

Integrating GPR and Geotechnical Investigation for Subsurface Failure Diagnosis: An FMEA and Asset Integrity Management Framework — A Case Study at Obafemi Awolowo University

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Abstract

Groundwater seepage into built infrastructure is a recurrent operational problem in tropical basement complex terrains, causing unplanned facility downtime, structural degradation, and escalating lifecycle maintenance costs. This paper presents a dual-method investigation integrating Ground Penetrating Radar (GPR) geophysical surveys with comprehensive geotechnical laboratory testing to diagnose chronic basement flooding at the Spider Building, Obafemi Awolowo University (OAU), Ile-Ife, Nigeria. Ten GPR traverse lines delineated four subsurface strata to 12 m depth, identifying Fractures F1 (≥ 2 m wide) and F2 (~ 1.2 m wide), and eleven micro-fractures. PQWT-S150 deep mapping confirmed a separate 3 m-wide aquifer fracture starting at 125 m depth beneath the F1 trace. Geotechnical tests on five soil samples identified Silty Sand (SM), Clayey Sand (SC), and Clay with low plasticity (CL) soils with low permeability (8.03×10^{-6} – 1.05×10^{-5} cm/s). Exploratory regression ($n = 5$; $R = 0.86$ – 0.98) indicated that percentage fines has potential as a maintenance monitoring proxy, requiring validation with larger datasets. These findings are synthesised into a Failure Mode and Effects Analysis (FMEA) matrix and an Asset Integrity Management (AIM) decision framework grounded in ISO 55000 and Reliability-Centred Maintenance (RCM) principles. A key finding is ‘priority inversion’ with rebar corrosion (RPN = 384). It is the highest-risk failure mode yet the least managed, because it is far less visible than flooding (RPN = 243). The paper demonstrates a generalisable IE/OM framework for evidence-based infrastructure maintenance management.

Keywords

Ground Penetrating Radar; Asset Integrity Management; FMEA; Groundwater Seepage; Reliability-Centred Maintenance; Basement Complex Nigeria.

1. Introduction

Infrastructure deterioration driven by groundwater seepage is a pervasive problem in tropical basement complex environments (Bogoslovsky and Ogilvy, 1970; Salako and Adepelumi, 2016). Seepage reduces soil bearing capacity, induces differential settlement, and renders critical spaces unusable. In built facilities, these effects translate directly into unplanned downtime, elevated corrective maintenance expenditure, and degraded service delivery — outcomes that IE/OM theory characterises as avoidable losses in system performance (Moubray, 1997). Traditional responses have been predominantly reactive, which is both economically inefficient and technically inadequate when the root cause lies in the deep subsurface.

This paper addresses that gap through a case study of the Spider Building at OAU Ile-Ife, Nigeria, whose basement has been unusable since construction due to chronic groundwater ingress. The specific IE/OM contributions are: (i) a DMAIC-structured dual-method investigation that explicitly links measurement choices to failure mechanism diagnosis; (ii) a Failure Mode and Effects Analysis revealing a priority inversion — the highest-risk failure mode (rebar corrosion) is the least operationally visible; and (iii) an Asset Integrity Management framework grounded in ISO 55000 and RCM that translates geophysical and geotechnical evidence into a risk-ranked, phased remediation roadmap. Together, these constitute a decision-support system for infrastructure maintenance management generalizable to the large stock of ageing institutional infrastructure in tropical developing countries.

2. Critical Review of Literature

2.1 Geophysical Methods for Groundwater Seepage Investigation

GPR provides high-resolution two-dimensional images of stratigraphy, fractures, and voids without subsurface excavation (Daniels, 2022; Annan, 2021). Recent multi-method studies confirm that single-method investigations risk misdiagnosis. For example, a study delineates porous subsurface units at the seepage source by combining GPR and electrical resistivity tomography (ERT) (Agbo et al., 2025). Singh et al. (2025) integrated methods in Jodhpur to confirm fractured zones as primary conduits; Wang et al. (2025) used transient electromagnetic surveys alongside ERT and self-potential to detect water-rich zones. A critical gap across this literature is the absence of deep characterisation tools — GPR at standard engineering frequencies is limited to 4–20 m, yet relevant aquifer systems in basement complex terrains often extend far deeper. The PQWT multi-method instrument (integrating electric, magnetic, high-density resistivity, and induced polarisation) addresses this limitation to depths of 150 m.

2.2 IE/OM Frameworks for Infrastructure Asset Management

Reliability-Centred Maintenance (RCM) prescribes that test methods must be matched to the failure mechanism under investigation (Moubray, 1997). FMEA ranks failure risks by Severity (S), Occurrence (O), and Detectability (D),

generating Risk Priority Numbers (RPNs) that guide resource allocation (Stamatis, 2003). ISO 55000 (2014) formalises Asset Integrity Management as a lifecycle decision framework integrating risk assessment, inspection planning, and maintenance optimisation. The ASME Asset Integrity Management of Critical Infrastructure conference (Salama et al., 2024) emphasised that the FMEA–AIM chain is only credible when scoring criteria are transparent and traceable — a methodological standard that motivates the explicit scoring rubric in Section 6.1. A critical observation from this review is that the application of FMEA and AIM to geotechnical seepage problems in sub-Saharan African institutional facilities is essentially absent from the published record.

