

REVIEW

Geo-Electro Systems in the Subsurface: Integrating Engineering Geology, Geotechnical Engineering, and Electrical Power Infrastructure

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ABSTRACT

Underground electrical infrastructure is gaining significance in response to urbanization and network densification, climate resilience requirements, and the broader energy transformation. However, even underground power systems are still regularly discussed within disciplinary silos, and there is little integration among engineering geology, geotechnical engineering, and electrical power engineering. This review establishes the concept of geo-electro systems for characterizing the subsurface environment where geological media, geotechnical behaviour, and electrical infrastructure are coupled and mutually dependent. The article is a synthesis of existing research on the geological and geotechnical constraints that influence buried cables, grounding, duct banks, cable tunnels, and underground substations, and pays special attention to the thermal behavior, ampacity, electrical resistivity, groundwater effects, deformation, corrosion, and lifecycle reliability. It also discusses the thermo-hydro-mechanical-electrical-chemical coupling mechanisms, system interfaces, strengths, and weaknesses of analytical, numerical, and data-driven models. It is based on this that the review argues that subsurface electrical infrastructure can no longer be considered a stand-alone resource buried in the ground, but rather a dynamic, coupled system in which performance changes with environmental and operational variations. This review proposes an integrative framework that links previously fragmented literature and enables more consistent design, risk assessment, monitoring, and future investigations. The review finds that subsurface power infrastructure needs to be resilient, efficient, and sustainable, which is only attainable through system-level integration.

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1. Introduction

Modern infrastructure systems are increasingly recognizing the subsurface as a vital field. The rapid pace of urbanization, the growth of underground space use, the shift to low-carbon energy sources, and the increasing need for resilient electricity infrastructure have all fostered interest in the performance of underground electrical power infrastructure^[1]. Buried transmission and distribution cables, grounding systems, underground substations, utility corridors in tunnels, and even new energy geostructures are no longer stand-alone engineering elements but rather part of a complex geologic and geotechnical system that is the major determinant of their behavior, reliability, and service lives. Practically, though, these systems are nevertheless still too frequently planned, designed, and managed within disciplinary silos. Engineering geologists specialize in stratigraphy, geomaterials, groundwater, and geological hazards; geotechnical engineers specialize in deformation, stability, bearing capacity, and soil-structure interaction; electrical engineers specialize in ampacity, insulation, fault behavior, earthing, and network reliability. However, these worries cannot be separated from the subsurface^[2–5].

This review uses the term geo-electro systems to refer to subsurface systems in which geological media, geotechnical behavior, and electrical power infrastructure are interrelated in a coupled, mutually interacting system. The term is to be broad enough to encompass more than just the co-location of cables or electrical assets in soil or rock. It focuses on the fact that the ground is not a passive host material but an active part of infrastructure performance. The types of soil, mineral content, soil density, saturation, thermal conductivity, electrical resistivity, groundwater flow, chemical aggressiveness, and discontinuities in rock masses may directly influence cable temperature increases, insulation degradation, grounding, corrosion, fault propagation, and long-term asset integrity. Meanwhile, heat loss to the subsurface during operation of electrical infrastructure may alter subsurface conditions through heat dissipation, forced moisture movement, drying-wetting cycles, physicochem-

ical modification, and stress redistribution. Such two-way interactions are becoming even more critical as infrastructure systems are challenged by higher load densities, increased underground congestion, and more demanding service demands^[6–8].

The need for a comprehensive view is especially pressing in the modern energy transition. The electrical grids are being redesigned to support distributed generation, integration of renewable power, electrified transport, data-intensive cities, and increased demands on reliability and resilience. Most of these developments are compelling utilities and planners to expand underground electrical infrastructure in cities, coastal areas, mountainous regions, and sensitive areas. Burying cables is commonly preferred for their efficiency in land use, aesthetic appeal, ability to withstand climatic conditions, and reduced susceptibility to external hazards. Nevertheless, the process of undergrounding electrical systems does not remove risk; it just shifts most of that risk to the subsurface domain, where geological uncertainty, geotechnical variability, groundwater processes, and thermal constraints can be challenging to characterize and extremely difficult to manage over long periods of operation^[9,10]. Breakages in such systems are expensive, disabling, and difficult to troubleshoot and fix. Consequently, it is not just an academic exercise to recognize that the coupled ground infrastructure system is not only necessary but also practical.

Although thermal rating of cables, grounding design, geoelectrical surveys, Thermo–Hydro–Mechanical/Thermo–Hydro–Mechanical–Chemical (THM/THMC) modelling, and asset management are established, they are rarely integrated around electrical power infrastructure as a coupled subsurface system. Geoelectrical methods characterize resistivity but do not treat cables as active thermal-hydraulic-chemical perturbators. THM/THMC studies often focus on energy geostructures, nuclear waste, or slopes, not on ampacity, earthing, and fault performance. Cable and grounding standards treat ground as a parameter or boundary, not a co-evolving state. This review's novelty is therefore not a new physical mechanism but an integrative framework: (i) a system definition and boundary criteria; (ii) coupling-

strength classification; (iii) explicit links between subsurface processes and electrical performance; (iv) a lifecycle workflow for design, monitoring, risk, and adaptive management. These contributions are testable by comparing integrated versus conventional design in cases of moisture-dependent ampacity, seasonal earthing, and thermal interference in congested corridors^[11].

There are several reasons this gap is important. Manufactured first, multi-physics coupling is the fundamental control of the behavior of subsurface electrical infrastructure. These processes are thermal, hydraulic, mechanical, chemical, and electrical, and they interact at the cable-soil interface, corridor, facility, and network levels. An example of this is that heat generated during cable operation may lower soil moisture in this area and, consequently, raise the cable's thermal resistivity, thereby further raising its temperature. In the same way, groundwater flow can either improve or worsen heat loss depending on local conditions, and it also affects corrosion and the transport of chemicals. Physical loading, settlement, desiccation cracking, cyclic wetting, and ground movement may alter the physical contacts between infrastructure and the surrounding media, with implications for structural integrity and electrical performance. The processes cannot be comprehensively explained by using single-discipline approaches^[12,13].

Second, the subsurface conditions are heterogeneous and uncertain. Soil and rock masses, in contrast to manufactured infrastructure components, are spatially variable, anisotropic, discontinuous, and time-varying. The characteristics of the host medium are influenced by geological history, weathering, depositional environment, tectonic structure, and hydrogeological evolution. These aspects not only dictate geotechnical performance but also the electrical and thermal conductivity of buried assets. Traditional engineering procedures tend to streamline this variability into averaged parameters or design values with a small range of definition. Such simplifications can be convenient, but they might not capture important local effects that govern hot spots, grounding inefficiency, localized degradation, unstable behavior, or localized performance across infrastructure corridors. A critical look at geo-electro systems may help determine where such simplifications are valid and where more integrated characterization is required^[14-16].

Third, new technologies are increasing the number of

systems within subsurface geo-electro interactions. Blurring of traditional disciplinary boundaries is energy geostructures, underground pumped or compressed energy structures, thermally active tunnels, cable tunnels, high-voltage direct current connections, smart underground utility corridors, and digitally monitored buried assets. These systems are increasingly designed to support and contain, as well as to have heat-exchange capacity, energy storage, conduct electrical energy, provide environmental buffering, and integrate infrastructure. This development requires novel conceptual models and design strategies to be able to take into consideration coupled behavior over the lifecycle of the asset, starting at the site selection and construction, continuing to operation, maintenance, and decommissioning^[17-19].

On this basis, the current article critically evaluates subsurface geoelectrical systems in a carefully interdisciplinary manner. Its main principle is that the operation of underground electrical power facilities cannot be properly understood without considering the geological context, geotechnical response, and electrical activity simultaneously. The review thus unites ideas and results that are otherwise scattered across the literature of engineering geology, geotechnics, underground infrastructure engineering, and power engineering. Instead of considering the ground as an external boundary condition of an electrical system, this article views geological media as a natural and active component of system behaviour. Similarly, it regards electrical infrastructure not merely as a burden on the ground, but as a dynamic source of thermal, hydraulic, and chemical disturbance that can restructure the local subsurface environment^[20,21].

The novelty of this review lies in four aspects. First, it introduces and develops the concept of geo-electro systems as a consistent framework for understanding the subsurface electrical infrastructure. Although similar themes have been considered previously, these investigations have typically been considered under a more limited title, like cable thermal analysis, grounding performance, underground utility engineering, or energy geostructures. This review offers a unifying language for integrating these topics and emphasizes their interdependence by suggesting a more systems-based approach.

Second, this article is a systematic connection between engineering geological controls, geotechnical behavior, and electrical performance. Most reviews discuss one or two

of these domains in detail. In this case, attention is paid to their intersection: the impact of lithology, structure, weathering, groundwater, and variability of geomaterials on electrical infrastructure; the impact of operational electrical loading on the mechanical and hydraulic condition of the ground; and the impact of coupled processes on design, risk, and long-term reliability. This integrative approach is particularly useful with buried and underground resources found in operationally or geologically challenging settings^[4].

Third, the review has a multi-physics and lifecycle view. It not only looks at the first installation or short-term performance, but also at the development of thermo-hydro-mechanical-electrical-chemical interactions over time and across project phases. This is significant because most of the significant risks in subsurface infrastructure, such as thermal-runaway tendencies, moisture redistribution, corrosion progression, material degradation, and slow geotechnical response, develop over time and are not captured by static design methods. Placing geo-electro systems within a lifecycle framework can help close the gap between design assumptions and operational reality.

Fourth, the paper determines new research and practice opportunities at the subsurface engineering-power infrastructure interface. These are built-in site characterization, computerized monitoring, physics-informed modeling, resilience-based design, sustainability assessment, and the unity of power infrastructure, underground energy, and smart-city systems. Through these syntheses, the review will not only summarise the current state of knowledge but help to establish a future research agenda for this dynamically developing area.

This review aims to achieve three goals: (1) to develop a conceptual understanding of geo-electro systems in the subsurface; (2) to synthesize the geological, geotechnical, and electrical conditions that control their behavior; and (3) to define knowledge gaps, methodological issues, and opportunities for integrated design and operation. In this way, the paper attempts to justify a move away from discipline-specific analysis toward understanding systems at the system level. This change is timely and needed, as subsurface electrical infrastructure should be able to accommodate future cities, energy systems, and climate-resilient

development^[22–26].

2. Conceptual Framework of Geo-Electro Systems in the Subsurface

2.1. Defining Geo-Electro Systems

The geo-electro systems can be described as coupled engineered-natural systems in which geological media, geotechnical response, and electrical power infrastructure interact over space and time. The idea goes beyond the traditional perception of soil and rock as physical support or burial cover of electrical assets. Rather, the ground should be perceived as a dynamic, living medium that controls heat transfer, moisture redistribution, electrical resistivity, mechanical confinement, chemical aggressiveness, and the propagation of failures. Electrical infrastructure, in turn, alters the surrounding subsurface by imposing thermal loading, altering stresses, electromagnetic influences, and changing physicochemical features. Reciprocity is the hallmark of a geo-electro system; hence, the ground influences infrastructure behavior, and infrastructure operation influences ground conditions^[27]. An example of this two-way structure and its main areas of engagement is conceptually depicted in **Figure 1**.

This definition is beneficial, as it shifts the analysis of components toward the interpretation of the system. The traditional engineering practice tends to divide tasks into areas: engineering geology addresses site conditions, geotechnical engineering addresses stability and deformation, and electrical engineering addresses power transmission, insulation, and fault performance. This is a convenient way of division that is, however, conceptually unsatisfactory. In subsurface settings, the interaction between these domains leads to performance and not the domains in isolation. Even a buried cable with good electrical characteristics can be poor when installed in poorly characterized soil with high thermal resistivity. On the other hand, the electrical reliability of a mechanically stable underground corridor can be called into question if underground geological processes are enhanced by corrosion risk or the performance of its grounding is compromised. The geo-electro framework thus offers a more realistic approach to the concept of underground power systems^[3,28,29].

