GEOTECHNICAL ENGINEERING

Intelligent IoT Monitoring of Underground and Deep Foundation Systems in Saudi Smart Cities under Vision 2030: Integrating Embedded Strain Sensors, Connected Data Loggers, and Real-Time Geotechnical Analytics

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Abstract

Underground foundations are essential to the safety of dense urban infrastructure, yet their deterioration and soil–structure interactions are difficult to observe once construction is complete. This review examines how embedded strain sensors, connected data loggers and real-time geotechnical analytics can support evidence-led monitoring of piles, retaining systems, buried assets and associated ground movements in Saudi smart cities. A focused critical synthesis of DOI-traceable research published from 2020 to 2025 evaluates sensing physics, sensor–soil coupling, field installation, communications, data assurance, model updating and decision governance. Particular attention is given to saline sabkha deposits, heterogeneous ground, extreme temperatures and the varying accessibility of deep foundations. The evidence indicates that distributed optical measurements can resolve localised strain patterns unavailable from sparse gauges, but raw readings cannot be interpreted as forces or settlement without temperature compensation, stiffness calibration and a defensible ground model. An integrated architecture is therefore proposed in which instrumented assets feed quality-controlled edge records into uncertainty-aware engineering assessments. The contribution is a testable design framework rather than a claim of validated Saudi field performance. Its practical value lies in specifying measurable commissioning criteria, accountable escalation procedures and staged evidence requirements for resilient infrastructure investment under Vision 2030.

Keywords: Deep foundation monitoring; distributed fibre-optic strain sensing; Internet of Things; geotechnical analytics; sensor calibration; digital ground models; Saudi Vision 2030

1 Introduction

Smart-city development depends on infrastructure whose most consequential elements often remain invisible. Deep piles, diaphragm walls, retaining structures and buried transport or utility corridors transfer forces through heterogeneous ground while responding to excavation, groundwater variation and construction sequencing. Conventional inspections generally observe accessible surfaces; intermittent settlement surveys and isolated gauges offer only partial evidence of changes occurring along a foundation shaft. Monitoring consequently needs to represent the mechanics of soil–structure interaction rather than merely generate more sensor readings. Field studies of instrumented piles demonstrate that continuous strain profiles can reveal load redistribution and local anomalies that discrete measurements may miss [1, 2].

For Saudi Arabia, the engineering case is differentiated by site conditions, not by a presumption that every new development requires the same digital system. Coastal sabkha can exhibit compressibility

and moisture-dependent behaviour; recent Saudi investigations show that excavation support and ground improvement require context-specific analysis [3, 4]. A Tabuk-focused foundation study likewise reports that performance predictions depend on improvement geometry and soil condition [5]. In other locations, competent rock, variable weathering or deep excavation adjacent to operational assets may create substantially different monitoring demands. A national deployment philosophy must therefore allow geotechnical design assumptions, local failure mechanisms and asset consequence to determine instrumentation.

This article asks how an integrated measurement-to-decision chain can transform strain observations into credible foundation intelligence. Its specific objectives are to compare complementary sensing modes; identify installation and transmission constraints; define a quality-assured analytical workflow; and propose verification criteria that connect monitoring to construction and maintenance decisions. The novelty is a geotechnically explicit architecture linking sensor transfer physics, connected logging and uncertainty-controlled operational response, rather than a generic catalogue of urban applications. No site measurements, experimental results or cost savings are invented.

2 Review design and evidence appraisal

The study adopts a structured, critical narrative review suited to a multidisciplinary question spanning foundation engineering, fibre-optic instrumentation, wireless communication and predictive modelling. The evidence window is restricted to publications dated 2020–2025. Candidate research was identified through topic-led searches for instrumented pile tests, distributed fibre sensing, soil deformation, underground digital twins, Internet-connected monitoring and Saudi ground conditions. Article titles, publication dates and reported digital object identifiers were checked against accessible journal, institutional or DOI-linked records. The attached smart-city review informed the article organisation and numbered reference convention only; it was not treated as direct evidence of foundation performance.

