



Spatial Analysis and Interpretation of Geological and Geotechnical Database: A Case Study of Riyadh, Saudi Arabia

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Received: 13 September 2023 / Accepted: 30 May 2024 / Published online: 27 June 2024
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Abstract

In light of the pressing need for optimizing the cost and efforts involved in geotechnical investigations, this study presents a spatial analysis and interpretation of geological and geotechnical database of Riyadh City. By consolidating available data from geotechnical investigation reports of the study area, spatial maps have been developed focusing on subsoil types and rock quality designation. The application of the geostatistical analyst extension in ArcMap highlights significant spatial variation in subsoil characteristics, leading to a more accurate zonation of geotechnical profile. It is emphasized that among several interpolation methods, the inverse distance weighting emerges as a better approach for representing these variations, enabling the creation of detailed geotechnical zonation maps. Considering its importance, the data on groundwater table depths at various locations were also retrieved and visualized illustrating the frequency of presence of groundwater in bedrock (limestones) or in the surface soils. This insight can be instrumental in strategizing groundwater pumping for water supply as well as designing dewatering systems for potential excavations in the study area. The findings of this study indicate that a GIS-based overview of subsoil profiles allows the construction engineers to plan and execute projects more effectively, resulting in considerable savings in time and financial resources associated with site investigations as well as contributing the sustainable development of infrastructure projects in the region.

Keywords Geodatabase · Spatial interpolation · Geographic information system · Subsurface mapping · Zonation maps

1 Introduction

With global economic growth fueling construction, there is a pressing need for thorough subsurface investigations to enable the development on challenging terrains, ensuring safety and cost efficiency. The aim of these investigations is to understand the soil's stratigraphy and behavior, traditionally through methods like drilling, test pits, and laboratory analyses [1]. As building codes evolve globally, the creation of geotechnical maps has become increasingly common, providing crucial data for planning and compliance, thereby streamlining construction projects for engineers, architects, and authorities. Subsoil exploration, combining literature and

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site methods, is vital for assessing soil suitability in construction [2]. Yet, the unavailability of preliminary data like geological maps and soil reports in some areas complicates on-site exploration planning. To overcome this, many countries have developed regional soil maps to guide design, construction, and compliance, aiding decision-making for authorities, engineers, and contractors by providing essential geotechnical insights [3–5]. Likewise, choosing the right foundation type and depth for a structure relies on subsurface exploration outcomes which yield data critical for analyzing bearing capacity, settlement, and potential effects of groundwater table fluctuations on these properties. Researchers have suggested a web-based GIS platform to compile and exhibit soil-boring and sounding data from various project databases, enhancing accessibility and utility [6–9]. Researchers have demonstrated how this application can improve the accessibility and usability of data for both public and private sectors. The benefits of GIS-based geotechnical information databases for urban planning and development have also been highlighted by [10–12].

The development of automated information systems and GIS for soil surveys was traced by Burrough [13]. He observed that soil data collection and relational database models have adapted to each other over time. He also noted a weak link between soil attributes and spatial data. Osipov et al. [14] detailed a comprehensive engineering geological zoning of Moscow, combining data on structural dynamics, geomorphology, geology, hydrogeology, and potential hazards to create a zoning map. They used a methodical approach, dividing the area into four taxonomic levels with an indexing system to denote different ranks. Similar studies have been conducted by [15–18] on geotechnical zonation based on SPT-N values. Masoud and Aal [19] have done the 3D geotechnical modeling of the soils in Riyadh City by performing the standard penetration tests. The authors also performed *rock quality designation* (RQD) and *unconfined compression strength* (UCS) tests for 238 samples from 154 boreholes in 15 districts of the city and developed zonation maps with construction favorability ratings for safe urban expansion. RQD serves as a standard method employed in the subsurface exploration to assess both qualitatively and quantitatively the quality of rock and the extent of jointing, fracturing, and shearing within a rock formation. RQD is quantified as the percentage of intact drill core pieces, each exceeding 10 cm in length, recovered during a single core run [20]. The RQD index (in percentage) is computed as $100 \times \frac{\sum (\text{Length of core pieces} \geq 10 \text{ cm})}{\text{Total length of core run, cm}}$.

Okur [21] assessed liquefaction hazards by gathering geological and geotechnical data and processing them into a 3D structural model. GIS-based subsurface model maps and liquefaction hazard maps were prepared. The authors believe that such visual models will help engineers and designers in

all aspects of future city development to protect against possible earthquake hazards. Cueto et al. [22] in a study concluded that geological testing, including geochemical, mineralogical, and petrographic analysis, prior to construction, helps anticipate ground behavior and mitigates geotechnical challenges, crucial for projects like Line-3 of the Riyadh Metro. Cueto et al. [23] presented the first comprehensive geotechnical assessment of Riyadh's underground geology, crucial for future urban infrastructure projects, especially in rapidly growing megacities lacking prior technical literature on subsurface conditions. Habibi et al. [24] described a method for village categorization using multi-criteria decision analysis. They identified seven criteria, rated with expert input, and employed super decision software for analytic hierarchy process (AHP) weighting. The outcome aids government and urban planners in strategic village development planning. Kokkala and Marinos [25] demonstrated managing geological and geotechnical data in databases for design and construction in civil protection, municipalities, and technical companies. They suggested a GIS-based method with geostatistical techniques and cross-validation to create geotechnical maps for areas at risk of liquefaction and settlement, aiding infrastructure project planning. Khan et al. [26] performed geotechnical characterization and statistical evaluation of alluvial soils of the Lahore city using ArcGIS package and presented the foundation design curves for both isolated and raft footings that demonstrated the practical utility of the study. Gangrade et al. [27] discussed how geotechnical parameters can be optimized for site investigations, potentially reducing uncertainties and resources required for project planning. Arnous [28] explored how spatial models of geotechnical conditions can aid in the planning for urban extensions, reflecting on the direct application in decision-making by local authorities. Chaminé and Fernandes [29] highlighted how geological and GIS-based tools can support engineering activities, likely offering insights into how these tools can streamline the decision-making process for infrastructure projects. Khan et al. [30] discussed the application of GIS techniques in geotechnical engineering, which could provide valuable insights into how GIS can facilitate decision-making and optimize site investigations.