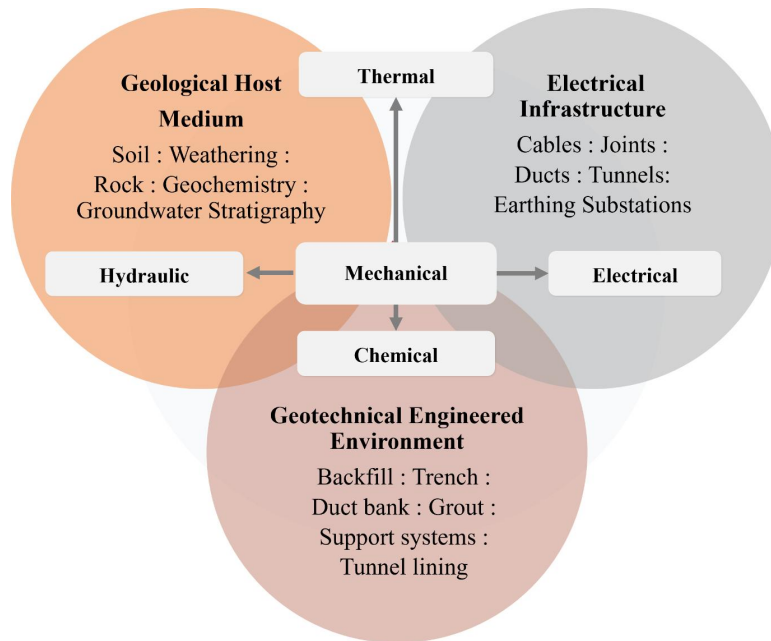


Figure 1. Conceptual framework of a subsurface geo-electro system showing interactions among geological media, the engineered geotechnical environment, and electrical power infrastructure.

Simultaneously, the concept must not be applied to the extent that it becomes less analytical. Not all buried electrical assets are equally important complex geo-electro systems. Coupling depends on the voltage level, thermal output, burial depth, groundwater regime, geological heterogeneity, construction method, and operational requirements. A significant conceptual framework should then differentiate between uncomplicated embedded property and extremely interactive systems with robust feedback loops that are enduring, resilient, and consequential for safety, performance, or lifecycle expenses.

2.2. System Components and Boundaries

The geo-electro system consists of three main elements, namely: the geological host medium, the engineered geotechnical environment, and the electrical power asset. The host geological medium consists of soil, rock, weathered profiles, discontinuities, pore fluids, and groundwater flow. These are the natural boundary conditions of the system, and are sometimes the most uncertain due to natural variability and incomplete characterization. The engineered geotechnical environment encompasses excavations, backfills, liners, grouts, foundations, retaining structures, and any alteration made to establish satisfactory installation and service conditions. It is the area where the natural ground condition is changed into an

engineered performance. The electrical power asset includes underground cables, joints, and ducts; grounding systems; underground substations; utility tunnels; and other support structures. These are the immediate carriers of electrical action, but are also the generators of thermal and occasionally chemical perturbations^[30].

Subsurface engineering seldom has fixed system boundaries. There are some physical, some operational, and some temporal. Considering insulation behaviour, the near field can extend by only tenths of a centimeter along a cable surface, whereas in the context of temperature plumes, groundwater effects, or stress redistribution in tunnel systems, the near field extends to meters or tens of meters. The boundary varies operationally with load intensity, cycling frequency, and fault events, as transient conditions can cause processes that are negligible in steady state to be active. The system is developed over time to go through the construction stage, then operation, and finally aging or even decommissioning. The correct analytical boundary is therefore problem-specific, and one of the general flaws in modern practice is the use of boundaries that are too narrow to accommodate delayed or indirect interactions^[31].

This problem is especially relevant to urban underground infrastructure, where several buried assets are co-located. The behavior of the system can be influenced by thermal interference between adjacent cables, drainage varia-

tions resulting from nearby structures, or ground movements related to nearby excavations. The conceptual boundary should thus incorporate both the external anthropogenic factors and the natural geological conditions. There is a sub-

surface electrical system embedded not only in geology but also in an evolving infrastructure landscape^[32]. **Table 1** summarizes the key elements, governing dimensions, and engineering meaning of subsurface geo-electro systems.

Table 1. Conceptual distinctions, principal components, and governing dimensions of subsurface geo-electro systems.

Component/Dimension	Description	Main Variables	Engineering Significance
Geological host medium	Natural soil, rock, weathered profiles, discontinuities, pore fluids, groundwater	Lithology, stratigraphy, mineralogy, permeability, saturation, groundwater flow	Controls thermal transfer, resistivity, deformation, corrosion environment, and geohazard exposure
Geotechnical environment	Engineered interface between ground and infrastructure	Backfill, bedding, compaction, support systems, trench geometry, tunnel lining	Modifies contact behavior, heat dissipation, stability, drainage, and long-term serviceability
Electrical infrastructure	Power assets located in subsurface settings	Cables, joints, ducts, grounding systems, substations, vaults, tunnels	Provide transmission, distribution, grounding, and conversion functions
Thermal processes	Heat generation and dissipation in coupled ground–asset systems	Thermal conductivity, heat capacity, ampacity, thermal gradients	Governs cable rating, overheating risk, and infrastructure efficiency
Hydraulic processes	Water movement and moisture redistribution	Saturation, suction, seepage, groundwater fluctuation, unsaturated flow	Influences thermal resistivity, corrosion, drainage, and long-term ground behavior
Mechanical processes	Stress, strain, settlement, swelling, and deformation	Stiffness, shear strength, compressibility, creep, expansion	Affects alignment, structural integrity, interface continuity, and durability
Electrical processes	Current flow, resistivity behavior, and fault-current dissipation	Resistivity, grounding resistance, current density, stray current	Determines safety, fault performance, and earthing effectiveness
Chemical processes	Material alteration and electrochemical interaction	pH, salinity, sulfates, redox conditions, corrosivity	Controls corrosion, material compatibility, and lifecycle degradation
Spatial scale	Range over which coupled interactions develop	Cable scale, trench scale, corridor scale, facility scale	Defines suitable level of site characterization and modeling
Temporal scale	Time over which processes evolve	Transient loading, seasonal cycles, long-term aging	Supports lifecycle-based design and monitoring

2.3. Coupled Processes and Interaction Mechanisms

Coupled thermo-hydro-mechanical-electrical and, in most instances, chemical processes control the behavior of geo-electro systems. These couplings are not just additive. They create a feedback loop that may either amplify or suppress the system response. One of the most commonly studied mechanisms is thermal loading due to energized cables. The thermal conductivity, thermal capacity, density, and moisture content of soil influence heat dissipation. The soil reaction to heating, however, is not an inert reaction. As temperatures rise, moisture can move away from heat sources, particularly in unsaturated soils, leading to local drying. This usually increases thermal resistivity and decreases heat-dissipation efficiency, further increasing cable temperature. What is obtained is an effect of non-linear feedback, which cannot be modeled with fixed-property design

assumptions^[33].

Hydraulic processes also play an important role. Under certain conditions, groundwater flow can enhance thermal dissipation through advective heat transport, but can also enhance chemical movement, corrosion, and local erosion or instability. With low permeability, heat can build up due to the predominance of conduction. Water and heat, and their pathways in layered or anisotropic ground, can be highly directional; therefore, the local geological structure is essential to the system's functioning. The hydrogeological regime is not a secondary control, but can frequently be a first-order control.

Mechanical coupling is provided through soil-structure interaction, changes in confinement, cyclic expansion and contraction, settlement, and stress redistribution. Whereas electrical infrastructure is commonly thought to be thermally receptive rather than mechanically susceptible, this is not the case. Deformation may change the alignment of cables,

the integrity of joints, contact resistance, the performance of trench backfills, and the performance of protective structures. Rock mass behavior, creep, swelling, or seismic loading can occur in tunnels and underground substations, posing a threat to the structural envelope and the structural reliability of electrical equipment. Mechanical stability is thus integral to electrical functionality^[34].

The ground is also acted upon by electrical processes. The electrical resistivity structure of subsurface materials, and therefore earthing systems, is directly dependent on mineralogy, porosity, saturation, salinity, and temperature. Local heating or electrochemical change may occur due to fault currents. Stray currents may also cause corrosion of metallic elements or other surrounding infrastructure in certain environments. The effects can be used to show that geo-electro interaction is not restricted to thermal cable analysis, but rather reflects the more general electrical behavior of the ground as a conductive and chemically active medium^[35].

2.4. Spatial and Temporal Scales of Behavior

The main difficulty in conceptualizing geo-electro systems is that the processes of interest are distributed in space and time. At the microscale, thermal and electrical properties are governed by mineral composition, pore structure, and fluid chemistry. Local transport and stress behavior are controlled at the mesoscale by the geometry of bedding, fissures, interfaces, and backfill. At a macro scale, the cumulative system response is affected by corridor orientation, topography, hydrogeological environment, and network structure. These scales are rather nested, and a simplification at one scale can mask important behavior at another.

Temporal scaling is also crucial. Other interactions are nearly instantaneous, such as transient thermal loading in current surges or electrical faults. The others are formed on a seasonal basis and include variations in moisture with climate and the rise and fall of groundwater. Others still develop over years or decades, such as corrosion, material degradation, creep, repeated thermal cycling, and progressive hydro-mechanical deformation of backfill or surrounding soil. A system that looks good under the circumstances of short-term commissioning may behave differently as time passes and properties change. This renders lifecycle thinking a crucial element of a sound framework^[36].

This means that design based on initial or steady-state

conditions is often inadequate. In most traditional models, soil properties are treated as fixed inputs, and operational conditions are treated as repeatable averages. However, in reality, the underground environment and the infrastructure load are dynamic. The future structures should then consider path dependency, in which past loading and environmental conditions affect current behaviour. This is particularly applicable to climates with high wetting-drying seasonality and networks with non-stationary renewable energy integration, in which loading profiles are becoming more non-stationary^[37].

2.5. Classification of Subsurface Geo-Electro Systems

Geo-electro systems can be categorized by functionality, environment, and coupling strength. They can be functionally divided into transmission and distribution systems, grounding and fault dissipation systems, underground enclosed systems (substations and cable tunnels), and new hybrid systems (energy geostructures). All of the classes are characterized by various dominant processes. The thermal and hydraulic interactions tend to govern buried transmission cables, whereas electrical resistivity structure and moisture conditions tend to have a more direct impact on grounding systems. The challenges in underground substations and utility tunnels are more pronounced under structural and environmental control, as the infrastructure induces greater geotechnical perturbation.

Setting systems can be found in soil, weathered rock, intact rock, coastal ground, reclaimed land, urban fill, or mountainous terrain. Such a difference is important because the same electrical asset does not behave identically under varying geological conditions. As an example, a design methodology intended for uniformly saturated clay cannot be used in fissured residual soil or fractured rock, where transport pathways and mechanical response are far more heterogeneous^[38]. The geologic context should not be treated as a background description; however, it is key to classification.

The degree of coupling is a second criterion for classification. Weakly coupled systems are those where the ground plays the principal supporting role, and the limits of operational feedback are small. The interactions are measurable in moderately coupled systems, e.g., thermal impacts on soil moisture or geotechnical impacts on cable bedding. Strongly coupled systems have long-lasting, reciprocal feedback that

have highly significant performance, maintenance, or hazard implications. It is analytically useful to identify these levels, as it allows one to determine when simplified methods can be used and when multi-physics analysis is required^[39].

2.6. Implications for Analysis and Design

The implied conceptual framework presented here is that subsurface electrical infrastructure should be considered a coupled system rather than an electrical asset installed in externally determined ground conditions. It demands a change in the profession's approach and culture. In methodology, the design must shift towards combined site characterization, parameter interpretation related to performance processes, and modeling approaches that acknowledge uncertainty and property development. There should be increased professional engagement of engineering geologists, geotechnical engineers, and power engineers at the initial stages of the project^[40].

One critical insight is that many infrastructure-related issues associated with component failures are, in fact, system failures due to incomplete representation of the subsurface environment. Poorly estimated thermal resistivity, failure to account for groundwater variability, overly simplified stratigraphy, and neglect of long-term ground changes can undermine technically sound infrastructure. The geo-electro systems can be described as having conceptual value, specifically in revealing these hidden dependencies. Integration is not, however, to be confused with analytical maximalism. Not all projects require a fully coupled numerical model or a comprehensive investigation program. The issue lies in determining at which point complexity has a significant impact on choices. The simplification and sophistication should then be supported by a mature framework, provided it is justified by the level of coupling, uncertainty, and the impact of failure. The geo-electro concept, in this sense, is not only descriptive; it also helps determine in which cases interdisciplinary depth is necessary and in which cases only traditional approaches suffice^[41–44].