Priority was given to studies offering physical experiments, field deployments, explicit measurement equations, sensor calibration or demonstrable validation against independent observations. Reviews were used to clarify technology boundaries and persistent uncertainties. Studies outside underground or foundation engineering were retained only when their methods directly informed data acquisition or digital representation. The selected 30 papers form a purposive technical corpus, not an exhaustive count of all published work. Accordingly, no database hit totals, pooled performance effect or universal accuracy estimate is claimed. Ma and colleagues' geotechnical synthesis helps distinguish fibre technologies, while civil infrastructure reviews establish the relevance and limits of connected sensing [6, 7].

The synthesis uses five appraisal dimensions: physical variable measured, installation representativeness, calibration and reference measurement, temporal continuity, and decision consequence. Evidence from full-scale pile testing carries more weight for shaft-load interpretation than a laboratory coupon result; a wireless prototype informs telemetry feasibility without proving geotechnical predictive accuracy. Regional transferability is examined explicitly, because moisture, cementation, salinity and temperature affect both mechanical response and sensor durability. This approach permits transparent engineering reasoning while acknowledging that heterogeneous studies cannot support a single quantitative benchmark.

3 Saudi ground conditions and priority failure mechanisms

Monitoring design begins with a ground model specifying lithological boundaries, groundwater conditions, foundation geometry and anticipated load paths. In coastal sabkha, soluble salts, weak cementation, compressibility and water exposure may produce settlement or loss of support that is not captured by a constant-stiffness approximation. Deep soil mixing and stone-column studies in Saudi settings illustrate why local construction methods and treatment effectiveness must enter the interpretation of observed deformation [3, 4]. In the Tabuk study, sensitivity to replacement ratio and binder conditions further cautions against transferring a laboratory-derived relationship without site checks [5].

Other priority mechanisms include differential movement of deep pile groups, shaft friction changes during groundwater drawdown, lateral bending caused by adjacent excavation, and structural distress where buried utilities cross variable fill. Rock-socketed systems introduce contact and interface uncertainties distinct from granular soils. The monitoring question should be phrased as a testable physical hypothesis: for example, whether a developing negative skin-friction zone is changing axial force; whether an excavation is driving curvature near a pile head; or whether a water leak is producing a progressively localised subsidence trough. Such hypotheses determine sensor orientation, reference gauges and the spatial frequency required to avoid missing a critical response.

A separate environmental envelope is also necessary. High ambient temperature, saline porewater, dust, site vibration and restricted maintenance access may degrade enclosures, connectors and bonding systems. Protection design should be evaluated against each exposure pathway rather than inferred from the nominal sensor specification. Consequently, the proposed Saudi framework distinguishes transferable sensing principles from performance outcomes requiring local commissioning and longitudinal confirmation.

4 Embedded sensing and interpretation of pile response

Electrical resistance gauges and vibrating-wire instruments remain useful because their readings are familiar to geotechnical engineers and can provide independent reference points. Their principal limitation is sparse spatial coverage. Fibre Bragg grating arrays add multiplexed local strain measurements, whereas Brillouin- and Rayleigh-based systems can generate distributed profiles along a protected cable. Monsberger and colleagues report practical benefits of continuous measurement along driven ductile piles, while bidirectional pile-load testing demonstrates how distributed observations support interpretation of shaft resistance and end bearing [1, 2]. The selection between these systems should follow the likely deformation wavelength, monitoring length, interrogation frequency and installation survivability.

Axial pile force is often estimated from strain using an axial stiffness relationship, $N(z) = E(z)A(z)\varepsilon(z)$, after removing thermal and initial-condition components. However, neither modulus nor effective composite area should be assumed uniform without justification. Variation in material stiffness, cracking, reinforcement and construction defects can bias a direct conversion. Research on wooden foundation piles illustrates the importance of spatially variable stiffness when interpreting distributed measurements [8]. Modern testing of long bored piles and cast-in-place foundations shows that fibre arrays can identify load-transfer characteristics, but the precision of inferred shaft resistance still depends on the differentiation and calibration of force profiles [9, 10].

