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Peat-Settlement Footprints in Industrial Facilities: The Role of Foundation Type in Shaping Damage Variations

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Abstract

Industrial facilities constructed on peat may exhibit different damage patterns even within the same site because their support systems translate ground movement into different structural responses. This study investigates foundation-dependent damage signatures at a crude palm oil bulking station in Kota Bangun, East Kalimantan. Evidence from 41 visual observation points, topographic measurements, two CPTu soundings, two boreholes with SPT, and non-destructive concrete and steel tests was integrated using a diagnostic comparative case-study approach. The site is underlain by fill over very soft and peaty layers, with an observed elevation loss of approximately 50–80 cm. Four damage signatures were identified: ground-supported elements followed soil settlement; shallow foundations developed settlement and angular distortion; limited or nonuniform pile support tended to rotate and distress connecting elements; and denser pile groups maintained better global geometry while concentrating damage at interfaces with ground-supported surroundings. Variations in concrete quality and steel deterioration were interpreted as local vulnerability factors rather than the sole cause of the site-wide damage pattern. The results demonstrate that foundation type controls how peat settlement is manifested as structural damage and should therefore guide monitoring, repair, strengthening, or reconstruction decisions.

Introduction

Peat is one of the most challenging geotechnical materials for industrial-facility development because of its high water content and void ratio, low unit weight and shear strength, and pronounced compressibility and creep. Consequently, deformation does not end with immediate settlement and primary consolidation but may continue as secondary compression throughout the service life. Settlement magnitude and rate are strongly affected by organic content, degree of decomposition, preconsolidation stress, permeability, and loading history; therefore, markedly different peat responses may occur within the same site (Li et al., 2020; Long et al., 2022; Mesri & Ajlouni, 2007; Peng et al., 2024; van Elderen et al., 2025).

The problem becomes more complex where peat is covered by fill and supports facilities with different foundation types. Fill placement increases effective stress and initiates consolidation, whereas variations in peat thickness and decomposition produce nonuniform spatial deformation. Experimental and numerical studies show that peat consolidation is time-dependent and cannot always be represented adequately as conventional soft mineral soil (Yamazoe et al., 2023; Zhang et al., 2020). Consequently, assessment of operating facilities should consider not only total settlement but also its spatial distribution and interaction with foundation and superstructure stiffness.

Uniform settlement can generally be tolerated provided that it does not impair function or operational elevation. Differential settlement, in contrast, produces angular distortion and force redistribution that may develop into floor and wall cracking, tie-beam failure, utility-level changes, column inclination, and structural rotation. Structural modelling on soft soil has shown that tie-beam configuration and support position influence cracking caused by support settlement (Tjitradi et al., 2021). From a geotechnical perspective, the low bearing capacity and high compressibility of peat are recognized constraints in Kalimantan, although available studies have focused more on stabilization and CBR improvement than on damage responses of operating facilities (Harwadi et al., 2022).

Within an industrial site, similar ground conditions can produce different damage patterns because each support system responds differently to peat settlement. Ground-supported and shallow-founded components tend to follow ground deformation, while pile-supported structures may develop rotation or interface distress where adjacent floors and utilities continue to settle. A similar response was reported by Khoeri et al. (2024). where differential settlement between pile- and ground-supported components caused excessive rotation and cracking. However, field comparisons linking peat stratification, foundation type, and damage variation across multiple facilities remain limited.

This study examines a crude palm oil collection and distribution facility at Liang, Kota Bangun District, Kutai Kartanegara Regency, East Kalimantan. The site was constructed on approximately 3.5 m of fill over peat layers with variable thickness of approximately 3-7 m. The initial investigation identified elevation differences of approximately 50-60 cm, cracking and failure of floors and tie beams, inclination of several structures, and contrasting responses between shallow- and pile-founded facilities. Material testing also indicated variations in concrete quality and steel thickness loss. Ground deformation, foundation type, and material condition were therefore evaluated together to distinguish the dominant mechanism from local vulnerability factors.

This study aims to identify the relationship between foundation type and variations in industrial-facility damage caused by differential settlement on peat. The evaluation integrates damage and elevation mapping, subsurface investigation, foundation-system characteristics, and testing of existing materials. Its main contribution is a foundation-dependent damage-signature framework that distinguishes the response of ground-supported slabs, shallow foundations, structures with limited pile support, and structures supported by denser pile groups. The framework is intended to provide a stronger diagnostic basis for selecting monitoring, local repair, foundation strengthening, or reconstruction measures in peatland facilities.

Research Method

Research Design and Study Area

A diagnostic case-study design with a cross-facility comparative approach was adopted. The study object is a crude palm oil collection and distribution facility at District, Kutai Kartanegara Regency, East Kalimantan. The site lies on a river plain that was filled before facility construction. The unit of analysis is not only the building as a whole, but the relationship among each facility, its foundation type, damage location, and surrounding elevation condition. This design enables comparison of damage variations within a broadly similar geotechnical environment while the load-transfer mechanisms differ among facilities.