Taken together, this framework forms the foundation for the subsequent parts of the review. It emphasizes that the subsurface is not a passive host or a purely geotechnical space, but a dynamic space in which electrical infrastructure and geologic processes co-produce system behavior. This co-production is essential for enhancing the reliability of de-

signs, the resilience of operations, and the scientific integrity of underground power infrastructure.

3. Geological and Geotechnical Controls on Subsurface Electrical Infrastructure

3.1. Geological Conditions as First-Order Controls on Infrastructure Performance

Geology is a key precondition for the performance of subsurface electrical infrastructure. Though electrical assets may be defined by voltage class, insulation technology, ampacity, or network functionality, their field characteristics are highly dependent on the characteristics and composition of the ground on which they are installed. The thermal, hydraulic, mechanical, and chemical environments surrounding buried and underground power systems are governed by the geological media, thereby regulating short-term operation and long-term reliability. Geology, in this sense, is not merely a subset of the site's description; it is a controlling variable in the behavior of infrastructure^[45].

This is influenced by lithology and depositional history. Different types of coarse-grained soils, fine-grained soils, residual materials, weathered rocks, and competent rock masses impose unique boundary conditions for heat transfer, groundwater flow, deformation, and construction viability. Geological origin can significantly influence fabric, mineralogy, anisotropy, and moisture retention behaviour, even within the same nominal soil type. An underground cable in a glacial till, such as can have very different local contacts and drainage conditions, much more heterogeneous than that of a uniformly laid alluvial silt or a constructed urban fill. These differences are important because the electrical conductivity of the material below ground is highly sensitive to the conditions in the vicinity, particularly the local material state and continuity. The simplified geotechnical descriptions used as sufficient to design shallow foundations may thus not be sufficient to interpret the operating environment of the subsurface power assets^[46].

Of particular importance is stratigraphic variability. Representative ground parameters are used to design many underground electrical systems, but in reality, subsurface conditions are discontinuous, layered, and spatially non-

stationary. A cable route traversing intermittent layers of clay, sand, weathered rock, and anthropogenic fill does not experience a single thermal or electrical environment but rather multiple environments. Such transitions may cause localized hot spots, non-uniform settlement, variations in grounding efficiency, and construction challenges that are not evident in route-average design values. This issue is more acute in urban corridors where engineered geology can be more intricate than the natural stratigraphy under it due to historical ground disturbance, the heterogeneity of trench backfills, utility congestion, and undocumented fills.

One of the most important implications is that the geological environment is to be viewed not purely in terms of classification but also in terms of the relevance of the processes involved. In the case of subsurface electrical infrastructure, the question of what material is there is not the most significant, but how that material mediates the flow of heat, water, stress, and electrochemical exchange under operational loading. This reframing shifts the discussion of geological studies to performance geology, where geological phenomena are judged based on their infrastructural implications^[47–49].

3.2. Soil and Rock Properties Relevant to Electrical Infrastructure

Of the numerous ground properties of interest to subsurface power systems, two of the most familiar are probably thermal conductivity and thermal resistivity, due to their direct impact on cable ampacity. But even in this, engineering practice tends to underestimate complexity. Thermal properties are not material constants that are independent of density, moisture content, degree of saturation, mineral composition, porosity, and fabric. Small changes in water content can cause large changes in thermal resistivity in unsaturated soils, especially in fine-grained or poorly compacted soils. Consequently, a material that is fine during installation could behave very differently under long-term heating or seasonal drying. The non-linearity and high state dependence may thus be hidden by the apparent simplicity of thermal design^[50].

The electrical resistivity is also of importance, particularly in grounding and earthing systems, dissipation of fault-current, and behavior of stray currents. The pore water content, electrolyte concentration, mineralogy, clay content,

temperature, and structural continuity control resistivity. It can be highly spatially variable over short distances, particularly in layered soils or fractured rock masses. Since the conductivity of the surrounding ground depends on the conductive paths it provides, local resistivity contrasts can dominate system behaviour. A uniform half-space design can thus be misleading when representing the real distribution of fault currents and safety margins in stratified or seasonally varying ground.

Mechanical properties are also important, though their contribution is often discussed independently of electrical performance. The deformation environment of buried assets is affected by stiffness, compressibility, shear strength, creep properties, and swelling potential. Differential settlement may affect cable alignment, duct integrity, joint performance, and drainage behavior. Large clays can subject buried systems to cyclic loading and displacement, and soft, compressible strata can undergo progressive settlement and changes in cover depth, contact conditions, or trench geometry. The stability of excavation and the long-term behaviour of tunnel-based infrastructure in the rock environment are controlled by discontinuity spacing, infill, weathering grade, and in situ stress conditions. Mechanical adequacy is thus not simply a structural factor but is coupled with thermal and operational performance through varying confinement, contact, and environmental control^[51].

The hydraulic properties add to the image. Groundwater flow, pore-water redistribution, and storage are controlled by permeability, unsaturated hydraulic conductivity, water retention behavior, and storage properties. These are the key properties of the dissipation of heat around energized cables and of seasonal or operational changes in moisture. Advective transport can be used to augment cooling in highly permeable media, but in low-permeability soils, heat can be trapped, leading to greater moisture gradients. The saturation flow behavior is of special significance since several cable systems operate in partially saturated soil, where the effects of capillaries, vapour movement, and the drying front influence the effective thermal conditions.

The consideration should also be on chemical properties. Soil and groundwater pH, redox, salinity, sulfate levels, organic matter, and dissolved species affect the risk of corrosion, material compatibility, and degradation over the long term. These effects are of particular concern in in-

stances where metallic sheaths, armoring, grounding grids, or support elements are exposed to chemically aggressive environments. Both swelling behavior and ionic conduction can also be influenced by clay mineralogy, thereby linking chemical composition to mechanical and electrical responses. This means that the applicable ground properties are not distinct classes but rather dimensions of a coupled host medium that interact^[52,53].

3.3. Groundwater Regime, Moisture Migration, and Hydrogeological Controls

One of the most powerful, but not always sufficiently incorporated, influences on underground electrical infrastructure is groundwater. It is more than the mere depth of the water table. The hydrogeological regime defines the availability of moisture, advective heat, chemical mobility, erosion potential, and time variability in thermal and electrical behaviors. Determining the reliability of buried electrical systems is, in most instances, less about the classification of the soil in a static condition than it is about the movement of water in the ground and the development of that movement under the conditions of climate and operation.

In terms of thermal performance, groundwater can be either advantageous or disadvantageous depending on the circumstances. Moving groundwater may also increase heat dissipation, especially in permeable formations, where it carries heat away from cables or underground installations. This can enhance cooling efficiency compared to conduction-dominated environments. Nevertheless, these advantages are highly site-dependent and should not be extrapolated in the absence of hydrogeological evidence. Groundwater flow can be heterogeneous or intermittent or localized to preferential routes such as fractures, coarse layers, or utility-created drainage areas. When these situations arise, some components of an asset may be over-cooled, while others are thermally constrained. The outcome is a geographically disordered performance that can put into question route-wide design suppositions^[54].

Of special interest is the movement of moisture across thermal gradients. Heating around energized cables can cause soil drying, particularly when the soil is not initially saturated and the water supply is restricted. Thermal resistivity and ampacity can be augmented through this process, forming a feedback mechanism that is one of the most signif-

icant geo-electrical interactions in cable systems. However, this effect level hinges on soil-water retention characteristics, permeability, backfill composition, climate, and groundwater connectivity. That is, the thermal problem cannot be discussed out of context. Ignoring designs, the assumption that thermal properties are constant, even though the physical basis of the properties is evolving, is practical in ignoring designs that ignore moisture migration.

Another complexity is the seasonal variation of groundwater. The electrical asset's underground conditions can differ significantly throughout the year in climates with high wet and dry seasons. Performance due to grounding might also be worse in dry seasons when resistivity increases and cable cooling conditions can be worse when near-surface soils are dry. On the other hand, wet seasons can enhance conductivity but also increase the risk of corrosion or alter mechanical support by softening and reducing suction. These seasonal inversions make the idea of one design condition more complex. The relevant condition might not be the average, but the time of critical combinations of load, dryness, temperature, and electrical demand^[55].

It is also important that the disturbance is hydrogeological in nature, resulting from construction. Local drainage conditions can be altered by trenching, dewatering, tunnel excavation, retaining systems, or backfill placement to change the direction of flow or form perched water zones. These changes can last long after installation and be incorporated within the operating environment. This is why it is not sufficient to describe the groundwater prior to construction; it is also necessary to determine how the project, per se, will alter the hydrogeological system. This is a repetitive weakness in traditional site investigation, in which pre-construction circumstances are recorded, yet there is an implicit assumption regarding post-construction groundwater behavior^[56].

3.4. Geological Hazards and Environmental Risks

Geological hazards also pose a variety of threats to subsurface electrical infrastructure, potentially compromising performance either directly or indirectly. Such hazards comprise landslides, subsidence, sinkholes, fault movement, liquefaction, seismic shaking, swelling ground, collapsible soils, erosion, and coastal or fluvial instability. They are more important in certain settings than in others, but the

main point is that underground electrical infrastructure is not safeguarded against geological risk merely by being underground. Burial in other situations has the opposite effect, exposing the victim to wind, icing, or wildfire, but also making the victim susceptible to concealed ground processes that are harder to monitor and mitigate^[57].

This trade-off is depicted by slope instability. Cables buried over unstable gradients can be subjected to shear, tension, and bending due to slow- or rapid-moving landslides. Even a small displacement of the ground may harm joints, bend ducts, or change cover geometry. Since these effects could be cumulative, they tend to be more sinister than disastrous structural failure. Equally, fault crossings not only present seismic design difficulties but also long-term alignment and strain problems. In areas where infrastructure is in contact with active structures or structures that may reactivate in the future, geological interpretation is required to guide route choices, contingency measures, and surveillance.

Karst landscapes, mining areas, and regions of groundwater abstraction or dissolution-sensitive formations are particularly susceptible to subsidence and sinkhole formation. The processes generate localized differential movement, which can be even more destructive of buried assets than uniform settlement. Consolidation and decomposition may also cause such issues in long-term reclaimed land or uncontrolled fill. Liquefaction and cyclic softening are other risks in seismic areas that may cause momentary weakness and substantial displacement of buried ducts, substations,

and cable trenches. Geohazards and electrical infrastructure thus interact both directly, through deformation and damage, and indirectly, through changes in groundwater conditions, access restrictions, and difficulties in responding to emergencies^[58].

Chemically aggressive ground also poses a risk to the environment. Corrosion can be accelerated, or the construction materials can be degraded by acid sulfate soils, saline groundwater, industrial contamination, and redox-active environments. This is common in coastal, estuarine, reclaimed, or previously industrial environments where underground infrastructure is increasingly becoming concentrated. A short geotechnical mindset that is bearing or settlement-oriented can overlook these longer-term threats to durability. Mechanical instability and geochemical aggressiveness must thus be considered to be part of the geological hazard framework.

One thing that stands out critically is that the effect of geological risks is usually measured in a discrete manner, whereas the infrastructure actually undergoes the same geological risks as interacting stresses. A location with seasonal drying, corrosive groundwater, as well as uneven settlement could be more prone to lifecycle risk compared to a location with a single major hazard. Risk assessment must then move beyond just the identification of single hazards to compound ground-risk assessment. **Table 2** synthesizes the key geological and geotechnical controls on the performance of subsurface electrical infrastructure and the engineering implications^[59,60].

Table 2. Geological and geotechnical controls on subsurface electrical infrastructure performance, associated mechanisms, and engineering concerns.