For laterally loaded or excavation-affected piles, diametrically opposed sensors can separate average axial strain from bending-related strain difference. The curvature estimate requires a known sensor separation, verified alignment and consideration of shear effects. Xue and colleagues developed an optical-frequency-domain-based inclination approach for pile deformation; rock-socketed composite pile research further demonstrates the need to interpret axial and circumferential response together rather than reduce structural behaviour to one axial trace [11, 12]. In a field deployment, inclinometer readings or surveyed head displacement remain essential checks on reconstructed deflection.

Anti-slide piles provide an instructive comparison with foundation piles exposed to lateral excavation effects. A field study combined fibre observations and strain-to-force conversion to examine an anti-slide pile under complicated ground movement [13]. The lesson is not that one monitoring algorithm applies to both structures; rather, several competing load paths may produce similar local strains. A defensible analysis must distinguish a change in external ground action from altered structural stiffness. Where bending direction is uncertain, multiple orientations and independent displacement measurements are preferable to a single longitudinal channel. This also motivates an explicit observability analysis before interpreting an anomaly as progressive failure.

5 Sensor–host coupling, calibration and installation

A fibre records deformation transmitted through coating, bonding material, protective cable and surrounding medium. It is not intrinsically a direct measurement of soil strain. Reviews of transfer mechanics show that adhesive properties, gauge length, temperature and substrate stiffness influence the correspondence between measured and actual deformation [14]. A correction method with variable shear-lag parameters demonstrates why a single universal transfer factor is difficult to defend [15]. For deep foundations, the distinction is especially important at the pile–soil interface where cracking, grouting quality or debonding may change local transfer independently of a genuine geotechnical event.

Soil-embedded installation introduces a second interface. Laboratory investigations of optical fibres in sand identify the importance of confining pressure, moisture state, grain characteristics and load cycling [16]. Gravel-soil work reports that deformation coordination needs to be quantified rather than assumed, and coupled numerical pull-out analyses explore the influence of anchorage and overburden on measured strain [17, 18]. These results support a simple commissioning rule: every sensor type requires a documented transfer model and representative site calibration, with distinct treatment of bonded-to-concrete, attached-to-steel and embedded-in-soil channels.

Installation planning should therefore precede reinforcement fabrication. Fibre routes need predictable orientation, adequate bending radii, mechanically protected transitions and sufficient slack at accessible connection points. The contractor must record splices, cable exits, installation depth, sensor identifier and as-built alignment. Protective conduits should be tested for unintended isolation from the structure. Baseline readings taken before concreting, after curing and before loading can distinguish construction effects from subsequent movement. Redundant measurement paths are especially valuable where replacement after burial would be impossible.

Temperature compensation is indispensable in hot climates: optical frequency shifts respond to thermal as well as mechanical strain, while long cables may traverse sharply different thermal environments. Reference fibres, temperature-only elements or colocated thermistors should be selected according to the interrogation method. Compensation coefficients require laboratory confirmation over the operational range and periodic field checks; simply subtracting ambient air

temperature cannot correct a subsurface gradient. Drift, hysteresis and mounting changes must enter the uncertainty budget. Fault-tolerant sensor design is consequently a combined materials, construction-quality and metrology task.

Instrument orientation also determines observability. A single axial trace cannot separate bending from direct compression, and a fibre installed far from the critical section may yield a misleading impression of stability. Before procurement, engineers should map each proposed parameter to the equation that converts it into a decision variable, state the assumptions in that equation, and identify at least one independent way to test those assumptions. Where the inference requires differentiation or integration, uncertainty amplification must be included in the acceptance plan. A redundant system is valuable only when its channels fail through meaningfully different mechanisms.

