urban science

MDPI

Article

The Body Underground: A Biological Framework for Infrastructure Health, Regulation and Resilience

Priscilla Nelson [1] and Richard Little [2,*]

[1] Department of Mining Engineering, Colorado School of Mines, Golden, CO 80401, USA; pnelson@mines.edu
[2] Department of Industrial and Systems Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180, USA
* Correspondence: rglaicp@gmail.com

Abstract

Underground infrastructure systems are typically managed as discrete technical assets rather than as integrated, adaptive systems. This paper develops the Body Underground framework, a structured biological analogy that synthesizes prior clinical and epidemiological metaphors into a multiscale conceptual model linking materials, facilities, networks, and governance. Building on Little's clinical framing of infrastructure health and Bardet and Little's epidemiological analysis of network failure clustering, the framework extends biological interpretation to anatomical, physiological, and homeostatic scales. The approach maps structural, hydraulic, sensing, protective, and regulatory functions to functional equivalents in living systems using explicit criteria of feedback, regulation, and measurability. The central objective of the study is to determine whether biological regulatory concepts—particularly homeostasis and hierarchical organization—can provide a coherent interpretive structure for understanding infrastructure health across material, facility, network, and governance scales. The resulting framework reframes resilience as dynamic regulatory balance rather than static robustness alone. It clarifies the methodological basis for constructing biological–infrastructure analogies, identifies measurable "vital signs" for infrastructure health, and outlines pathways toward operational translation through integrated monitoring and governance feedback. While conceptual in nature, the framework provides a structured synthesis linking material science, infrastructure engineering, systems resilience theory, and policy coordination. By organizing resilience concepts through cross-scale regulatory logic, the Body Underground model offers a coherent structure for integrating monitoring, diagnosis, and governance in the proactive management of underground infrastructure systems.

Keywords: infrastructure health; urban systems; community resilience; underground systems

Check for updates

Received: 3 February 2026
Revised: 17 March 2026
Accepted: 18 March 2026
Published: 4 April 2026

1. Introduction—From Mechanical Metaphor to Homeostatic Systems

Urban underground infrastructure systems—water distribution, transportation tunnels, energy corridors, subsurface storage, and communication networks—are typically managed as collections of discrete technical assets. Resilience is often framed in terms of redundancy, robustness, and recovery capacity at the component or network level [1]. However, existing frameworks currently do not provide an integrated model that links material behavior, network interdependence, sensing architecture, and governance feedback into a unified explanatory structure and diagnostic tool.

Bio-medical metaphors have periodically been invoked to bridge this gap. Little [2] introduced a "clinical" approach to infrastructure health, building on diagnostic algorithms from emergency medicine, to position the engineer as diagnostician responsible for ongoing assessment and treatment. Bardet and Little [3] extended this analogy to epidemiology, demonstrating that infrastructure failures cluster in space and time, mimicking the response of human populations to disease outbreaks. These contributions provided compelling evidence that infrastructure systems exhibit dynamic behavior analogous to living organisms and could be amenable to diagnosis and intervention similar to medical protocols. Figure 1 traces this intellectual progression from a purely mechanistic perspective to the continually evolving biological analog that is described in this paper.

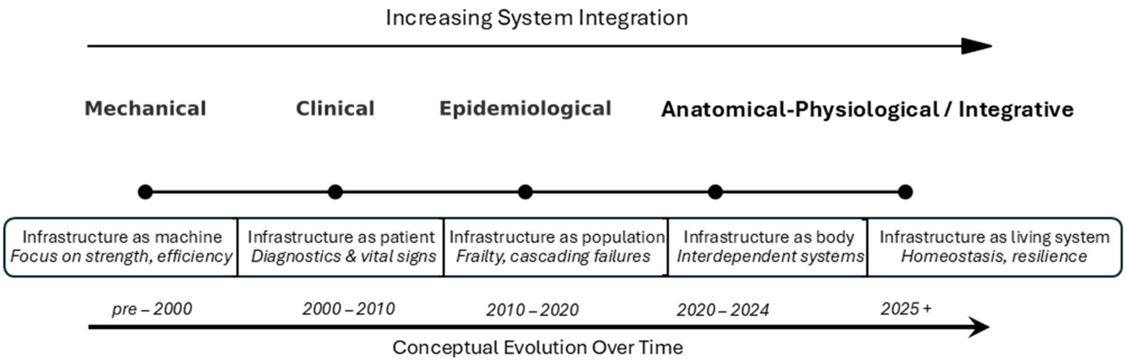

Figure 1. Evolution of the biological analogy in infrastructure thinking.

Yet these analogies have largely remained at the level of metaphor or partial mapping. A comprehensive multiscale framework—linking anatomy, physiology, regulation, and governance—has not been systematically articulated. The existing resilience literature often treats robustness, adaptability, and recovery as parallel attributes rather than as interdependent regulatory processes despite calls in the research literature for improved resilience methods and metrics that are both multidisciplinary and more holistic. For example, although biomimicry has produced an extensive literature, it is mostly comparative in nature and does not address potential linkages between infrastructure health management and preventive medicine. Hayes, Desha, & Baumeister [4] found that "Despite increasing biomimicry research, enquiry into infrastructure opportunities for biomimicry has been limited, and the potential for biomimicry to support regenerative performance in infrastructure has not been explored." Quinlan et al. [5] take a broad view of resilience as a property of complex adaptive systems that is not adequately addressed by engineering measures alone. At the same time, in their comprehensive review of resilience metrics, Sathurshan et al. [6] conclude "…it is vital that any disaster framework establishes a set of key resilience performance indicators. Such performance indicators can be relied upon in different phases of a disaster to consistently measure progress before, during, and after earthquakes and to make well informed resilience investment decisions for future risks." Further support for new approaches may be found in Almaleh [7], who posits that "Given the rapidly expanding understanding of Smart ICIs, it is imperative that all stakeholders confront these challenges head-on and endeavor to develop even more precise and effective resilience metrics and models." and Helmrich et al. [8], who present compelling evidence that resilient infrastructure practice only occasionally aligns with resilience principles from the natural world.

This paper advances the Body Underground framework as a structured conceptual synthesis that integrates prior biological interpretations into a coherent cross-scale model that aligns well with the principles of resilience engineering [9]. The framework extends the clinical and epidemiological perspectives into anatomical, physiological, and homeostatic domains, providing a unified logic for understanding and managing the health of underground systems as regulated, feedback-driven organisms.