Ground Factor	Characteristics	Primary Effect on Infrastructure	Typical Engineering Concern
Lithology	Soil or rock type, mineral composition, texture	Controls thermal, hydraulic, electrical, and mechanical properties	Inappropriate route assumptions; variable performance along corridor
Stratigraphic variability	Layering, heterogeneity, discontinuities	Produces local contrasts in heat transfer, resistivity, and settlement	Hot spots, differential movement, uneven grounding behavior
Groundwater regime	Water table, seepage paths, seasonal fluctuation	Affects cooling, corrosion, pore pressure, and conductivity	Seasonal performance change; drainage and durability issues
Unsaturated soil behavior	Suction, moisture retention, drying–wetting response	Alters thermal resistivity and stiffness under heating	Ampacity reduction; shrinkage and cracking around cables
Permeability and flow regime	Conductive versus advective transport potential	Influences heat dissipation and chemical transport	Overheating in low-permeability soils; corrosion in aggressive flow environments
Mechanical compressibility	Settlement and deformation potential	Changes in alignment, contact conditions, and serviceability	Joint distress, duct deformation, burial-depth change
Expansive or collapsible ground	Volume instability under moisture change	Causes cyclic or sudden displacement	Cable strain, trench distress, enclosure damage

Table 2. Cont.

Ground Factor	Characteristics	Primary Effect on Infrastructure	Typical Engineering Concern
Corrosive environment	Salinity, pH, sulfates, contaminants	Accelerates degradation of metallic elements	Earthing deterioration, sheath corrosion, reduced design life
Fractured or weathered rock	Discontinuity-controlled behavior	Creates anisotropic flow and uneven support conditions	Tunnel instability, localized inflow, variable thermal behavior
Geohazards	Landslides, subsidence, liquefaction, faulting	Imposes ground movement and instability	Service interruption, structural damage, recovery challenges

3.5. Geotechnical Design Considerations for Buried and Underground Power Assets

Traditional geotechnical design for subsurface electrical infrastructure has focused on constructability, stability, and structural support. Although these are vital, they cannot be relied upon alone. Design should also take into account the impact of the geotechnical decisions on the electrical and thermal performance. This is especially noticeable in trench backfill, bedding materials, duct banks, tunnel lining, and foundation systems of underground substations. Compaction-easy materials or structural-adequate materials might be thermally suboptimal; vice versa, hydraulically unstable materials might be selected that are chemically aggressive and/or mechanically weak unless specified.

A key example is backfilling design. Buried cable systems are now commonly used with engineered thermal backfills, although their performance in the field is determined not solely by their nominal thermal conductivity but also by compaction quality, moisture retention, resistance to segregation, compatibility with adjacent soils, and long-term stability during repeated heating and wetting-drying cycles. A backfill that has been tested under favorable conditions in the laboratory can fail in the field, either due to loss of moisture or discontinuity of contact with native soil. In geotechnical design, consideration should thus not only be on the initial placement, but also the sustainability of the required properties over time^[61].

There is also a need for an integrated consideration of burial depth and cover geometry. Increased depth can enhance resistance to surface disturbance and thermal variability in certain situations, but can also make excavation more difficult, groundwater more accessible, and repair more challenging. The shallower burial can lead to more seasonal variations and unintentional damage to cables. The optimum depth does not exist, and the correct answer depends on the interplay among ground conditions, loading profile,

accessibility, and external risks. The same applies to the spacing of the cable, the duct layout, and the tunnel cross-section layout, where thermal interference, constructability, and geotechnical stability must be weighed.

In underground substations and utility tunnels, geotechnical design also covers excavation support, groundwater behavior, lining behavior, long-term deformation, and serviceability under operational heating. In rock, design should take into consideration block stability, squeezing or swelling, and groundwater inflow. The problems in soil are basal stability, retaining wall deformation, and the influence of adjacent structures. The difficulty is that electrical plants frequently set very tight limits on environmental factors, access, and reliability, and thus are not as tolerant of geotechnical uncertainty as many conventional underground spaces. Consequently, geotechnical design ought to be performance-based and clearly connected to operational requirements, rather than an enabling phase performed prior to the commencement of electrical design^[62].

3.6. Ground Investigation, Site Characterization, and Monitoring

Due to the high level of impact of geological and geotechnical conditions on underground electrical infrastructure, the quality of site characterization is determining. Numerous failures or inefficiencies in underground power systems, however, have their origins in investigations that were sufficient for general civil works, but not for geo-electro performance evaluation. The properties that can be most important to thermal behavior, electrical resistivity, moisture migration, and chemical aggressiveness may be missed by standard borehole logs, index tests, and observations of the groundwater. It is not just a question of more data only, but rather a question of other data processed in an integrated framework.

The optimal investigation plan should thus be a combi-

nation of geological mapping, stratigraphic profiling, hydrogeological analysis, laboratory testing of thermal and electrical properties, and geotechnical testing of deformability and strength. Characterization of groundwater, temperature monitoring, and resistivity surveys can be of particular use where there is a planned grounding system or high-load cable corridors. Nonetheless, it is not sufficient to collect data. The choice of parameters should be based on the interaction of the infrastructure with the ground in the actual operating conditions, such as seasonal changes and loading conditions in the future^[63].

A significant issue is spatial representativeness. Linear infrastructure routes, traversing non-uniform terrain or urban fill sequences, may be unsuitable for point investigations. Boreholes that are sparsely spaced can miss local, but important heterogeneities which can be important to interpolate. The emphasis of route-based characterization should also be made on transitions, anomalous zones, and mapping of uncertainty as opposed to just using average profiles as the sole means of characterization. It is among the fields in which geological understanding cannot be done away with: it offers the conceptual coherence to realistically interpret thin data.

Monitoring is to be seen as an extension of site characterization into the operation period. Temperature, moisture, resistivity, deformation, and groundwater observations can indicate that the presumed design considerations are continuing to be used. This kind of monitoring is particularly useful in high-value or high-consequence assets, where real-time knowledge of ground-infrastructure interaction can enhance reliability, as well as maintenance planning. The wider meaning here is that the characterization must be lifecycle-based. Since the subsurface varies with time and under the loading of the infrastructure, the ground condition that is pertinent is not just that which is met when the investigation is conducted but the changing condition that is met during operation^[53,64–66].

3.7. Critical Perspective

The main idea gained after this overview of the geological and geotechnical controls is that electrical infrastructure at the subsurface level is controlled by a heterogeneous, dynamic, and only partially known host medium. It is natural to simplify this complexity to some design parameters, but this does not necessarily reflect the mechanisms by which performance is actually controlled. Geology controls not only

the location of structures that may be constructed, but also their behavior when excited. Geotechnical response not only affects structural safety but also thermal efficiency, durability, and fault resilience. Hydrogeology not only influences drainage and construction feasibility but also temperature fields, resistivity patterns, and long-term degradation pathways.

It is not the discipline coordination but the conceptual integration that is the critical challenge. Site characterization, design, and risk management should shift away from the belief that geological and geotechnical conditions present a fixed backdrop to electrical design. They belong to the system per se. This understanding is necessary to enhance the integrity of buried cables, grounding networks, underground substations, and new geoelectrical infrastructure amid more strenuous service requirements. Section 4 continues this by examining how these controls manifest across various types of subsurface electrical power infrastructure and their specific operational needs^[67].

4. Electrical Power Infrastructure in Subsurface Settings

4.1. Types of Subsurface Electrical Infrastructure

The subsurface electrical infrastructure comprises a wide range of assets that vary in physical appearance, voltage, installation technique, and intended use, yet are all based on the underlying ground environment. The most widespread type is buried transmission and distribution cables that are placed directly in the soil, in engineered backfill, or in ducts or conduit banks^[68]. They are now extensively deployed in cities, transport corridors, environmentally sensitive landscapes, and areas where overhead infrastructure is constrained by land use, safety, aesthetics, or climate exposure. Although they are simply defined as underground cables, their dynamics are influenced by a broader infrastructural assemblage encompassing joints, terminations, protective coverings, trench geometry, drainage provisions, and the surrounding geomaterials.

A second significant category is cable duct banks, utility tunnels and underground cable galleries. These systems are more physically secure, offer more controlled routing, and can be serviced or expanded more easily than direct-

buried installations. Nevertheless, they cause other thermal and environmental regulation problems. Heat dissipation in ducted systems depends not only on the host ground but also on the conduit material, air gaps, spacing, and encasement arrangement. Ventilation, humidity, seepage, and structural confinement are also part of the electrical performance of cable tunnels and galleries. These systems are thus more a transition to a more mediated form of geo-electrical interaction rather than an escape from it^[69].

A third type comprises grounding and earthing systems, such as ground rods, grounding grids, counterpoise conductors, and other fault-current dissipation systems. These differ from cable systems since the ground is not just the host medium but an electrically active component. They are directly dependent on soil and rock resistivity, saturation state, salinity, layering, and seasonal environmental change. In practice, grounding systems can be both geographically extensive and functionally linked to substations, buried cable circuits, converter stations, renewable energy systems, and transport electrification networks. They thus play a key role in the integrity of the broader power system's safety and operations.

The fourth category consists of underground substations, transformer vaults, switching chambers, converter stations, and other enclosed electrical facilities. They are typically installed where there is limited surface land or in cases where there is a strategic, environmental, or planning advantage to underground development. Such facilities require a higher level of structural engineering, hydrogeology,

thermal management, ventilation, access planning, and electrical safety than buried cables. They are not as linear and are more spatially concentrated than cable infrastructure, and can be more susceptible to compound failures from flooding, localized heat buildup, fire, and limited access for maintenance.

Those with space or functional interaction with other subsurface assets are becoming a new category of systems, called hybrid and multi-functional systems. Some examples are integrated utility corridors, metro and transport tunnels that carry power systems, underground data-energy corridors, and infrastructure that is linked with energy geostructures or underground storage systems. The systems are indicative of a wider trend toward denser, more networked utilization of underground space. They are important not only for their ability to engineer complexity but also because electrical performance is increasingly reliant on cross-infrastructure interactions, including thermal interference, construction sequencing, groundwater disturbance, and common resilience constraints^[70].

Collectively, all these forms of infrastructure demonstrate that there is no single design logic to subsurface electrical systems. **Table 3** compares the main types of subsurface electrical infrastructure, the processes they primarily couple, and their design. The dominant processes in direct burial, ducted systems, grounding networks, and underground facilities differ, but share the same underlying principle: once electrical infrastructure is underground, the ground is no longer the setting for the functional system but part of it^[71].

Table 3. Types of subsurface electrical infrastructure, dominant coupled processes, principal performance criteria, and design challenges.

Infrastructure Type	Typical Application	Dominant Coupled Processes	Main Performance Criteria	Principal Design/Operation Challenges
Direct-buried power cables	Urban distribution and transmission corridors	Thermal-hydraulic-mechanical	Ampacity, insulation protection, service continuity	Moisture-sensitive thermal behavior, route heterogeneity, difficult fault repair
Duct banks/conduit systems	Dense urban corridors, planned utility routes	Thermal-mechanical-hydraulic	Protection, organization, maintainability	Reduced heat dissipation, settlement, water ingress, thermal interference
Cable tunnels/galleries	High-capacity corridors, multiple circuits	Thermal-mechanical-hydraulic-electrical	Ventilation, accessibility, service reliability	Heat buildup, seepage, structural maintenance, common-cause failures
Grounding/earthing systems	Substations, cable systems, converter stations	Electrical-hydraulic-chemical	Fault-current dissipation, touch/step safety	Resistivity variability, corrosion, seasonal drying, space limitations
Underground substations/vaults	Dense urban or strategic sites	Thermal-hydraulic-mechanical-electrical	Safety, continuity, ventilation, equipment protection	Flooding, fire safety, access constraints, environmental control

Table 3. *Cont.*

Infrastructure Type	Typical Application	Dominant Coupled Processes	Main Performance Criteria	Principal Design/Operation Challenges
Hybrid utility corridors	Multi-service underground systems	Multi-physics and cross-infrastructure coupling	Spatial efficiency, resilience, maintainability	Thermal interference, maintenance conflicts, cascading failures

4.2. Functional Requirements and Performance Criteria

The performance of electrical infrastructure installed below ground must be compared against a list of requirements that are more extensive than those applied to most above-ground systems. Underground assets should at least meet the electrical continuity, thermal adequacy, mechanical stability, safety, durability, and maintainability. The difficulty with subsurface environments, however, is that these criteria are closely related and, in some cases, complementary. A mechanically robust design can be thermally inefficient, a design that provides the best thermal performance can become more difficult to maintain, and a design that meets the initial electrical design can fail due to long-term hydrogeologic change^[72].

