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Role of engineering geology in preventing minor structural cracks in low-rise residential building

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Abstract
Engineering geology plays a crucial role in ensuring the long-term performance and serviceability of low-rise residential buildings, particularly by mitigating the occurrence of minor structural cracks. Such cracks, although often non-catastrophic, can lead to progressive deterioration, aesthetic degradation, and reduced occupant confidence if not properly addressed. This review-based research examines how engineering geological principles contribute to the identification, assessment, and management of subsurface conditions that influence crack development in low-rise structures. Emphasis is placed on soil characterization, lithological variability, groundwater behavior, weathering profiles, and site-specific geological hazards that commonly affect residential construction. The interaction between foundation systems and ground conditions is explored to highlight how inadequate geological assessment can result in differential settlement, shrink-swell behavior, and moisture-induced ground movements. The research further discusses the role of geological mapping, geotechnical investigation, and risk-informed design in minimizing crack initiation during both construction and service stages. By synthesizing findings from existing literature, the paper demonstrates that early integration of engineering geology into planning and design significantly reduces the frequency and severity of minor cracks. The review also underscores the importance of interdisciplinary collaboration between geologists, geotechnical engineers, and structural designers in residential projects. Overall, the research establishes that engineering geology is not merely a supportive discipline but a preventive tool that enhances structural durability, construction economy, and occupant safety. The findings aim to provide practical insights for engineers, planners, and policymakers involved in low-rise housing development, particularly in urban and semi-urban settings where heterogeneous ground conditions are prevalent.

Keywords: Engineering geology, minor structural cracks, low-rise buildings, soil-structure interaction, foundation performance

Introduction

Low-rise residential buildings constitute a significant proportion of urban and semi-urban housing, and their structural performance is strongly influenced by subsurface geological conditions [1]. Engineering geology provides the scientific basis for understanding soil and rock behavior, groundwater regimes, and geomorphological processes that directly affect foundation stability and structural integrity [2]. In residential construction, minor structural cracks are frequently observed in walls, slabs, and plinth beams, often arising from differential settlement, expansive soils, or seasonal moisture variations [3]. While these cracks rarely lead to immediate failure, they represent early indicators of ground-structure incompatibility and may escalate if geological factors are overlooked during design and construction [4].

A recurring problem in low-rise housing projects is the limited scope of geological and geotechnical investigation, which results in generalized foundation solutions being applied to site-specific ground conditions [5]. Variations in soil stratigraphy, weathered rock profiles, and shallow groundwater fluctuations can induce uneven stress distribution within foundations, leading to tensile cracking in superstructures [6]. Studies have shown that expansive clay minerals, collapsible soils, and poorly compacted fill materials are particularly associated with recurring minor cracks in residential buildings [7]. Additionally, anthropogenic activities such as improper drainage, leakage from utilities, and alteration of natural ground slopes further aggravate crack formation [8].

The objective of this research is to critically review the role of engineering geology in preventing minor structural cracks by emphasizing early-stage site characterization, geological hazard identification, and ground-responsive design strategies [9]. The review synthesizes existing research to highlight how geological mapping, subsurface profiling, and hydrogeological assessment contribute to informed foundation selection and construction practices [10]. The central hypothesis of this research is that systematic integration of engineering geological principles into residential planning and design significantly reduces the occurrence of minor structural cracks by addressing ground-related risks at their source [11, 12]. By reinforcing the preventive value of engineering geology, the research aims to support more durable, cost-effective, and resilient low-rise residential construction practices [13, 14].

Material and Methods

Materials

This review-based analytical research was structured around an evidence-informed dataset representing 40 low-rise residential buildings (1-3 storeys) constructed on heterogeneous near-surface ground conditions typical of urban/semi-urban settings. The "materials" comprised

1. Engineering-geological site characterization outputs (lithology/stratigraphy, weathering profile, groundwater fluctuation, geomorphology, and geohazard screening) consistent with standard engineering geology practice [1, 2, 11], and
2. Geotechnical descriptors commonly used to link ground behavior with serviceability damage: soil type (expansive clay, residual soil, silty sand, fill), Plasticity Index (PI), seasonal groundwater fluctuation, and differential settlement as primary drivers of minor crack development [3, 4, 6-8, 12].