This interpretation aligns with resilience engineering perspectives that view complex systems as adaptive entities whose stability depends on feedback, sensing, and response rather than static structural robustness alone. By framing infrastructure systems as regulatory hierarchies, the Body Underground framework connects material behavior, network interdependencies, and governance decision-making within a resilience-oriented analytical structure.

The central propositions of this paper are:

- Biological analogies become analytically useful when constructed through functional equivalence (feedback, regulation, exchange) rather than metaphorical similarity.
- Infrastructure resilience is more coherently understood as dynamic homeostatic regulation than as static robustness or redundancy alone.
- A hierarchical biological structure—cells, tissues, organs, systems, organism—provides a systematic crosswalk linking material science, facility design, network behavior, and governance feedback.

Accordingly, the central research objective of this paper is to develop and articulate a structured conceptual framework that links underground infrastructure systems to biological regulatory principles across hierarchical scales. The study asks whether biological concepts such as anatomy, physiology, and homeostasis can provide a coherent interpretive structure for understanding infrastructure health, monitoring system performance, and integrating engineering, sensing, and governance processes within a unified resilience framework.

The contribution of this work is integrative and structural. It does not introduce new empirical datasets; rather, it formalizes a framework that connects previously fragmented biological interpretations into a multilevel model that can guide monitoring, diagnosis, intervention, and policy design. By clarifying mapping criteria and scale relationships, the framework reduces arbitrariness in analogy construction and identifies measurable indicators ("vital signs") that would support proactive and timely intervention.

The remainder of the paper proceeds as follows. Section 2 describes the conceptual construction of the framework and the criteria used to map biological systems to infrastructure functions. Section 3 presents the hierarchical structure of the Body Underground across material, component, facility, network, and governance scales. Section 4 discusses implications for integration, monitoring, and policy. Section 5 outlines limitations and pathways for operationalization as well as research opportunities to address them.

Scope, Positioning, and Conceptual Rigor

This paper advances a structured conceptual framework rather than an empirical or quantitative model. Its objective is not to test performance metrics or propose universal thresholds, but to formalize a cross-domain interpretive structure that integrates biological and infrastructure systems thinking.

The Body Underground framework is positioned as a theory-building synthesis. It builds upon established infrastructure–health and resilience scholarship and extends prior biological metaphors into a multiscale, functionally grounded model. The contribution lies in organizing dispersed analogies into a coherent hierarchy that links material behavior, facility performance, network interdependence, sensing architecture, and governance feedback.

Rigor in this context is evaluated through three criteria:

- Functional equivalence: Biological mappings are constructed only where engineering systems exhibit comparable regulatory or exchange functions (e.g., circulation, sensing, feedback, protection), rather than superficial metaphorical similarity.

- Cross-scale coherence: The framework maintains internal consistency across hierarchical levels, ensuring that material-scale processes plausibly propagate to system-scale behavior.
- Operational plausibility: Proposed "vital signs" and regulatory analogs correspond to measurable quantities or observable governance processes in contemporary infrastructure systems.

The framework does not claim biological identity between organisms and infrastructure. It does not assert that deterioration mechanisms are physiologically causal in the biological sense. Rather, it proposes that regulatory principles common to both domains—feedback, exchange, adaptation, hierarchical organization—provide a structured lens for integrating resilience concepts that are otherwise treated independently.

As a conceptual contribution, the framework's validity rests on explanatory coherence, interdisciplinary consistency, and its capacity to generate testable propositions. Empirical validation would require future work applying the framework to specific facilities or networked systems, developing composite health indices, and evaluating whether homeostatic interpretations improve diagnosis or decision-making relative to conventional approaches.

The scope of this paper is therefore architectural rather than empirical: it establishes the structural logic of the analogy, defines mapping criteria, and outlines a pathway toward operational translation while acknowledging its limits.

2. Framework Construction Methodology

The Body Underground framework was developed through structured conceptual synthesis where biological–infrastructure mappings were evaluated according to explicit criteria of functional equivalence, measurability, and cross-scale consistency rather than empirical experimentation. This section describes the procedure used to construct, refine, and validate the biological–infrastructure mappings, with attention to reducing arbitrariness and ensuring cross-scale coherence.

2.1. Literature Lineage and Conceptual Foundations

The framework builds on three established strands of scholarship:

- Clinical infrastructure health, introduced by Little [2], which reframes asset management through diagnostic and preventive logic supported by algorithmic decision-making.
- Infrastructure epidemiology, articulated by Bardet and Little [3], which demonstrates spatiotemporal clustering of network failures analogous to the "harvesting" of the medically compromised during disease spread.
- Urban metabolism and systems scaling, including Wolman's metabolic framing in "The Metabolism of Cities," [10], which posits that urban systems possess a physiology of flows that parallels biological metabolism and the more recent examination of the relationships between urban design and biology by Narraway et al. [11]. Bettencourt et al. [12] conducted empirical scaling research which later confirmed that urban indicators obey organism-like allometric laws, and Samaniego & Moses [13] found that road networks follow vascular-system geometries, reinforcing the view of cities as living bodies.

Rather than introducing a new metaphor, this work synthesizes and extends these perspectives into a unified multiscale model. The objective was to formalize previously separate biological interpretations into a structured hierarchy linking material, facility, network, and governance scales that could serve as the basis for infrastructure health monitoring and management.

2.2. Criteria for Biological–Infrastructure Mapping

To avoid superficial or decorative metaphors, biological mappings were included only when they satisfied explicit functional criteria. Three conditions were required:

- Regulatory Function: The infrastructure element must participate in feedback, sensing, exchange, or protective processes analogous to those observed in biological systems.
- Measurable State Variables: The mapped function must correspond to observable engineering quantities (e.g., stress, flow, pressure, deformation, latency) or identifiable governance mechanisms.
- System Contribution: The mapped function must contribute to maintaining system stability, adaptation, or continuity under disturbance.

Mappings based solely on visual resemblance or linguistic similarity were excluded. For example, the term "artery" was used only where transport conduits distribute flow in a networked branching pattern with pressure regulation characteristics, not merely because a tunnel resembles a tube.

This functional equivalence criterion distinguishes structural analogy from metaphorical description.

2.3. Hierarchical Construction Procedure

The framework was constructed hierarchically, beginning at the material scale and proceeding upward to governance scale. Each level was mapped to its biological counterpart using iterative refinement.

The mapping sequence followed:

Cellular Level → Materials: Mineral grains, pores, bonds, and composites were interpreted as structural and reactive units responsible for strength, permeability, and sensing capacity.

Tissue Level → Components and Interfaces: Liners, joints, membranes, and transition zones were interpreted as connective tissues regulating stress and exchange.