6 Connected logging, communications and continuity

Connected data loggers form the boundary between physical measurement and operational analytics. Each record should preserve original units, sensor identifier, measured value, timestamp, calibration version, instrument status, supply voltage and data-quality flags. The sampling interval must follow expected dynamics: slow consolidation may permit infrequent observations, while excavation stages or load tests justify denser acquisition. A fixed citywide rate would waste energy at stable assets and obscure short-lived changes at critical sites. Construction-monitoring reviews describe the need to align measurement design with the operational activity being observed [19].

Communication choices should reflect an honest assessment of underground propagation. Wireless attenuation is affected by soil conductivity, moisture and burial depth; research on magnetic-induction underground networks explains why ordinary above-ground radio assumptions may fail beneath soil [20]. One practical architecture keeps interrogators and short cable connections underground only where necessary, routes protected links to an accessible surface gateway, and uses cellular or low-power radio for backhaul. Remote geotechnical sensor prototypes demonstrate adaptable telemetry choices, but their performance must be validated against actual enclosure placement and interference at the project site [21].

Reliable logging depends on continuity, not uninterrupted connectivity. An edge device should buffer records locally, label missing intervals, preserve measurement order and transmit in batches when the link returns. A geotechnical acquisition platform that combines local storage with cloud transmission illustrates the merit of this fallback design [22]. Clock synchronisation matters because strain, pore pressure, weather, structural loading and site-activity logs may otherwise appear correlated at the wrong moment. Synchronisation status and delay between acquisition and server arrival should be observable system variables, not hidden implementation details.

Security and maintainability are equally technical requirements. Remote devices need authenticated identities, encrypted transport, controlled firmware changes, protected service access and a record of who changed an alarm threshold. Edge filters should never destroy raw evidence used for engineering dispute resolution. For high-consequence assets, communication loss requires a specified fallback inspection route instead of being interpreted as structural stability. Ownership of the network, device certificates, calibration logs and data repository should be allocated in contracts before the system is commissioned.

Data schemas should remain intelligible beyond the construction consortium. An asset record needs coordinate reference, depth datum, pile identification, orientation, installation date and configuration

history; otherwise longitudinal comparisons may join unrelated channels. Engineering units must be explicit at capture, rather than reconstructed from a dashboard label. The same principle applies to firmware and calibration changes: they should create versioned events, not silently rewrite the historical series. Standards-based interfaces can support eventual exchange with municipal asset management, but data interoperability should be assessed through a worked handover rather than assumed from the presence of an application interface.

7 Real-time geotechnical analytics

A defensible analytical chain begins with plausibility checks rather than machine learning. First, the system rejects impossible formats and marks out-of-range electronics. Second, it screens step changes against instrument reset, temperature variation, cable faults and construction records. Third, it converts corrected measurements into mechanical indicators using documented constitutive assumptions. Fourth, it compares these indicators with independent measurements and a site-specific numerical or analytical model. Finally, it assesses whether an observed change is persistent, causally plausible and approaching a response threshold. The order prevents a visually persuasive dashboard from disguising poor measurement quality.

Strain gradients are informative but sensitive to noise. Deriving shaft friction from the difference between adjacent axial-force estimates can magnify sensor errors; spatial smoothing must therefore preserve real interfaces and avoid generating artificial peaks. Where ground settlement rather than pile load is the outcome, the mapping from cable strain to displacement requires an appropriate deformation model. Experimental pipe–soil interaction work and fibre-based subsidence monitoring show both the potential of distributed readings and the challenge of converting them into interpretable movements [23, 24]. Instrumented immersed-tunnel joints likewise demonstrate that the sensor geometry must encode the displacement component of interest [25].

Anomaly detection should be physically constrained. A rapid strain excursion with no matching load, pore-pressure or construction event may indicate instrumentation failure; a slower coherent change across adjacent sensors may deserve engineering investigation. Trend decomposition can separate seasonal cycles and staged excavation effects, provided baseline periods are sufficiently long. Statistical classifiers may help prioritise observations, but they should report confidence, training domain and missing-data sensitivity. A change in risk status must be traceable to the raw observations, their corrections, model settings and a responsible reviewer.

