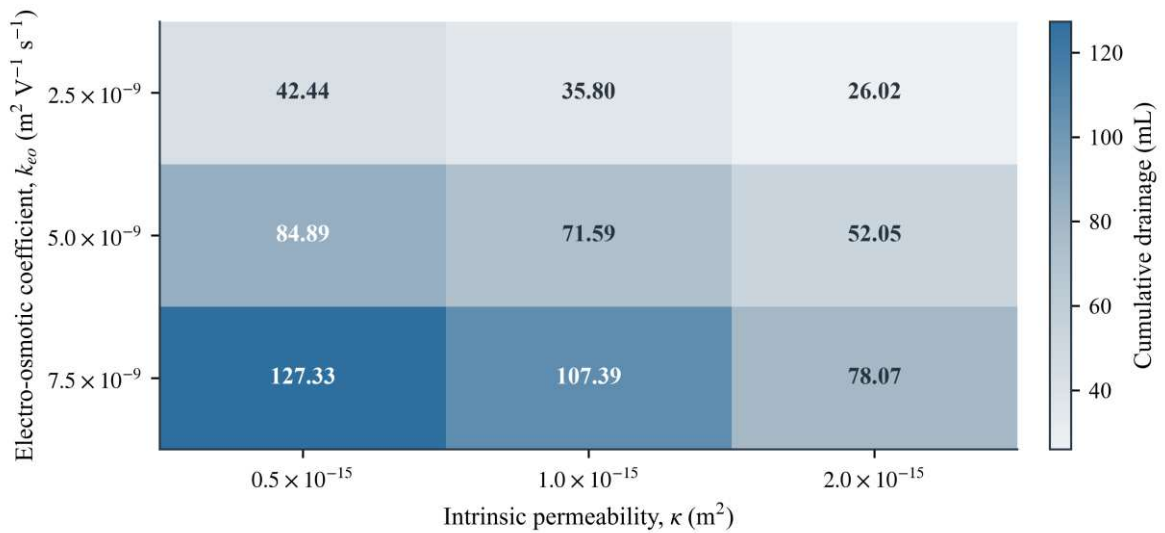


Fig. 7. Sensitivity of predicted 0–600 s cumulative cathodic drainage at 20 V to the electro-osmotic coefficient and intrinsic permeability.

5.6 Mesh, storage, and electrode-spacing cases

The predicted cumulative discharge was insensitive to further mesh refinement. Relative to the 7479-element fine mesh, the normal and extra-fine meshes changed 600-s cumulative drainage by -0.10% and -0.14% , respectively. The fine mesh was therefore retained for the parametric studies. The mesh-independence results are summarized in Table 3.

Mesh	Elements	Minimum quality	Drainage (mL)	Difference (%)
Normal	6370	0.529	71.5196	-0.1
Fine	7479	0.5717	71.5937	0.0
Extra fine	11932	0.5551	71.495	-0.14

Table 3. Mesh-independence results at 20 V and the baseline material parameters.

Storage sensitivity was much larger than the numerical discretization error. Increasing S_p delayed pressure development and maintained a larger late-time outlet flux; cumulative drainage increased from 52.05 to 84.89 mL over the tested range. S_p must consequently be fitted to measured transient drainage or suction rather than selected only from a literature range. The storage-coefficient sensitivity results are summarized in Table 4.

S_p (Pa ⁻¹)	Q at 60 s (mL/min)	Q at 600 s (mL/min)	Drainage (mL)
0.5×10^{-7}	8.9713	2.2393	52.0475
1.0×10^{-7}	9.3354	4.7817	71.5937
2.0×10^{-7}	9.3774	7.199	84.8858

Table 4. Sensitivity to the pressure-form storage coefficient at 20 V.

With the electrode number and domain size fixed, 600-s cumulative drainage increased from 65.70 to 71.60 mL as horizontal spacing increased from 6 to 10 cm. By contrast, decreasing vertical row spacing from 10 to 6 cm increased cumulative drainage from 71.60 to 80.01 mL. The horizontal cases simultaneously changed lateral coverage and distance to the sealed side boundaries, while the vertical cases changed inter-row electric paths. These results demonstrate geometry sensitivity but do not yet establish an optimum arrangement. The effects of horizontal electrode spacing and vertical row spacing are shown in Fig. 8.

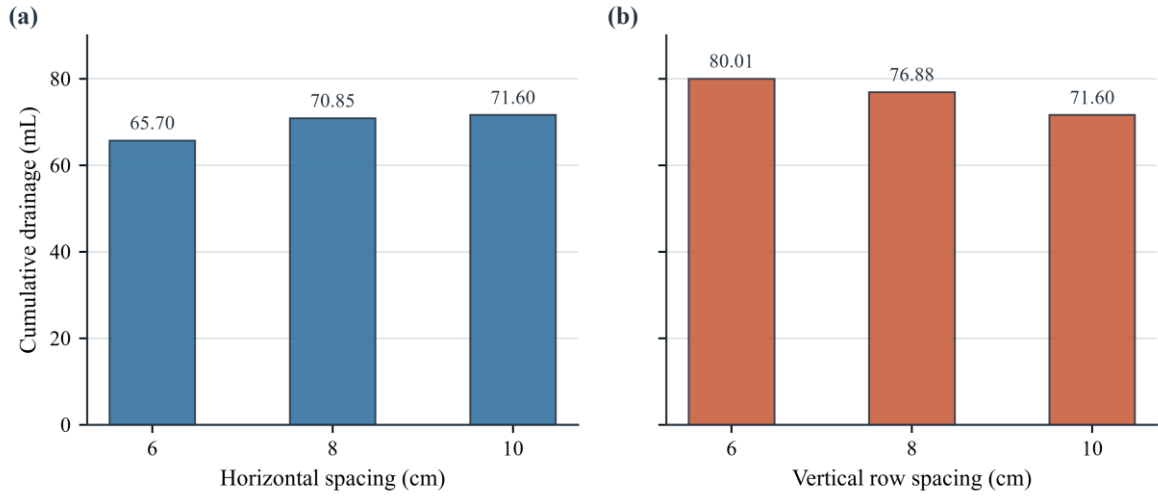


Fig. 8. Effect of electrode arrangement on predicted 600-s cumulative cathodic drainage at 20 V: (a) horizontal electrode spacing; and (b) vertical row spacing.

5.7 Finite cathodic drain conductance

Replacing the ideal $p = 0$ cathodic outlet with the total-flux condition in Eq. (18) substantially reduced predicted discharge. At $C_d = 10^{-12}$, 10^{-11} , and 10^{-10} m/(Pa s), cumulative drainage over 600 s was 1.64, 13.75, and 51.52 mL, respectively, compared with 71.59 mL for the ideal outlet. At lower conductance the outlet flux increased gradually as pressure developed near the cathode, whereas the ideal outlet produced an initially large flux followed by depletion-driven decay. The result confirms that tube perforations, filter fabric, pipe resistance, and outlet elevation cannot be omitted from quantitative calibration (Shang, 1998; Ren and Wang, 2024). Figure 9 compares the drainage-rate histories and cumulative drainage for the different cathodic drain conductances.