Organ Level → Functional Facilities: Tunnels, shafts, pipelines, and reservoirs were interpreted as specialized organs performing transport, storage, or structural roles.

System Level → Networked Infrastructure: Interconnected lifeline systems were interpreted as coordinated organ systems governed by sensing and feedback.

Ecosystem Level → Governance and Policy: Institutional structures, regulatory frameworks, and funding mechanisms were interpreted as coordinating and endocrine-like regulators.

These relationships are graphically depicted in Figure 2, which also reveals that at each stage, downward and upward feedback pathways were explicitly examined to ensure cross-scale consistency. For example, material degradation processes must plausibly propagate to facility performance and eventually influence network reliability or governance decisions. This bidirectional consistency check reduced the risk of isolated or internally inconsistent mappings.

2.4. Handling Competing Analogies and Boundary Conditions

Not all infrastructure features map cleanly to biological systems. Where multiple biological analogs were plausible, preference was given to the mapping that:

Best preserved regulatory logic;

Maintained cross-scale coherence;

Avoided anthropomorphic overextension.

In some cases, no functional biological equivalent exists. For example, infrastructure systems do not self-reproduce biologically, and institutional adaptation may be significantly slower than physiological adaptation. Such divergences are acknowledged explicitly in the limitations section.

The framework therefore distinguishes between:

Structural analogs (e.g., skeleton–structure);

Regulatory analogs (e.g., nervous system–sensor network);

Metabolic analogs (e.g., energy throughput–resource transformation);

Non-equivalent domains, where analogy is inappropriate.

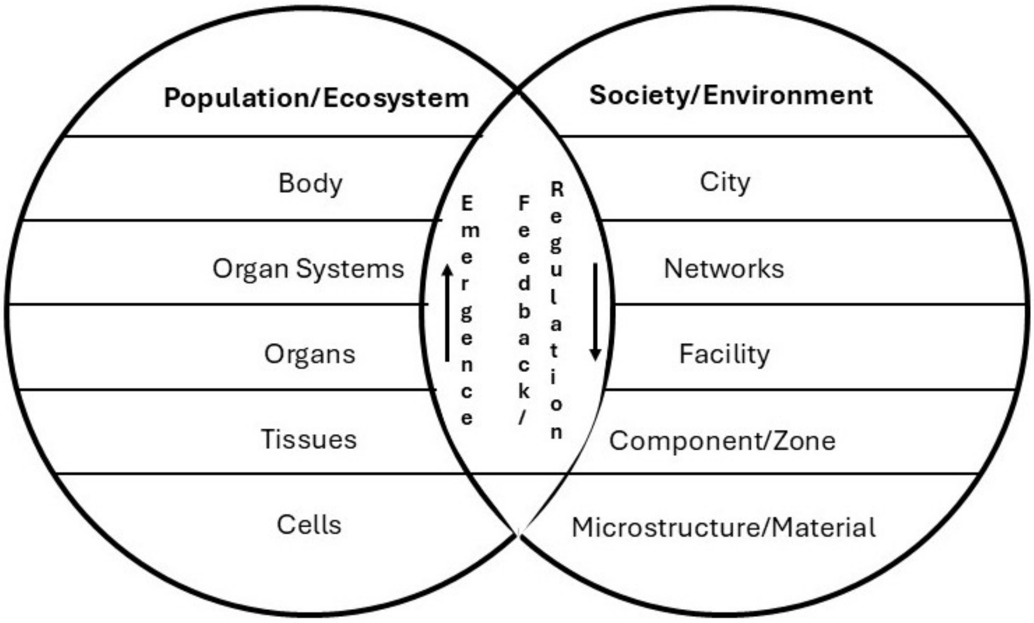

Figure 2. Hierarchical relationships between biological and infrastructure elements illustrating bidirectional feedback between infrastructure performance and governance response.

2.5. Conceptual Validation and Internal Consistency

Conceptual validation was conducted through iterative internal consistency testing:

Does each mapped subsystem exhibit identifiable feedback behavior?

Do failure modes correspond to breakdowns in regulation rather than merely mechanical rupture?

Can "vital signs" be defined at each hierarchical level?

Does governance plausibly act as coordinating regulator?

Where inconsistencies emerged, mappings were refined or removed.

This structured procedure transforms the Body Underground from narrative metaphor into a functionally grounded conceptual model.

2.6. Pathway to Operational Translation

While the present work remains conceptual, its structure supports future empirical development. Operational translation would involve:

- Defining composite health indices from identified vital signs;
- Testing predictive validity of homeostatic interpretations against conventional performance models;
- Evaluating whether feedback-based governance improves early intervention outcomes.

These steps, summarized in Table 1, are not claims of demonstrated performance but are proposed as future research directions that can be pursued in concert with new and novel directions guided by emerging medical models. For example, infrastructure research can further build on bio-medical paradigms and algorithms to take advantage of a wealth of untapped knowledge for prolonging and sustaining productive infrastructure life. See, for example, [14–16].

Table 1. Hierarchical scales and proposed research directions.

Scale	Core Function	Research/Diagnostic Gap	Example Application
Micro (Cells)	Material durability, sensing, self-healing	Long-term behavior of smart materials and microbial cements	Self-healing concrete in saturated soils
Meso (Tissues)	Component interaction, coupled behavior	Stress–seepage coupling and interface degradation	Lining–ground interaction under cyclic load
Macro (Organs)	Facility-level performance	Propagation of local failure and repair across organs	Tunnel or shaft response under variable stress
System (Body)	Network integration, feedback coordination	Modeling interdependencies and cascading effects	Multi-network coupling of power, water, and transport
Societal (Ecosystem)	Governance, ethics, and equity	Incorporation of social justice and sustainability metrics	ESG frameworks in infrastructure planning

3. Multiscale Framework Articulation: From Materials to Governance

Living systems maintain complexity through hierarchical organization: cells form tissues, tissues form organs, organs form coordinated systems, and systems interact within broader ecosystems. The Body Underground framework adopts this structure to organize underground infrastructure across nested physical and institutional scales. The purpose of this section is not to report empirical findings, but to articulate the framework's hierarchical architecture and demonstrate cross-scale consistency.

3.1. Material Scale (Cellular Analog)

At the smallest scale, underground systems are composed of materials—mineral grains, pores, bonds, reinforcements, and composites—that determine strength, permeability, deformability, and chemical reactivity.

The biological analog at this level is the cell: a fundamental structural and reactive unit that responds to environmental stimuli. In infrastructure, material microstructure governs load transfer, fluid migration, corrosion susceptibility, and crack propagation.