Electrical functionality is the most important requirement. Power has to be delivered or handled by cables, joints, substations, and grounding systems, which can perform their functions under both normal and abnormal operating conditions. Nevertheless, under subsurface conditions, electrical performance cannot be determined without environmental support. How effectively a cable can carry current, such as its resistance to heat dissipation, is determined by its ability to dissipate heat into adjacent soil or a building enclosure. The ground's conductive properties can change with time, affecting the safety of an earthing system. Underground performance criteria should therefore be construed as system criteria rather than component criteria.

Of particular concern is thermal adequacy, as underground systems lack the direct cooling to the atmosphere that overhead infrastructure provides. Permitted operating temperatures, thermal gradient, emergency loading capacity, and post-overload recovery all require the thermal performance of the host environment. These are not the only problems with high-voltage transmission cables. Thermal constraints can also be an issue in medium-voltage systems in high-density urban corridors, cable galleries, and underground substations, especially when many circuits are co-located or subject to limited ventilation. Thermal performance must

then not be viewed as a local cable-rating problem but as a key design requirement for underground networks^[73].

Mechanical and geotechnical requirements are also basic. Underground assets should be able to withstand settlement, redistribution of stress, external loading, disturbance of the construction process, and potential geohazard impacts without losing serviceability. But the structural question of whether a system is intact or not is not the standard one. In underground electric systems, even in the absence of overt structural failure, minor displacements, variations in confinement, or deterioration of contact conditions can have disproportionate operational impacts. Mechanical standards should thus comprise maintenance of functional geometry and environmental wholeness, rather than survival despite collapse or breakage.

The concept of maintainability is a more significant aspect of underground design than it is commonly recognized in design practice. Malfunctions in buried or enclosed electrical facilities are usually more difficult to detect, locate, access, and remedy than those in overhead systems. It follows that reliability cannot be specified in terms of the likelihood of failure alone, but also in terms of the hardness of recovery and the impact of delayed response. A system that is efficient in a steady state but almost unreachable in an emergency may not be a high-performing system from a lifecycle perspective^[74].

The immediate implication is that performance requirements for subsurface infrastructure must be incorporated, rather than discipline-based ones. The electrical, thermal, mechanical, and operational needs should be evaluated in unison throughout the system's service life. In the absence of such integration, the designs could meet formal requirements in each domain yet remain susceptible at the system level.

4.3. Thermal Behavior and Ampacity of Buried Cables and Related Systems

One of the most determining factors in subsurface electrical infrastructure is thermal behavior, since the carrying

capacity of a system of buried cables in terms of current-carrying capacity, or ampacity, is dictated by the surrounding environment's ability to absorb and dissipate heat. In overhead systems, a relatively responsive cooling mechanism is through convective and radiative cooling of the atmosphere. Underground, on the other hand, the heat has to be conducted through cable insulation, bedding material, backfill, ducts, or tunnel air, and finally to soil, rock, groundwater, or structural enclosure. This inherently constrains the underground thermal field further and makes it more vulnerable to material variability.

The effective thermal resistance of the cable-ground system is not merely a simple factor in determining buried cable ampacity, but the most critical factor in determining the cable's ampacity. The thermal conductivity, density, moisture content, and degree of saturation of soils, as well as the burial depth, circuit spacing, type of backfill, and stratigraphy in the immediate vicinity, all affect the generation of heat transfer, and the development of thermal plumes is affected by the burial depth, circuit spacing, type of backfill, and local stratigraphy. These effects are frequently simplified in standard rating calculations, yet in reality can vary significantly along a route. Consequently, localized subsurface conditions might dominate the thermal bottleneck of a cable circuit instead of route-average properties.

One of the key problems is that thermal properties are dynamic. Heat can cause drying of unsaturated soil around energized cables, decrease moisture content, and increase thermal resistivity. This feedback can significantly decrease cooling efficiency and, thus, practical amplitude compared to the original design assumptions. It has a significant impact on fine-grained or partially saturated soils, where water redistribution strongly influences heat transfer. Ampacity in such environments is not a predetermined value but a dynamically evolving feature of the ground's changing thermal and hydraulic conditions^[75].

Additional complexity is introduced by related systems such as duct banks and cable tunnels. Ducted systems can also have their thermal resistance increased by air voids, conduit material, and the geometry of encasements, even when the surrounding ground is conductive. The problem in tunnels and galleries changes to combined conduction, convection, and ventilation. This heat buildup can be an issue on the system level, particularly with several high-load circuits

crammed into a small area. In this way, the thermal issue of underground infrastructure is not limited to directly buried cables but applies to a variety of underground arrangements.

The more analytical argument here is that ampacity is not to be regarded as an electrical property of an asset. It is part of the infrastructure and its environment. Designs that do not account for route-dependent thermal behaviour or moisture movement, or thermal interference, can be formally consistent with standard assumptions but may perform conservatively poorly or, worse, unsafely under actual operating conditions^[76].

4.4. Grounding, Earthing, and Electrical Resistivity Issues

Grounding and earthing systems are among the clearest examples of the active role of the subsurface in electrical infrastructure. Their purpose is to dissipate fault currents, stabilize reference potentials, and reduce risks to equipment and human safety. Unlike buried cables, whose primary interaction with the ground is often thermal and mechanical, earthing systems depend directly on the electrical behavior of the soil and rock mass. This makes subsurface electrical resistivity a first-order design parameter.

Electrical resistivity is governed by a combination of saturation, pore-fluid chemistry, porosity, mineralogy, clay content, temperature, and geological layering. As a result, the ground cannot be assumed to behave as a homogeneous conductor. Even where average resistivity values appear acceptable, stratification, localized dry zones, fractured rock, or anthropogenic fill can produce strong spatial variation in conductive pathways. The performance of a grounding network therefore depends not only on the total amount of conductive material installed but on how current is distributed through a heterogeneous subsurface medium^[77].

Seasonal and operational variability complicate the issue further. Drying of near-surface soils can increase resistivity significantly, reducing the effectiveness of earthing systems during hot or drought periods. Groundwater fluctuation, salinity changes, freezing in cold environments, and thermal effects associated with current flow may all alter the resistivity field over time. This temporal instability is important because grounding systems are often assessed using one-time measurements or simplified design models. Such methods may obscure the fact that the most critical condition

is often not the average state but the least conductive period during which fault protection is most compromised.

There is also a durability dimension. Grounding components are commonly metallic and may be exposed to corrosive soils, saline groundwater, stray currents, or chemically aggressive fill materials. Over time, corrosion can reduce cross-sectional area, alter contact conditions, and impair long-term fault-current dissipation. Conductive enhancement materials may also change behavior through leaching, drying, or chemical transformation. Thus, resistivity issues are inseparable from lifecycle reliability.

A critical perspective is that grounding design has often relied on compensatory strategies, such as adding more electrodes or extending the grounding field, rather than more refined subsurface characterization. While such approaches may be practical, they are not always feasible in dense urban settings or in environments where adjacent infrastructure, corrosion risk, or land constraints limit grounding geometry. In those contexts, electrical resistivity must be treated not as a generalized soil property but as a dynamic geo-electrical condition requiring site-specific interpretation^[78].

4.5. Failure Modes, Degradation Mechanisms, and Reliability Concerns

Subsurface electrical infrastructure failures are seldom due to a solitary mechanism. In many instances, it develops through synergistic degradation mechanisms involving thermal stress, moisture alteration, chemical assault, mechanical agitation, or interfacial corrosion. This is among the reasons why underground systems are challenging to manage: the triggering cause can be hidden, the damage can accumulate over time, and the eventual failure can be unexpected after a long history of dormant susceptibility.

In the case of buried cables, typical degradation mechanisms include thermal overstress, insulation degradation, water ingress, sheath damage, joint defects, and focal overheating due to ineffective heat dissipation. Such mechanisms tend to interplay. Higher temperatures can hasten insulation degradation, and moisture ingress can impair dielectric integrity and alter local thermal conditions. Stress concentrations can be caused by differential settlement, construction damage, or slight variations in bedding continuity, which do not become apparent until joints or bends begin to fail. Cable reliability in this sense is not limited to the quality of

manufacture but also to the permanence of the surrounding subsurface environment^[79].

Grounding systems deteriorate due to corrosion, drying, resistivity loss, loss of effective contact with the soil, and material deterioration from repeated or environmental exposure to faults. Subsurface elements such as substations and cable tunnels are prone to flooding, ventilation conduction, limited fire conduction, seepage corrosion, and structural-environmental interactions, which affect equipment performance. The effects of failure in these closed systems can be magnified by hard-to-reach locations, slow recovery, and ripple-over effects on numerous circuits or components.

One of the most significant reliability problems is that underground assets are often evaluated positively because they are not fully exposed to surface risk factors such as wind, ice, or vegetation. It is so, but it may create the false impression of natural safety. The less visible yet equally significant risks to underground infrastructure include hydrogeological change, unseen corrosion, thermal accretion, geotechnical movement, and challenging diagnostics. Reliability analysis should thus consider not only the lower exposure to surface events but also the greater reliance on subsurface conditions, which are harder to verify and more costly to clean up.

Recoverability is another critical problem. A system with a comparatively low likelihood of failure but with high service risk may occur when faults are difficult to detect and repairs are slow and disruptive. This is particularly important in densely populated cities, where excavation can affect traffic, other utilities, and public safety. The concept of reliability in the subsurface environment must be interpreted as a blend of robustness, detectability, accessibility, and repairability, rather than a restricted element failure rate^[80].

4.6. Impacts of Urbanization, Renewable Energy Integration, and Network Expansion

The strategic significance of subsurface electrical infrastructure is rising due to broader changes in cities and energy infrastructure, driving the expansion of power assets underground. One of the primary factors is urbanization. With increased urban concentration, surface space is increasingly contested, planning regulations get more restrictive, and there is a need to develop land-efficient, visually non-obtrusive infrastructure. One commonly suggested way to respond to these pressures is to underground electrical sys-

tems. Nevertheless, urbanization does not simply increase the amount of subsurface infrastructure; it alters the conditions under which it must operate. The complexity of underground operations is exacerbated by congested utility corridors, anthropogenic fill, disturbed groundwater regimes, heat-island effects, and continuous nearby construction.

The integration of renewable energy is an extra pressure. High wind, solar, storage, and distributed generation power systems exhibit more fluctuating, bidirectional flows than traditional centralized systems. This variability may translate into more dynamic cable loading, increased thermal cycling, and additional requirements for converter stations, substations, and grounding systems. In other areas, the facilities required to transport renewable generation to urban areas where the demand is located may entail long underground transmission lines or strategically located converter stations in geologically challenging locations. Therefore, decarbonization has the potential to indirectly increase the importance of geoelectrical constraints^[81].

Subsurface development is also a result of broader-scale network expansion. Transport electrification, the expansion of infrastructure that consumes large amounts of data, and rising demands for reliability all require strengthening of distribution and transmission systems. In fully developed urban networks, this growth is often not possible merely through the expansion of existing surface corridors. Rather, utilities are exploring deeper, denser, and more integrated underground solutions. However, this growth lowers the redundancy margins when several important circuits are pooled in common corridors, tunnels, or facilities. It can also introduce cross-infrastructure vulnerabilities, meaning that the failure of one underground system will affect many others.

One crucial aspect is that these trends not only increase the prevalence of subsurface electrical infrastructure but also make it more impactful. The underground shift is commonly explained through the prism of resilience, sustainability, and compatibility with urban environments, yet it introduces novel systemic reliance on the geological definition, thermal regulation, groundwater management, and lifecycle tracking. That is, urbanization and the energy transition do not merely heighten the need for underground infrastructure; they also heighten the cost of not understanding the subsurface.

