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Risk-Informed Foundation Optioneering in Karst Terrain: From Geotechnical Risk to Sustainable Development

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Abstract

This study shows that risk-informed geotechnical decision-making provides a clear and reliable foundation for demonstrating sustainability outcomes in karst-affected construction projects across the Middle East. Karst terrain is common in the region and creates significant uncertainty that, if not addressed early, can transfer risks related to safety, project schedule, high material consumption, and elevated carbon emissions to the construction phase. Current practices often respond to this uncertainty with conservative, material-heavy solutions that increase these risks during construction, extend timelines, and increase cost and embodied-carbon consumption.

To tackle these issues, the study introduces a design-stage framework in which the Sustainable Development Goals are not used as fixed design rules. Instead, SDGs 3, 8, 12, and 13 naturally arise as outcomes of managing project-specific risks related to safety, project schedule, material usage efficiency, and embodied carbon. Applying this methodology to a high-load building on karstic limestone in Saudi Arabia demonstrates its practical benefits. Comparative analysis shows that a piled foundation better localises and manages karst risks compared to a raft foundation with probing and grouting. This results in lower construction risk exposure (SDG 3), a more predictable project schedule and procurement (SDG 8), reduced material use (SDG 12), and significantly lower embodied carbon in the design stage (SDG 13). Carbon impacts are presented as comparative indicators that reflect uncertainties in regional emissions.

These findings illustrate that sustainable outcomes in rock engineering can be advanced by integrating SDG evidence generation into standard risk-based design processes. Further case studies across different geological formations, foundation types, and load classes are needed before the approach can be considered generally applicable.

Keywords

Karst risk management, Foundation optioneering, Risk-informed geotechnical design, Sustainable development goals (SDGs), Embodied carbon in ground engineering.

1 Introduction

In 2015, all United Nations (UN) member countries, including those in the Middle East, pledged to achieve the 17 Sustainable Development Goals (SDGs) by 2030 (UNDESA 2015). Four SDGs are directly relevant to construction: SDG 3 (health and safety risk management), SDG 8 (decent work, labour productivity, and schedule certainty), SDG 12 (efficient use of raw materials), and SDG 13 (reduced greenhouse gas emissions). The Middle East is undergoing rapid development through initiatives such as Saudi Arabia's Vision 2030 (Saudi Vision 2023), creating significant pressure to deliver projects sustainably. However, achieving SDGs 3 and 8, for example, is hindered by limited awareness of Safety in Design (SiD) among regional practitioners. A survey of 29 geotechnical professionals found that only 30% were "very knowledgeable" in SiD, consistent with findings from Hassanain et al. (2022), and both studies emphasise the need for earlier design-stage integration of safety principles. Regarding SDGs 12 and 13, designers often favour conservative approaches, such as geotechnical engineers addressing cavity risks. Karst formations are widespread across the Arabian Gulf, including the Jubaila Limestone in Saudi Arabia and the Simsima Limestone in Qatar (Mansour et al. 2024; Nawaz et al. 2020). Cavities, fractured zones, and highly weathered rock create geotechnical uncertainties that commonly drive engineers toward conservative, material-intensive solutions (Waltham 2005). This is compounded by the late availability of geotechnical data and tight project schedules, resulting in excess material consumption, elevated embodied carbon, higher costs, and increased construction safety risks. Carbon quantification is further complicated by reliance on Western benchmarks that may not reflect regional manufacturing conditions (Rasha et al. 2022).

This study aims to establish a systematic method for managing risks associated with achieving SDGs 3, 8, 12, and 13 in construction projects across the Middle East. Through a case study from the Arabian Peninsula, this paper illustrates how geotechnical engineers can apply a risk-informed decision framework to aid in foundation selection in karst terrains, thereby advancing the four SDGs.