Threshold governance is a three-part process: a measurement trigger prompts technical checking; a performance trigger initiates intervention planning; and a safety trigger activates the approved emergency procedure. Values must derive from design predictions, observational-method limits, construction stage and consequence classification, rather than arbitrary universal percentages. Alarm systems should retain a record of clearance reasoning to prevent repeated, unexplained dismissal of warnings. Real-time means information arrives soon enough to affect a decision; it does not imply that every engineering interpretation is automated.

A useful verification exercise is to inject controlled faults into a non-critical replica of the processing chain. Examples include reversed sensor polarity, delayed packets, a failed thermistor, a mislabelled depth and an abrupt but physically implausible shift. The expected output is not merely detection; the system should explain whether to quarantine the reading, retain a warning or request inspection. Such tests expose hidden dependencies between telemetry and engineering inference before an

incident forces decisions under uncertainty. The acceptance record should include both false positives and missed detections, with an explanation of their practical consequence.

Direct displacement devices remain valuable because geometric movement is often closer to a serviceability criterion than local strain. Research on a spring-shaped optical displacement sensor demonstrates a distinct measurement option for settlement, including calibration of range and repeatability [26]. Such an instrument does not remove the need for a stable reference point; instead, it complements distributed strain where a clear displacement path is available. A sensible network may therefore employ sparse displacement references to anchor a dense fibre field. Sensor fusion should respect these different measurement definitions rather than average numbers that describe unlike physical quantities. The resulting assessment can then distinguish local bending from ground movement and improve the explanation given to the engineer.

8 Digital ground models and uncertainty

A digital representation becomes useful when it connects geometry, ground investigation, asset history and live sensor evidence. Urban underground digital-twin research emphasises the gap between static three-dimensional visualisation and models that can support iterative engineering decisions [27]. Fusion of geotechnical and geophysical information offers a route to spatially richer ground property models, although sparse borehole control remains a limitation [28]. A construction-oriented semantic model can organise asset identifiers, sensor coordinates and measurement provenance so that data from contractors remain interpretable after handover [29].

The proposed analytical core combines a mechanistic baseline with monitored deviations. A finite-element or simplified interaction model predicts expected strain, wall displacement and settlement under each planned loading stage. Observations update uncertain parameters such as interface stiffness, groundwater response or effective support conditions, subject to physical bounds. A residual between model and measurement is not automatically damage: it may identify a wrong input, an unrecorded construction action or a sensor problem. The appropriate response is diagnosis, not an immediate categorical prediction of failure.

Uncertainty should be displayed alongside estimates. Relevant components include instrument precision, installation transfer, temperature compensation, spatial interpolation, soil property variability and model-form error. Recent deep-excavation research demonstrates how digital modelling and uncertainty-informed learning can be combined for risk assessment [30]. That result does not justify importing a trained predictor unchanged into Saudi ground. Local model evaluation should use chronological hold-out periods, independent surveyed movements, contrasting geological zones and explicit error bounds. Prediction intervals that fail to contain observed values require recalibration and temporary reliance on conservative engineering limits.

A trustworthy decision interface therefore shows time series, reference baseline, corrected observation, prediction interval, relevant design limit and supporting event log in one view. Asset colour codes alone are insufficient; an engineer must be able to determine which signal changed, why it matters and which evidence supports the response. This distinction makes the digital model an auditable operational instrument rather than an ornamental three-dimensional display.

9 Integrated monitoring architecture and use cases

Figure 1 translates the sensing principles into a deployment concept for a bored pile beside a monitored excavation. It distinguishes sensing elements fixed to a reinforcement cage from pore-pressure and surface-settlement references, then locates the protected logger above the excavation influence zone. Figure 2 expresses the companion information architecture: raw evidence passes through timestamp verification, thermal correction, engineering inference and governed escalation. The figures are original conceptual representations, not diagrams extracted from the cited studies.