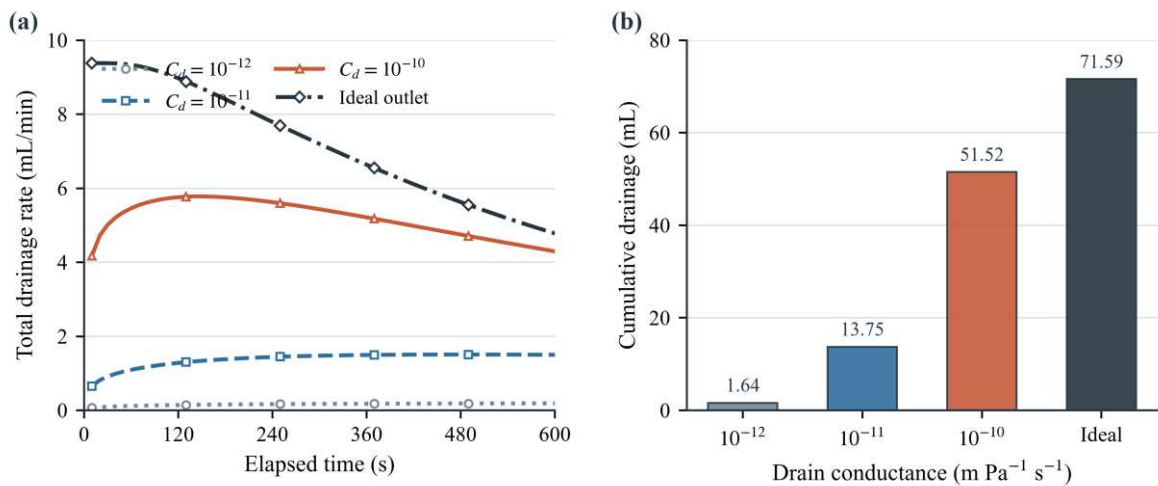


Fig. 9. Effect of cathodic drain conductance at 20 V: (a) time-dependent total cathodic drainage rate; and (b) cumulative drainage over 600 s. C_d is expressed in m/(Pa s).

5.8 Three-dimensional cathode inclination

The 3D model resolved the nonuniform electric and suction fields around the inclined tubular electrodes. At the measured and fully embedded 20° inclination used for field visualization, the 600-s mean and maximum computed suctions were 23.08 and 89.54 kPa, respectively. These values describe the present pressure-form parameter set and should not be compared directly with field suction until the initial state, retention relation, and tensiometer response are measured. The three-dimensional electric-potential and suction fields for the 20° case are shown in Fig. 10.

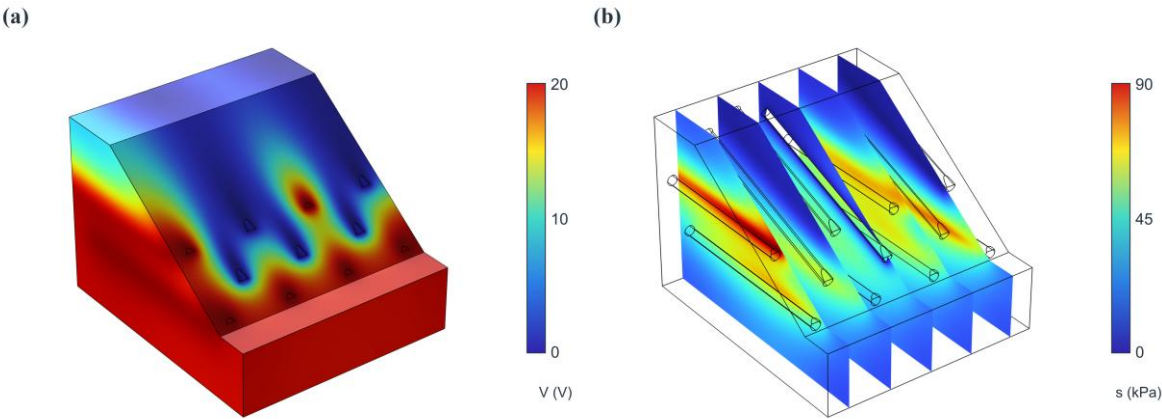


Fig. 10. Geometry-matched three-dimensional model with a 5-cm toe platform, 10-cm crest platform, and fully embedded 20° upward cathode inclination from the slope-face outlet toward the soil interior at 600 s: (a) electric-potential field; and (b) suction slices through the inclined tubular electrodes. The pressure field is provisional pending suction calibration.

The 10°, 20°, and 30° cases produced 600-s cumulative drainage values of 69.88, 60.74, and 53.06 mL, respectively. Their corresponding currents were 0.867, 0.688, and 0.545 A, while provisional drainage-energy ratios were 24.2, 26.5, and 29.2 mL/Wh. The 10° volume exceeded the fully embedded 20° volume by 15.0%, which was larger than the +1.92% baseline-to-fine mesh difference. Thus, the present constant-property model predicts greater absolute drainage at 10° than at 20° under the specified coordinates and lengths. The 30° case cannot be ranked independently because local crest intersection reduces its effective embedded length. The inclination comparisons are shown in Fig. 11 and summarized in Table 5. The mesh check for the 20° case is reported in Table 6.

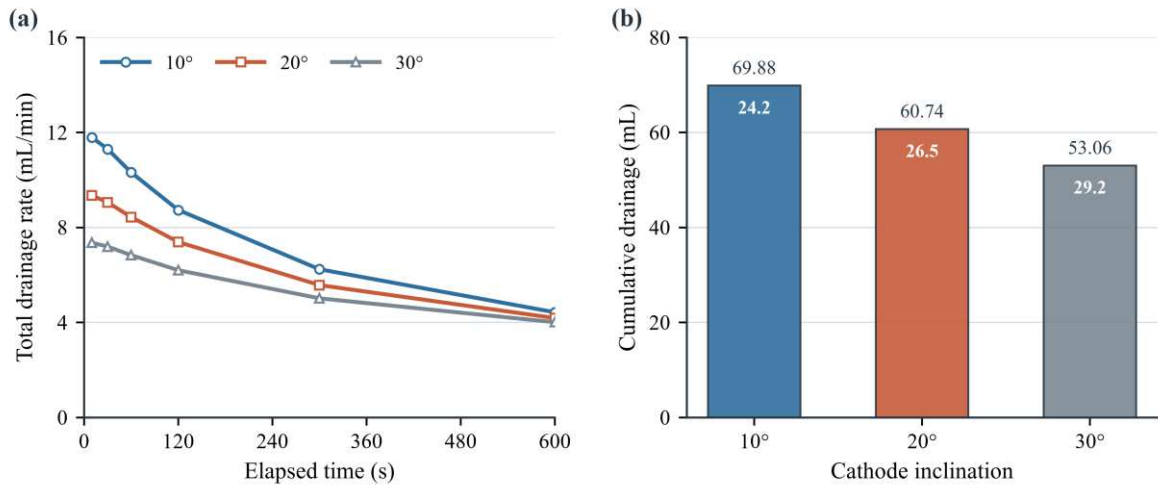


Fig. 11. Three-dimensional upward cathode-inclination cases at 20 V: (a) time-dependent total cathodic drainage rate; and (b) cumulative drainage over 600 s. Text within each bar gives provisional drainage per electrical energy input. Only the 30° case is constrained by local crest intersection.