3. Study Area and Problem Statement

The Spider Building (07°31'22"N, 04°31'44"E) is a landmark academic facility at OAU Ile-Ife, Nigeria. Its basement has experienced persistent groundwater inundation during the April–October wet season since construction, rendering it entirely non-functional. Geologically, the site lies at the boundary of granite gneiss (GGn) and banded gneiss (BGn) units, with mica schist (Ms) to the east (Boesse, 1989). The structural geology map reveals multiple bedrock depression axes and fault systems intersecting the site (Olorunfemi and Okhue, 1992). The loss of the basement space represents a material reduction in facility capacity utilisation, justifying a structured diagnostic investigation. As confirmed by the GPR basemap (Figure 5), the basement floor was constructed in proximity to a fractured bedrock zone. This follows a pattern of insufficient pre-construction subsurface investigation recurring across building failure case studies in southwestern Nigeria (Joseph et al., 2023; Alabi et al., 2024).

4. Methodology

4.1 Research Design: DMAIC Framework

The investigation is structured around the DMAIC (Define–Measure–Analyse–Improve–Control) framework, used here as an organising logic that makes explicit how each phase of data collection serves a different diagnostic and remediation function. The Define phase mapped seepage failure modes and spatial extent, directly shaping GPR traverse placement. The Measure phase acquired GPR, PQWT, and geotechnical data; under RCM principles, the selection of PQWT deep mapping was driven by the Define phase finding that the failure mechanism involved a deep aquifer, which standard GPR alone could not characterise. The Analyse phase included fracture mapping, regression analysis, and construction of the FMEA matrix. The Improve phase yielded the AIM decision framework, incorporating risk-ranked priorities and phased intervention strategies. The Control phase specified sensor-based monitoring and reassessment protocols to ensure sustained performance, enable real-time anomaly detection, and support continuous improvement of the system.

4.2 GPR Data Acquisition and Processing

GPR data were collected using a GSSI SIR-3000 system. Three antenna frequencies were deployed: 100 MHz (nominal penetration ~20 m), 200 MHz (~8 m), and 400 MHz (~4 m), allowing multi-scale characterisation from shallow stratigraphy to deep fracture zones. Ten traverse lines (TR1–TR10) were established across and around the Spider Building footprint, with a cumulative profile length of approximately 428 m. Figure 1 shows the spatial layout of traverse lines and trial pit locations at the study site. Data were processed using RADPRO software (background removal, NMO correction, trace equalisation, median filtering, and automatic gain control) and interpreted using a five-class radar facies scheme following Adepelumi and Fayemi (2012).

4.3 PQWT-S150 Deep Fracture Mapping

To characterise Fracture F1 beyond GPR penetration limits, a PQWT-S150 instrument was deployed along the F1 fracture trace. The instrument integrates electric, magnetic, high-density resistivity, and induced polarisation methods to generate rock density profiles to a depth of 150 m. Profile maps were generated to determine the width, depth, extent, and aquifer connectivity of the fracture system beneath the Spider Building.

4.4 Geotechnical Laboratory Testing

Five soil samples were retrieved from hand-dug trial pits (PT1–PT5) at depths of 3.0–3.6 m. Water was encountered in Pit 3 at a depth of 3.4 m, which was adopted as the reference groundwater level for all pits. All tests were performed in accordance with BS 1377 (1990): natural moisture content, specific gravity, particle-size analysis, Atterberg limits (liquid limit by Casagrande apparatus; plastic limit by thread rolling), standard Proctor compaction, unconsolidated-undrained (UU) triaxial shear strength, oedometer consolidation (yielding C_c , M_v , and C_v), and falling-head permeability. Trial pit locations were collocated with GPR traverse lines to ensure that geotechnical data directly calibrated geophysical interpretations at each sampling point.

4.5 Regression Analysis and Stress Modelling

Pearson correlation coefficients (R) were computed between percentage fines (%F), shear strength (τ), permeability (K), coefficient of consolidation (C_v), and coefficient of volume compressibility (M_v). To avoid multicollinearity (Dunlop and Smith, 2003), only %F was retained as the index predictor after confirming its high correlation with G_s and PI. All results are treated as exploratory, given $n = 5$. Vertical and horizontal effective stress profiles (S'_V , S'_H) were derived from the GPR-delineated stratigraphy using unit weights from Proctor compaction tests and pore-water pressure profiles from the estimated water table depth of 3.4 m.

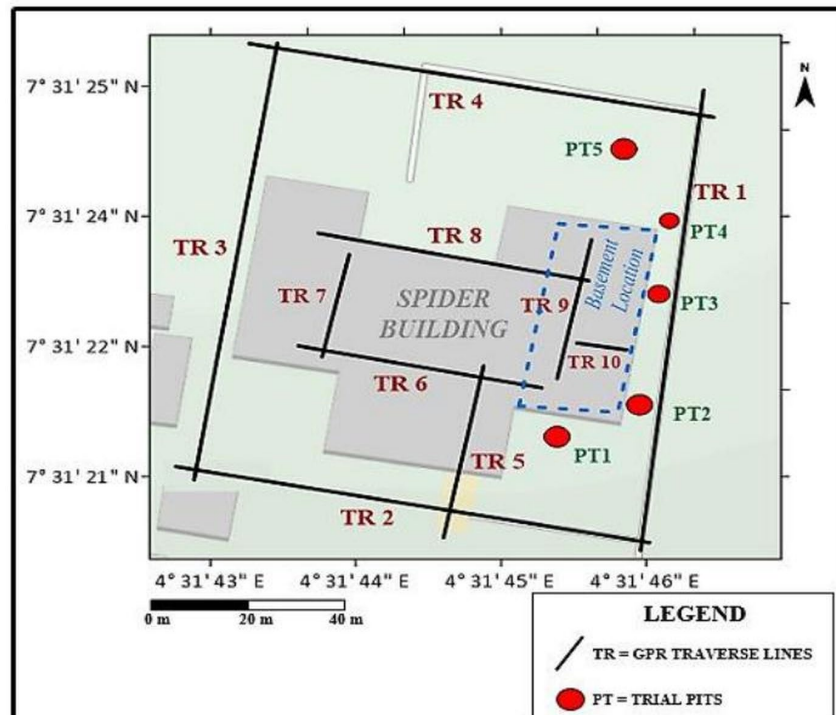


Figure 1. GPR traverse lines (TR1–TR10) and trial pit locations (PT1–PT5) at the Spider Building, OAU Ile-Ife (Bobola, 2022)