Data Sources and Field Investigation

The dataset comprised primary field-assessment data and secondary information including structural drawings, foundation information, construction history, and previous ground-investigation records. Primary investigation included visual inspection, topographic measurement, CPTu, boreholes and SPT, rebound-hammer testing, steel hardness testing, and ultrasonic thickness testing. Data collection focused on the onshore Bulking Station; the jetty and dolphin were excluded because they were outside the research question. The field and secondary data used in the diagnostic analysis, together with their respective analytical roles, are summarized in Table 1.

Table 1. Data Sources and Their Roles in the Analysis

Data	Coverage	Role in the analysis
Visual inspection	41 observation points on seven facility groups	Identification of cracks, delamination, local buckling, weld damage, tilting, and functional disturbance
Topographic survey	Facility area tied to BM using GNSS and Total Station	Comparison of actual elevations, floor slopes, and spatial deformation patterns
CPTu	CPTU-01 and CPTU-02 to 17.9 m; predrilled to 6 m	Soil behavior type, cone resistance, and identification of weak compressible layers
Borehole and SPT	BH-01 to 28 m and BH-02 to 26 m	Subsurface stratification, groundwater depth, and depth of competent bearing layers
Rebound hammer	18 concrete test locations	Screening of concrete uniformity and separation of material-related damage from ground-deformation effects
Hardness test	13 steel elements	Screening of steel strength consistency
Ultrasonic thickness test	22 steel measurement locations	Quantification of thickness loss and evaluation of corrosion contribution

Source: Authors' compilation based on geotechnical investigation, structural assessment, field survey, testing records, and available project documents (2026).

Damage-Severity Classification

Damage severity was classified using an operational field-screening framework developed for this study. The framework follows the general assessment principles of ISO 13822:2010, ISO 16311-2:2024, ACI CODE-562-25, and ACI 364.1R-19, which emphasize documented condition surveys, observable distress, safety and serviceability implications, and further evaluation of potentially dangerous conditions. However, these references do not prescribe the four severity categories or their specific thresholds. Therefore, four categories were defined using observable indicators related to cracking, deformation or inclination, serviceability impairment, element instability, connection separation, and partial collapse. Each observation point was assigned to the highest category indicated by its observed condition. The terms hazardous and very hazardous represent screening priorities for further engineering assessment and intervention, rather than formal code-based declarations of structural safety or failure.

Table 2. Operational criteria for field damage-severity classification

Category	Classification	Operational indicators	Screening implication
1	Minor	Hairline or localized cracking; slight surface deterioration; no visible inclination, separation, or functional disturbance	Routine maintenance and periodic observation
2	Moderate	Clearly visible cracking; minor floor slope or localized deformation; early joint opening; limited serviceability disturbance without apparent instability	Detailed inspection and scheduled corrective action
3	Hazardous	Wide or propagating cracks; pronounced inclination or differential movement; substantial joint separation; local buckling or loss of function; indications of reduced element stability	Prompt engineering evaluation, access control where necessary, and corrective intervention
4	Very hazardous	Partial collapse; severe separation; major instability; loss of support or load-transfer continuity; conditions presenting an immediate risk to users or operations	Immediate restriction or isolation, followed by detailed structural assessment and emergency intervention

Source: Developed by the authors with reference to the general assessment principles of ACI Committee 364 (2019); ACI Committee 562 (2025); ISO 13822 (2010); ISO 16311 (2024)

Foundation-System Classification

Facility foundation systems were classified according to their dominant load-transfer mechanism using available drawings, pedestal and pile configurations, structural layout, and the relationship between floors and foundation elements. Four operational classes were defined: (1) ground-supported systems, comprising slabs or facility components that transfer loads directly through the fill and consequently follow ground deformation; (2) shallow-foundation systems, comprising isolated, strip, or raft foundations that transfer structural loads to the fill–peat system; (3) hybrid/limited/nonuniform pile-supported systems, in which piles support only selected components, pile spacing or length is nonuniform, or piled elements are connected to adjacent ground-supported floors; and (4) dense pile-group systems, comprising regularly arranged piles that support the principal structural loads and extend beyond the compressible layer. Interfaces between ground-supported and pile-supported components were recorded as transition zones because differences in support stiffness and settlement response can generate rotation, separation, and localized distress. Where complete as-built records were unavailable, the classification was cross-checked against exposed foundation details, structural configuration, and observed movement patterns, and the associated evidence level was reported.