2 Methodology

This study adopts a structured, risk-informed design methodology for foundation selection in karst terrain. In this framework, SDGs 3, 8, 12, and 13 are treated as derived outcomes of engineering decisions taken to manage project-specific geotechnical risks, rather than as fixed design targets. The methodology integrates hazard identification, risk assessment, option development, and risk control within Stages 1–3 of the RIBA Plan of Work 2020 (RIBA 2020), where design interventions have the greatest influence on safety, programme, material demand, and embodied carbon (Pantelidou et al. 2012). The four SDGs are operationalised through specific sub-targets relevant to construction practice: SDG 3 via sub-target 3.9 (reduction of deaths and illnesses from hazardous conditions); SDG 8 via sub-target 8.8 (protection of labour rights and promotion of safe working environments); SDG 12 via sub-target 12.2 (sustainable management and efficient use of natural resources); and SDG 13 via sub-target 13.2 (integration of climate change measures into policy and planning). This mapping is an adaptation for geotechnical design practice; the indicators used are proxies for these sub-targets rather than direct measures of UN reporting metrics (UNDESA 2015).Fig. 1 summarises the workflow.

2.1 RIBA Stage 1: hazard identification and objective definition

The process begins with the identification of karst-related hazards using available geological and geotechnical evidence, including historical records, geological mapping, borehole data, and geophysical survey outputs. Indicators such as core loss, drilling anomalies, and variable ground response are used to define the presence and spatial variability of potential cavities and fractured zones. In parallel, project objectives are established through Value Engineering (VE) function analysis (SAVE 2007 and Mahmoud and Deab 2021), which translates design drivers into explicit engineering criteria, including structural performance, constructability, and carbon management in accordance with PAS 2080.

2.2 RIBA Stage 2: risk assessment and option development

Identified hazards are translated into project risks through a structured assessment aligned with ISO (2018a), based on the evaluation of likelihood and consequence under geotechnical uncertainty. The output is a risk profile describing the likely effects of ground conditions on construction safety (SDG 3), programme reliability and procurement (SDG 8), material demand (SDG 12), and embodied carbon (SDG 13). This risk profile provides the basis for option development.