The framework proposition at this scale is:

Material-scale processes function as regulatory units when they exhibit responsive behavior (e.g., stress redistribution, self-healing reactions, sensing capability) that influences higher-scale stability.

Examples include:

Microcrack formation influencing structural stiffness;

Chemical reactions altering permeability;

Embedded sensing materials transmitting deformation signals.

Material degradation at this scale represents the earliest stage of pathology in the hierarchical model.

3.2. Component Scale (Tissue Analog)

Components and interfaces—liners, joints, membranes, drainage layers, transition zones—integrate materials into functional assemblies. Their performance depends not only on intrinsic material properties but on interface behavior and coupling.

The biological analog is connective tissue: structures that transmit force, regulate exchange, and maintain cohesion among cells and organs.

At this level, failure often emerges from:

Interface debonding;

Differential movement;

Localized seepage concentration;

Thermal incompatibility.

The framework emphasizes that early dysfunction frequently originates at interfaces rather than within homogeneous materials, mirroring biological tissue vulnerability.

Monitoring at this scale focuses on localized deformation, moisture migration, chemical gradients, and bond integrity.

3.3. Facility Scale (Organ Analog)

Distinct underground facilities—tunnels, shafts, pipelines, reservoirs, caverns—perform specialized functions analogous to organs in biological systems.

Examples include:

Transport tunnels functioning as circulation conduits;

Reservoirs as storage and buffering organs;

Ventilation shafts as respiratory regulators;

Retaining systems as skeletal supports.

The key analytical shift at this level is recognizing that facilities do not operate in isolation. Their performance depends on integration with sensing systems, flow regulation, and adjacent structures.

Failure at the organ scale typically reflects:

Impaired flow regulation;

Structural overstress;

Loss of protective redundancy.

The proposition at this scale is:

Facility resilience depends on the coordination of structural integrity, flow regulation, sensing feedback, and protective redundancy.

3.4. Network Scale (System Analog)

At the network level, facilities interconnect to form lifeline systems—water, energy, transportation, communication. Here, resilience becomes a property of coordination rather than individual strength.

The biological analog is the organ system (e.g., circulatory, nervous), where distributed components cooperate through feedback and redundancy.

Key characteristics at this scale include:

Flow distribution under variable demand;

Cascading failure potential;

Latency in sensing and response;

Redundancy and rerouting capacity.

Epidemiological clustering of failures, as identified by Bardet and Little [2], operates at this scale. Disturbances propagate through shared vulnerabilities and interdependencies.

The framework proposition is:

Network resilience emerges from feedback speed, redundancy distribution, and coupling management rather than from overdesign of individual components.

3.5. Governance Scale (Ecosystem Analog)

Beyond physical systems lies the institutional and policy environment that shapes maintenance priorities, investment cycles, inspection regimes, and emergency response.

The biological analog at this level is the endocrine and regulatory ecosystem: distributed signaling systems that coordinate long-term adaptation.

Governance influences:

Funding allocation (resource metabolism);

Regulatory thresholds (stability boundaries);

Monitoring mandates (sensory architecture);

Institutional learning (immune memory).

The framework emphasizes that infrastructure resilience cannot be fully explained at the material or facility scale alone; governance acts as a regulatory overlay that modulates the behavior of lower hierarchical levels.

Misalignment at this scale—such as deferred maintenance incentives or fragmented oversight—can amplify pathology despite material adequacy.

3.6. Cross-Scale Feedback and Emergence

A defining feature of biological hierarchy is bidirectional feedback:

Bottom-up emergence: Material degradation influences facility behavior; facility dysfunction propagates to network instability.

Top-down regulation: Governance decisions alter inspection frequency, which affects the detection of material degradation.

The Body Underground framework therefore treats resilience as emergent from multi-level feedback coordination.

Figure 2 illustrates these bidirectional flows, emphasizing that system health depends on communication across scales rather than static strength at any single level.

3.7. Analytical Implications of Hierarchy

The hierarchical articulation supports three analytical implications:

Diagnosis should identify the scale at which dysfunction originates.

Monitoring strategies should include representative vital signs at each hierarchical level.

Governance decisions should explicitly consider cross-scale propagation pathways.

By organizing infrastructure through biological hierarchy, the framework clarifies where regulatory capacity exists and where breakdowns in feedback occur. This can help in identifying preventative steps that can be taken to avoid or mitigate system failure. For example, Neumann & Cohen [17] and Saha et al. [18] among others, have shown that clinical preventive care can drive beneficial outcomes in patient health that are both measurable and cost-effective while Keller & Owen [19] and Stenström et al. [20] have shown that preventive maintenance of infrastructure assets is generally more cost-effective than corrective action.

4. Functional Regulation: Physiology, Vital Signs, and Homeostasis

Anatomy describes structural organization; physiology describes regulation. In biological systems, survival depends on dynamic exchange of matter, energy, and information under changing conditions. The Body Underground framework applies this regulatory perspective to underground infrastructure, emphasizing feedback, flow control, and adaptive response rather than static structural strength. This section articulates how regulatory processes operate across infrastructure systems and how they may be observed through measurable "vital signs."

4.1. Circulation and Exchange

Circulation in biological systems distributes nutrients, oxygen, and signaling molecules. In underground infrastructure, circulation corresponds to regulated movement of water, energy, air, materials, and people through networked conduits.

Flow regulation governs:

Hydraulic pressure stability;

Energy distribution balance;
Ventilation exchange efficiency;
Demand–capacity alignment.
Failure in circulation typically manifests as:
Blockage (sediment accumulation, fouling, obstruction);
Leakage or uncontrolled discharge;
Over-pressurization;
Network bottlenecks.

These processes are described mechanistically through fluid dynamics, thermodynamics, and systems theory. The biological analogy provides a regulatory lens, not a substitute for governing equations.

4.2. Stress Response and Structural Adaptation

All infrastructure systems operate under variable loading. Stress response corresponds to how structural elements absorb, redistribute, and recover from imposed forces.

Healthy regulatory behavior includes:
Elastic deformation within allowable limits;
Dissipation of transient loads;
Redistribution of stress through redundancy.
Pathological behavior emerges when:
Fatigue accumulates faster than repair;
Deformation exceeds reversible thresholds;
Monitoring latency prevents early intervention.

This regulatory framing aligns with resilience engineering literature that defines system performance under disturbance in terms of adaptive capacity rather than static safety margins.

4.3. Immune Function and Protective Redundancy

Biological immune systems detect threats, isolate disturbances, and promote repair. In infrastructure systems, immune analogs include:
Monitoring networks;
Early-warning thresholds;
Emergency shutoff systems;
Redundant pathways;
Post-event analysis and design adaptation.