5. Results

5.1 GPR Subsurface Characterisation

Analysis of the ten processed radargrams revealed a consistent four-layer stratigraphy: (1) Topsoil (0–2.5 to 4.0 m, planar-smooth reflections); (2) Weathered Zone (2.0–4.1 m thick, chaotic high-amplitude reflections indicating elevated moisture); (3) Partly Weathered/Fractured Basement (3.3–6.4 m thick, short-discontinuous reflections); and (4) Fresh Basement (>10 m, smooth-free reflections where the GPR signal was attenuated). The radargram of Traverse Line 1 (Figure 2) reveals two macro-fractures at approximately 9.2 m depth in the fractured basement: F1 (≥ 2 m wide) and F2 (~ 1.2 m wide), both serving as conduits for vertical water movement as indicated by the zones of discontinuity. One micro-fracture (MF1) was also identified on TR1 at approximately 15.8–17.0 m horizontal distance, showing sub-planar displacement of soil layers consistent with clay plasticity behaviour.

The radargram of Traverse Line 6 (Figure 3), which runs directly adjacent to the basement footprint, reveals a total of seven micro-fractures (MF2–MF7) distributed across the weathered and fractured basement zones between 0 m and 10 m depth. The concentration of these micro-fractures immediately adjacent to the basement — combined with the chaotic high-amplitude reflections in the fractured basement zone at 8.5–9.3 m — confirms a high-density fracture network that serves as an aquifer and channelling system for groundwater seepage toward the building. Eleven micro-fractures in total (MF1–MF11) were mapped across TR1, TR6, TR8, and TR10.

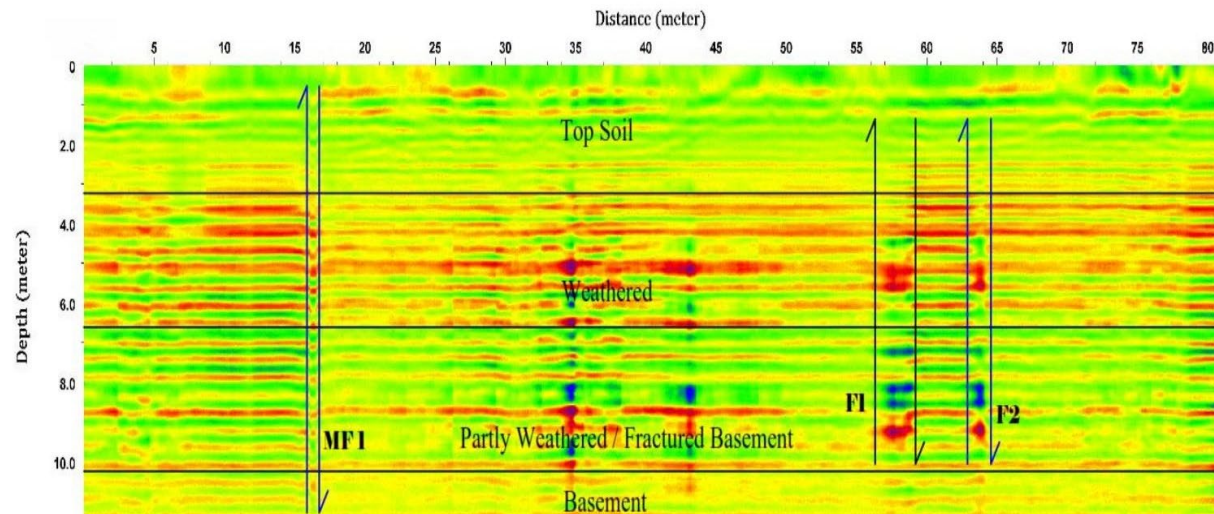


Figure 2. GPR radargram of Traverse Line 1, showing four subsurface strata, Fractures F1 and F2, and Micro-fracture MF1. Zones of discontinuity are indicated by vertical arrows (Bobola, 2022)