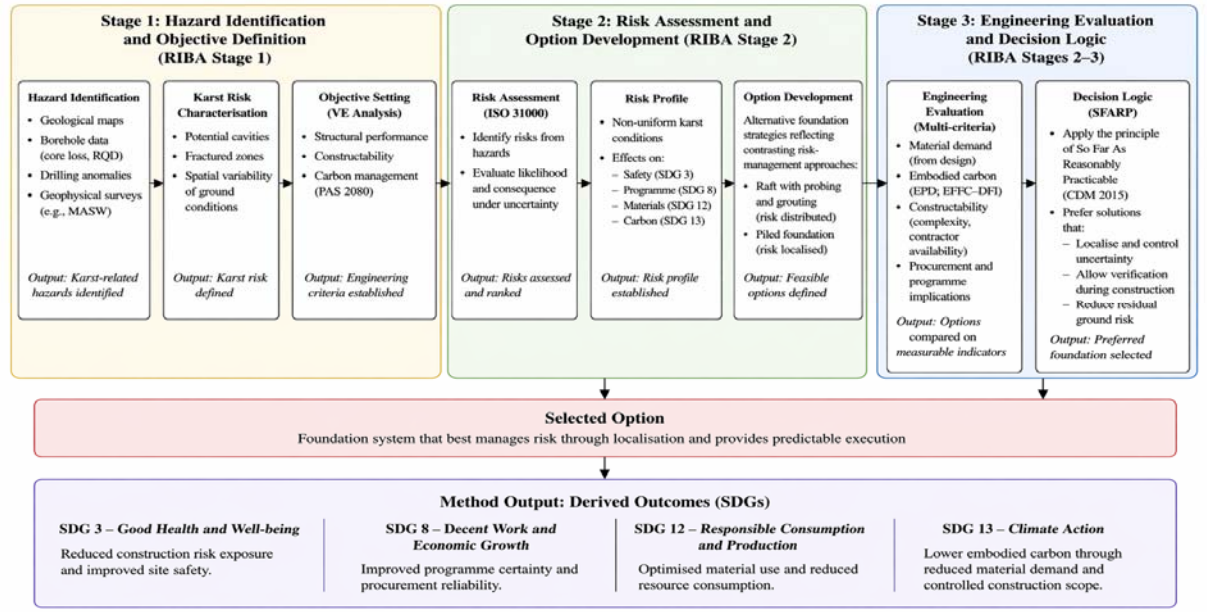


Fig. 1 Risk-informed geotechnical optioneering workflow across RIBA Stages 1–3.

2.3 RIBA Stages 2-3: engineering evaluation and decision logic

As part of the value engineering process, each option is evaluated through a multi-criteria engineering assessment comprising: (i) material demand estimated from the proposed design, (ii) embodied carbon assessed using the EFFC–DFI methodology (EFFC and DFI 2013), (iii) constructability, including execution complexity and contractor availability, and (iv) procurement and programme implications. This converts qualitative differences between options into measurable engineering indicators for direct comparison. Foundation selection is then undertaken using engineering judgement guided by the principle of reducing risks to a level that is So Far as Reasonably Practicable (SFARP), consistent with CDM 2015 (HSE 2015). Preference is given to solutions that control uncertainty through risk localisation, allow verification during construction, and reduce exposure to residual ground risk, rather than to options that depend on extensive area-wide treatment. The selected solution must perform at least as well as all alternatives across the four SDG-linked indicators. When full dominance is not achieved, the option that performs better on most criteria is preferred, and the rationale is documented in the risk register to ensure transparency and traceability.

2.4 Method output

The output of the methodology is a traceable evidence framework linking ground conditions, engineering decisions, and project outcomes. Improved safety, programme certainty, material efficiency, and lower embodied carbon are therefore interpreted as consequences of effective geotechnical risk management within the design process, rather than as independent sustainability checks.

3 Results and Discussion

This section validates the framework defined in Section 2 by demonstrating its step-by-step application to the foundation design of an iconic building in Radiyah, KSA, under an average net bearing pressure of approximately 500 kPa at foundation level. Each sub-section corresponds to a framework step and shows the inputs used, the decisions taken, and the SDG-relevant outcomes produced.

3.1 Preparation and Brief Stage

The building rests on the Jubaila Limestone Formation, which features thick layers of moderately strong aphanitic and calcarenitic limestone. Near the ground surface, this formation is usually highly weathered and fractured, but it becomes more intact a few meters below the surface (SGS, 1991). The initial geotechnical investigation (GI), part of a larger district development project, involved nine boreholes within the building site and probing records beneath proposed isolated footings. The data review showed Unconfined Compressive Strength (UCS) values ranging from 5.25 MPa to 48.5 MPa, with an average around 20 MPa. Borehole core recovery data were classified in accordance with EN ISO 14689 (ISO 2018b). Using this classification and recovery data, Jubaila Limestone (JL) can be divided into three sub-layers: Highly Weathered Jubaila Limestone (HWJL), Moderately Weathered

Jubaila Limestone (MWJL), and Slightly Weathered/Fresh Jubaila Limestone (FJL). Overall, the rock formation is primarily classified as FJL, with some areas of MWJL and HWJL. Twenty-eight probing points indicated the presence of cavity potential, mostly concentrated on the western side of the plot. The boreholes suggest a low risk of cavities, but the probing data raise concerns about possible karst features. This uncertainty is a key geotechnical risk that affects construction safety (SDG 3), project schedule (SDG 8), and material efficiency (SDG 12).