Angle	Q60	Q600	Volume	Current	Energy	mL/Wh
10°	10.316	4.428	69.876	0.867	2.889	24.183
20°	8.437	4.184	60.741	0.688	2.295	26.469
30°*	6.833	4.009	53.06	0.545	1.816	29.215

Table 5. Three-dimensional inclination results at 20 V. Q is in mL/min, volume in mL, current in A, and 600-s energy in Wh.

*The 30° middle and upper cathodes locally intersect the flat crest.

Mesh	Elements	Min. quality	Q600	Volume	Difference
Coarse	32426	0.1957	3.8917	56.6134	-6.80%
Baseline	90636	0.2219	4.1841	60.7409	0
Fine	293399	0.2005	4.2701	61.9066	+1.92%

Table 6. Three-dimensional mesh check for the 20° case. Difference is relative to the baseline cumulative volume; Q600 is in mL/min.

5.9 Geometry-matched three-dimensional voltage cases

At the measured 20° cathode inclination, independent 0, 8, 12, 20, 25, and 30 V simulations gave 600-s cumulative drainage values of 0, 24.30, 36.44, 60.74, 75.84, and 91.01 mL, respectively. Current and the computed pressure-derived suction were also directly proportional to voltage. This exact proportionality is a consequence of the constant σ , κ , κ , S_p , and ideal drained-cathode boundary, rather than an experimentally validated high-voltage response. In particular, the model cannot reproduce the measured 25–30 V drainage plateau. The 0-V numerical value is zero because the initialized pressure field and closed hydraulic boundaries

produce no gravity-drainage baseline; it is therefore not a substitute for a 0-V physical control. The discrepancy is positive diagnostic evidence that moisture-dependent transport, finite cathodic conductance, electrical polarization, or time-dependent conductivity must be calibrated in the next model. The three-dimensional voltage-case results are shown in Fig. 12.

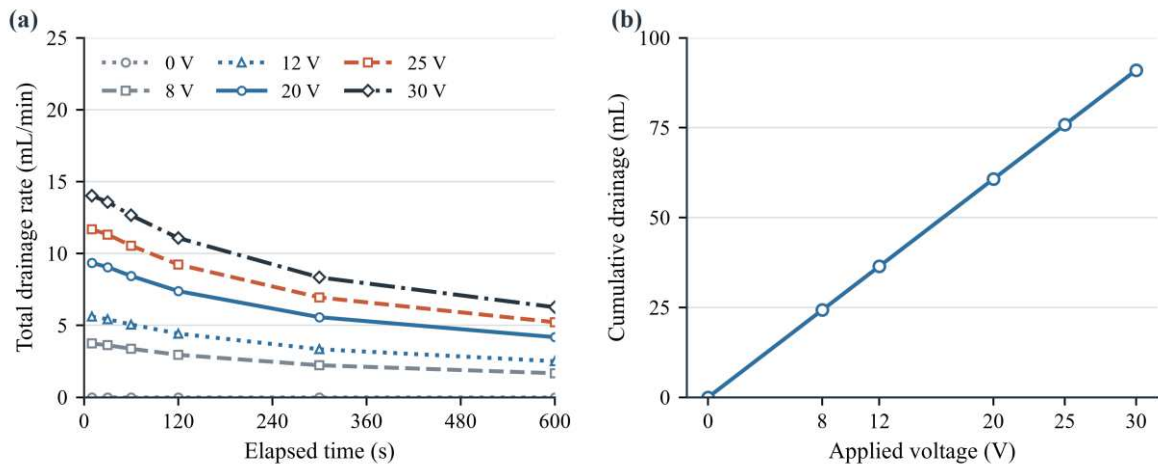


Fig. 12. Geometry-matched three-dimensional voltage cases at a 20° upward cathode inclination: (a) time-dependent total cathodic drainage rate; and (b) cumulative drainage over 600 s. The exact linear voltage scaling reflects the constant-property formulation.

5.10 Exploratory strength-reduction stability scenario

For the untreated initial-strength case, maximum element sizes of 0.20, 0.10, and 0.05 m gave last-converged continuation factors of 3.568, 3.510, and 3.466, respectively. The baseline-to-fine difference was 1.25%. At $h_{\max} = 0.10$ m, one-way transfer of the 10°, 20°, and 30° mean simulated suctions gave last-converged factors of 4.238, 4.134, and 4.163, corresponding to provisional increases of 20.7%, 17.8%, and 18.6% relative to the baseline untreated case. Local constitutive iteration failed before the displacement stop criterion was met, so these values bound the last numerically converged states and are not formally bracketed collapse factors. Figure 13 presents the mesh-convergence results and the last-converged continuation factors for the exploratory scenarios.

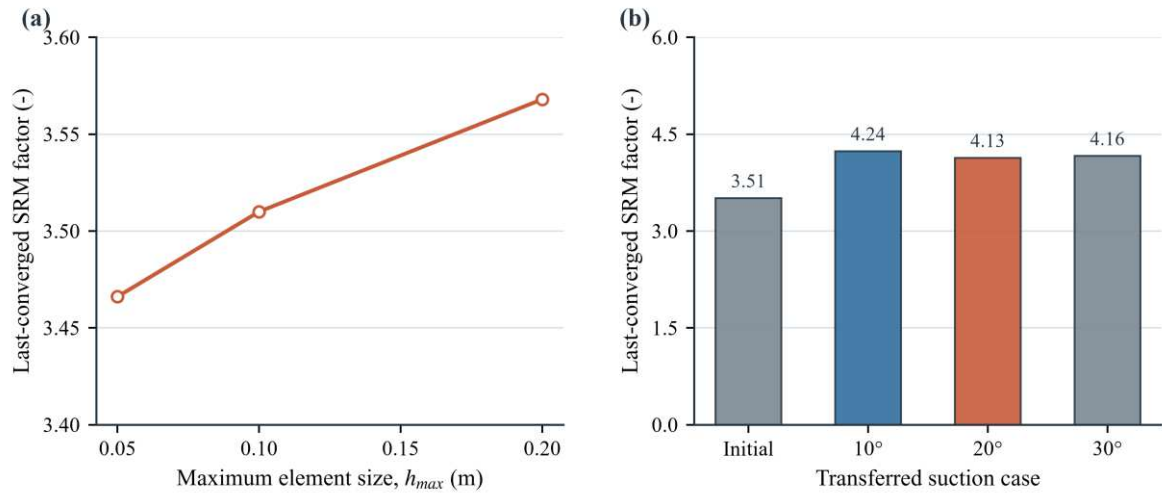


Fig. 13. Strength-reduction analysis of a 10× prototype slope: (a) mesh convergence of the initial-state last-converged factor; and (b) last-converged factors after transferring mean simulated suction through an apparent-cohesion scenario. Local constitutive nonconvergence terminated the continuation sequence; the values are not experimentally calibrated safety factors.