In this regard, future planning should no longer be

based on the premise that undergrounding is always desirable. The real issue is which geological, geotechnical, thermal, and operating conditions enable underground electrical systems to provide better performance throughout their life cycle. That question cannot be answered by simple spatial or aesthetic reasoning, but rather by an integrated assessment. Electrical infrastructure in the ground is at the heart of modern power systems, yet its effectiveness will be determined by whether the expansion is accompanied by correspondingly advanced treatment of the ground as a component of the infrastructure^[82–84].

5. Coupled Processes, System Behavior, and Modeling Approaches

5.1. Thermo-Hydro-Mechanical-Electrical-Chemical Coupling Mechanisms

Coupled thermo-hydro-mechanical-electrical-chemical processes determine the behavior of subsurface geo-electro systems, the interactions of which are usually non-linear, path-dependent, and highly site-dependent. Even though these processes are often the focus of part studies, they are important in that none of them occurs in isolation after the electrical infrastructure is undergrounded^[85]. The subsurface is transformed into a reactive environment where dissipation of energy, flow of water, redistribution of stress, electrochemical reactions, and transformation of materials coexist and change with time.

The entry point to analysis is often thermal effects, as electrical power infrastructure, particularly buried cables and enclosed underground facilities, emits heat when powered. However, the thermal field about a cable or a grounding constituent is not just a passive gradient within an unchanging medium. The heating changes the state of the surrounding soils and rocks, especially in areas where unsaturated conditions dominate. Differences in moisture content between heat sources may develop as the diffusion of liquid flows or vapor intensifies, forming local drying regions that raise thermal resistivity and decrease the heat dissipation efficiency. One of the most obvious instances of coupled behavior is this feedback: electrical loading produces heat; thermal change due to hydraulic change; heat change due to hydraulic change; hydraulic change due to thermal change; thermal change due to hydraulic change. The resultant response is not propor-

tional to the load alone, but rather depends on the changing condition of the ground^[86].

Mechanical behavior is introduced into the system by the expansion and contraction caused by temperature, suction and effective stress variations, settlement, swelling, and redistribution of stresses around excavations or support systems. Such effects are particularly significant when the repeated loading cycles result in a cumulative response. Under certain conditions, heating in soils could decrease suction or alter stiffness, whereas drying could lead to shrinkage, cracking, or loss of contact between engineered backfills and other materials. Thermal gradients may act in concert with discontinuities, groundwater pressures, and the stresses imposed by excavations to change the deformation patterns in cable tunnels or underground chambers in rock masses. Mechanical changes can do more than just endanger structural integrity; they can also change thermal contacts, drainage routes, and component positioning and indirectly affect electrical performance.

This coupling also incorporates electrical processes. Ground resistivity is a function of saturation, salinity, temperature, pore structure, and mineralogy, such that the conductive nature of the subsurface changes with the change of the environment, as well as the operation of infrastructure. Fault currents, stray currents and potential gradients can cause localized heating, speed up electrochemical reactions or react with metallic infrastructure outside the main electrical system. Materials and interfaces are, in turn, modified by chemical processes. The effective behaviour of the system can vary over time, even when the system has been built and the grounding elements have corroded, or the metallic sheaths have degraded, or the mineral has precipitated or dissolved, or the backfills have been chemically altered^[87].

The value of chemical coupling can be underestimated since it usually operates at longer timescales than thermal or electrical transients. The slower processes often control the lifecycle performance, however. A thermally sufficient system at commissioning can be compromised due to corrosion modifying conductive pathways, salts migrating and altering the conductivity of pore-fluid, or due to repeated thermal cycling altering the microstructure of backfill materials. What is important is that coupled behavior is not merely a question of simultaneous physics, but rather a question of temporal interaction in which short-term operational pro-

cesses and long-term material evolution co-produce system performance.

5.2. Soil-Structure-Cable and Rock-Structure-Cable Interaction

The connection between electrical assets and the ground around them is mediated by engineered structures and interfaces; thus, soil-structure-cable and rock-structure-cable interactions are central to system behavior. This interaction is much more extensive than the traditional soil-structure interaction, since the performance measures of interest are not only displacement and stability but also heat transfer, electrical continuity, contact behavior, and environmental control. The cable or electrical element itself is not merely a piece of space in the ground, but rather a component of an interface system, the quality of which is to be judged by whether design assumptions will be true in service.

In the case of directly buried cables, the contact between cable bedding, thermal backfill, and natural soil is crucial. Good thermal performance requires not only the nominal properties of each material but also the continuity of contact, compaction quality, moisture retention, and resistance to segregation or cracking. Even small cracks, desiccation-induced separation, or heterogeneous compaction may cause a significant change in thermal transfer. Here, the quality of geotechnical installation is a factor that determines the electrical performance. It is a theme of geo-electro systems: the difference between the quality of civil construction and electrical functionality is less evident underground than disciplinary practice is inclined to think.

In duct banks and conduits, interaction is more layered. The cable puts heating and stress on the walls of the conduits, internal fillers or air spaces, structural encasement, and the surrounding soils. The system acts as a composite medium and structural setup that either dampens or increases local ground variability. Likewise, the existence of liners, support structures, and void spaces in tunnels or underground substations alters the electrical asset coupling between the electrical asset and the host geology. Physical phenomena such as rock mass behavior, tunnel convergence, inflow of water, and degradation of linings can influence the service environment of cables or equipment by altering temperature, humidity, accessibility, and structural constraints^[88].

An analytical observation is that interfaces tend to be

the weakest aspect in characterization and design. The characteristics of materials can be determined in the laboratory, and the dimensions of structural components can be determined with reasonable certainty, but interface behavior under a combination of thermal, hydraulic, and mechanical loads is far more difficult to characterize. These interfaces develop over time. In certain environments, contact can be enhanced by consolidation or deteriorated by shrinkage, creep, vibration, repeated heating or groundwater activity, etc. This makes interface behavior one of the main sources of variation between field performance and design models. The full development of a sound knowledge of subsurface electrical systems must thus not focus on the properties of components but also on the continuity and change of the interfaces between them^[89].

5.3. Effects of Environmental Loading and Operational Conditions

The subsurface electrical infrastructure is subject to environmental loading and operational forces that can significantly change system behavior over time. Environmental loading involves seasonal variations in moisture, groundwater, and ambient temperature, ground movement due to earthquakes or other geohazards, and anthropogenic disturbance from neighboring construction or utility work^[90]. Operational conditions include the magnitude of load, cyclic loading, overload events, fault conditions, network reconfiguration, and maintenance interventions. The point of concern is that environmental and operational factors are not separate; they frequently interact to influence the latency of vulnerabilities, which may hold or develop into critical ones.

Of particular importance is seasonal variability. In most environments, the worst-case scenario for underground cable systems is not high electrical load per se, but the combination of high load with dry ground and high ambient temperatures. In this case, the reduced availability of moisture may enhance thermal resistance, and the system is under thermal pressure during operation. In the case of grounding systems, the resistivity increases in the dry season can impair fault-current dissipation at the time network conditions are also stressed. It implies that design methods using annual averages or fixed boundary conditions can overlook the operating ranges that determine real risk^[58].

Another dimension arises from load cycling. Renew-

able integration, distributed generation, electric mobility, and dynamic demand patterns are contributing to increased variability and non-stationary loading in modern grids. The thermal fields in the ground might thus be transient rather than quasi-steady, and cyclic effects can produce progressive redistribution of moisture, progressive material fatigue, or non-recoverable interface changes. Technically compliant infrastructure under steady-state assumptions may behave differently under high-frequency variability in operations. This is especially applicable in the case of circuits in groups or tunnel systems, or congested corridors where there is thermal interference.

Another system resilience test is extreme events. Couplings that are not readily visible during normal operation may be disclosed by fault currents, flooding, rapid draw-down or recharge of groundwater, local slope movement, or accidental excavation around buried assets. Important features of such events are that they not only pose a threat of instant failure but can also have an irreversible effect on the surrounding subsurface environment. A flood can alter the chemical or hydraulic regime; a fault event can cause local heating and expedite degradation; local construction can change the drainage or stress conditions of an existing cable corridor. Operational evaluation should thus take into account the potential that environmental shocks reorganize the geo-electro system itself^[91–93].

The bigger picture is that performance standards cannot be developed with reference to normal service conditions. They should also cover the response of the system to variable, compounded and extreme conditions with time. In underground infrastructure, resilience is not about isolated design margins but rather the ability of the interconnected ground-asset system to adapt to change without excessive reliance on unfavorable feedback regimes.

5.4. Laboratory Testing and Field-Scale Experimental Studies

Experimental investigations provide the empirical foundation for the study of coupled processes in geo-electro systems, yet they also demonstrate the challenge of replicating field behavior in controlled experiments. The laboratory test has been particularly useful for determining thermal conductivity, thermal resistivity, moisture retention behavior, electrical resistivity, and thermal behavior of the backfill materials.

The importance of such tests lies in demonstrating that key parameters are highly dependent on density, saturation, mineral composition, and temperature. They are also used to compare alternative backfills, cable bedding materials, and conductive enhancement media of grounding systems.

But there are inherent limitations in laboratory testing. Specimens tend to be small, fairly homogeneous, and subject to simplified boundary conditions, compared to real subsurface systems, which are heterogeneous, layered, and subject to dynamic hydraulic and thermal fields. Mechanisms can be identified in the lab, but processes that are scale-dependent (e.g., preferential flow, route-scale variability, interface degradation, or long-term coupled evolution) are usually difficult to model. This is why the immediate mapping of laboratory-derived properties into design models can be deceptive unless the representativeness of the tested state is taken into account.

Field-scale studies are needed to give a counterbalance. Instrumented cable test beds, monitored trenches, full-scale trials of thermal backfills, tunnel monitoring, and in situ resistivity surveys are used to reveal the nature of coupled processes under realistic conditions. These experiments are especially useful for capturing dynamic moisture movement, thermal coupling between circuits, groundwater effects, and the separation between nominal material characteristics and actual in-service characteristics. Field studies have constraints, however. They are costly, frequently location-specific, and not easily generalized, as every system monitored represents some unusual combination of geology, quality of construction and operating history^[94].

The most fruitful plan of experiment is not, then, to oppose laboratory and field studies as rival sources of truth, but as opposite scales of evidence. Mechanisms and parameter dependencies are best assessed through laboratory work, and system emergence, validation, and practical significance through field studies. The scales should be explicitly linked by a mature research framework and not used to replace one another.

5.5. Analytical, Numerical, and Data-Driven Modeling Approaches

Simplified analytical formulations of subsurface geoelectro systems have been developed to more complex numerical and hybrid models. Analytical models remain effective

because they are transparent, computationally efficient, and provide a clear understanding of the dominant control variables. In thermal cable analysis, e.g., simplified conduction-based solutions remain foundational to many engineering standards and design tools. Their long-term usefulness lies in their practicality and in helping with quick design iterations. But their shortcomings are also quite evident: they usually assume homogeneous material behavior, simplified geometry, steady or idealized transient behavior, and weak coupling between thermal and hydraulic effects.

Numerical models have broadened the capability to model layered ground, intricate geometry, overland water flow, transient loading, mechanical deformation, and coupled multiphysics behavior. Particularly notable in the analysis of thermal fields around cables, grounding system behavior in stratified media, and the thermo-hydro-mechanical behavior of tunnels and underground facilities are the use of finite element and finite volume methods. These models provide a far richer framework for incorporating geological heterogeneity and operational variability. However, they also pose new risks. Model sophistication may go beyond data quality, making an impression of accuracy that is not backed by site characterization. In reality, the numerical method is frequently not a limiting factor, but rather parameter, interface, and boundary condition uncertainties^[94].

There is a growing interest in data-driven approaches to supplement physics-based models. Machine learning, reduced-order surrogates, and sensor-informed predictive systems can enable real-time evaluation, anomaly detection, and optimization of operations. They are most endearing to the extent that infrastructure is instrumented and historical data can be used to learn repeating patterns of loading and response. Nonetheless, purely data-driven methods have major limitations in subsurface systems due to the sparsity of observations, the lack of failure data, and the fact that most governing processes are non-stationary. In the absence of a physical interpretation, predictive models can perform well under known conditions but fail during transitions between environmental regimes or when rare events occur.