Consider an excavation adjacent to an existing pile group. The preliminary ground model identifies the likely lateral influence zone and predicts curvature at selected depths. Opposed fibre runs quantify differential strain, while an inclinometer independently checks bending interpretation. The gateway records each excavation stage and correlates readings with support installation. If observed movement exceeds the expected envelope, the engineer first verifies coupling and temperature correction, then reassesses support assumptions before authorising any operational response. This sequence can prevent both needless stoppages from instrument faults and delayed investigation of a coherent structural trend.

A second use case concerns a foundation or buried service located above potentially eroding ground. A distributed optical route can identify spatial changes, but strain alone cannot establish leak location or cavity size. Complementary flow records, pore-pressure observations and targeted ground investigation remain necessary. Studies of subsidence and tunnel-joint deformation illustrate how sensor topology governs what can legitimately be inferred [24, 25]. The principal benefit of the connected platform is the ability to relate these separate evidence streams through a shared, time-stamped asset model.

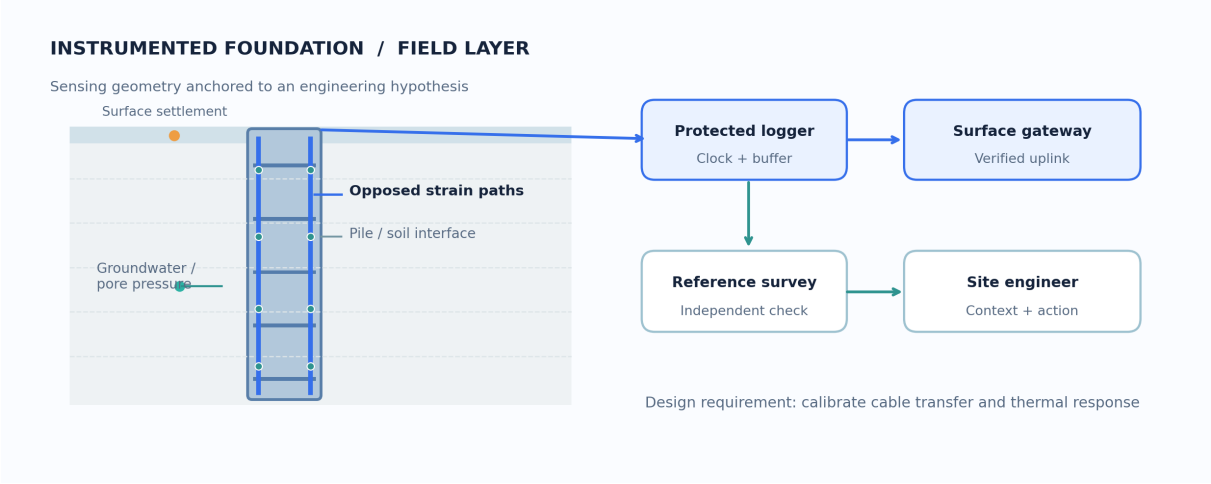


Figure 1. Conceptual arrangement of foundation instrumentation, protected logging and independent geotechnical reference measurements.