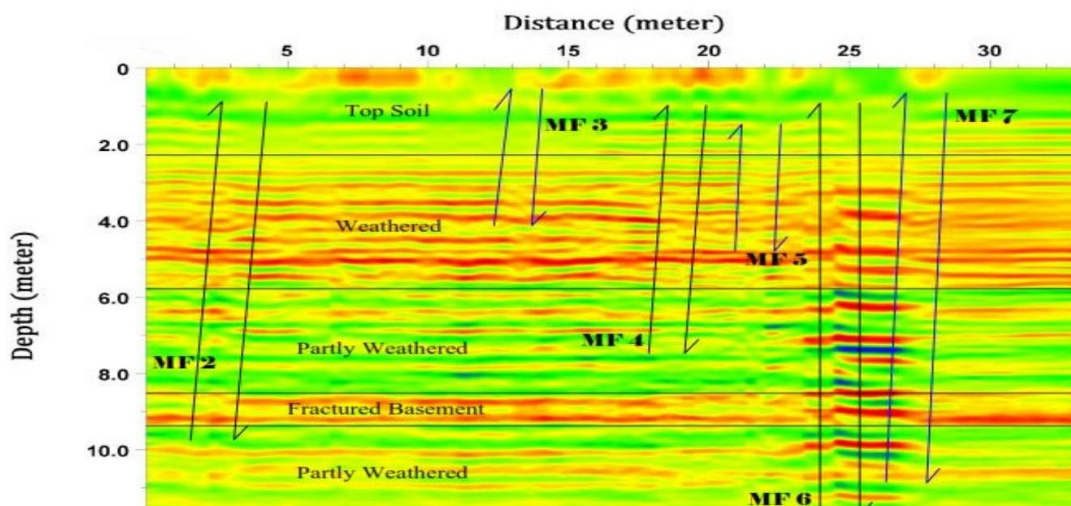


Figure 3. GPR radargram of Traverse Line 6, showing seven micro-fractures (MF2–MF7) distributed across the weathered and fractured basement zones directly adjacent to the Spider Building basement footprint (Bobola, 2022)

5.2 PQWT Deep Fracture Characterisation

The PQWT-S150 profile along the Fracture F1 trace (Figure 4) delineated five rock density layers to 150 m depth: Low density rock (0–15 m), containing the GPR-identified strata and Fracture F1; Slightly Medium density basement (15–42 m); Medium density rock (42–102 m); Slightly High-density rock (102–117 m); and High-density basement (>117 m). Within the deepest high-density layer, a separate wide fracture — estimated at least 3 m wide — was identified starting at 125 m depth, directly beneath the F1 trace identified by GPR. This deep fracture cuts across all overlying layers and serves as a large aquifer for groundwater storage and as a sustained conduit for upward groundwater movement to the surface. This finding is critical for remediation planning: it confirms that the seepage recharge source is a regional-scale aquifer at depth, which shallow surface drainage or shallow membrane waterproofing cannot intercept.

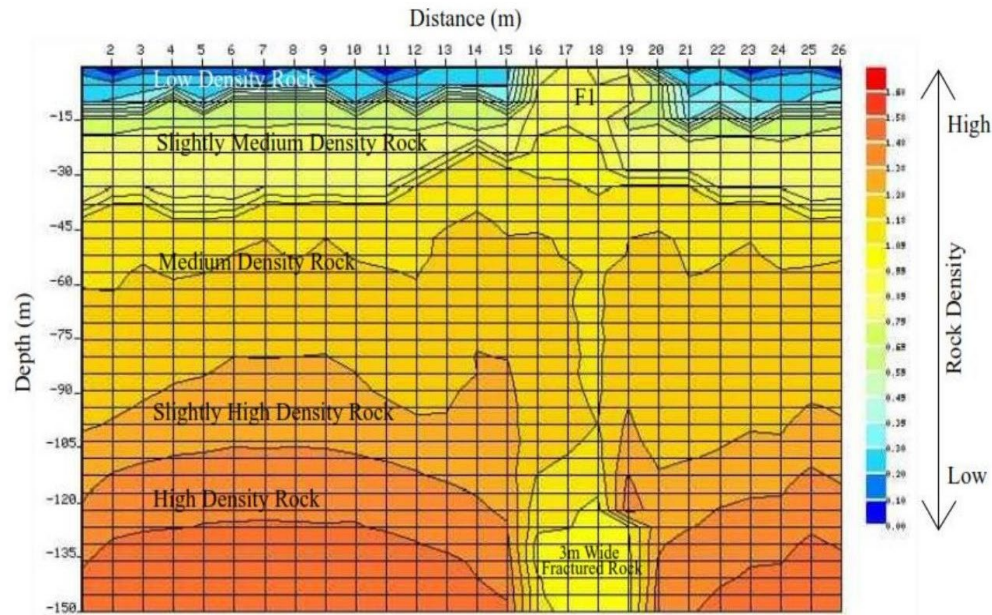


Figure 4. PQWT-S150 rock density profile along Fracture F1 trace to 150 m depth. Five density layers are delineated; the 3 m-wide deep fracture aquifer begins at 125 m (Bobola, 2022)

5.3 Fracture Basemap

Figure 5 presents the basemap of the study area showing the spatial distribution of the two macro-fractures (F1, F2) and all eleven micro-fractures delineated from the GPR radargrams. The fractures and micro-fractures are concentrated on the north-east side of the Spider Building, directly beneath and adjacent to the basement floor area (indicated by the dashed blue boundary). This spatial pattern confirms that the basement was constructed over a zone of fractured bedrock — a conclusion with direct implications for the original site investigation, which evidently did not detect these near-surface fracture zones. The proximity of Trial Pit 3 to Fractures F1 and F2 explains the elevated natural moisture content (20.13%) and lowest shear strength (38 kN/m²) recorded at that location.