5.11 Numerical verification and global sensitivity

The one-dimensional numerical histories were visually indistinguishable from the analytical series. On the fine mesh, relative L2 errors were 0.118% for cathodic flux and 0.103% for sealed-end pressure over 5–600 s. In the two-dimensional finite-drain case, fine-to-extra-fine refinement changed cumulative drainage by -0.043% , and decreasing the strict BDF step from 2 to 1 s changed it by $+0.013\%$. Across all 48 Latin hypercube cases, the largest weak-form normalized mass imbalance after 10 s was 0.003%. These checks are substantially smaller than the parameter-induced spread and support use of the model for comparative screening. The analytical and numerical histories are compared in Fig. 14, and the numerical verification and conservation checks are summarized in Table 7.

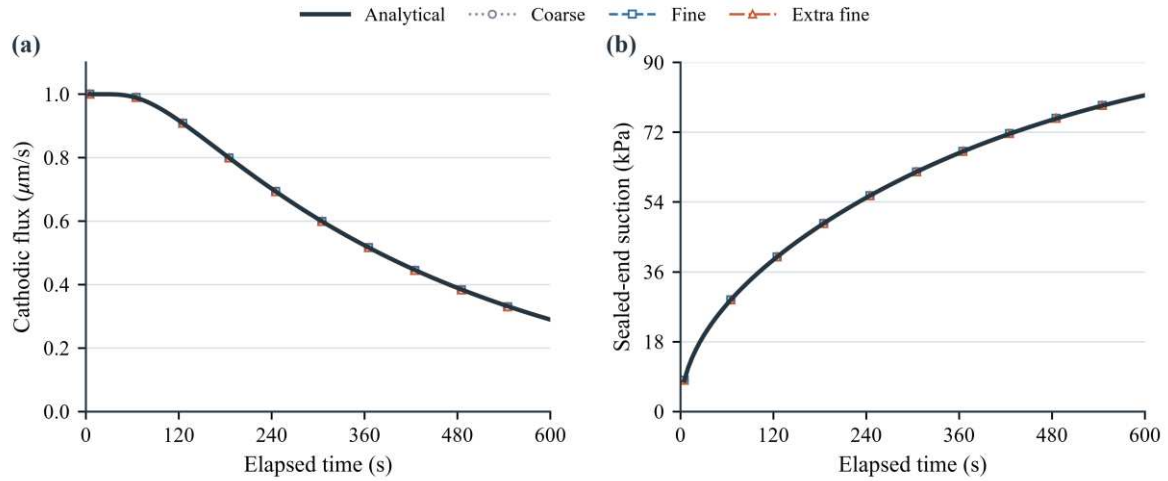


Fig. 14. One-dimensional verification of the total-flux implementation: (a) cathodic flux; and (b) suction at the sealed end. The analytical result is the cosine-series solution after subtraction of the steady linear pressure field.

Verification item	Comparison	Difference/error
1D analytical flux	Fine mesh vs series, 5–600 s	0.118% relative L2
1D analytical pressure	Fine mesh vs series, 5–600 s	0.103% relative L2
2D spatial discretization	Fine vs extra fine	−0.043% cumulative drainage
2D temporal discretization	2 s vs 1 s strict BDF	+0.013% cumulative drainage
Weak-form mass closure	48 global cases, $t \geq 10$ s	$\leq 0.003\%$ imbalance

Table 7. Numerical verification and conservation checks for the expanded two-dimensional study.

The 48 global cases gave 600-s cumulative-drainage 5th, median, and 95th percentiles of 1.92, 13.08, and 58.08 mL. Drain conductance was dominant ($\rho = 0.902$; $\beta = 0.823$), followed by a positive keo effect and a negative permeability effect in the standardized main-effect model. The conductivity coefficient was near zero after simultaneous adjustment because σ controls electrical current in the constant-property formulation but does not enter the hydraulic flux magnitude directly at prescribed voltage. Sp changed the transient shape and showed a non-monotonic or interaction-sensitive main effect. The regression R^2 was 0.834 and six-fold cross-validated R^2 was 0.757; the difference confirms that rank and regression coefficients are screening measures, not a complete variance decomposition. The global sensitivity coefficients are shown in Fig. 15 and listed in Table 8.

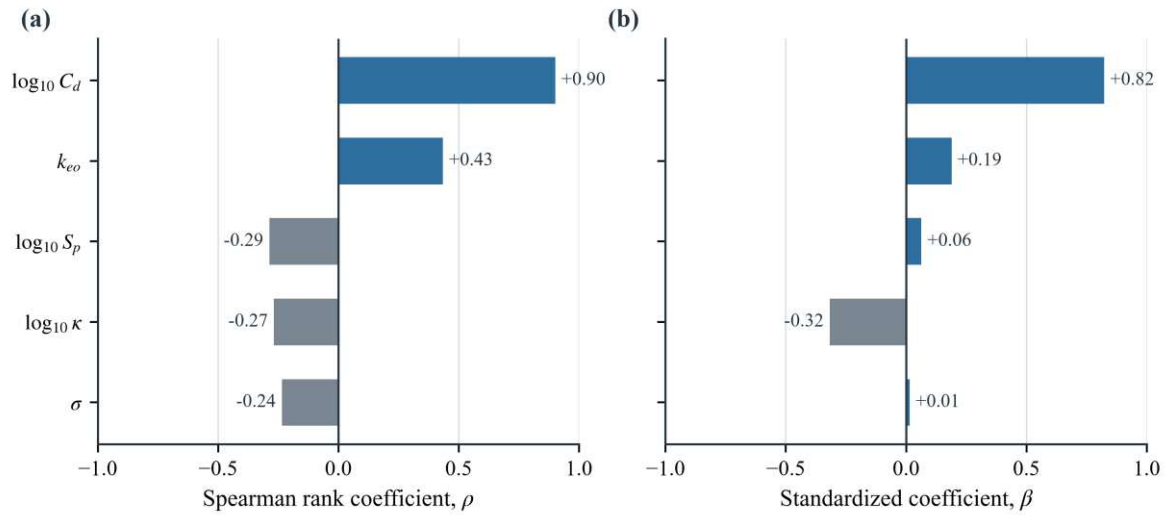


Fig. 15. Global sensitivity of 600-s cumulative cathodic drainage from the 48-point Latin hypercube design: (a) Spearman rank coefficients describing monotonic influence; and (b) standardized simultaneous main-effect regression coefficients. Blue and grey bars denote positive and negative effects, respectively.