Table 3. Operational criteria for foundation-system classification

Support-system class	Technical classification criteria	Expected movement response
Ground-supported system	Loads are transferred directly through slabs, pavement, or fill without identified structural foundations	Follows ground settlement and distortion
Shallow-foundation system	Structural loads are carried by isolated, strip, or raft foundations within shallow compressible strata	Settlement, differential settlement, and rotation
Hybrid/limited/nonuniform pile-supported system	Piles support only selected components; pile length, spacing, or distribution is nonuniform; or piled elements are connected to ground-supported components	Differential movement, rotation, interface separation, and localized distress
Dense pile-group system	Principal structural loads are supported by a regular and closely spaced pile group extending to competent strata	Relatively small structural settlement, with possible distress at interfaces with settling ground-supported components

Source: Developed by the authors based on available foundation records, structural configuration, and field

Topographic and Geotechnical Evaluation

The topographic survey was referenced to a permanent benchmark established in the WGS 1984/UTM Zone 50S coordinate system. The benchmark coordinates were determined through static GNSS observations, whereas facility detail points were measured using GNSS-RTK and a Total Station. The survey data were processed into elevations and contours to identify elevation differences, floor slopes, and spatial relationships between deformation and damage locations. However, construction-stage and as-built elevations tied to the same permanent benchmark were unavailable. Consequently, the survey results were interpreted as estimated elevation loss and observed elevation differences rather than absolute settlement measurements.

Subsurface conditions were evaluated by combining two CPTu soundings undertaken in 2026 with two boreholes and SPT. CPTu terminated at 17.9 m after predrilling to 6 m through dense fill. Cone resistance and friction ratio were interpreted using Soil Behaviour Type classification to distinguish fine-grained soils, silt-sand mixtures, and sand. BH-01 and BH-02 reached 28 m and 26 m, respectively, and were used to trace very soft layers, peaty strata, groundwater levels, and the depth of more competent bearing layers. Because CPTu did not record the 0-6 m interval and investigation points were limited, spatial interpretation was restricted to facility-zone scale and was not used to overstate local variations between individual structures.

Damage-Signature Analysis

The analysis comprised four stages. First, each facility was paired with its foundation-system category. Second, field findings were summarized into response indicators: vertical settlement, rotation or inclination, cracking and failure of connecting elements, local steel deformation, and functional disturbance. Third, the indicators were compared across foundation categories to identify dominant damage patterns. Fourth, the comparison was triangulated against soil stratification, current elevation, and material-test results. A pattern was classified as a settlement-related damage signature when its form and location were consistent with the load-transfer path and differential foundation movement, while material testing did not indicate sufficient degradation to explain the damage independently.

The analysis output was a foundation-type/damage-pattern matrix containing ground condition, deformation mode, affected elements, damage level, and most likely mechanism. The analysis was descriptive-comparative and was not intended as statistical inference for a population. Diagnostic reliability was maintained through consistency among evidence sources and explicit recording of data limitations, particularly the small number of ground-investigation points, absence of continuous settlement monitoring, and incomplete as-built information.

Results and Discussion

Subsurface Conditions and Settlement Evidence

The subsurface investigation confirmed a vertically heterogeneous soil profile. Very soft and peaty layers occurred below approximately 3.5-6.0 m of fill. At BH-01, the critical zone extended from approximately 4 to 10 m depth with N-SPT values of about 1-2, whereas N-SPT values greater than 30 became dominant only below approximately 16 m. BH-02 showed an earlier strength increase, although its near-surface strata remained very soft to soft. CPTU-01 and CPTU-02 also indicated low cone resistance in fine-grained layers below the fill, with higher resistance developing only in deeper sand. Differences between BH-01 and BH-02 demonstrate that the thickness and stiffness of the compressible zone were not uniform across the site.

The sixth-year survey identified estimated elevation losses of approximately 0.50–0.80 m at several ground-supported components. These values indicate substantial relative vertical deformation within the facility but should not be interpreted as absolute settlement measurements. The observed elevation differences were generally accompanied by sloping floors, cracking, separation, and deformation at interfaces between components with different support systems. This spatial consistency supports the interpretation of differential ground movement, although the magnitude at each location remains subject to uncertainty associated with the absence of construction-stage or as-built elevations tied to the same permanent benchmark.

Figure 1. compares the estimated field elevation loss with the reported settlement estimates at years 3 and 6. The estimated elevation loss of approximately 0.50–0.80 m is comparable in order of magnitude to the predicted settlement of 0.608 m at year 3 and 0.809 m at year 6.