in the Study Area

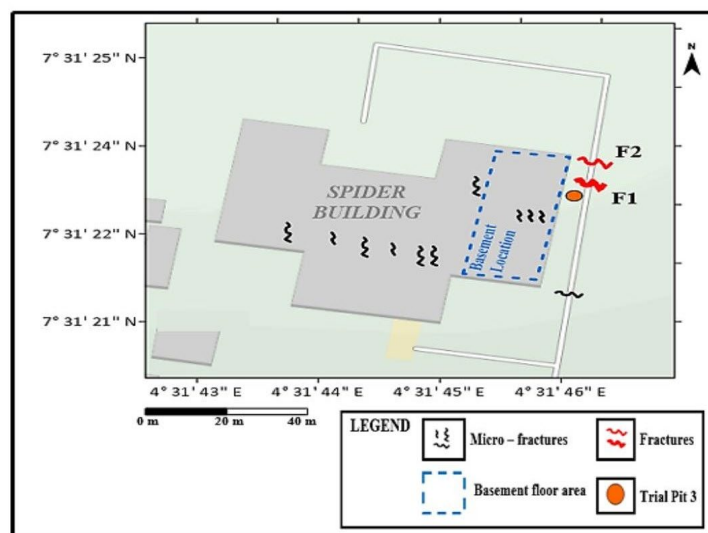


Figure 5. Basemap showing zones of fractures (F1, F2) and micro-fractures at the Spider Building site. The dashed blue boundary marks the basement floor area; the orange circle marks Trial Pit 3 (Bobola, 2022)

5.4 Geotechnical Classification

Table 1 summarises the index and engineering properties of the five soil samples. Soils range from Silty Sand (SM) at PT1 to Clayey Sand (SC) at PT2, PT4, and PT5, with Clay of low plasticity (CL) at PT3. All samples display low to intermediate plasticity (PI: 4.5–14.3%), consistent with weathered residual soils of the OAU granite gneiss terrain.

Table 1. Summary of soil classification and geotechnical properties (PT1–PT5; Bobola, 2022)

Parameter	PT1 (3.0 m)	PT2 (3.2 m)	PT3 (3.6 m)	PT4 (3.4 m)	PT5 (3.3 m)
NMC (%)	11.76	13.94	20.13	15.26	13.56
Specific Gravity G _s	2.46	2.71	2.77	2.73	2.67
Gravel (%)	5.12	10.53	8.35	12.31	9.75
Sand (%)	61.77	44.02	36.88	38.72	46.35
Fines (%)	33.11	45.45	54.77	48.98	43.90
LL / PL / PI (%)	31/26/4.5	32/19/13.3	37/22/14.3	32/19/12.5	36/23/13.4
USCS Classification	SM — Silty Sand	SC — Clayey Sand	CL — Clay (low pl.)	SC — Clayey Sand	SC — Clayey Sand
Shear Strength τ (kN/m ²)	61	48	38	43	49
Permeability K (cm/s)	1.05×10^{-5}	8.34×10^{-6}	8.03×10^{-6}	9.09×10^{-6}	8.76×10^{-6}
Compression Index C _c	0.166	0.149	0.136	0.136	0.110
MDD (Mg/m ³)	1.89	1.79	1.94	1.84	1.86

Permeability coefficients (8.03×10^{-6} – 1.05×10^{-5} cm/s) are classified as low, consistent with the compressible sandy clay classification. PT1 (SM, lowest fines, highest K and τ) is most susceptible to seepage flow by virtue of higher hydraulic conductivity. PT3 (CL, highest fines = 54.77%, lowest τ = 38 kN/m²) is most vulnerable to bearing capacity failure under saturation. The elevated NMC of PT3 (20.13%) reflects its proximity to Fractures F1 and F2 as confirmed by the basemap.

5.5 Regression Analysis

Table 2 presents the exploratory Pearson correlation coefficients between soil index and geotechnical properties. The near-unity correlation between τ and % fines ($R = 0.98$) and between K and % fines ($R = 0.88$) suggests that percentage fines is a practical and low-cost proxy for both shear strength and permeability in this soil type, allowing maintenance teams to estimate engineering risk from a single sieve analysis. However, with only $n = 5$ data points (3 degrees of freedom), confidence intervals around R are wide and the correlations may reflect a sampling artefact; they are therefore treated as hypothesis-generating throughout this paper.

Table 2. Exploratory Pearson correlation coefficients (R) between soil index and geotechnical properties ($n = 5$; hypothesis-generating only)

Variable Pair	R	Interpretation
τ vs. % Fines	0.98	Lower % fines $\rightarrow$ higher τ ; these soils carry more seepage flow risk (higher K)
K vs. % Fines	0.88	Lower % fines $\rightarrow$ higher K (more permeable)
τ vs. K	0.86	Lower % fines simultaneously increases both K and τ
C _v vs. τ	0.90	Faster-consolidating soils tend to be stronger
C _v vs. K	0.77	More permeable soils consolidate faster (moderate correlation)
C _v vs. % Fines	0.89	Higher % fines $\rightarrow$ lower coefficient of consolidation

The dual seepage risk pattern emerging from Table 2 is notable: soils with lower % fines carry greater seepage flow risk (higher K, higher τ); soils with higher % fines carry greater bearing capacity risk under saturation (lower τ , lower K but also lower strength). Both failure pathways are simultaneously active at this site. Validation with $n \geq 20$ samples from deeper boreholes is recommended before these relationships are applied predictively. Regarding FMEA robustness, a ± 1 variation applied to any single S, O, or D score does not alter the RPN ranking order, confirming that the priority inversion finding is stable under modest scoring uncertainty.

5.6 Vertical and Horizontal Stress Analysis

Table 3 presents the vertical and horizontal effective stress profile computed from the GPR-delineated stratigraphy with unit weights from Proctor tests and pore-water pressures from the water table at 3.4 m. Poisson's ratio was set to 0.35 for the unsaturated topsoil and 0.50 for the saturated weathered and partly weathered clay layers, following standard geotechnical practice for soft to medium clays (Arora, 2008).