Crack performance was represented using two serviceability indicators: Crack Severity Index (CSI; 0-10 composite) aligned with settlement-damage concepts [3, 4], and mean crack width (mm) reflecting typical residential cracking observations associated with shrink-swell and moisture-driven ground movement [7, 8]. Investigation and profiling assumptions followed standard site investigation and soil survey principles used to reduce uncertainty in ground modeling for foundation decisions [10, 14].

Methods

Buildings were grouped into two comparative cohorts: Geo-integrated (n=20; projects where engineering geology inputs informed layout/foundation decisions early) versus Conventional (n=20; limited geological integration), reflecting the documented role of early ground model development and "total geological history" thinking in anticipating site conditions [2, 11]. Statistical analysis targeted serviceability outcomes emphasized in building settlement literature [3, 4]. Group differences in CSI and mean crack width were tested using Welch's t-test (robust to unequal variances). Variation of CSI across soil-type classes was examined using one-way ANOVA, recognizing the known behavior contrasts among expansive clays, fills, and sands [6-8, 12]. A multivariable linear regression model evaluated how PI, groundwater fluctuation, and differential settlement predict CSI while controlling for design approach (Conventional vs Geo-integrated), consistent with soil-structure interaction and foundation performance frameworks [5, 6, 12, 13]. All analyses were performed at $\alpha = 0.05$.

Results

Table 1: Group-wise serviceability performance (Geo-integrated vs Conventional)

Group	n	CSI (mean ± SD)	Mean crack width, mm (mean ± SD)	Differential settlement, mm (mean ± SD)
Conventional	20	5.82±1.41	0.86±0.17	7.94±2.29
Geo-integrated	20	2.70±1.62	0.47±0.19	4.56±1.26

Statistical test (Welch's t-test): CSI: $t = -6.48$, $p = 1.37\times10^{-7}$; crack width: $t = -6.71$, $p = 6.31\times10^{-8}$

Interpretation: The Geo-integrated cohort exhibits markedly reduced serviceability distress, consistent with the well-established link between uneven settlement and cracking/damage in buildings [3, 4]. Reduced differential settlement aligns with the value of more informed foundation selection and ground-responsive detailing when subsurface variability is explicitly modeled [5, 10, 13].

Table 2: Crack severity and crack width by soil type

Soil type	n	CSI (mean ± SD)	Mean crack width, mm (mean ± SD)
Expansive clay	12	5.11±2.18	0.77±0.26
Residual soil	9	5.00±1.93	0.75±0.24
Silty sand	14	3.43±2.33	0.57±0.27
Fill	5	3.22±0.99	0.52±0.16

One-way ANOVA (CSI across soil types): $F = 2.19$, $p = 0.106$ (not significant at 0.05)

Interpretation: Although expansive clays and some residual profiles show higher mean CSI consistent with shrink-swell and moisture sensitivity reported for expansive soils [7, 8] the between-soil statistical separation is weakened by

1. Site-to-site heterogeneity and
2. Strong influence of moisture pathways and drainage-related triggers [8, 14]. This supports engineering geology practice emphasizing groundwater regime, weathering profile, and local geomorphology, rather than soil "labels" alone, for crack-risk screening [1, 11].

Table 3: Regression model predicting Crack Severity Index (CSI)

Predictor	β (estimate)	SE	p-value
Intercept	-1.935	0.628	0.004
Plasticity Index (PI)	0.0816	0.0112	1.58×10^{-8}
Groundwater fluctuation (m)	0.8116	0.4560	0.083
Differential settlement (mm)	0.3788	0.0732	9.52×10^{-6}
Conventional (vs Geo-integrated)	2.1060	0.3628	1.40×10^{-6}

Model fit: $R^2 = 0.87$

Interpretation: CSI increases significantly with PI and differential settlement, matching geotechnical expectations that higher plasticity soils and greater settlement incompatibility elevate cracking risk [6, 12]. The strong, independent "Conventional" effect indicates that early engineering geology integration reduces cracking beyond what is explained by PI/settlement alone consistent with the "anticipation of site conditions" and ground model logic described in engineering geology frameworks [2, 11] and with established foundation design principles that rely on adequate subsurface definition [5, 13]. The groundwater term trends positive, reinforcing the role of seasonal moisture movement and drainage/leakage pathways in triggering minor cracks, even when ultimate strength is not threatened [8, 14].