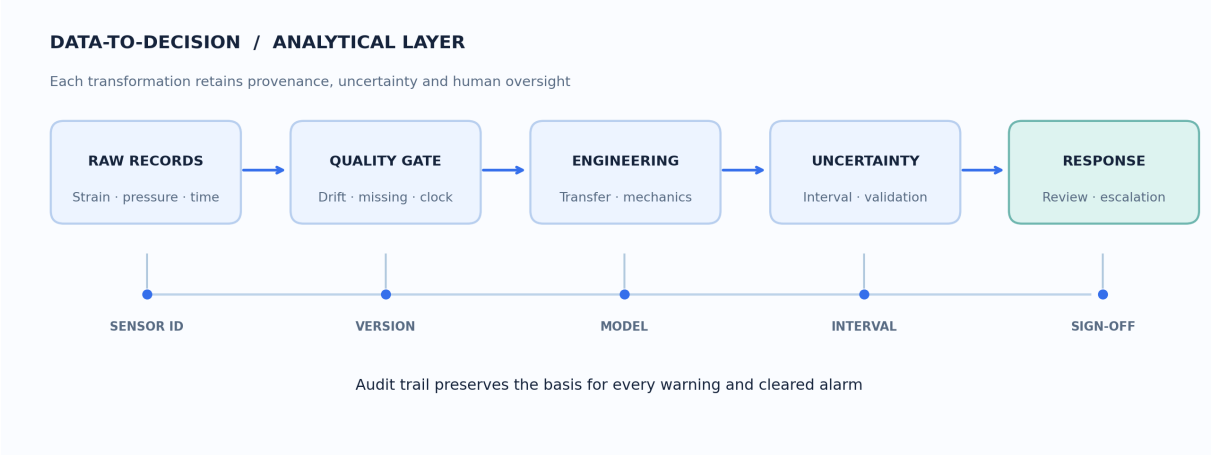


Figure 2. Traceable transformation from raw sensor data to quality-controlled engineering interpretation and accountable operational response.

10 Evidence-based deployment and validation

Table 1 compares sensor families by measurable quantity and interpretive limitation. It should be read as a selection guide rather than a performance ranking: a high-resolution fibre is not preferable when it cannot survive installation, and a simple gauge may be the most useful independent reference. Table 2 defines staged acceptance tests for an operational monitoring chain, beginning with bench calibration and ending with maintained performance across construction stages. Acceptance values must be project-specific and documented before testing.

Pilot selection should represent difficult ground conditions and real construction interfaces instead of only convenient laboratory locations. A test installation ought to include a deliberately diverse set of loads, temperature conditions and communication interruptions. Measurement repeatability, latency, percentage of valid records, estimated deformation error and alarm decision time should be reported separately. Combining these into an opaque overall score would conceal the cause of underperformance. Where independent survey or static loading is unavailable, the review recommends describing the output as an unvalidated indicator rather than an engineering measurement suitable for design reassessment.

Financial evaluation must include cable protection, excavation interfaces, interrogator access, sensor replacement risk, data hosting and engineering interpretation time. An inexpensive node may become costly if installation failure necessitates rework; conversely, an expensive distributed network may be unjustified for low-consequence assets already served by reliable surveys. A lifecycle business case should compare alternative inspection and monitoring strategies under the same consequence assumptions. Benefits such as fewer closures or longer asset life remain hypotheses until measured against a documented operational baseline.

Commissioning should include a handover rehearsal in which a maintenance engineer who did not design the installation retrieves a raw signal, identifies its location, explains its correction and follows the approved response procedure. If this cannot be completed without assistance from the original vendor, the monitoring platform is operationally fragile regardless of its sensor resolution. Continued competence requires training, periodic threshold review and budgeted calibration. These requirements make the platform a managed engineering service rather than a one-time installation.

Evaluation across changing construction phases must avoid information leakage. A forecasting model trained on measurements recorded after an excavation stage cannot be claimed to predict that stage independently. Calibration data should be separated from later tests by time and, where feasible, by location. Retaining a simple mechanistic benchmark is important: a sophisticated learner adds value only if it improves error characterisation or decision usefulness relative to a transparent baseline. Engineers should report whether alerts arose before, during or after observable deformation, since an accurate retrospective classification does not establish early-warning capability. For procurement, a demonstrable reduction in uncertainty at a consequential decision point is more meaningful than a favourable aggregate accuracy figure.

Table 1. Comparison of sensor technologies for underground and deep foundation monitoring.

Sensing mode	Primary output	Practical strength / limitation	Required verification
Vibrating-wire / electrical gauge	Local axial strain or stress proxy	Mature reference measurement; sparse coverage	Gauge calibration, thermal drift and embedment position
Multiplexed fibre Bragg grating	Local strain at many selected points	Flexible targeted sensing; spacing must match failure mode	Temperature cross-sensitivity and connector integrity
Distributed Brillouin sensing	Strain profile over long routes	Continuous load-transfer trends	Spatial averaging, bond transfer and instrument access
Distributed Rayleigh / OFDR	High-resolution strain or curvature patterns	Localised anomaly identification	Range, temperature control and cable damage
Inclinometer / settlement survey	Independent displacement reference	Geometrically interpretable cross-check	Survey datum, frequency and access constraints

Table 2. Stage-gated verification matrix for a connected geotechnical monitoring system.