Table 3. Vertical and horizontal effective stress profile; water table at 3.4 m depth (Bobola, 2022)

Layer	Thick. (m)	γ (kN/m ³)	ν	SV (kN/m ²)	U (kN/m ²)	S'V (kN/m ²)	S'H (kN/m ²)
Topsoil (unsaturated)	3.4	17.46	0.35	59.37	—	59.37	31.97
Weathered (saturated clay)	3.2	21.76	0.50	129.01	31.39	97.62	97.62
Partly Weathered (sat. clay)	3.6	21.76	0.50	207.36	66.71	140.65	140.65

The stress profile in Table 3 is visualised in Figure 6 as a vertical stress diagram. At the base of the partly weathered layer (~10.2 m depth), the horizontal effective stress S'H reaches 140.65 kN/m². The equality of S'V and S'H in the saturated layers ($\nu = 0.50$) confirms an isotropic stress state typical of soft to medium saturated clays. This isotropic state drives groundwater flow laterally in all directions toward the low-pressure basement cavity. Critically, the mobilised shear stress in the partly weathered layer exceeds the shear strength of the CL soil at PT3 ($\tau = 38$ kN/m²), confirming that seepage-induced bearing capacity loss is an active failure mode, not merely a potential one.

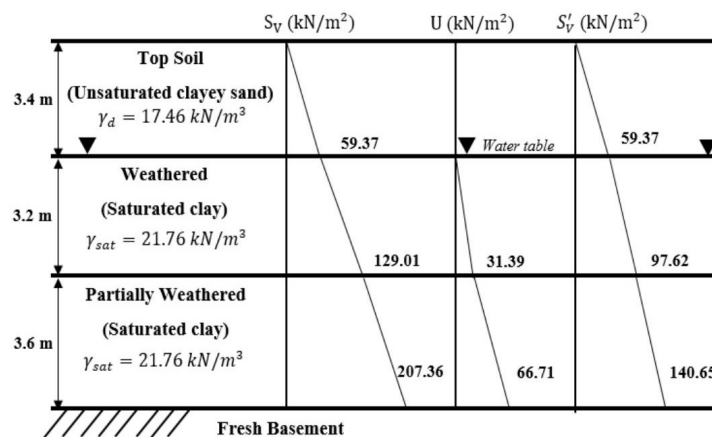


Figure 6. Vertical stress diagram showing total vertical stress (SV), pore-water pressure (U), effective vertical stress (S'V), and effective horizontal stress (S'H) for the three subsurface layers. Water table is at 3.4 m depth (Bobola, 2022)

6. FMEA and Asset Integrity Management Framework

6.1 Failure Mode and Effects Analysis

The FMEA maps each subsurface finding to a facility-level failure mode scored on Severity (S), Occurrence (O), and Detectability (D) on a 1–10 scale ($RPN = S \times O \times D$). Table 4 defines the scoring rubric with anchor values at 1, 5, and 10. Every score in the FMEA matrix (Table 4) is anchored to specific geophysical or geotechnical evidence from Sections 4–5. The Detectability scale is inverted relative to intuition: a higher D score means the failure is harder to detect, and therefore contributes more to risk. Table 5 presents the full FMEA matrix. Each failure mode's S, O, and D scores are justified by specific evidence: rebar corrosion receives $O = 8$ because the basement has been continuously wet for decades; it receives $D = 6$ because detection requires a half-cell potential survey or carbonation depth test, which routine visual inspection cannot provide. Basement flooding receives $D = 3$ because standing water is immediately visible. Micro-fracture propagation receives the highest detectability penalty ($D = 7$) because it is invisible from the surface and requires dedicated geophysical resurvey to track.

Table 4. FMEA scoring rubric (S = Severity, O = Occurrence, D = Detectability; scale 1–10; higher D = harder to detect)

Score	Severity (S)	Occurrence (O)	Detectability (D)
1	No effect on function	Failure almost impossible	Near-certain detection before functional failure
5	Moderate degradation; facility partly functional	Occasional; seasonal pattern observed	Detectable by periodic inspection
10	Catastrophic; irreversible structural failure	Failure near-certain / ongoing	Undetectable without specialist equipment

Table 5. FMEA matrix for seepage-related failure modes ($RPN = S \times O \times D$; all scores justified by evidence from Sections 4–5)

Failure Mode	Root Cause & Score Justification	Potential Effect	S	O	D	RPN
Rebar/steel corrosion	Continuous moisture (PT3 NMC=20.13%); decades of basement saturation. S=8: irreversible capacity loss is safety-critical. O=8: corrosion is ongoing; basement has been wet since construction. D=6: requires half-cell potential survey; not detectable by visual inspection.	Loss of rebar cross-section; reduced structural capacity; long-term collapse risk	8	8	6	384
Basement flooding via F1/F2	F1 (≥ 2 m wide, 9.2 m depth, GPR TR1) + 3 m wide aquifer at 125 m (PQWT). S=9: complete facility non-functionality. O=9: flooding recurs every wet season. D=3: standing water is directly visible.	Complete facility non-functionality; safety hazard; loss of academic capacity	9	9	3	243
Differential settlement	CL soil PT3: $\tau=38$ kN/m ² , $C_c=0.136$, NMC=20.13%. S=8: structural cracking and serviceability loss. O=7: long-duration seasonal saturation at PT3 location. D=4: requires tiltmeters; early-stage settlement not visually detectable.	Structural cracking; loss of serviceability; building envelope failure	8	7	4	224
Soil bearing capacity loss	S/H=140.65 kN/m ² at 10.2 m exceeds PT3 $\tau=38$ kN/m ² (Table 3 stress analysis). S=9: foundation distress; progressive failure. O=6: requires sustained saturation; stress analysis confirms active risk. D=4: requires piezometer monitoring; not visually detectable.	Foundation distress; progressive soil failure; slope instability	9	6	4	216
Micro-fracture propagation	11 micro-fractures on TR1, TR6, TR8, TR10 (GPR). S=6: gradual expansion of flow paths. O=5: driven by seasonal hydrological cycling. D=7: invisible from surface; requires dedicated ERT or GPR resurvey.	Expanding flow paths; accelerating seepage rates over time	6	5	7	210

The RPN values in Table 5 are visualised in Figure 7. The priority inversion is the paper's key IEOM finding: rebar corrosion (RPN = 384) outranks visible basement flooding (RPN = 243) because consequence-weighted risk, not operational visibility, is the correct prioritisation criterion. This inversion is structurally invisible to conventional reactive management, which responds to what is seen (flooding) rather than what is most dangerous (silent structural degradation). The result has direct implications for maintenance budget allocation.