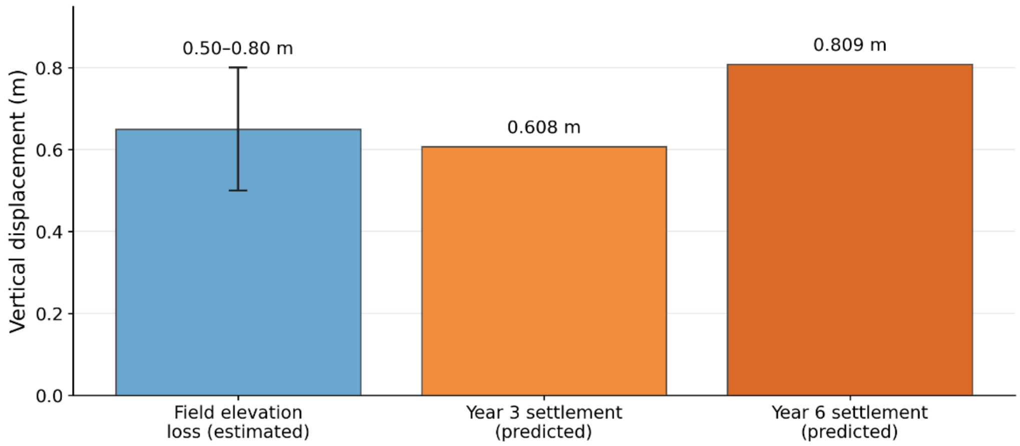


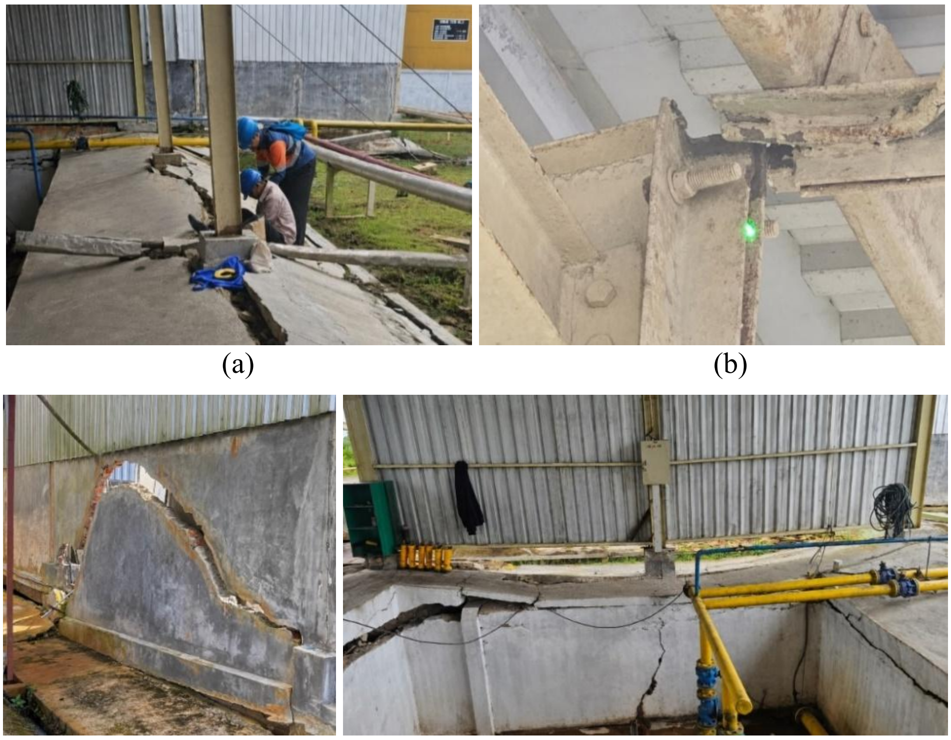
Figure 1. Comparison of estimated field elevation loss and predicted consolidation settlement
Source: Authors' compilation based on geotechnical investigation, structural assessment, field survey, testing records, and available project documents (2026).

Elevation mapping indicated a field elevation loss of approximately 0.50-0.80 m in facility components that followed ground movement. This is of the same order as the one-dimensional consolidation estimates reported in the technical assessment: approximately 0.608 m at year 3 and 0.809 m at year 6. The comparable order of magnitude supports consolidation as the dominant mechanism but is not treated as full validation because initial elevations, fill-stage records, and continuous settlement monitoring were incomplete. The analysis indicated more than 90% primary consolidation after approximately six years; residual deformation is therefore expected to be governed mainly by secondary compression and local peat variability.

Peat interpretation in this study was based mainly on borehole logs, CPTu response, and consistency with the deformation pattern. Organic content, fibre content, degree of humification, and peat-specific consolidation tests were unavailable. This limitation is important because mineral-soil index parameters, particularly Atterberg limits, are not necessarily representative of peat behaviour (O'Kelly, 2015). Settlement predictions are therefore treated as estimates based on the available profile and require calibration against field monitoring. The observed behaviour is consistent with Li et al. (2020), who showed that organic content, water content, and degree of humification produce nonlinear compressibility relationships. Long et al. (2022) likewise showed that site-to-site peat variability affects stiffness, yield stress, and permeability parameters controlling settlement. Thus, differing facility responses within one site need not arise from load differences alone but may result from the combined effects of peat heterogeneity and foundation-system stiffness.

Observed Damage across Facility Groups

Figure 2 presents representative damage associated with different support conditions, including ground-following floor deformation, distress at a structural connection, wall collapse associated with severe support incompatibility, and cracking around a settled facility component.



(a) (b)

(c) (d)

Figure 2. Representative field damage: (a) cracked and sloping floor; (b) distress at a structural connection; (c) wall collapse associated with differential settlement; and (d) cracking and separation around a settled facility component.

Source: Authors' field documentation (2026).