Acceptance stage	Test focus	Required evidence
Bench calibration	Sensor response across load and temperature	Traceable calibration curve and repeatability envelope
Installation acceptance	Survival, location and strain transfer	As-built route plus baseline versus independent reference
Telemetry resilience	Interrupted connection and time synchronisation	No silent data loss; verifiable backfill after reconnection
Engineering validation	Reconstructed force or movement	Error envelope against survey or load-test measurements
Operational handover	Threshold response and user competence	Documented trigger, accountable sign-off and audit trail

11 Limitations, research priorities and governance

The evidence base remains uneven. Many reported evaluations concern controlled loading or individual field demonstrations, whereas long-term coupled behaviour in saline soils and heavily serviced urban corridors is less well characterised. Sensor survival, calibration drift and subsurface radio reliability may dominate the operational error budget, yet papers often emphasise short-term

measurement resolution. Transfer studies provide mechanisms for interpreting discrepancies, but site-specific coefficients and accessible reference observations are still required [14, 16, 17].

A Saudi research programme should prioritise paired optical and conventional instrumentation on selected test piles, verified temperature compensation, multi-season observation of representative sabkha deposits and repeatable benchmarking of deformation reconstruction. It should also test how sensors behave across grout defects, construction impacts and changes in groundwater chemistry. Experiments should preregister acceptance variables and report failed channels rather than excluding them silently. Open, anonymised examples of sensor faults and false alarms would improve the ability of future models to distinguish instrument behaviour from physical deterioration.

Governance must preserve engineering responsibility. A project owner should define risk appetite and information retention; the designer should establish allowable deformation and revision rules; contractors should deliver certified as-built sensor maps; and independent reviewers should approve threshold changes affecting safety. Cybersecurity specialists are responsible for platform controls but cannot certify geotechnical validity. This separation of duties prevents automation from becoming a substitute for professional judgement while allowing secure, repeatable analysis at city scale.

Scientific reproducibility would improve if field reports separated observed measurements, inferred quantities and decisions in their released datasets. The axial strain itself is an observation; reconstructed axial force is a model-dependent estimate; a decision to stop excavation is an operational judgement. Conflating these layers can make a persuasive case history difficult to scrutinise. Future benchmark datasets should include raw and processed signals, ground profiles, design stage, instrumentation faults, metadata on weather and temperature, and the full audit trail for alarms. Sensitive asset details can be protected without withholding essential metrological information.

Therefore, every pilot should publish a compact evidence dossier linking the geological model, sensor installation record, calibration coefficients, independent checks, alarm history and engineering disposition. This dossier allows reviewers to assess whether monitoring actually reduced decision uncertainty across changing loads, temperatures, groundwater conditions and construction stages.

12 Conclusions

Integrated monitoring of underground foundations is technically plausible when physical sensing, connected acquisition and geotechnical interpretation are designed as one system. The reviewed evidence supports distributed strain sensing for identifying spatial load-transfer patterns, local deformation and buried-asset movements, but also shows that sensor–host coupling and stiffness assumptions govern the reliability of derived forces. Data loggers improve continuity and traceability only when they preserve raw observations, time alignment and fault states. Uncertainty-aware models can strengthen engineering decisions, yet a digital representation cannot compensate for missing ground investigation or unverified field calibration.

For Saudi smart cities, the recommended pathway is selective, hazard-led instrumentation followed by independent validation and accountable escalation. Priorities include representative local trials in saline and heterogeneous deposits, documented thermal correction, secure edge-to-cloud records and explicit tests of prediction reliability. The proposed architecture aligns infrastructure intelligence with the resilience ambitions of Vision 2030 without claiming field results not yet demonstrated. Its

success should be judged through measured decision quality, defensible intervention and lifecycle evidence, rather than sensor count or dashboard sophistication.

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