6.2 Asset Integrity Management Decision Framework

The AIM framework (Table 6) translates the FMEA RPN rankings into a phased intervention roadmap under ISO 55000 (2014) principles: risk-ranked prioritisation, phased implementation matched to institutional capital budgets, and monitoring integration to enable transition from time-based to condition-based maintenance. Each intervention is explicitly linked to the FMEA evidence that mandates it. Priority 1 (half-cell potential survey for rebar corrosion) is scheduled immediately because the RPN of 384 represents the highest structural risk and the intervention has minimal cost relative to consequence. Priority 2 (deep curtain grouting along F1/F2) is mandated specifically by the PQWT finding of a 3 m-wide aquifer at 125 m depth: the deep recharge source means that shallow membrane waterproofing alone would provide only temporary relief. Priorities 3–5 address the remaining failure modes through a combination of ground improvement, drainage, and condition-based monitoring.

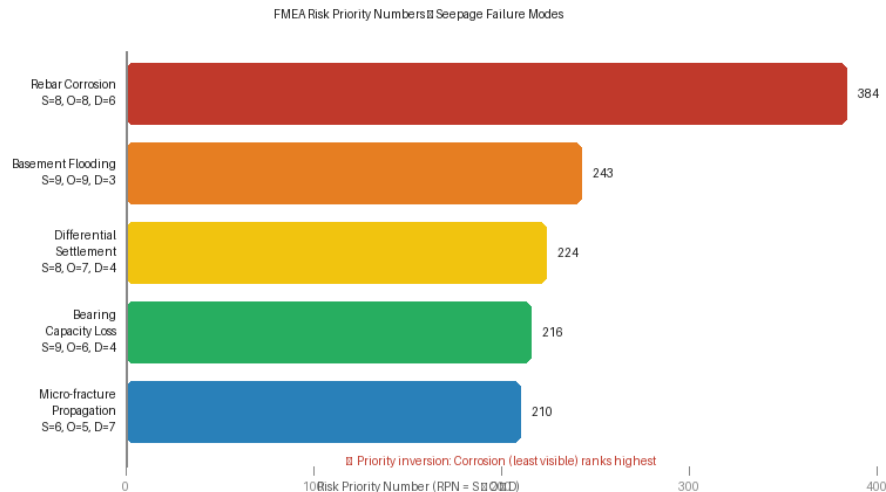


Figure 7. FMEA Risk Priority Numbers for the five seepage-related failure modes. Rebar corrosion (RPN = 384, least visible) ranks highest — a priority inversion that is invisible to conventional reactive maintenance

Table 6. Asset Integrity Management (AIM) decision framework — risk-ranked intervention roadmap with IE/OM rationale and monitoring KPIs

P	Failure Mode	Recommended Intervention	IE/OM Rationale (ISO 55000 / RCM)	Horizon	RPN	Monitoring KPI
1	Rebar corrosion	Half-cell potential survey (ASTM C876); carbonation depth test; epoxy-coat or cathodic protection on high-risk zones	RCM: prevent irreversible capacity loss. ISO 55000 Cl. 6.4: critical assets require condition-based inspection. RPN: 384→~128 post-survey (D: 6→2).	Immediate (0–6 months)	384	Half-cell ≤ -275 mV CSE; re-inspect biannually
2	Basement flooding	Cement-bentonite grout curtain wall along F1/F2 trace (2 m centres, ≥ 15 m depth); crystalline waterproofing membrane on basement walls and floor	RCM: PQWT evidence mandates deep grouting — the 125 m aquifer cannot be intercepted by shallow membrane alone. ISO 55000: highest-visibility failure mode. RPN 243.	Short-term (6–18 months)	243	Basement dry full wet season; piezometer water table
3	Differential settlement	Compaction grouting at PT2/PT3/PT4 locations (target MDD ≥ 1.94 Mg/m ³); install tiltmeters and settlement monitoring points at basement columns	RCM: shift to predictive monitoring for settlement. ISO 55000 Cl. 6.3: risk-based inspection programme. RPN 224.	Medium-term (12–24 months)	224	Settlement < 10 mm total; tiltmeter readings monthly
4	Bearing capacity loss	Perimeter French drain and sump pump system to reduce hydrostatic head; piezometers at PT3 to confirm drawdown; design to maintain driving stress below $\tau = 38$ kN/m ²	RCM: reduce driving stress below shear strength threshold (Table 3 evidence). ISO 55000: prevent progressive failure mode. RPN 216.	Medium-term (12–24 months)	216	Piezometer confirms WT below critical depth; pump operation log
5	Micro-fracture propagation	Biennial dipole-dipole ERT resurvey to track fracture growth; ISRM toughness test on deep fracture zone; archive baseline GPR radargrams for change detection	RCM: condition-based monitoring. ISO 55000 Cl. 6.7: monitoring and review. Reduces D: 7→3, RPN: 210→~90. Recurring obligation.	Long-term (24–36 months); biennial	210	No new fractures on ERT resurvey; RPN target < 100