The functional equivalence lies in threat detection and containment, not in biological causality.

An important distinction is that infrastructure immunity depends heavily on institutional learning and policy response, whereas biological immunity operates through cellular memory. This difference underscores the importance of governance-scale regulation in maintaining system resilience.

4.4. Vital Signs: Selection Criteria and Measurement Domains

Vital signs in biological medicine represent measurable indicators of regulatory stability. Translating this concept to infrastructure requires explicit selection criteria.

A candidate infrastructure vital sign must satisfy:
Sensitivity to early-stage degradation or instability;
Measurability using existing instrumentation;
Relevance to service continuity or risk propagation;
Interpretability within engineering theory.
Based on these criteria, representative vital signs include:

Stress and strain (structural loading balance);
Pore pressure or hydraulic head (circulatory stability);
Deformation and displacement (chronic imbalance detection);
Corrosion rate or chemical potential (material degradation rate);
Temperature or thermal flux (energy exchange stability);
Flow throughput and demand variability (metabolic rate);
Communication latency (feedback speed).

Each corresponds to established measurement methods (e.g., fiber-optic sensing, piezometers, InSAR, corrosion probes, SCADA analytics). Table 2 relates vital signs for infrastructure to their biological analog along with their diagnostic value and possible monitoring methods. These values would inform management algorithms as to the nature and timing of preventative or restorative actions as described by Salehi & Veitch [21] and Miranda, Moldovan & Moutinho [22].

Table 2. System vital signs for underground infrastructure.

Vital Sign	Measurement Domain	Physiological Analog	Interpretation/Diagnostic Value	Example Monitoring Method
Stress & Strain	Geomechanics/Structural physics	Muscular tension	Balance between load and support; early detection of overstress or fatigue	Fiber-optic strain sensing; inverse finite-element analysis
Pore Pressure/ Hydraulic Head	Hydrogeology/Fluid dynamics	Circulatory pressure	Efficiency of drainage, risk of saturation or liquefaction	Piezometers; transient flow simulation
Deformation & Displacement	Structural mechanics	Postural alignment	Settlement or creep indicating chronic imbalance	InSAR, extensometers, surface surveys
Chemical Potential/ Corrosion Rate	Geochemistry/ Electrochemistry	Cellular metabolism	Environmental aggressivity; rate of material degradation	Corrosion sensors; reactive transport modeling
Temperature/Thermal Flux	Thermodynamics	Body temperature	Heat exchange and metabolic inefficiency	Distributed temperature sensing; coupled heat–mass transport
Energy Throughput/ Flow	Systems dynamics	Metabolic rate	Demand vs. capacity; network stress and fatigue	SCADA energy analytics, process control
Communication Latency	Cyber-physical systems	Neural response time	Responsiveness of sensing and control networks	Data latency metrics; AI anomaly detection

The framework does not prescribe universal thresholds. Rather, it organizes measurable quantities into a regulatory interpretation of system health. Empirical research will be required to determine the "normal range" that the vital signs for various infrastructure systems should fall within.

4.5. Pathology and Cautionary Distinction

Table 3 maps common infrastructure deterioration mechanisms to biological disease analogs (e.g., blockage–atherosclerosis; fatigue–osteoporosis; cascading failure–systemic shock). These mappings are heuristic and pedagogical.

https://doi.org/10.3390/urbansci10040201

Table 3. Common biological pathologies and their infrastructure analogs.

Biological Analogy	Infrastructure Manifestation	Mechanism/Cause	Example
Atherosclerosis	Clogging of drainage or ventilation systems	Accumulation of sediment, corrosion products, or biological growth	Blocked culverts, fouled filters
Osteoporosis	Structural weakening or fatigue	Loss of density, cyclic loading, or material aging	Cracking in tunnel linings, joint degradation
Ischemia	Restricted energy or resource flow	Network bottlenecks, power or pump failure	Regional power outage, reduced water supply
Inflammation	Localized stress or expansion	Differential strain, reactive swelling, or corrosion	Expansive clay heave, spalling concrete
Sepsis	System-wide contamination or cascading failure	Cross-system infection via shared media	Contaminated aquifer causing service shutdown
Cancerous Growth	Uncontrolled expansion or extraction	Overdevelopment, unregulated excavation	Sinkhole formation from subsurface overmining

It is essential to distinguish between:

Metaphorical similarity (shared regulatory breakdown patterns);

Causal equivalence (biological disease processes).

The value of the analogy lies in recognizing patterns of regulatory breakdown, not in implying shared biological causation. For example, infrastructure corrosion is governed by electrochemical kinetics, not inflammation pathways. Network congestion arises from hydraulic and operational constraints, not arterial plaque.

4.6. *Stress–Response Trajectories and Regulatory Thresholds*

Infrastructure performance under disturbance can be conceptualized as a stress–response trajectory:

Stage I: Elastic response (reversible disturbance);

Stage II: Accumulating microdamage (progressive degradation);

Stage III: Functional impairment (loss of regulatory stability);

Stage IV: Collapse (systemic failure).

Figure 3 illustrates the generalized relationship between stress (disturbance level) and system performance for living and engineered systems for these four stages. Under mild disturbance, function degrades elastically and recovers fully—an adaptive response comparable to muscle training. Under sustained stress, the system enters a nonlinear region of progressive damage, analogous to chronic disease. Without intervention, it crosses a threshold into collapse—irreversible organ failure. This staged interpretation aligns with nonlinear performance models in resilience engineering as described by Yodo & Wang [23], where systems transition from stable basins of attraction into instability when feedback is insufficient. The framework reframes resilience as: "The capacity to maintain regulatory feedback within adaptive bounds under variable stress."