Integration, not replacement, is the most promising direction, then. Analytical models can still be useful in screening and conceptual intuition; site-specific coupled analysis requires numerical models; and data-intensive tools can be more helpful in making predictions and condition evaluation,

as long as they are grounded in physical arguments. There is no single modeling paradigm that would suffice in geo-electro systems. **Table 4** summarizes the main modeling methods and monitoring tools for geo-electro systems, along

with their advantages and shortcomings. The difficulty lies in balancing the complexity of the models with the needs of decision-making without deceiving about the uncertainty and data constraints^[3,6,29].

Table 4. Modeling approaches and monitoring tools for geo-electro systems: Purposes, strengths, limitations, and suitable applications.

Approach/Tool	Main Purpose	Strengths	Limitations	Most Suitable Use
Analytical models	First-order estimation of thermal/electrical behavior	Fast, transparent, useful for screening	Simplified geometry and material assumptions	Early design, sensitivity checks, standard compliance
Numerical multi-physics models	Coupled THMEC simulation	Can represent heterogeneity, transient loading, and complex geometry	Data-intensive, uncertain parameterization, higher complexity	Critical assets, difficult geology, tunnel systems, detailed design
Probabilistic/uncertainty models	Risk-informed performance assessment	Captures variability and confidence bounds	Requires structured uncertainty data	Route selection, design margins, lifecycle planning
Data-driven/machine learning models	Pattern recognition and prediction from monitored data	Useful for anomaly detection and operational support	Weak extrapolation beyond observed conditions	Condition assessment, operational forecasting
Distributed temperature sensing	Thermal monitoring along cables/tunnels	High spatial coverage, real-time or near real-time	Does not directly explain the cause of anomalies	Hot-spot detection, load management
Resistivity surveys/measurements	Assessment of grounding environment and moisture condition	Useful for earthing design and seasonal comparison	Sensitive to interpretation and environmental variability	Grounding design, monitoring of resistivity change
Settlement/deformation monitoring	Detection of geotechnical change	Directly tracks serviceability risk	May not capture hidden environmental causes	Tunnel systems, unstable corridors, critical joints
Groundwater and moisture monitoring	Hydrogeological condition tracking	Links thermal and corrosion behavior to field state	Requires long-term maintenance	Sites with variable saturation or seepage

5.6. Uncertainty, Scale Effects, and Model Validation Challenges

There is no external complication of geo-electro modeling; it is a characteristic of the problem. Predictive confidence is limited by geological heterogeneity, incomplete site study, changing boundary conditions, uncertain interface behavior, and insufficient long-term monitoring. This is added to by scale effects. Measurements at the specimen scale might not reflect trench-, corridor-, and facility-scale behavior. Local anomalies can control failure and go unobserved in route-averaged models. On the other hand, highly detailed local models can fail to capture broader interactions within the system that are realised when the network or seasonal loading occurs^[95].

Among the hardest to validate is the fact that field performance data are usually piecemeal. Temperature measurements do not necessarily have simultaneous moisture measurements; defects may manifest as failures without explaining the causal history; a model calibrated in the laboratory may work well over short periods but become out of

balance over longer periods as the state of the material varies. Validation is thus hardly an act. It needs to be viewed as an iterative process where models are being revised as the monitoring data gets more and more, and as the evolving system tells which couplings are really active.

The temptation to equate calibration with validation is also a critical issue. A model can be optimised to mimic a small dataset and still be inaccurate regarding the mechanisms that will be important in the future. This is especially acute in highly parameterized numerical or data-driven models. In the case of subsurface electrical infrastructure, falsifiability, sensitivity analysis, and clear representation of uncertainty ranges should therefore be prioritized in robust modeling over single-value prediction. The decision-makers will often require an understanding not only of the most probable but also of the possible spectrum of undesirable results in a fluctuating environment^[96–98].

Practically, this implies that model results ought to be adaptive and management-oriented rather than deterministic. Not necessarily the most complex, but the ones that help clarify which uncertainties have a material impact on perfor-

mance and where further research or monitoring would most enhance confidence are the most useful models. With geoelectro systems, modeling is not important in that it removes uncertainty, but it aids in organizing the same.

6. Design, Risk Management, and Emerging Applications

6.1. Integrated Design Principles for Geo-Electro Systems

A break with the sequential disciplinary processes in which geological characterization, geotechnical design, and electrical design are treated mainly as independent processes is needed to design geoelectrical systems in the subsurface. This type of compartmentalization could be acceptable in simple installations on foreseeable ground, but would progressively fail as underground electrical infrastructure extends into denser, deeper, hotter, and more geologically diverse environments. The main design concept of geo-electro systems, then, is integration: the ground should not be viewed as a passive boundary condition but rather as the active component of infrastructure functioning^[99].

The integrated approach to design starts with the fact that key performance variables are co-produced by various domains. The ampacity of cables is a factor of the electrical loading and thermal-hydraulic ground behavior. Grounding performance is not only dependent on the electrode configuration but also on the spatial and temporal organization of the subsurface resistivity. The underground substations rely not just on structural support, but also on hydrogeological, thermal rejection, and long-term environmental stability. These interdependencies imply that design parameters cannot be chosen in isolation, risking inconsistent assumptions. A cable route selected for convenience may subsequently incur thermal penalties or groundwater issues that cannot be addressed economically through electrical upgrades.

The design process must thus be performance-based and mechanism-based. Rather than using set typologies or nominal parameter values, designers ought to recognize the most prevalent coupled processes that are likely to dominate performance at a particular location and then select layouts, materials, depths, and support systems based on this information. At certain locations, thermal control will prevail, and engineered backfill, spacing, and hydrogeological inter-

pretation will become decisive. In other cases, it could be geohazard avoidance or the ability to withstand deformation or grounding reliability that is the decisive factor. The usefulness of the geo-electro framework is that it helps determine which interactions are significant enough to warrant further design consideration.

Proportional complexity is another important principle. Integration does not imply that all projects need to be fully coupled and exhaustively site investigated using numerical simulation. Instead, the level of design effort must be proportional to the coupling intensity, uncertainty, asset criticality, and failure consequence. Simplifying complex systems can be cheap, whereas simplifying simple systems can create long-term weaknesses that are much more expensive than short-term design enhancements. A good design is not about as much sophistication as possible, but about judicious simplification, knowledgeably informed by interdisciplinary knowledge^[6,100].

The last principle is alignment of the lifecycle. Numerous underground systems are pegged to meet the conditions of commissioning, but are far less well pegged to property evolution, seasonal variations, accessibility to maintenance, or changed loading during decades of service. An integrated design approach should thus not just address whether the system is initially working, but also whether the assumptions on which the design is based stand the test of time as the ground and the network evolve. The integrated design, monitoring, and adaptive management of the geo-electro systems lifecycle-oriented workflow is shown in **Figure 2**.

6.2. Risk Assessment, Resilience, and Lifecycle Performance

The conventional component-based reliability measures are not sufficient to represent a risk in subsurface geo-electro systems. Since underground power resources operate in heterogeneous and dynamic geological media, failure often arises from interacting processes that span disciplinary boundaries. Risk assessment should thus shift from single-hazard identification to system-based analysis of coupled vulnerabilities, exposure routes, and recovery limits.

A good place to begin is to differentiate between inherent ground risk and risk that is caused by infrastructure. Geological variability, hydrogeological uncertainty, corrosive

environments, fault zones, landslide potential, settlement potential, and site conditions all contribute to inherent ground risk. Infrastructure-related risk is a situation in which the local subsurface state is altered by thermal loading, excavation, dewatering, or changes in drainage or the installation of grouped utilities, resulting in new hazards. The two tend to be mixed up. Even what seems to be a manageable site under

pre-construction conditions can become more susceptible when excavation of a tunnel changes the moisture distribution or groundwater regime. This is why, in many cases, the use of a static risk matrix tends to downplay subsurface uncertainty: it is more likely to categorize hazards as existing in advance of the infrastructure in question rather than as co-evolutionary with it^[101].

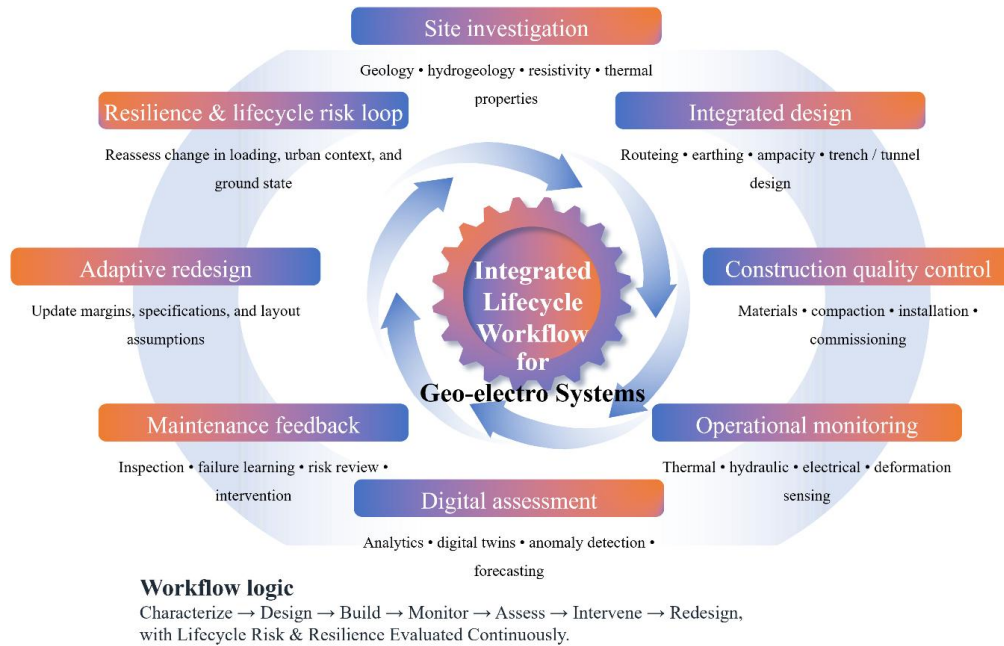


Figure 2. Integrated lifecycle workflow for the design, monitoring, risk assessment, and adaptive management of subsurface geo-electro systems.

Resilience offers a broader view than reliability, encompassing disturbance tolerance, continuity of functions, and recovery following disruption. Resilience in underground electrical systems is not simply about avoiding system failure but also about configurations in which faults are hard to detect, isolate, and fix. A buried cable system, which is highly inaccessible due to limited access, whose route conditions are uncertain, and which has high thermal interference between circuits, can be statistically reliable under normal conditions but operationally weak under abnormal conditions. Similarly, a sub-ground substation can be safe with respect to surface risks but very susceptible to flooding or to failure in smoke management. The geometry of failure consequences, the availability of affected components, and the rate of recovery to safe operation should therefore be considered in resilience analysis.

Lifecycle performance introduces a time aspect that

is critically relevant in geo-electro systems. The loading regimes are not fixed, and neither are ground conditions. Seasonal drying, groundwater variation, corrosion, repeated thermal cycling, urban densification, nearby excavation, and the use of networks can all cause the system behavior to deviate from the design assumptions. Risk management must thus be dynamic, not a one-time event. This involves considering monitoring, inspection, and re-evaluation as components of the system risk architecture rather than as add-ons to operations.

The critical analytical implication is that lifecycle risk is usually controlled through gradual transformation rather than abrupt events. Underground infrastructure sometimes collapses catastrophically, and more frequently, it becomes increasingly intolerant of stress over time as environmental and material changes accumulate. An effective risk system should be able to detect such trajectories in time, before it is

too late to act^[102].

6.3. Asset Monitoring, Condition Assessment, and Digitalization

Geo-electro systems are especially useful for monitoring because most of the most useful variables are obscured, distributed, and time-dependent. Compared to above-ground infrastructure, where the visible nature of the infrastructure can frequently provide direct insight into degradation or damage, underground infrastructure can only be inspected indirectly to determine how ground conditions and the infrastructure's behavior are changing. Monitoring is thus not diagnostic in nature, but epistemic. It helps eliminate doubt about whether or not the coupled system is actually acting as postulated.