7. Discussion

7.1 IE/OM Contributions

This paper makes three contributions framed in IE/OM terms. First, as a decision-support system, the dual GPR–PQWT investigation structured by DMAIC demonstrates how measurement choices must be driven by failure mechanism diagnosis under RCM principles. The PQWT finding of a 3 m-wide aquifer at 125 m depth changes the remediation decision from shallow waterproofing (inadequate) to deep curtain grouting (necessary) — a decision that cannot be made without the evidence. Interpretations are supported by converging multi-method evidence from GPR, PQWT, and geotechnical testing; deeper borehole validation is nonetheless recommended to confirm fracture connectivity and aquifer extent.

Second, acting as a tool for risk prioritization under uncertainty, FMEA highlights priority inversions that remain structurally invisible to reactive management. Rebar corrosion (RPN = 384) ranks above flooding (RPN = 243) because consequence-weighted risk, not visibility, is the correct prioritization criterion. It highlights the primary advantage of FMEA compared to intuitive management, directly impacting how maintenance budgets are allocated. Third, as a maintenance optimization framework, the AIM roadmap shifts the maintenance regime from entirely reactive (current state) to a four-mode strategy. They are corrective, preventive, predictive, and condition-based — phased over 36 months to match institutional budget constraints. Implementing Priorities 1–3 would increase the planned maintenance ratio from near-zero to approximately 60–70%, consistent with documented 3–5× cost efficiency gains of planned over reactive maintenance (Salama et al., 2024; Wireman, 2004).

7.2 Limitations and Future Work

The geotechnical dataset is constrained to five trial pits, each extending to depths of 3.0–3.6 m. Future work should include deeper boreholes (≥ 10 m). It should also incorporate a larger sample size ($n \geq 20$) to validate the exploratory regression relationships. The FMEA scores involve expert judgment due to the absence of quantitative failure rate data. Time-series monitoring data—such as water table levels, crack width, and settlement records—would enable calibration of occurrence probabilities with observed failure rates.

The ISRM toughness test on the deep fracture zone (Priority 5, Table 6) would determine whether the 3 m-wide aquifer fracture is still actively propagating. AI-enabled sensor networks and real-time monitoring (Salama et al., 2024) represent the next frontier for upgrading this framework from periodic survey-based to continuous condition assessment. Future work will also explore multi-objective optimization of intervention scheduling, explicitly modelling cost–risk trade-offs across the five AIM priorities to support capital budget allocation decisions.

8. Conclusions

This paper presents a general IE/OM framework. It combines dual-method geophysical investigation with FMEA-based maintenance planning. The framework is generalizable to other cases. It provides results that are not achievable with conventional reactive facility management. The dual GPR–PQWT investigation, structured by DMAIC, produced a root-cause diagnosis that distinguishes the symptom (basement flooding driven by shallow Fractures F1 and F2 at 9.2 m depth) from the underlying mechanism: sustained deep aquifer recharge from a separate 3 m-wide fracture starting at 125 m depth, confirmed by PQWT. This distinction is practically decisive — it mandates deep curtain grouting over shallow waterproofing, a conclusion that shallow GPR alone could not support. Interpretations are underpinned by converging evidence from GPR, PQWT, and geotechnical testing, though deeper borehole validation is recommended to confirm fracture connectivity and aquifer extent.

The FMEA analysis revealed a priority inversion that is the paper’s principal IEOM contribution: rebar corrosion (RPN = 384) is the highest-risk failure mode yet receives the least management attention, because it is the least visible ($D = 6$, requiring specialist testing) compared to flooding (RPN = 243, $D = 3$, immediately visible). A ± 1 variation in any single score does not alter this ranking, confirming it is robust under scoring uncertainty. Facility managers operating reactively will systematically under-invest in the structurally critical failure mode. At the same time, it progresses undetected — a pattern with direct implications for the allocation of maintenance budgets across ageing institutional infrastructure. The AIM decision framework translates this finding into a five-tier, 36-month remediation roadmap, shifting the maintenance regime from entirely reactive to predominantly planned and predictive, consistent with world-class maintenance benchmarks.

The supporting geotechnical findings confirm that SM, SC, and CL soils exhibit low permeability (8.03×10^{-6} – 1.05×10^{-5} cm/s) and present a dual seepage risk: soils with lower percentage fines carry more seepage flow risk due to higher hydraulic conductivity, while soils with higher percentage fines carry greater bearing capacity risk under saturation. Exploratory regression analysis ($R = 0.86$ – 0.98 ; $n = 5$) suggests that percentage fines may serve as a practical proxy for maintenance monitoring; however, validation with a larger dataset is required before predictive application. Effective stress analysis confirmed that horizontal effective stresses of 140.65 kN/m^2 in the saturated substrata represent an active, not merely potential, risk to the weathered and partly weathered layers adjacent to the basement.

Future work will address three priorities: deeper boreholes (at least 10 m) with $n \geq 20$ samples to validate the regression relationships; time-series monitoring data to calibrate FMEA occurrence probabilities with observed failure rates; and multi-objective optimization of intervention scheduling to explicitly model cost–risk trade-offs across the five AIM priorities. The framework demonstrated here is generalizable wherever geophysical investigation data is retrieved, and FMEA-based maintenance planning is applicable. It is particularly relevant to the large stock of ageing institutional infrastructure in tropical developing countries.

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