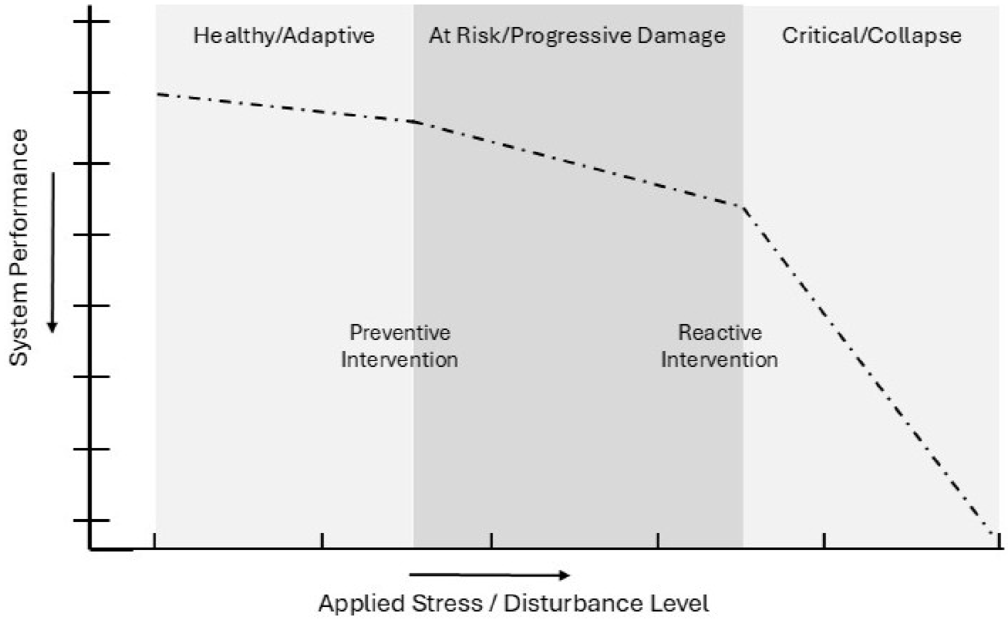

Figure 3. Conceptual depiction of the four stages of stress response.

4.7. Homeostasis as Dynamic Regulation

Homeostasis in biological systems refers to maintaining dynamic equilibrium through feedback loops. In underground infrastructure, homeostasis corresponds to the co-ordinated operation of sensing, control, and response mechanisms that maintain safe functional ranges.

Examples include:

Drainage systems regulating pore pressure in response to rainfall;

Ventilation systems adjusting airflow to pollutant concentrations;

Load management redistributing stress during peak demand.

Homeostatic interpretation emphasizes:

Feedback speed;

Threshold design;

Adaptive flexibility;

Recovery efficiency.

This shifts resilience away from overdesign toward responsive regulation.

4.8. Operational Pathway: From Vital Signs to Governance Feedback

While conceptual, the framework suggests a practical sequence:

Identify scale-specific vital signs;

Integrate monitoring into unified dashboards;

Define adaptive thresholds (not fixed binary limits);

Establish governance protocols for early intervention;

Incorporate post-event learning into updated standards.

This pathway does not require universal indices but supports iterative operational refinement.

The following two case vignettes illustrate how the Body Underground framework differs from a conventional mechanistic approach to a real physical problem. The holistic interpretation offered by the Body Underground produces a broad systemic solution rather than a narrower approach focused solely on the performance of a single component; in medical terms, treating the disease rather than just the symptoms.

Case Vignette 1: Tunnel Ventilation as Respiratory Regulation

Context

A metropolitan transit tunnel system experienced recurring short-duration service disruptions due to elevated particulate concentrations and intermittent ventilation shutdowns. Conventional maintenance focused on mechanical reliability of fan units and compliance with air-quality thresholds.

Conventional Interpretation

The system was treated as a collection of mechanical components. When particulate concentrations exceeded regulatory limits, ventilation fans were activated at maximum capacity. Maintenance schedules prioritized equipment uptime.

This approach addressed symptoms but did not reduce recurrence frequency.

Body Underground Interpretation

Within the physiological framework, the ventilation network functions analogously to a respiratory system regulating exchange between internal and external environments.

Diagnostic reframing focused on:

Airflow distribution balance (circulation efficiency);

Sensor latency in detecting pollutant buildup (nervous system response);

Feedback delay between detection and actuation (regulatory loop speed);

Localized zones of poor exchange (alveolar dead space analog).

Monitoring analysis revealed that particulate accumulation occurred in microenvironments with delayed sensor response and uneven airflow distribution. Ventilation capacity was adequate, but regulatory coordination was inefficient.

Intervention Shift

Rather than increasing fan capacity, the system implemented:

Distributed sensor placement in stagnant zones;

Adaptive airflow modulation based on localized measurements;

Reduced response latency through automated feedback.

The result was reduced peak concentration frequency and improved service continuity without increasing mechanical redundancy.

Framework Implication

The biological analogy shifted the diagnostic focus from equipment strength to regulatory balance and feedback coordination. It emphasized sensing architecture and response speed as resilience variables rather than solely mechanical capacity.

Case Vignette 2: Water Main Break Clustering as Epidemiological Propagation

Context

A municipal water distribution network experienced temporally clustered main breaks during winter freeze events. Traditional analysis evaluated pipe age, material type, and individual failure rates.

Conventional Interpretation

Each pipe segment was assessed independently. Replacement prioritization was based primarily on age and historical break frequency.

However, failure events continued to cluster spatially and temporally.

Body Underground Interpretation

Using the epidemiological lens (after Bardet & Little), clustered failures were interpreted as population-level vulnerability rather than isolated defects.

Diagnostic reframing examined:

Spatial adjacency of aging segments (shared exposure);

Pressure fluctuations transmitted through network loops (circulatory stress);

Soil frost heave interactions (external stressor);

Maintenance deferral patterns in specific districts (governance-scale regulatory imbalance).

Cluster analysis revealed that break propagation was influenced by hydraulic pressure redistribution following initial failures. Localized stress transfer increased vulnerability in adjacent segments.

Intervention Shift

Instead of replacing pipes solely by age ranking, the city:

Modeled network-level stress redistribution during freeze events;

Identified high-influence nodes with amplification potential;

Prioritized reinforcement of segments whose failure propagated stress;

Adjusted pressure management during peak freeze periods.

Break clustering frequency declined in subsequent seasons.

Framework Implication

The epidemiological interpretation shifted focus from individual asset failure probability to network-level regulatory propagation. It emphasized contagion dynamics and interdependence as resilience determinants.

5. Implications for Integration, Monitoring, and Governance

The Body Underground framework is intended as an organizing structure for integrating material behavior, network dynamics, and institutional decision-making. This section outlines implications for interdisciplinary integration, monitoring design, governance practice, and policy development.

5.1. Integration Across Disciplines

Underground infrastructure systems are typically managed within disciplinary silos: Geotechnical engineering focuses on structural stability, hydraulic engineering on flow control, electrical engineering on sensing networks, and policy specialists on funding and regulation. Resilience research similarly treats robustness, redundancy, and recovery as parallel constructs.

By organizing infrastructure through anatomical and physiological hierarchy, the framework provides a cross-domain vocabulary centered on regulation and feedback. Structural members, flow conduits, sensing systems, protective redundancies, and governance oversight can be interpreted as coordinated regulatory subsystems rather than isolated technical domains. This perspective is particularly relevant for infrastructure systems characterized by strong interdependencies, where disturbances in one subsystem may propagate across multiple networks through shared physical or operational coupling.