The project aims to consider constructability, local contractor availability, and sustainability as key project objectives. The Client did not set specific carbon targets, which aligns with PAS 2080:2023 (BSI 2023) guidelines. In such cases, the Designer should collaborate with the asset owner or manager to establish these targets. Since this project supports KSA's Vision 2030 for environmental sustainability, the team agreed to prioritise designs that reduce the carbon footprint, aiming to cut it by half as per UNFCCC (2023). Function analysis was conducted using the value engineering methodology, which confirmed that the foundation's primary function is to safely support the superstructure loads. The design objectives and all functions were identified. Because the project falls under Category 3 (GC3) per Eurocode 7 (BSI 2013) due to its complex ground conditions, an extensive Geotechnical Investigation program was planned. This included drilling 37 rotary-cored boreholes to depths of up to 40 meters in accordance with the Saudi Building Code (SBCNC 2018). It also involved performing a MASW geophysical survey over the entire site, spanning 7.2 kilometres on a 5 m by 5 m grid.

3.2 Concept Design and Spatial Coordination Stages

Phase 2 GI findings included multiple drill-bit drops, core loss between 0.5 m and 1.55 m, and drilling-fluid losses in more than half of the boreholes. MASW profiles indicated shear-wave velocities of 500 m/s to 3,500 m/s, suggesting fractured or vuggy horizons but no extensive open cavities. Two technically viable foundation solutions were developed: a raft foundation incorporating probing and grouting, and a piled foundation with pile caps. Each proposed design solution should be evaluated to confirm that risks are managed to the extent of So Far as Reasonably Practicable (SFARP) in accordance with the CDM 2015 regulations (HSE 2015). The raft option involves uncertainty in scope, programme, and cost due to the varying sizes of subsurface cavities. Risk is spread across the entire raft area and necessitates expert grouting contractors, rigorous quality checks, and extra verification boreholes. Conversely, piling provides greater predictability of scope and performance, with risks confined to specific pile locations assessed during drilling. The karst risk assessment indicates that the proposed foundation systems do not sufficiently mitigate this risk during the design phase, given the residual risk associated with karstic formation. Therefore, this residual risk was transferred to the construction stage. A qualified contractor should be appointed to oversee risk management during construction. From a procurement perspective, raft foundations require specialist, qualified subcontractors that may not be readily available in KSA. Piling is a common technique in the country, facilitating easier procurement and execution. This analysis indicates that piling offers better risk management than raft foundations. For such projects, an Early Contractor Involvement (ECI) procurement strategy, introduced in KSA law (MOF 2019), was recommended to enhance risk management.

The piling method involves installing bored piles beneath pile caps. The estimated concrete volume for this method is about 26% of the volume required for a raft, excluding grouting quantities. Designers can use tools such as the EFF CDFI carbon calculator or an equivalent to estimate the carbon emissions of each design. The Author has received funding from WSP to develop the first carbon calculator for geotechnical applications in the Middle East. The collected environmental product declaration (EPD) reveals a notable difference in emissions compared to the EFFC–DFI data. For example, the steel emissions factor from EFFC–DFI is 1597.7 kg CO2e per unit, whereas local EPDs range from 1120 to 2413 kg CO2e per unit. This variability is likely due to differences in the manufacturing technology of steel reinforcement. Mahmoud et al. (2021) showed that cement and steel are the main contributors to total embodied carbon emissions, so contributions from water and aggregate were considered negligible. The piling option uses 592 tonnes of cement and 313 tonnes of steel, resulting in 1,176 tonnes of embodied carbon emissions. In contrast, the raft foundation requires 950 tonnes of cement and 1,311 tonnes of steel, resulting in a total of 3,609 tonnes of emissions. This indicates that the piling method reduces embodied carbon emissions by roughly 67% compared to the raft foundation, excluding any grout quantities associated with the raft foundation. Grouting quantities were excluded because no defined treatment scope was available at the design stage as a direct consequence of residual karst uncertainty.