Across 41 observation points in seven facility groups, damage was not uniformly distributed. The Office-Laboratory-Chemical Store was dominated by cracking, with moderate corrosion and incomplete welds in steel elements. The Reception Tank combined cracked and sloping floors, weld damage, moderate corrosion, and wall cracking in a differential-settlement zone. The Kernel Reception exhibited the most complex distress, including local buckling of CNP sections, pedestal failure, detached or failed bracing, floor settlement, wall collapse, and grade-beam failure. The Boiler Station showed repeated column and floor cracking and delamination, a foundation crack, and inclination of the Generator Fuel Tank. The Weighbridge and Guard House primarily showed cracking and delamination, whereas two

Storage Tank foundation points showed delamination without global deformation comparable to the other facility groups.

The relationship between peat settlement, foundation characteristics, and observed damage was evaluated through an evidence-chain approach. For each facility, the available foundation information, dominant support system, expected movement mechanism, observed damage pattern, and evidence level were examined together. Ground-supported slabs and shallow foundations tended to follow deformation of the fill and underlying peat, producing tilting, cracking, and differential settlement. Pile-supported structures transferred their principal loads to deeper strata, but adjacent floors, utilities, and connecting components could continue to settle, causing separation and deformation incompatibility. Hybrid, limited, or nonuniform pile systems showed more complex responses, including rotation and localized distress associated with differences in support stiffness. These relationships are therefore interpreted as diagnostic associations supported by multiple consistent observations, rather than proof of a single cause, because complete foundation records and long-term monitoring data were unavailable.

Table 4 summarizes the evidence linking the support-system characteristics, available foundation information, dominant movement, observed damage, and confidence level for each facility group.

Table 4. Relationship between Facility Support Systems, Dominant Movement, and Observed Damage

Facility group	**Points**	**Support system**	**Dominant movement**	**Observed damage**	**Evidence level**
Office–Laboratory–Chemical Store	4	Shallow foundations	Settlement and limited angular distortion following fill–peat deformation	Diagonal wall cracking and local cracking around columns and slab–wall interfaces	Moderate
Reception Tank	8	Hybrid system comprising ground-supported floor areas connected to or adjacent to stiffer structural supports	Vertical floor settlement and relative displacement at floor–support interfaces	Cracked and sloping floor, wall cracking, differential elevation, damaged welds, and localized separation	High
Kernel Reception	7	Mixed support system involving shallow or ground-following components and restrained pedestal-supported structural elements	Severe differential settlement, angular distortion, and relative movement between floor, pedestals, and superstructure	Pedestal and tie-beam failure, wall collapse, floor settlement, local buckling, and detached or failed bracing	High
Boiler Station	14	Mixed foundation system comprising structural pedestals, equipment foundations, ground-supported floors, and locally supported tanks	Combined vertical settlement, local rotation, and interface displacement	Column and floor cracking, delamination, foundation cracking, and tilting of the generator fuel tank	Moderate–High
Weighbridge	5	Predominantly shallow or ground-interacting support system	Local settlement and possible angular distortion	Column cracking and delamination	Low–Moderate
Guard House	1	Shallow foundations	Local movement could not be reliably distinguished from material-related cracking	Localized wall or structural cracking	Low
Storage Tank	2	Relatively dense pile-group support beneath the principal tank structure, with surrounding ground-supported components	Limited global movement of the main tank structure, with possible relative settlement of surrounding ground-supported elements	Localized foundation delamination without pronounced global tilting or settlement	Moderate

Source: Authors' compilation based on geotechnical investigation, structural assessment, field survey, testing records, and available project documents (2026).

As shown in Table 4, the observed damage was more strongly associated with differences in support stiffness and movement compatibility than with the facility function itself. Ground-supported and shallow-supported components predominantly followed fill–peat settlement, resulting in floor depression, cracking, and angular distortion. Hybrid systems experienced more severe distress at interfaces where settling floors or shallow elements were restrained by pedestals or stiffer supports. In contrast, the storage tanks supported by relatively denser pile groups maintained better global geometry, although localized deterioration remained evident at the foundation surface and surrounding interfaces.

The strongest evidence was obtained for the Reception Tank and Kernel Reception because the observed floor settlement, tie-beam failure, wall distortion, and support-interface damage were directly consistent with differential ground movement. Evidence for pile-dependent rotation and pile-group stability was rated moderate because complete pile layouts, pile integrity results, and continuous inclination measurements were unavailable. These interpretations should therefore be verified using as-built drawings, elevation monitoring, and pile-integrity testing.

Damage severity was assigned to each of the 41 visual observation points using the most critical defect recorded at that location. The provisional classification identified 10 minor points (24.4%), 15 moderate points (36.6%), 11 hazardous points (26.8%), and five very hazardous points (12.2%). Thus, 16 of the 41 points, or approximately 39.0%, were classified as hazardous or very hazardous. The distribution among facility groups is presented in Table 5.