In the case of buried cable systems, electrical indicators, including insulation condition, partial discharge, sheath integrity, and fault occurrence, have traditionally been used for condition assessment. These are fundamental; however, when isolated, they are not complete when treated without considering the surrounding subsurface environment. Temperature, distributed thermal, moisture, resistivity, settlement, and groundwater monitoring can indicate that the environment is already corroding but not yet exhibiting any electrical symptoms. This is particularly necessary where thermal margins are small or where local variations in soil conditions can cause incipient hot spots.

In grounding systems, performance is more difficult to monitor, since current diffuse pathways in the subsurface, and changing environmental conditions are at play. However, recurrent resistance measurements, corrosion evaluations, seasonal functioning surveillance, and resistivity surveys would provide clues as to whether the system is behaving as anticipated in the design or not. Monitoring temperature, humidity, seepage, deformation, and ventilation performance in underground substations and cable tunnels is integrated because electrical equipment is embedded in a coupled underground microenvironment rather than a fixed structural enclosure^[103].

Such information can be used in new ways through digitalization. The increasing accessibility of distributed sensing, remote telemetry, data integration systems, and predictive analytics opens the prospect of viewing underground infrastructure as a dynamically monitored system, rather than

a buried resource inspected primarily when issues emerge. Physics-informed asset models and digital twins can bridge the gap between operational information and knowledge of subsurface processes, particularly when used to update thermal, hydraulic, or reliability studies over time. What they promise, however, must be taken with a grain of salt. Digital tools do not eliminate the need for good geological and geotechnical interpretation; they just provide more continuous information on which to test or verify it.

False confidence is a key danger of digitalization. Rich data streams can foster the illusion that you have a system that is completely observable when, in reality, most of the processes that govern this system are indirect, sparse, or loosely measurable. Those strategies that involve a combination of sensor data, physically grounded models, and explicit uncertainty interpretation are therefore the most effective for digital condition assessment. Geo-electro systems make the most of data that contribute to understanding which assumptions are breaking down, rather than those that, in general, add to the mass of uncontextualized observations^[104].

6.4. Sustainability and Environmental Impacts

The concept of the sustainability of subsurface electrical systems is often viewed positively: undergrounding minimizes visual intrusion, liberates surface space, may mitigate susceptibility to certain climate-related risks, and can enable tighter, more efficient urban growth. These are actual benefits, but the critical sustainability analysis should also consider the environmental impacts and resource implications of the subsurface construction and operation. The fact that underground infrastructure is not exposed or land-efficient does not necessarily make it sustainable.

The impacts of construction are often significant. Excavation, disposal of spoils, dewatering, production of backfill and tunnel-lining materials, and the embodied energy of underground structures can entail high environmental costs. Trenching or tunneling can modify groundwater flow paths, drainage, or even geochemical conditions in sensitive hydrogeological environments. Material intensity can also be enhanced by using special backfills, conductive materials, corrosion-resistant metals, and heavy civil works, which are not as simple as surface substitutes. A sustainability assessment should thus involve the entire infrastructural footprint and not just operational land-use benefits^[82].

The concept of operational sustainability is not as simple as it may seem. Ineffective thermal design causes higher losses and can reduce the effective use of installed infrastructure, while corrosion or hydrogeological instability can decrease service life and raise replacement frequency. On the other hand, properly designed underground systems can operate efficiently for extended periods with comparatively minimal visual and land-use impacts. The sustainability question is therefore closely related to lifecycle performance: systems that are hard to maintain, tend to accumulate degradation, or require frequent maintenance might not be as sustainable in practice as their design justification would indicate.

Ecosystem and urban-environment considerations exist, too. Construction in the underground area can disrupt tree roots, urban groundwater, soil processes, archeological stratification, or land management pollutants. Under climate change, underground facilities in coastal or low-lying regions may be more exposed to fluctuating groundwater levels and flooding. These problems support the idea that sustainability is not a generalized idea about undergrounding but rather a site- and system-specific phenomenon.

A more positive sustainability approach to geo-electro systems is to maximize the contact between infrastructure and ground, compared to simply reducing the surface area effects. The underground electrical infrastructure can be made even more sustainable through better route selection, less overexcavation, thermally efficient, long-lasting materials, coordinated underground planning, and long-service-life design. In this regard, sustainability depends on combined subsurface stewardship just as much as on engineering effectiveness^[105–107].

6.5. Interfaces with Energy Geostructures, Underground Energy Storage, and Smart Infrastructure

The interface of geo-electro systems with other subsurface energy-related activities is an important emerging direction. The list of ways in which the subsurface is involved in energy systems is growing to include energy geostructures, underground thermal storage, compressed or pumped storage systems, hydrogen-related subsurface infrastructure, and smart utility corridors. This development questions the

conventional disciplinary limits, as the ground is no longer solely a support medium for electrical resources; it is increasingly involved in multifunctional energy transfer and infrastructure integration^[108].

A good example is energy geostructures. Buried electrical systems can be combined with foundations, retaining walls, or tunnels, whose thermal behavior depends on the ground's temperature and moisture content and whose thermal performance relies on the thermal capacity of the surrounding ground. In some configurations, the interaction is potentially synergistic, but in others, it is conflicting. Local thermal fields, groundwater behaviour, or moisture conditions can be modified by heat extraction or injection, which can affect cable ampacity or material durability. Likewise, underground thermal or energy storage facilities can alter the background temperature regimes, hydrochemical conditions or geotechnical stresses around electrical infrastructure. Such developments suggest that underground planning in the future will not only need co-location management but also coupled resource management.

This integration is extended to smart infrastructure corridors. With cities aiming to unify utilities underground, electrical infrastructure can be combined with telecommunications, district energy, transport infrastructure, water systems, and sensor networks. The benefits include coordinated access, reduced surface disruption, and improved spatial efficiency. Cross-system dependence can also be enhanced by shared corridors. When critical infrastructures are centralized, there is a high possibility of thermal interference, ventilation bottlenecks, exposure to flooding, conflicts on maintenance, and common-cause failure. The effectiveness of smart underground infrastructure is thus pegged on the ability to integrate it as a systems issue, but not as a spatial packing problem.

The greatest lesson here is that geo-electro systems are being brought closer to reality with the emergence of applications. Subsurface electrical infrastructure can no longer be universally considered an isolated asset that interacts only with geology. It is becoming entrenched in a more extensive, energized, and digital underground ecosystem. This increases the stakes of analysis, as the inability to grasp a single interaction can impact a variety of infrastructures simultaneously^[108,109].

6.6. Future Research Directions and Interdisciplinary Opportunities

The future of geo-electro systems lies in the continued development of scientific knowledge and the professional integration of these systems. One of the first research priorities is enhancing the representation of coupled processes under realistic field conditions. There has been significant advancement in the study of thermal analysis, resistivity modeling, and geotechnical characterization, yet there is still no complete integration of these fields, particularly in transient loading, seasonal soil variability, and long-term material degradation. Further field-calibrated, lifecycle-oriented studies are required to identify in which instances simplified assumptions hold and in which cases they can be misleading.

Uncertainty-aware modeling and decision support is a second priority. Spatial variability and temporal change are still obscured by deterministic parameter sets that serve as the basis for many underground infrastructure decisions. The research needs to shift toward structures that explicitly account for uncertainty in geological frameworks, hydraulic dynamics, interface dynamics, and shifting operational regimes. These frameworks would be particularly useful for route choice, thermal design margins, grounding strategy, and maintenance planning.

A third opportunity is to relate monitoring to design responses. The distributed sensing and digital asset systems are growing rapidly, yet their value will be constrained without a connection to transparent physical models and engineering-implementable boundaries. Studies are thus needed not only to develop new sensing technologies but also to explore how observed data could be utilized to inform revisions of design assumptions, instigate adaptive management, and enhance successive projects^[67,110,111].

Lastly, perhaps the most significant interdisciplinary opportunity lies in institutional change rather than technical change. The same underground systems are often being worked on by engineering geologists, geotechnical engineers, power engineers, hydrogeologists, corrosion and infrastructure planners, but with different conceptual models and varying definitions of risk. According to the geo-electro view, most chronic failures of comprehension do not stem from technical and scientific unsophistication but from the lack of a common language of analysis across these disciplines. Further development will thus rely on the development of

integrative methods, common design criteria, and educational frameworks that better reflect the coupled nature of subsurface infrastructure.

7. Conclusions

This review has posited that subsurface electrical power infrastructure should not be viewed as a collection of isolated engineered structures installed beneath the ground, but rather as a component of an integrated geoelectrical system in which geological media, geotechnical behavior, and electrical activity interact continuously. The surrounding ground serves as a dynamic, active medium for buried cables, duct banks, cable tunnels, grounding systems, and underground substations, where thermal dissipation, electrical resistivity, groundwater effects, mechanical stability, chemical aggressiveness, and the long-term reliability of assets are governed. The main conclusion is thus both conceptual and technical: the underground is not only the place where infrastructure is located, but also a component of the mechanism by which it functions. An important contribution of the review has been to demonstrate that numerous practical problems in underground power systems stem from a lack of discipline. Traditionally, engineering geology has been lithological, structural, weathering, and hydrogeological; geotechnical engineering has been deformation-based, stability-based, supporting, and soil-structure interaction-based; electrical engineering has been ampacity-based, insulation-based, earthing-based, and fault performance-based. These spheres, however, cannot be separated in the sphere. Thermal loading changes moisture and soil conditions; groundwater conditions affect cooling and corrosion; mechanical disturbance affects contact behavior and serviceability; and electrical operation itself is a perturbation of the ground. The performance of infrastructure is therefore a result of coupled system behavior rather than of individual material or component characteristics.

It has also been noted in the review that the behavior of geo-electro systems is multi-physics, multi-scale, and time-dependent. Thermal, hydraulic, mechanical, electrical, and chemical processes all couple through feedback mechanisms that can enhance local vulnerability, especially in areas where operational loading, seasonal environmental changes, and ground heterogeneity converge. This renders simplified design assumptions potentially troublesome when applied in

crowded urban corridors, under complex geologic conditions, or to long-lived, critical assets. Simultaneously, the review has emphasized that integration should not be associated with unwarranted analytical complexity. The difficulty lies in determining when more sophisticated characterization and modeling are required due to more robust coupling, greater uncertainty, or a greater impact of failure.

The other significant conclusion is that lifecycle thinking is crucial. Numerous underground structures are planned for initial or nominal conditions, but the environment in which they are served is changing through cycles of drying and wetting, groundwater movement, corrosion, repeated thermal loads, surrounding urban development, and network reconfiguration. Reliability in the subsurface is not just about starting with high design quality, but also about the system's ability to accommodate environmental and operational changes over time. This understanding would redirect the focus from unchanging compliance to adaptive risk management, monitoring, and condition-based operation.

The review also indicates that undergrounding is not inherently better, as it can be applied to modern power systems. Underground infrastructure can provide clear benefits in land-use efficiency, visual impact, and defense against certain surface hazards, but it also presents less obvious thermal, hydrogeological, geotechnical, and maintenance-related limitations. In this regard, undergrounding tends to replace one risk environment with another rather than eradicating risk. Good decision-making thus requires consideration of the overall geo-electro context of a project, such as conditions on routes, long-term servicing, and recoverability in the event of a failure, as well as broader interactions with urban and energy system change.

In the future, the article suggests a few priorities for research and practice. To start with, site characterization must be made more performance-based by relating geological and geotechnical observations to the most pertinent coupled processes to the electrical infrastructure. Second, uncertainties, scale dependence, and property development should be modeled more transparently. Third, monitoring and digitalization must not only be used to gather additional data but also to challenge the system's assumptions and enable adaptive management of assets. Fourth, new interfaces with geostructures of energy, underground storage, and smart utility corridors demand novel types of interdisciplinary planning that ac-

knowledge the subsurface as a collective and active infrastructure space.

To conclude, the idea of geo-electro systems offers a helpful, integrative approach to the re-conceptualization of underground electrical infrastructure, both scientifically and engineering-wise. It assists in integrating various strands of literature, demystifying the importance of coupled ground-infrastructure behavior, and aiding a move away from a discipline-independent design and to system-level insight. Such an approach will be more critical as cities grow denser, networks expand, and the energy transition relies more on subsurface space to provide resilient, efficient, and sustainable power infrastructure.

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