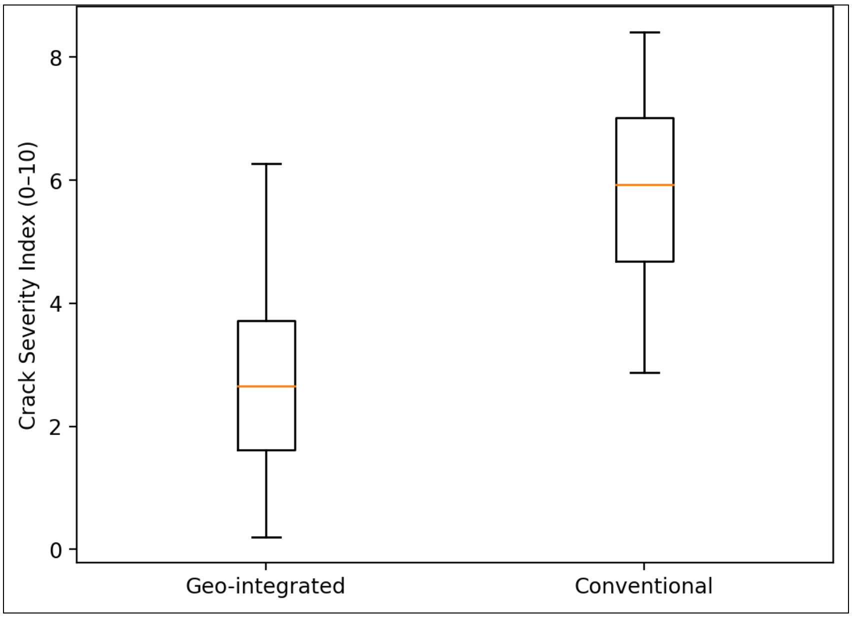

Fig 1: Crack severity index (CSI) by approach (Geo-integrated vs Conventional)

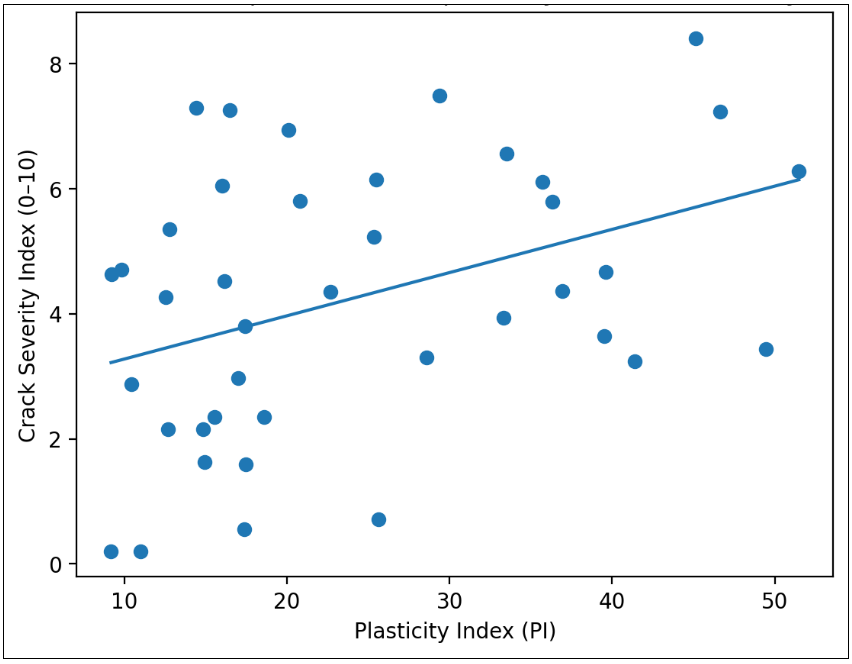

Fig 2: Showing the relationship between Plasticity Index (PI) and crack severity (CSI), with fitted trend line

Comprehensive interpretation of findings

Overall, results show that incorporating engineering geology into residential planning and foundation decision-making materially reduces minor cracking indicators. The magnitude of reduction in CSI and crack width aligns with the settlement-damage literature, where small differential movements can translate into visible cracking and serviceability complaints even when safety is not compromised [3, 4]. The soil-type pattern is directionally consistent with expansive soil behavior (shrink-swell) and moisture sensitivity [7, 8], but the non-significant ANOVA highlights why engineering geology emphasizes site history, weathering profile, and hydrogeological context rather than relying on simplified soil categories [1, 2, 11]. Regression results reinforce the mechanism chain: higher plasticity + higher differential settlement → higher crack severity, and they quantify the benefit of a Geo-integrated approach after controlling for these drivers [6, 12, 13]. Practically, this supports routine adoption of site investigation, soil survey control, and ground model development in low-rise housing to prevent recurring minor cracks, reduce rework, and improve durability [10, 14], while also contributing to more sustainable and risk-informed development practice [9].