Parameter	Spearman ρ	Standardized β
keo	+0.435	+0.189
log10(kappa)	-0.268	-0.318
log10(Sp)	-0.287	+0.063
sigma	-0.235	+0.015
log10(Cd)	+0.902	+0.823

Table 8. Global sensitivity statistics for 600-s cumulative cathodic drainage.

5.12 Smoothed intermittent-operation cases

At 20 V, reducing nominal duty cycle from 1.00 to 0.25 reduced 3600-s cumulative drainage from 71.71 to 16.52 mL but increased modelled drainage efficiency from 5.41 to 7.99 mL/Wh. At 25 V the corresponding values changed from 89.64 to 20.65 mL and from 4.32 to 6.39 mL/Wh. Thus, lower duty cycles traded treatment rate and final mean suction for energy efficiency. The 20-V cases were more efficient than the 25-V cases at every duty cycle because the present linear electrical model makes power scale approximately with voltage squared while hydraulic response scales approximately with voltage. This numerical mechanism cannot reproduce the observed high-voltage plateau or electrode polarization and is not an operating recommendation. The intermittent-operation results are compared in Fig. 16 and summarized in Table 9.

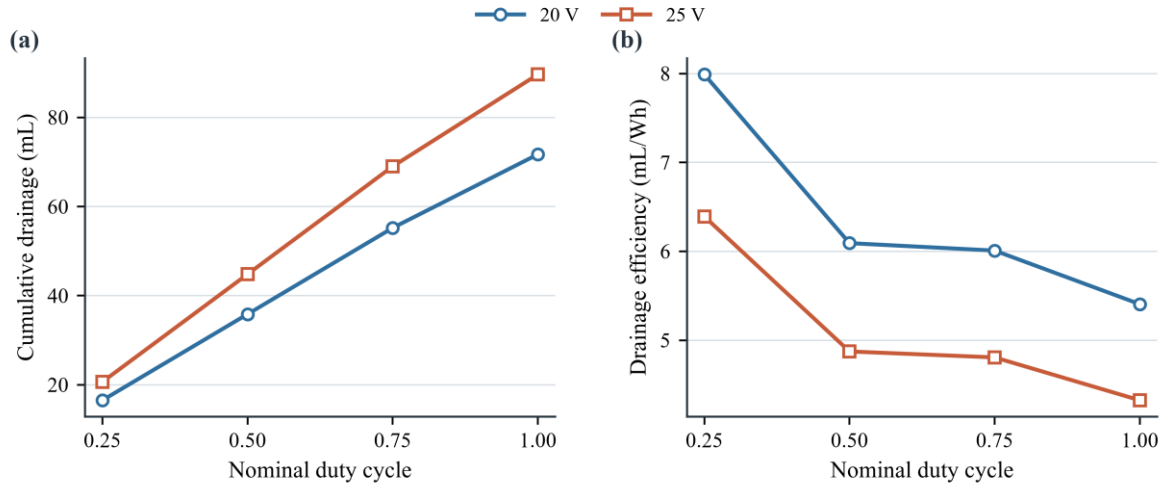


Fig. 16. Smoothed intermittent-voltage cases over 3600 s: (a) cumulative drainage; and (b) drainage per unit modelled electrical energy. Each cycle was 300 s and voltage transitions were smoothed over approximately 15–20 s.

Voltage (V)	Duty	Drainage (mL)	Energy (Wh)	mL/Wh	Mean suction (kPa)
20	1.00	71.71	13.266	5.41	26.66
20	0.75	55.21	9.188	6.01	20.52
20	0.50	35.85	5.885	6.09	13.33
20	0.25	16.52	2.068	7.99	6.14
25	1.00	89.64	20.728	4.32	33.32
25	0.75	69.01	14.356	4.81	25.65
25	0.50	44.81	9.195	4.87	16.66
25	0.25	20.65	3.231	6.39	7.68

Table 9. Comparative drainage, energy, and final mean suction for the smoothed operational cases.

6. Discussion

6.1 Interpretation and design implications

The experiment documents directional water collection through embedded perforated cathodes in a slope geometry. The response is consistent with classical electro-osmotic transport, but the test does not establish that all collected water was electrically mobilized because a gravity-drainage control is absent. Drainage also did not scale linearly with power. Cathodic water availability, growing unsaturation, local resistance, electrode contact, and outlet capacity can constrain discharge even when current continues to increase (Reddy et al., 2006; Kaniraj and Yee, 2011; Martin et al., 2019; Sugiyama et al., 2023).

The plateau is particularly relevant to expansive soil. Removing water can increase effective stress and shear strength, but excessive or spatially nonuniform drying can produce shrinkage cracks that become preferential infiltration paths during later rainfall. A practical system should therefore be controlled by cumulative drainage, water content or suction—not voltage alone. Intermittent operation or staged voltage may reduce energy use and allow moisture redistribution. Polarity reversal can improve spatial uniformity, but its effect on electrode reactions and ion migration must be monitored. Wetting–drying studies show that crack development and strength evolution depend on soil fabric and cycle history (Morris et al., 1992; Albrecht and Benson, 2001; Tang et al., 2011; Chaduvula et al., 2017; Tu et al., 2022), while cyclic electro-osmosis can alter both drainage and energy demand (Sun et al., 2022).

The total-flux formulation clarifies an implementation error that can otherwise undermine numerical results. When k_{eo} and σ are spatially constant and electric potential satisfies a Laplace-type equation, the divergence of electro-osmotic flux inside the domain may be close to zero. A model that adds only $\nabla \cdot (k_{eo} \nabla V)$ as a volumetric source can therefore predict little effect, even though water should cross a drained cathode boundary. Including q_{eo} in both domain mass conservation and boundary flux correctly represents water redistribution and discharge. The strong conductance sensitivity found here is consistent with studies using vertical or continuous drainage boundaries (Shang, 1998; Jiang et al., 2023; Ren and Wang, 2024).

The global design changes the interpretation of the earlier one-factor cases. The strong Cd ranking shows that an ideal $p = 0$ cathode can dominate the predicted benefit and should not be treated as a neutral modelling choice. The negative adjusted κ effect is also conditional on sealed external boundaries: increased hydraulic redistribution can offset cathodic discharge in this finite domain. These findings support robust parameter rankings and uncertainty bands rather than a single optimum. The intermittent cases similarly define a Pareto-type trade-off between drainage, suction, and energy, but electrochemical and thermal feedbacks remain absent.

6.2 Are the tested conditions sufficient?

The conditions are sufficient for a proof-of-concept report but not for optimization or quantitative validation. Experimentally, the five voltage levels were not replicated, drainage was counted rather than measured volumetrically, the sequential loading may confound voltage with progressive dewatering, and no 0-V control, pressure/suction history, temperature record, or pH record is available. The analytical benchmark, convergence checks, weak-form mass closure, global design, and cross-validation now establish numerical consistency and model-internal robustness. They do not establish that the selected k_{eo} , κ , Sp , Cd , or suction–strength transfer

represents the tested soil. The spacing studies still confound spacing with boundary distance, and the 30° study still confounds angle with effective embedded length. Consequently, the expanded matrix supports parameter screening and operational trade-off analysis, but not a field optimum or validated stability gain.