Raft foundations can have widely varying costs because of subsurface cavity networks, making it difficult to accurately forecast budgets. In contrast, pile foundations offer more predictable costs, as they are based on a specific design and can be verified during pile installation and load testing. From an economic perspective, piling is more cost-effective, with an estimated cost of 6 million Saudi Riyals (SAR) compared to nearly 10 million SAR for raft foundations, excluding grouting. No dedicated Phase 2 GI programme was commissioned for this project; the detailed design was therefore completed using only Phase 1 data. Residual risk was managed through conservative pile specification and communicated to the contractor via the CDM 2015 health and safety file. The carbon estimates should therefore be interpreted as indicative comparative values subject to this uncertainty.

3.3 Discussion

The options were assessed through a risk-informed optioneering process that considers construction safety exposure (SDG 3), constructability, procurement and project schedule reliability (SDG 8), material usage (SDG 12), and indicative embodied carbon (SDG 13). In comparing raft foundations (with probing and grouting) to piling, the latter demonstrates superior performance in health, safety, and environmental impact, as demonstrated in the preceding analysis. Raft construction involves a two-stage process, probing and grouting, followed by raft placement. There is uncertainty regarding timelines due to variable ground conditions. Piling also consists of two stages, pile installation and pile cap casting, but offers greater project schedule predictability. Quality control for raft foundations depends on grouting records and additional borehole investigations, whereas piling benefits from standardised testing methods. This comparison indicates that the piling method more effectively meets the design objectives and consistently outperforms the raft foundation alternative across all functional criteria. This assessment aligns well with the recommendations of Wagener and Von (1984), who recommended using piles for high loads in karst and rafts for light- to medium-load conditions. Table 1 presents a risk-informed comparison of foundation options and the associated evidence supporting SDGs 3, 8, 12, and 13.

Table 1. Risk-informed comparison of foundation options and associated evidence supporting SDGs 3, 8, 12, and 13.

SDG #	Risk Indicator	Piling	Raft after Probing and Grouting
3	Health and safety during construction	Risk exposure largely confined to pile locations. Lower material quantities indicate reduced worker exposure to activities such as material handling, dust exposure, and plant operations.	Risk exposure distributed across the full foundation footprint. Higher material quantities indicate increased worker exposure related to probing, grouting, and associated construction activities.
8	Project schedule reliability and specialist procurement	Lower programme and delivery risk supported by a well-established piling practice in KSA. Indicative cost is around six million SAR.	Potential project prolongation and programme risk due to reliance on specialist grouting subcontractors and uncertainty in treatment extent. Indicative cost is about ten million SAR (excluding grouting).
12	Material inefficiency	Reduced material demand: 592 t cement and 313 t steel.	Increased material demand: 950 t cement, 1,311 t steel, with additional grouting materials.
13	Embodied carbon	Indicative embodied carbon is around 1,176 t CO_2e (design stage comparative estimate).	Indicative embodied carbon is around 3,609 t CO_2e (design stage comparative estimate).

4 Summary and Conclusions

This study explores how risk-informed foundation optioneering in karst terrain can provide evidence during the design phase to support Sustainable Development Goals (SDGs) 3, 8, 12, and 13. By conducting comprehensive geotechnical risk management, the study compares two foundation alternatives for a high-load building in Saudi Arabia. Analysis results show that early design choices strongly influence construction safety, project schedule reliability, material usage efficiency, and embodied carbon. The case study reveals that a piled foundation localises geotechnical uncertainty, enhances constructability and procurement certainty, reduces material use, and significantly lowers embodied carbon compared to a raft foundation with probing and grouting. Overall, these findings suggest that treating SDGs as outcomes of geotechnical risk management, rather than as fixed design

targets, offers a practical and reproducible approach to sustainability reporting in ground engineering. Future research should apply this method across different geological contexts and foundation types and include region-specific environmental product declarations to reduce uncertainties in carbon data. In addition, it can investigate how construction-stage monitoring and digital tools can further align risk management with sustainable development objectives.

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