Table 5. Provisional Distribution of Damage Severity among Facility Groups

Facility group	Observation points, n	Category 1: Minor	Category 2: Moderate	Category 3: Hazardous	Category 4: Very hazardous
Office–Laboratory–Chemical Store	4	3	1	0	0
Reception Tank	8	0	1	7	0
Kernel Reception	7	0	0	2	5
Boiler Station	14	4	8	2	0
Weighbridge	5	2	3	0	0
Guard House	1	1	0	0	0
Storage Tank	2	0	2	0	0
Total	**41**	**10**	**15**	**11**	**5**
Percentage	**100%**	**24.40%**	**36.60%**	**26.80%**	**12.20%**

Source: Authors' analysis of 41 field observation points (2026).

As shown in Table 5, damage severity was not uniformly distributed among the facility groups. The Kernel Reception contained all five very hazardous observations, associated with pedestal failure, broken bracing, detached structural members, severe ponding, and wall and tie-beam collapse. The Reception Tank was dominated by hazardous observations associated with cracked and sloping floors, damaged welds, and differential movement. In contrast, the Office–Laboratory–Chemical Store, Weighbridge, Guard House, and Storage Tank were dominated by minor or moderate surface defects without comparable evidence of global deformation or functional failure.

The comparison by support-system class in Table 6 provides a more direct indication of the role of foundation response.

Table 6. Provisional Damage-Severity Distribution by Dominant Support-System Class

Support-system class	Facility groups represented	Points	Minor	Moderate	Hazardous	Very hazardous
Ground-supported or shallow-supported system	Office–Laboratory–Chemical Store, Reception Tank, Weighbridge, and Guard House	18	6	5	7	0
Hybrid, limited, or nonuniform support system	Kernel Reception and Boiler Station	21	4	8	4	5
Relatively dense pile-group support	Storage Tank	2	0	2	0	0
Total	**Seven facility groups**	**41**	**10**	**15**	**11**	**5**

Source: Authors' analysis of 41 field observation points (2026).

Ground-supported or predominantly shallow-supported facilities contained seven hazardous observations among 18 points (38.9%), indicating visible deformation or pronounced differential movement. Hybrid, limited, or nonuniform support systems exhibited the broadest severity range and contained all five very hazardous points. These failures were concentrated at interfaces among floors, pedestals, tie beams, and structural frames, where differences in support stiffness generated deformation incompatibility. The relatively dense pile-supported Storage Tank showed only moderate localized deterioration and no documented hazardous or very hazardous global deformation.

Figure 3 presents the percentage distribution of damage-severity categories across the dominant support-system classes, allowing comparison despite differences in the number of observation points.

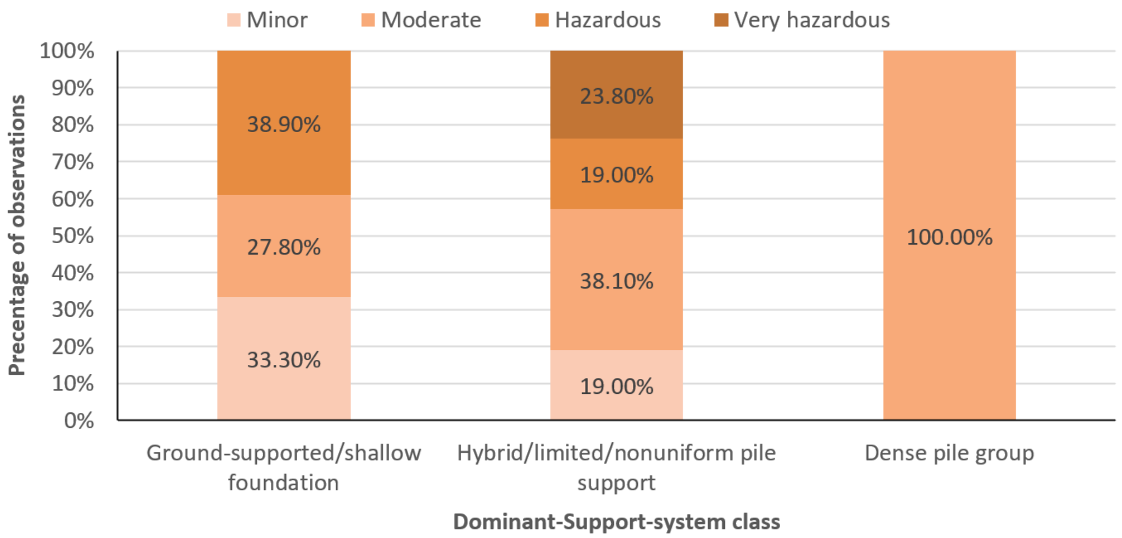


Figure 3. Percentage distribution of damage-severity categories according to the dominant support-system class.

Source: Authors' analysis based on the data presented in Table 6.

As shown in Figure 3, the observed damage did not follow a uniform pattern across the facility groups. The most severe damage occurred in transition zones combining ground-supported elements with components restrained by pedestals or stiffer foundations. Conversely, facilities with more uniformly distributed pile-group support visually maintained better global geometry, although surface deterioration remained possible. This finding supports Tjitradi et al. (2021), who showed that tie configuration and support position alter settlement-induced cracking, while the present case extends the comparison from one frame to several industrial facilities with different support systems.