This perspective encourages:

Cross-disciplinary monitoring design (linking structural, hydraulic, and sensing data);

Joint failure analysis across lifeline systems;

Design standards that incorporate feedback speed and detection capability as resilience variables.

Rather than replacing existing engineering models, the framework offers a structure for integrating them into a holistic regime for managing infrastructure health and performance.

5.2. Monitoring Architecture and Diagnostic Logic

Traditional infrastructure assessment relies heavily on periodic inspection and threshold-based compliance. The physiological interpretation shifts emphasis toward continuous regulatory monitoring.

Practical implications include:

Defining vital signs at each hierarchical scale;

Prioritizing early-warning indicators over post-failure metrics;

Integrating distributed sensor data into coherent diagnostic dashboards;

https://doi.org/10.3390/urbansci10040201

Aligning threshold triggers with adaptive ranges rather than binary limits.

This does not imply abandoning safety factors or deterministic analysis. Instead, it supplements them with feedback-informed interpretation, consistent with contemporary resilience engineering approaches that emphasize adaptive capacity.

5.3. Governance as Regulatory Coordination

Infrastructure resilience depends not only on physical systems but on institutional feedback mechanisms. Funding cycles, inspection mandates, emergency response protocols, and regulatory enforcement collectively determine whether early warning signals translate into intervention.

Within the Body Underground framework, governance functions analogously to regulatory coordination systems. It influences:

Monitoring coverage;

Maintenance prioritization;

Redundancy investment;

Data transparency;

Cross-agency communication.

Failures at the governance scale often manifest as delayed response to detectable degradation, fragmented oversight, or underinvestment in preventive measures. Incorporating regulatory feedback into resilience planning requires:

Clear decision protocols linked to monitoring signals;

Cross-system communication standards;

Institutional learning mechanisms after disturbance events.

This interpretation aligns with resilience literature emphasizing adaptive governance and interdependency management.

5.4. Equity and Distribution of Infrastructure Risk

Infrastructure failure risk is not evenly distributed. Aging systems, deferred maintenance, and limited monitoring capacity often coincide with resource-constrained communities. A regulatory interpretation of resilience highlights that vulnerability can arise from insufficient feedback and protection rather than solely from material weakness.

Operational implications include:

Incorporating social consequence metrics into maintenance prioritization;

Ensuring monitoring infrastructure is equitably distributed;

Linking resilience investment to service continuity in vulnerable areas.

The framework does not prescribe policy thresholds, but it underscores that regulatory imbalance at the governance scale can propagate material and network-level risk.

5.5. Operational Roadmap for Conceptual Translation

Although the framework is conceptual, a staged pathway for translation is feasible:

Identify representative vital signs for selected facilities or networks.

Integrate monitoring data into unified dashboards emphasizing regulatory trends.

Establish adaptive response thresholds tied to governance protocols.

Evaluate performance relative to conventional compliance-based approaches.

Refine thresholds and indicators through iterative learning.

This approach allows for pilot implementation without requiring comprehensive restructuring of existing regulatory systems.

5.6. Limitations of the Biological Analogy

The biological framework definitely has boundary conditions that may limit or preclude its application in some circumstances. These include:

https://doi.org/10.3390/urbansci10040201

- Infrastructure systems do not self-reproduce or evolve genetically.
- Institutional feedback may operate on slower time scales than biological regulation.
- Some infrastructure types (e.g., static storage facilities) have limited functional analogy to circulatory or metabolic systems.
- Observability constraints may prevent the accurate identification of certain "vital signs."

The biological analogy is most appropriate where systems exhibit dynamic regulation, feedback, and interdependence. It is less informative for isolated or purely static structures. The framework should therefore be applied as an interpretive structure, not as a literal biological equivalence.

5.7. Summary of Implications

The Body Underground model contributes by:

Providing a structured cross-scale hierarchy;

Emphasizing feedback as the central resilience mechanism;

Integrating monitoring and governance into resilience interpretation;

Clarifying how material, facility, network, and institutional scales interact.

Its value lies in organizing resilience concepts into a coherent regulatory logic rather than in replacing established analytical methods and is supported by the findings of authors such as Naghshbandi et al. [24].

6. Conclusions

This paper has presented the Body Underground framework as a structured conceptual synthesis linking biological regulatory principles to underground infrastructure systems. Building on prior clinical and epidemiological analogies, the framework extends biological interpretation into anatomical, physiological, and hierarchical domains to organize material behavior, facility performance, network interdependence, and governance feedback within a unified structure.

The central argument is that infrastructure resilience can be more coherently interpreted as dynamic regulation—analogous to homeostasis—rather than as static robustness or redundancy alone. By emphasizing feedback, exchange, and cross-scale coordination, the framework provides a structured lens for integrating monitoring, design, and policy.

Three contributions are advanced. Together these contributions provide a structured conceptual bridge between engineering analysis, systems resilience theory, and governance decision-making in infrastructure management:

- A formalized set of criteria for biological–infrastructure mapping based on functional equivalence rather than metaphorical similarity;
- A multiscale hierarchical model linking materials, components, facilities, networks, and governance;
- An operationally oriented interpretation of "vital signs" as measurable indicators of regulatory stability.

The framework is conceptual and does not claim empirical validation within this study. Its validity rests on internal coherence, cross-scale consistency, and operational plausibility. Future research should test whether homeostatic interpretation improves early detection of degradation, enhances cross-system coordination, or supports more adaptive governance relative to conventional compliance-based models.

Several limitations warrant attention. Infrastructure systems do not replicate biological organisms, and institutional adaptation operates on different temporal scales than physiological response. Not all underground systems exhibit clear regulatory analogs, and monitoring constraints may limit the identification of meaningful vital signs. The framework should therefore be applied as a structured interpretive model rather than as literal biological equivalence.

Despite these limitations, the Body Underground provides an integrative structure that connects materials science, systems engineering, and governance within a shared regulatory logic. Its primary value lies in organizing resilience concepts into a coherent cross-scale model that supports interdisciplinary dialog and structured operational translation for proactive management of infrastructure health. Going forward, infrastructure research can further build on bio-medical paradigms and algorithms to take advantage of a wealth of untapped knowledge for prolonging and sustaining productive infrastructure life.