Where further physical model tests are impractical, the defensible paper position is a verified numerical method and parametric study with qualitative experimental support. Validation can be strengthened without repeating the full slope programme by comparing against analytical solutions, published benchmarks, conservation, mesh/time convergence, and any independent historical time series that can be recovered. These checks reduce numerical error but cannot remove parameter uncertainty. The 2D model is therefore retained as the primary screening tool, the 3D model as a geometry check, and strength reduction as an exploratory scenario.

6.3 Validation strategy under constrained physical testing

The completed verification hierarchy is sufficient for a numerical-method manuscript, provided all dimensional drainage and suction predictions remain explicitly conditional on the assumed parameter bounds. The archived slope test contributes the device geometry, directional drainage observation, and current scale. It is not used to fit hydraulic parameters. If any limited confirmatory testing becomes possible, priority should be given to a small number of instrumented runs rather than repeating every voltage.

A minimum future set would include a 0-V gravity control and one or two energized conditions with volumetric $Q(t)$, current, suction or pore pressure, temperature, and pH. One energized history may calibrate the hydraulic parameters and the other should remain a hold-out comparison. Until such data exist, the reported uncertainty bands and rankings are more defensible than unique calibrated values. Table 10 summarizes the available evidence, its limitations, and the remaining validation requirements.

Evidence purpose	Conditions	Status	Decision evidence
Existing physical evidence	Sequential 8, 12, 20, 25, 30 V	Completed; unreplicated	Device geometry, directional drainage, and current scale only
Analytical verification	One-dimensional single-drain series solution	Completed	Flux and pressure relative L2 errors below 0.12%
Numerical quality control	Mesh, strict time step, and weak-form mass closure	Completed	Discretization effects below 0.05%; mass imbalance below 0.003%

Evidence purpose	Conditions	Status	Decision evidence
Global robustness	48-point Latin hypercube across five uncertain parameters	Completed	Rankings, uncertainty range, and cross-validated main effects
Minimum future physical check	0 V plus one calibration and one hold-out energized condition	Optional; preferably $n \geq 3$	Volumetric $Q(t)$, $I(t)$, suction/pressure, temperature, and pH

Table 10. Evidence matrix for a numerical-method paper under constrained physical testing. Completed numerical checks improve implementation credibility but do not constitute soil-parameter validation.

7. Conclusions

- Perforated tubular cathodes produced visible directional drainage in the slope model, but the unreplicated drop counts are qualitative proof-of-concept evidence rather than hydraulic calibration data.
- A boundary-consistent formulation must add $q_{eo} = -ke_o \nabla V$ to the Darcy/Richards flux and apply hydraulic conditions to the total flux; the one-dimensional benchmark verified cathodic flux and sealed-end pressure with relative L2 errors below 0.12%.
- Fine-to-extra-fine mesh refinement and 2-to-1-s time-step refinement changed 600-s cumulative drainage by -0.043% and $+0.013\%$, while weak-form mass imbalance remained below 0.003% after 10 s.
- Across 48 Latin hypercube cases, finite cathodic drain conductance was the dominant control on cumulative drainage ($\rho = 0.902$; $\beta = 0.823$); the 5th, median, and 95th percentiles were 1.92, 13.08, and 58.08 mL.
- Smoothed intermittent operation reduced total drainage and final suction but increased modelled water removed per unit energy at lower duty cycles; this is a conditional numerical trade-off, not an operating recommendation.
- The 3D angle and strength-reduction results remain exploratory because spacing, boundary distance, effective embedded length, retention behaviour, and suction-dependent strength have not been independently validated.
- When further physical slope testing is impractical, the paper is defensible as a verified numerical method and global parametric study with qualitative device evidence, provided no optimum voltage, angle, spacing, or stability gain is claimed.

Data availability

The underlying photographs, videos, and preliminary drainage records are held in the Ya'an expansive-soil project archive.

References

- Albrecht, B.A., Benson, C.H., 2001. Effect of desiccation on compacted natural clays. *Journal of Geotechnical and Geoenvironmental Engineering* 127(1), 67–75. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2001\)127:1\(67\)](https://doi.org/10.1061/(ASCE)1090-0241(2001)127:1(67)).
- Alonso, E.E., Gens, A., Josa, A., 1990. A constitutive model for partially saturated soils. *Géotechnique* 40(3), 405–430. <https://doi.org/10.1680/geot.1990.40.3.405>.
- Asadi, A., Huat, B.B.K., Nahazanan, H., Keykiah, H.A., 2013. Theory of electroosmosis in soil. *International Journal of Electrochemical Science* 8(1), 1016–1025. [https://doi.org/10.1016/S1452-3981\(23\)14076-4](https://doi.org/10.1016/S1452-3981(23)14076-4).
- Burnotte, F., Lefebvre, G., Grondin, G., 2004. A case record of electroosmotic consolidation of soft clay with improved soil–electrode contact. *Canadian Geotechnical Journal* 41(6), 1038–1053. <https://doi.org/10.1139/t04-045>.
- Casagrande, L., 1949. Electro-osmosis in soils. *Géotechnique* 1(3), 159–177. <https://doi.org/10.1680/geot.1949.1.3.159>.
- Chaduvula, U., Viswanadham, B.V.S., Kodikara, J., 2017. A study on desiccation cracking behavior of polyester fiber-reinforced expansive clay. *Applied Clay Science* 142, 163–172. <https://doi.org/10.1016/j.clay.2017.02.008>.
- Chien, S.C., Ou, C.Y., Lee, Y.C., 2010. A novel electroosmotic chemical treatment technique for soil improvement. *Applied Clay Science* 50(4), 481–492. <https://doi.org/10.1016/j.clay.2010.09.014>.
- Deng, A., Zhou, Y., 2016a. Modeling electroosmosis and surcharge preloading consolidation. I: Model formulation. *Journal of Geotechnical and Geoenvironmental Engineering* 142(4), 04015093. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0001417](https://doi.org/10.1061/(ASCE)GT.1943-5606.0001417).
- Deng, A., Zhou, Y., 2016b. Modeling electroosmosis and surcharge preloading consolidation. II: Validation and simulation results. *Journal of Geotechnical and Geoenvironmental Engineering* 142(4), 04015094. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0001418](https://doi.org/10.1061/(ASCE)GT.1943-5606.0001418).
- Esrig, M.I., 1968. Pore pressures, consolidation, and electrokinetics. *Journal of the Soil Mechanics and Foundations Division* 94(4), 899–921. <https://doi.org/10.1061/JSFEAQ.0001178>.
- Feng, J., Shen, Y., Liu, H., Shi, W., 2022. An analytical solution of electroosmotic consolidation concerning effective voltage attenuation. *Acta Geotechnica* 18(3), 1169–1177. <https://doi.org/10.1007/s11440-022-01671-w>.
- Fourie, A.B., Johns, D.G., Jones, C.J.F.P., 2007. Dewatering of mine tailings using electrokinetic geosynthetics. *Canadian Geotechnical Journal* 44(2), 160–172. <https://doi.org/10.1139/t06-112>.
- Fourie, A.B., Jones, C.J.F.P., 2010. Improved estimates of power consumption during dewatering of mine tailings using electrokinetic geosynthetics. *Geotextiles and Geomembranes* 28(2), 181–190. <https://doi.org/10.1016/j.geotexmem.2009.10.007>.
- Fredlund, D.G., Morgenstern, N.R., Widger, R.A., 1978. The shear strength of unsaturated soils. *Canadian Geotechnical Journal* 15(3), 313–321. <https://doi.org/10.1139/t78-029>.
- Gan, Q., Zhou, J., Li, C., Zhuang, Y., Wang, Y., 2022. Vacuum preloading combined with electroosmotic dewatering of dredger fill using the vertical-layered power technology of a novel tubular electrokinetic geosynthetics: Test and numerical simulation. *International Journal of Geomechanics* 22(1), 05021004. [https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0002211](https://doi.org/10.1061/(ASCE)GM.1943-5622.0002211).