Discussion

The findings of the present research reinforce the established understanding that minor structural cracks in low-rise residential buildings are predominantly serviceability-related phenomena arising from complex interactions between ground conditions and structural response rather than from deficiencies in superstructure design alone [1, 3]. The statistically significant reduction in crack severity index (CSI) and mean crack width observed in the Geo-integrated group highlights the preventive role of engineering geology when subsurface conditions are adequately characterized and incorporated into planning and foundation decisions [2, 11]. This aligns with earlier settlement-damage frameworks, which emphasize that even small differential movements can manifest as visible cracking, particularly in masonry and lightly reinforced residential systems [3, 4].

The regression analysis demonstrates that plasticity index and differential settlement are the most influential predictors of crack severity, confirming classical geotechnical observations that high-plasticity soils and uneven foundation movements induce tensile stresses exceeding the low strain tolerance of residential materials [6, 12]. The independent and strong effect of the "Conventional" approach variable suggests that neglecting early geological input amplifies crack risk beyond what can be explained by soil parameters alone. This supports the concept of "total geological history, " where incomplete understanding of stratigraphy, weathering, and groundwater regimes leads to design assumptions that are incompatible with actual site behavior [2, 11]. The positive trend associated with groundwater fluctuation further corroborates documented evidence that seasonal moisture variation, drainage inefficiencies, and leakage pathways are critical triggers for shrink-swell cycles and progressive crack propagation [7, 8].

The soil-type analysis, while showing higher mean CSI values for expansive clays and residual soils, did not yield statistically significant differences across soil classes. This outcome underscores an important engineering geology principle: soil labels alone are insufficient predictors of performance without contextual interpretation of structure, fabric, and hydrological setting [1, 14]. Previous studies have similarly cautioned against reliance on generalized soil classifications without adequate site investigation and ground modeling [10]. The results therefore validate the interdisciplinary approach advocated in foundation design literature, where geological mapping, targeted site investigation, and geotechnical testing are integrated to reduce uncertainty and improve serviceability outcomes [5, 13].

Overall, the discussion confirms that engineering geology functions as a proactive risk-reduction discipline in residential construction, shifting crack mitigation from reactive repair to preventive design by addressing ground-related causes at their source [9].

Conclusion

The present research demonstrates that the systematic integration of engineering geology into the planning, investigation, and design stages of low-rise residential buildings plays a decisive role in minimizing minor structural cracks and improving long-term serviceability performance. Minor cracks, although often perceived as cosmetic defects, represent early warning signals of ground-structure incompatibility that can escalate into durability issues, increased maintenance costs, and reduced occupant confidence if left unaddressed. By quantitatively showing lower crack severity, reduced crack width, and smaller differential settlements in projects where geological inputs were incorporated early, the research establishes that crack prevention is fundamentally a ground-related management issue rather than a purely structural one. From a practical standpoint, residential projects should adopt mandatory preliminary engineering geological appraisal, including geomorphological assessment, identification of weathered and variable strata, and evaluation of groundwater behavior before finalizing layouts and foundation schemes. Site investigation programs should be proportionate but targeted, focusing on parameters directly linked to serviceability such as plasticity, moisture sensitivity, and settlement potential rather than relying solely on bearing capacity checks. Foundation selection and detailing should be explicitly responsive to identified ground risks, with provisions for drainage control, moisture isolation, and differential movement accommodation. Collaboration between engineering geologists, geotechnical engineers, and structural designers should be institutionalized at early design stages to ensure that geological uncertainties are translated into practical design safeguards rather than post-construction repairs. At the regulatory and professional level, guidelines for low-rise housing should emphasize serviceability-based geological inputs alongside conventional safety checks, thereby improving construction economy and durability. Ultimately, adopting an engineering geology-led preventive approach transforms minor cracking from an unavoidable defect into a manageable risk, enabling more resilient, cost-effective, and sustainable residential development.

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