Material Condition as a Contributing Factor

Rebound-hammer testing at 18 locations produced estimated cube compressive strengths of approximately 142.6–584.2 kg/cm². The lowest values occurred in the Oil Reception grade beam, the Kernel Reception grade beam and pedestal, and Sediment Pond elements, whereas the highest value occurred in a pile. The wide range indicates nonuniform concrete quality. However, rebound-hammer results are surface-screening measurements and may be affected by surface condition and carbonation; therefore, they should not be treated as definitive in-situ compressive strength without correlation with core-test or complementary NDT results (Khoeri, et al., 2024) Low values were therefore interpreted as factors that may increase vulnerability to cracking or delamination rather than independent evidence for the cause of settlement and inclination.

Hardness testing of 13 steel elements gave estimated tensile strengths of approximately 415.6-471.4 MPa. Ultrasonic thickness testing at 22 locations indicated thickness loss of 0-2.6 mm; the greatest loss occurred at the bottom plate of Storage Tank 1, whereas most other elements showed smaller reductions. These results confirm localized degradation requiring repair, but their distribution does not explain the overall pattern of depressed floors, transition-zone wall cracking, or structural inclination. Material condition is therefore interpreted as a co-factor: locally reduced capacity may accelerate damage manifestation when a structure is forced to accommodate incompatible foundation deformation. The measured ranges obtained from the concrete and steel screening tests are summarized in Figure 4.

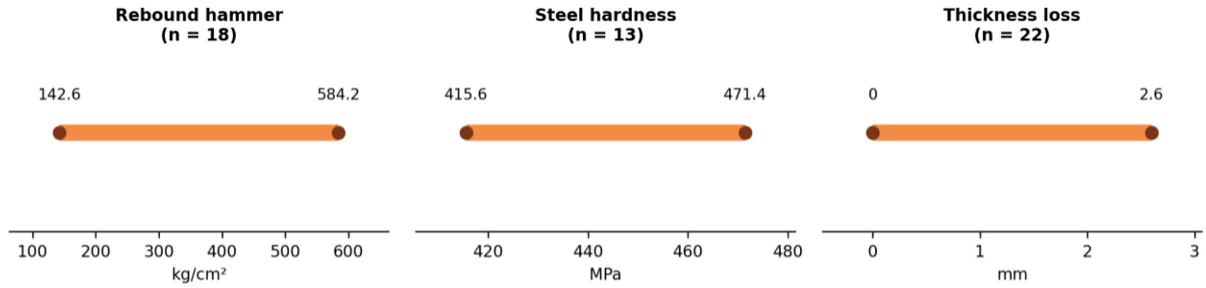


Figure 4. Measured ranges from concrete and steel screening tests.
Source: Authors' analysis based on field test results (2026).

Foundation-Dependent Damage Signatures

Cross-facility comparison produced four damage signatures. First, components supported directly by fill followed ground consolidation and exhibited elevation loss, sloping floors, slab cracking, and ponding. Second, shallow foundations experienced greater translation and distortion because their loads and deformation interacted directly with the fill-peat system. Dominant damage comprised foundation cracking, grade-beam failure, and wall distortion. Third, structures with limited or nonuniform pile support tended to rotate. Piles reduced absolute vertical settlement at support points, but nonuniform stiffness among supports could incline columns or tanks and impose distress on connecting elements. Fourth, denser pile groups produced better global stability because loads were transferred beyond the compressible strata. Nevertheless, floors surrounding pedestals and other ground-supported components could settle relative to the main structure. Pile foundations therefore changed the damage form from global settlement to differential movement at interfaces. Comparable interface distress was identified by (Khoeri, Badaruddin, et al., 2024), where differential settlement between pile-supported and ground-supported pipeline segments produced excessive rotation and cracking. The dominant movement, characteristic damage signature, and strength of evidence associated with each support system are summarized in Table 7.

Table 7. Foundation-Dependent Damage Signatures

Support system	Dominant movement	Damage signature	Evidence strength
Ground-supported slab/facility	Vertical settlement following fill-peat compression	Floor depression, cracking, slope, ponding, separation from pedestal	High
Shallow foundation	Settlement and angular distortion	Foundation/tie-beam cracks, wall distortion, local collapse	High
Limited or nonuniform pile support	Rotation and differential pile response	Tilted columns or tanks; distress at braces and joints	Moderate
Dense pile group with ground-supported surroundings	Small global movement but relative displacement at interfaces	Stable main structure; local floor/pedestal separation or surface deterioration	Moderate

Source: Authors' synthesis based on foundation information, field observations, and assessment results.

The causal chain in Figure 5 summarizes the principal interpretation: peat heterogeneity produces settlement gradients; foundation type converts these gradients into translation, rotation, or relative movement; and the structural response manifests as distinct damage signatures.