Author Contributions: Conceptualization, P.N. and R.L.; methodology, P.N.; writing—original draft preparation, P.N. and R.L.; writing—review and editing, R.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Argyroudis, S.A. Resilience metrics for transport networks: A review and practical examples for bridges. In *Proceedings of the Institution of Civil Engineers-Bridge Engineering*; Thomas Telford Ltd.: London, UK, 2022; Volume 175, pp. 179–192. [CrossRef]
2. Little, R.G. A clinical approach to infrastructure asset management? In *Framing the Challenge of Urban Infrastructure Systems (ASCE)*; American Society of Civil Engineers: Washington, DC, USA, 2008.
3. Bardet, J.-P.; Little, R. Epidemiology of urban water distribution systems: Modeling main breaks and failure clustering. *Water Resour. Res.* **2014**, *50*, 5658–5675. [CrossRef]
4. Hayes, S.; Desha, C.; Baumeister, D. Learning from nature–Biomimicry innovation to support infrastructure sustainability and resilience. *Technol. Forecast. Soc. Change* **2020**, *161*, 120287. [CrossRef]
5. Quinlan, A.E.; Berbés-Blázquez, M.; Haider, L.J.; Peterson, G.D. Measuring and assessing resilience: Broadening understanding through multiple disciplinary perspectives. *J. Appl. Ecol.* **2016**, *53*, 677–687. [CrossRef]
6. Sathurshan, M.; Saja, A.; Thamboo, J.; Haraguchi, M.; Navaratnam, S. Resilience of critical infrastructure systems: A systematic literature review of measurement frameworks. *Infrastructures* **2022**, *7*, 67. [CrossRef]
7. Almaleh, A. Measuring resilience in smart infrastructures: A comprehensive review of metrics and methods. *Appl. Sci.* **2023**, *13*, 6452. [CrossRef]
8. Helmrich, A.M.; Chester, M.V.; Hayes, S.; Markolf, S.A.; Desha, C.; Grimm, N.B. Using biomimicry to support resilient infrastructure design. *Earth's Future* **2020**, *8*, e2020EF001653. [CrossRef]
9. Madni, A.M.; Jackson, S. Towards a conceptual framework for resilience engineering. *IEEE Syst. J.* **2009**, *3*, 181–191. [CrossRef]
10. Wolman, A. The metabolism of cities. *Sci. Am.* **1965**, *213*, 178–193. [CrossRef]
11. Narraway, C.L.; Davis, O.S.; Lowell, S.; Lythgoe, K.A.; Turner, J.S.; Marshall, S. Biotic analogies for self-organising cities. *Environ. Plan. B Urban Anal. City Sci.* **2020**, *47*, 268–286. [CrossRef]
12. Bettencourt, L.M.A.; Lobo, J.; Helbing, D.; Kühnert, C.; West, G.B. Growth, innovation, scaling, and the pace of life in cities. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 7301–7306. [CrossRef] [PubMed]
13. Samaniego, H.; Moses, M.E. Cities as organisms: Allometric scaling of urban road networks. *J. Transp. Land Use* **2008**, *1*, 21–39. [CrossRef]
14. Panahi, O. Algorithmic Medicine. *J. Med. Discov.* **2025**, *2*, 00182.
15. Phillips, S.P.; Spithoff, S.; Simpson, A. Artificial intelligence and predictive algorithms in medicine: Promise and problems. *Can. Fam. Physician* **2022**, *68*, 570–572. [CrossRef] [PubMed]
16. Bellazzi, R.; Ferrazzi, F.; Sacchi, L. Predictive data mining in clinical medicine: A focus on selected methods and applications. *Wiley Interdiscip. Rev. Data Min. Knowl. Discov.* **2011**, *1*, 416–430. [CrossRef]

17. Neumann, P.; Cohen, J.T. Cost savings and cost-effectiveness of clinical preventive care. *Synth. Proj. Res. Synth. Rep.* **2009**, 48508. Available online: https://www.researchgate.net/publication/51766836_Cost_savings_and_cost-effectiveness_of_clinical_preventive_care (accessed on 16 March 2026).
18. Saha, S.; Hoerger, T.J.; Pignone, M.P.; Teutsch, S.M.; Helfand, M.; Mandelblatt, J.S.; US Preventive Services Task Force. The art and science of incorporating cost effectiveness into evidence-based recommendations for clinical preventive services. *Am. J. Prev. Med.* **2001**, *20*, 36–43. [CrossRef] [PubMed]
19. Keller, S.; Owen, A. A Comprehensive Cost-Benefit Analysis of Preventive Maintenance Versus Corrective Maintenance: Assessing the Financial Impact and Operational Benefits in Engineering. 2025. Available online: https://www.researchgate.net/profile/Antony-Owen/publication/389501396_A_Comprehensive_Cost-Benefit_Analysis_of_Preventive_Maintenance_Versus_Corrective_Maintenance_Assessing_the_Financial_Impact_and_Operational_Benefits_in_Engineering/links/67c51c56207c0c20fa9ed5c6/A-Comprehensive-Cost-Benefit-Analysis-of-Preventive-Maintenance-Versus-Corrective-Maintenance-Assessing-the-Financial-Impact-and-Operational-Benefits-in-Engineering.pdf (accessed on 16 March 2026).
20. Stenström, C.; Norrbin, P.; Parida, A.; Kumar, U. Preventive and corrective maintenance–cost comparison and cost–benefit analysis. *Struct. Infrastruct. Eng.* **2016**, *12*, 603–617. [CrossRef]
21. Salehi, V.; Veitch, B. Measuring and analyzing adaptive capacity at management levels of resilient systems. *J. Loss Prev. Process Ind.* **2020**, *63*, 104001. [CrossRef]
22. Miranda, T.; Moldovan, I.D.; Moutinho, J. Geotechnical monitoring in the digital age. In *Transportation Geotechnics for Green, Digital and Modern Infrastructures*; Correia, A.G., Pinto, A., Neves, J., Fortunato, E., Eds.; CRC Press: Boca Raton, FL, USA, 2026; Chapter 6; pp. 145–164. Available online: https://books.google.com/books?id=NTyxEQAAQBAJ&lpg=PA1&pg=PA1#v=onepage&q&f=false (accessed on 16 March 2026).
23. Yodo, N.; Wang, P. Engineering resilience quantification and system design implications: A literature survey. *J. Mech. Des.* **2016**, *138*, 111408. [CrossRef]
24. Naghshbandi, S.N.; Varga, L.; Purvis, A.; Mcwilliam, R.; Minisci, E.; Vasile, M.; Troffaes, M.; Sedighi, T.; Guo, W.; Manley, E.; et al. A review of methods to study resilience of complex engineering and engineered systems. *IEEE Access* **2020**, *8*, 87775–87799. [CrossRef]