Gray, D.H., Mitchell, J.K., 1967. Fundamental aspects of electro-osmosis in soils. *Journal of the Soil Mechanics and Foundations Division* 93(6), 209–236. <https://doi.org/10.1061/JSFEAQ.0001053>.

Harris, A., Nosrati, A., Addai-Mensah, J., 2018. The influence of pulp and interfacial chemistry and mode of electrical power input on electroosmotic dewatering of Na-exchanged smectite dispersions. *Applied Clay Science* 162, 214–222. <https://doi.org/10.1016/j.clay.2018.06.017>.

Huang, M., Jia, C.Q., 2009. Strength reduction FEM in stability analysis of soil slopes subjected to transient unsaturated seepage. *Computers and Geotechnics* 36(1–2), 93–101. <https://doi.org/10.1016/j.compgeo.2008.03.006>.

Iwata, M., Tanaka, T., Jami, M.S., 2013. Application of electroosmosis for sludge dewatering—A review. *Drying Technology* 31(2), 170–184. <https://doi.org/10.1080/07373937.2012.691592>.

Jayasiri, N., Fourie, A., Vulpe, C., 2025. Influence of initial water content and voltage gradient on electroosmotic dewatering of ultra-fine soils using novel electrokinetic geosynthetics. *Geotextiles and Geomembranes* 53(6), 1623–1643. <https://doi.org/10.1016/j.geotexmem.2025.08.006>.

Jiang, L., Qin, A., Li, L., Meng, H., 2023. Analytical solution of electroosmotic-surge preloading coupled consolidation for unsaturated soil via electric prefabricated vertical drains. *Transportation Geotechnics* 42, 101088. <https://doi.org/10.1016/j.trgeo.2023.101088>.

Kalumba, D., Glendinning, S., Rogers, C.D.F., Tyrer, M., Boardman, D.I., 2009. Dewatering of tunneling slurry waste using electrokinetic geosynthetics. *Journal of Environmental Engineering* 135(11), 1227–1236. [https://doi.org/10.1061/\(ASCE\)0733-9372\(2009\)135:11\(1227\)](https://doi.org/10.1061/(ASCE)0733-9372(2009)135:11(1227)).

Kaniraj, S.R., Yee, J.H.S., 2011. Electro-osmotic consolidation experiments on an organic soil. *Geotechnical and Geological Engineering* 29(4), 505–518. <https://doi.org/10.1007/s10706-011-9399-8>.

Lan, T., Zhang, R., Yang, B., Meng, X., 2022. Influence of swelling on shear strength of expansive soil and slope stability. *Frontiers in Earth Science* 10, 849046. <https://doi.org/10.3389/feart.2022.849046>.

Ling, J., Han, B., Xie, Y., Dong, Q., Sun, Y., Huang, B., 2017. Laboratory and field study of electroosmosis dewatering for pavement subgrade soil. *Journal of Cold Regions Engineering* 31(4), 04017010. [https://doi.org/10.1061/\(ASCE\)CR.1943-5495.0000136](https://doi.org/10.1061/(ASCE)CR.1943-5495.0000136).

Lockhart, N.C., 1983. Electroosmotic dewatering of clays, III. Influence of clay type, exchangeable cations, and electrode materials. *Colloids and Surfaces* 6(3), 253–269. [https://doi.org/10.1016/0166-6622\(83\)80017-1](https://doi.org/10.1016/0166-6622(83)80017-1).

Lockhart, N.C., Stickland, R.E., 1984. Dewatering coal washery tailings ponds by electroosmosis. *Powder Technology* 40(1–3), 215–221. [https://doi.org/10.1016/0032-5910\(84\)85067-6](https://doi.org/10.1016/0032-5910(84)85067-6).

Lu, N., Likos, W.J., 2006. Suction stress characteristic curve for unsaturated soil. *Journal of Geotechnical and Geoenvironmental Engineering* 132(2), 131–142. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2006\)132:2\(131\)](https://doi.org/10.1061/(ASCE)1090-0241(2006)132:2(131)).

Martin, L., Alizadeh, V., Meegoda, J., 2019. Electro-osmosis treatment techniques and their effect on dewatering of soils, sediments, and sludge: A review. *Soils and Foundations* 59(2), 407–418. <https://doi.org/10.1016/j.sandf.2018.12.015>.

Morris, P.H., Graham, J., Williams, D.J., 1992. Cracking in drying soils. *Canadian Geotechnical Journal* 29(2), 263–277. <https://doi.org/10.1139/t92-030>.

Mualem, Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research* 12(3), 513–522. <https://doi.org/10.1029/WR012i003p00513>.