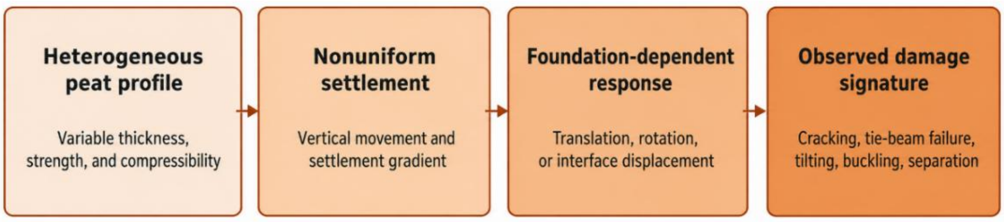


Figure 5. Conceptual mechanism linking peat heterogeneity, foundation response, and damage signature
Source: Developed by the authors based on the present findings and relevant literature

Evidence strength for the first and second categories was rated high because surface deformation, cracking, and connecting-element failures were directly observed and were consistent with the compressible soil profile. Evidence for pile-supported categories was rated moderate because as-built pile configurations were incomplete and individual pile integrity had not been confirmed. Rotation caused by differential pile-group response is therefore the most likely diagnosis but requires verification through pile-integrity testing, periodic inclination surveys, and elevation monitoring.

Mechanism and Engineering Implications

The evidence indicates a staged mechanism. Fill and facility loads increased stress in the peat; variations in peat thickness and properties produced nonuniform settlement; differences in foundation stiffness converted ground deformation into translation, rotation, or relative movement; and the resulting deformation manifested as cracking, grade-beam failure, local buckling, connection damage, or functional disturbance. This mechanism explains why adjacent facilities exposed to the same broad geotechnical setting can display different damage forms.

The findings agree with long-term field evidence showing that early embankment response is governed mainly by load magnitude, whereas long-term deformation is controlled by peat consolidation and creep (Long et al., 2023). Recent mechanistic review indicates that viscous peat compression involves micropore-water expulsion, fibre reorientation, particle interaction, and organic-matter decomposition (van Elderen et al., 2025). At industrial sites on peaty soils, spatial soil variability and loading history have likewise produced nonuniform settlement (Ulusay et al., 2010). Completion of most primary consolidation therefore does not imply that damage progression has ceased; residual slow movement may continue to widen cracks and increase elevation incompatibility at floor, pedestal, pipe, and main-structure interfaces.

In practice, intervention should not be standardized solely according to surface damage type. Ground-following floors require elevation restoration and separation details from rigid elements; severely distorted shallow foundations require evaluation for underpinning or reconstruction; pile-supported structures require pile-integrity and pile-group-response assessment; and local defects arising from concrete quality, corrosion, or welds should be repaired as separate capacity and durability issues. Settlement plates, elevation-control points, crack gauges, and tilt monitoring are required to distinguish stable damage from continuing movement.

The main contribution of this study is to show that peat-settlement footprints cannot be assessed solely from settlement magnitude. Foundation type controls how settlement is translated into damage: flexible systems follow ground movement, shallow systems distort, limited pile systems tend to rotate, and stiffer pile groups shift damage concentration to interfaces. This damage-signature framework can support preliminary diagnosis at other industrial facilities on organic soils, provided that it is calibrated to local stratification, loading history, and foundation configuration.

Conclusion

This study demonstrates that damage to industrial facilities on peat does not follow a single pattern. Field elevation loss of approximately 0.50-0.60 m, very soft and peaty strata below the fill, and agreement in order of magnitude with consolidation estimates support ground settlement as the dominant mechanism. Its structural manifestation, however, is controlled by foundation type and support-system uniformity.

Four damage signatures were identified. Ground-supported facilities tended to exhibit floor depression, inclination, cracking, and ponding. Shallow foundations showed settlement and angular distortion that developed into foundation cracking, tie-beam failure, and wall distortion. Limited or nonuniform pile support tended to convert settlement into rotation and distress in connecting elements. Denser pile groups maintained better global geometry but transferred damage concentration to interfaces with floors or other components that continued to follow ground movement.

Variations in concrete quality, corrosion, steel thickness loss, and connection defects acted as local vulnerability factors that may accelerate damage manifestation but were insufficient to explain the cross-facility spatial pattern. Intervention decisions should therefore separate material repair from control of ground deformation and foundation response. Priorities include periodic elevation surveys, settlement plates, crack gauges, tilt monitoring, verification of as-built configuration, and pile-integrity testing where rotation is present. These findings are diagnostic for a case study and should be calibrated using monitoring data before strengthening or reconstruction is designed.

Author Contributions

Conceptualization, H.K. and M.A.K.; Methodology, H.K. and D.N.; Software, M.A.K.; Validation, H.K. and M.A.K.; Formal Analysis, M.A.K. and N.R.Q.; Investigation, D.N.; Resources, M.A.K. and N.R.Q.; Data Curation, N.R.Q.; Writing – Original Draft Preparation, H.K.; Writing – Review & Editing, H.K. and D.N.; Visualization, N.R.Q.; Supervision, H.K.; Project Administration, D.N.

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability

The datasets generated during and/ or analyzedduring the current study are available from the corresponding author on reasonable request.

Use of Generative AI

No generative AI was used.

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