- Ng, C.W.W., Shi, Q., 1998. A numerical investigation of the stability of unsaturated soil slopes subjected to transient seepage. *Computers and Geotechnics* 22(1), 1–28. [https://doi.org/10.1016/S0266-352X\(97\)00036-0](https://doi.org/10.1016/S0266-352X(97)00036-0).
- Niu, G., Sun, D., Kong, L., Shao, L., Wang, H., Wang, Z., 2024. Investigation into the shear strength of a weakly expansive soil over a wide suction range. *Acta Geotechnica* 19(5), 3059–3073. <https://doi.org/10.1007/s11440-024-02246-7>.
- Ou, C.Y., Chien, S.C., Yang, C.C., Chen, C.T., 2015. Mechanism of soil cementation by electroosmotic chemical treatment. *Applied Clay Science* 104, 135–142. <https://doi.org/10.1016/j.clay.2014.11.020>.
- Probstein, R.F., Hicks, R.E., 1993. Removal of contaminants from soils by electric fields. *Science* 260(5107), 498–503. <https://doi.org/10.1126/science.260.5107.498>.
- Rabie, H.R., Mujumdar, A.S., Weber, M.E., 1994. Interrupted electroosmotic dewatering of clay suspensions. *Separations Technology* 4(1), 38–46. [https://doi.org/10.1016/0956-9618\(94\)80004-9](https://doi.org/10.1016/0956-9618(94)80004-9).
- Reddy, K.R., Urbanek, A., Khodadoust, A.P., 2006. Electroosmotic dewatering of dredged sediments: Bench-scale investigation. *Journal of Environmental Management* 78(2), 200–208. <https://doi.org/10.1016/j.jenvman.2005.04.018>.
- Ren, Q., Wang, Y., 2024. Theoretical and experimental study on the consolidation of soil with continuous drainage boundary under electroosmosis–surcharge preloading. *Scientific Reports* 14(1), 31532. <https://doi.org/10.1038/s41598-024-83348-w>.
- Shang, J.Q., 1998. Electroosmosis-enhanced preloading consolidation via vertical drains. *Canadian Geotechnical Journal* 35(3), 491–499. <https://doi.org/10.1139/t98-018>.
- Shen, Y., Feng, J., Ma, Y., Liu, H., 2019. Two-dimensional electroosmotic consolidation theory of nonlinear soil voltage distribution characteristics. *Advances in Civil Engineering* 2019, 7354873. <https://doi.org/10.1155/2019/7354873>.
- Sugiyama, Y., Hashimoto, N., Couture, C., Takano, D., 2023. Electrochemical perspective on the applicability of electroosmosis for clay consolidation. *Journal of Applied Electrochemistry* 54(5), 1057–1073. <https://doi.org/10.1007/s10800-023-02018-3>.
- Sun, Z., Gao, M., Xu, L., 2019. Performance and energy consumption of electric vertical drains used in soft clay consolidation. *Soil Mechanics and Foundation Engineering* 56(1), 59–64. <https://doi.org/10.1007/s11204-019-09570-1>.
- Sun, Z., Wu, T., Yao, K., Kasu, C.M., Zhao, X., Li, Z., Gong, J., 2022. Consolidation of soft clay by cyclic and progressive electroosmosis using electrokinetic geosynthetics. *Arabian Journal of Geosciences* 15(13), 1193. <https://doi.org/10.1007/s12517-022-10380-3>.
- Sun, Z., Qing, Y., Zhang, C., Eugene, B.D., 2024. Electroosmosis and electrophoresis in soft clay under direct current electric field. *Heliyon* 10(7), e28718. <https://doi.org/10.1016/j.heliyon.2024.e28718>.
- Sutar, A.A., Rotte, V.M., 2024. A novel test set up to study three-dimensional electrokinetic dewatering of dredged soil. *Journal of Environmental Management* 370, 122611. <https://doi.org/10.1016/j.jenvman.2024.122611>.
- Tang, C.S., Cui, Y.J., Shi, B., Tang, A.M., Liu, C., 2011. Desiccation and cracking behaviour of clay layer from slurry state under wetting–drying cycles. *Geoderma* 166(1), 111–118. <https://doi.org/10.1016/j.geoderma.2011.07.018>.
- Tu, Y., Zhang, R., Zhong, Z., Chai, H., 2022. The strength behavior and desiccation crack development of silty clay subjected to wetting–drying cycles. *Frontiers in Earth Science* 10, 852820. <https://doi.org/10.3389/feart.2022.852820>.
- van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* 44(5), 892–898. <https://doi.org/10.2136/sssaj1980.03615995004400050002x>.
- Wan, T.Y., Mitchell, J.K., 1976. Electro-osmotic consolidation of soils. *Journal of the Geotechnical Engineering Division* 102(5), 473–491. <https://doi.org/10.1061/AJGEB6.0000270>.

- Wang, L.J., Wang, Y.M., Liu, S.H., Huang, P.H., 2021a. Analytical investigation of electroosmotic consolidation in unsaturated soils considering the coupling effect and a nonuniform initial water content. *International Journal of Geomechanics* 21(8), 06021018. [https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0002053](https://doi.org/10.1061/(ASCE)GM.1943-5622.0002053).
- Wang, L.J., Shen, C.M., Liu, S.H., Alonso, E., Huang, P.H., 2021b. A hydro-mechanical coupled solution for electro-osmotic consolidation in unsaturated soils considering the decrease in effective voltage with time. *Computers and Geotechnics* 133, 104050. <https://doi.org/10.1016/j.compgeo.2021.104050>.
- Wu, H., Hu, L., Qi, W., Wen, Q., 2017a. Analytical solution for electroosmotic consolidation considering nonlinear variation of soil parameters. *International Journal of Geomechanics* 17(5), 06016032. [https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0000821](https://doi.org/10.1061/(ASCE)GM.1943-5622.0000821).
- Wu, H., Qi, W., Hu, L., Wen, Q., 2017b. Electro-osmotic consolidation of soil with variable compressibility, hydraulic conductivity and electro-osmosis conductivity. *Computers and Geotechnics* 85, 126–138. <https://doi.org/10.1016/j.compgeo.2016.12.026>.
- Wu, H., Hu, L., Wen, Q., 2017c. Numerical simulation of electro-osmotic consolidation coupling non-linear variation of soil parameters. *Computers & Geosciences* 103, 92–98. <https://doi.org/10.1016/j.cageo.2017.03.002>.
- Yuan, J., Hicks, M.A., 2016. Numerical simulation of elasto-plastic electro-osmosis consolidation at large strain. *Acta Geotechnica* 11(1), 127–143. <https://doi.org/10.1007/s11440-015-0366-z>.
- Yüksek, S., 2022. Electroosmotic dewatering of iron ore tailings: A laboratory study to improve geotechnical properties. *Advances in Civil Engineering* 2022, 7662997. <https://doi.org/10.1155/2022/7662997>.
- Zhang, H., Zhou, G., Zhong, J., Shen, Z., Shi, X., 2017. Effect of nanomaterials and electrode configuration on soil consolidation by electroosmosis: Experimental and modeling studies. *RSC Advances* 7(20), 12103–12112. <https://doi.org/10.1039/C6RA26674F>.
- Zhang, L., Hu, L., 2022. Numerical simulation of electro-osmotic consolidation considering tempo-spatial variation of soil pH and soil parameters. *Computers and Geotechnics* 147, 104802. <https://doi.org/10.1016/j.compgeo.2022.104802>.
- Zhao, X., Liu, Y., Cao, W., Gong, W., 2024. Semi-analytical solution for two-dimensional electro-osmotic consolidation of double-layered soil. *Geotextiles and Geomembranes* 52(1), 121–131. <https://doi.org/10.1016/j.geotexmem.2023.09.007>.
- Zhou, Y., Deng, A., Fu, J., 2019. Modelling electro-osmosis–surcharge preloading combined consolidation of unsaturated soils. *Computers and Geotechnics* 114, 103145. <https://doi.org/10.1016/j.compgeo.2019.103145>.