The diversity of subsoils significantly influences project viability due to soil's heterogeneous and anisotropic qualities, making profiles vary widely across locations. Al-Refeai and Al-Ghamdy [31] effectively detailed the geological and soil features across Saudi Arabia's various regions. Rashwan [32] aimed to find a solution to the quick selection of the dam's location to avoid the impact of damage floods. The spatial analyst (tools in ArcGIS) and GeoEye satellite imagery were used with the DEM derived from LiDAR data to obtain a quick solution for selection of a suitable location of the dams. Abdelrahman et al. [33] evaluated the geotechnical properties of the near-surface geological units in Makkah

Al-Mukarramah and found that the soil materials vary from soft to very dense materials where SPT ranges from 4 to more than 50 and increases with depth. The rock quality spans from very poor to good where RQD changes from 0 to 80%. The ground conditions of Makkah can be differentiated into eight subsoil and rock units with various geotechnical properties. Masoud et al. [34] built 3D models using 189 samples collected from 92 boreholes in Medina, Saudi Arabia. The geotechnical properties were spatially rendered in 3D to enable city planners to predict and locate risk zones in urban underground spaces.

Extensive work has been conducted by the Saudi Geological Survey (SGS) and other organizations to develop detailed geological maps for various regions of Saudi Arabia. However, only limited work has been done on spatial mapping of geotechnical characteristics of various soils in Saudi Arabia. This study aimed to investigate the potential use of GIS in developing soil characteristic maps for Riyadh City. Such a study could assist researchers and related industries in validating their field results, increasing their confidence in project execution, and enabling them to save precious resources. The present research takes advantage of the spatial continuity and variability of important geotechnical parameters to develop a user-friendly geodatabase based on the soil type and RQD at various depths. The geodatabase is an ArcMap object-relational database model that can store attributes and spatial data together in a well-connected form, significantly improving the portability, sharing, and management of geotechnical data. It is worth mentioning that in many cases RQD is the only information available for describing rock discontinuities and its application in assessing engineering properties like deformation modulus, unconfined compressive strength, shear wave velocity, etc., has been firmly established [35–37].

2 Study Area and its Geological Framework

Riyadh is the capital and largest city in Saudi Arabia. It is also the capital of Riyadh Province and belongs to the historical regions of Najd and Al-Yamama, which are situated in the center of the Arabian Peninsula on a large plateau. The Riyadh province accommodates a population of approximately 7.3 million, with around 5.7 million residing in Riyadh City, underscoring its pivotal position in the region and the substantial infrastructure development requirements anticipated in the coming years [38]. The Riyadh City lies between 46.5° and 47° longitude and 24.5° and 25.0° latitude at approximately 600 m above the mean sea level. As shown in Fig. 1, Riyadh City is situated in a hot desert climate, and the temperatures during the summer months are extremely hot. A temperature fluctuation of up to 15 °C on a daily basis is frequently observed. Winter temperatures

typically soar around 20 °C but can plunge to below 5 °C. These climatic conditions intensify evaporation, resulting in an evaporation-to-precipitation ratio of 1:30 [39]. While most years are characterized by aridity, rainfall occurs sporadically at intervals of 7–10 years, often with high intensity over short durations. This pattern leads to flash floods and the accumulation of high salt concentrations, accompanied by significant soil erosion along the horizontal flow [19].

As far as the local geology of the study area as shown in Fig. 2, the Riyadh City is situated on the alluvial plain formed by Wadi Batha and the tributary of Wadi Hanifah. These channels are primarily filled with unconsolidated, weakly cemented deposits consisting mainly of silts and sands. These deposits have the potential to create shallow, unconfined aquifers with water ranging from fresh to brackish [40]. Likewise, the predominant limestone rock formations in Riyadh have significant propensity for the formation of sinkholes which have been identified as one of the most significant geological hazards in this area [41]. Limestone and gypsum are identified as the primary rock types prone to dissolution and the Riyadh region exhibits prevalent karst formations, whose formation depends on specific conditions such as presence of soluble minerals like carbonate-rich deposits and evaporites in the host rock, availability of an unsaturated water source capable of dissolving these minerals, existence of a hydraulic gradient facilitating water flow through the rock, and presence of an outlet for discharging mineralized water. Karst aquifers, formed by carbonate-sulfate formations spanning from the Lower Jurassic (Sulayy) to the Lower Cretaceous (Yamama), are identified in the subsoil of Riyadh. Karst features in Riyadh pose potential geotechnical hazards due to the existence of cavities within limestone units of the Jubaila, Arab, and Sulayy formations, ranging in size from centimeters to meters. These karstic cavities are classified into Type A cavities which result from water percolating through joints, causing rock dissolution via chemical and mechanical processes and Type B cavities arising from the dissolution of more soluble materials like anhydrite, resulting in larger cavities than Type A, potentially leading to the collapse of overlying layers [38].

3 Data and Methodology

The study began with the demarcation of the study area as shown in Fig. 1 for which considerable borehole database was available. The borehole data from geotechnical investigation reports of various construction projects in the study area was collected from organizations such as Gulf Engineering House, Riyadh Geotechnique & Foundations, Dar Al Riyadh, GTC Engineering, and Soil & Foundation Company.

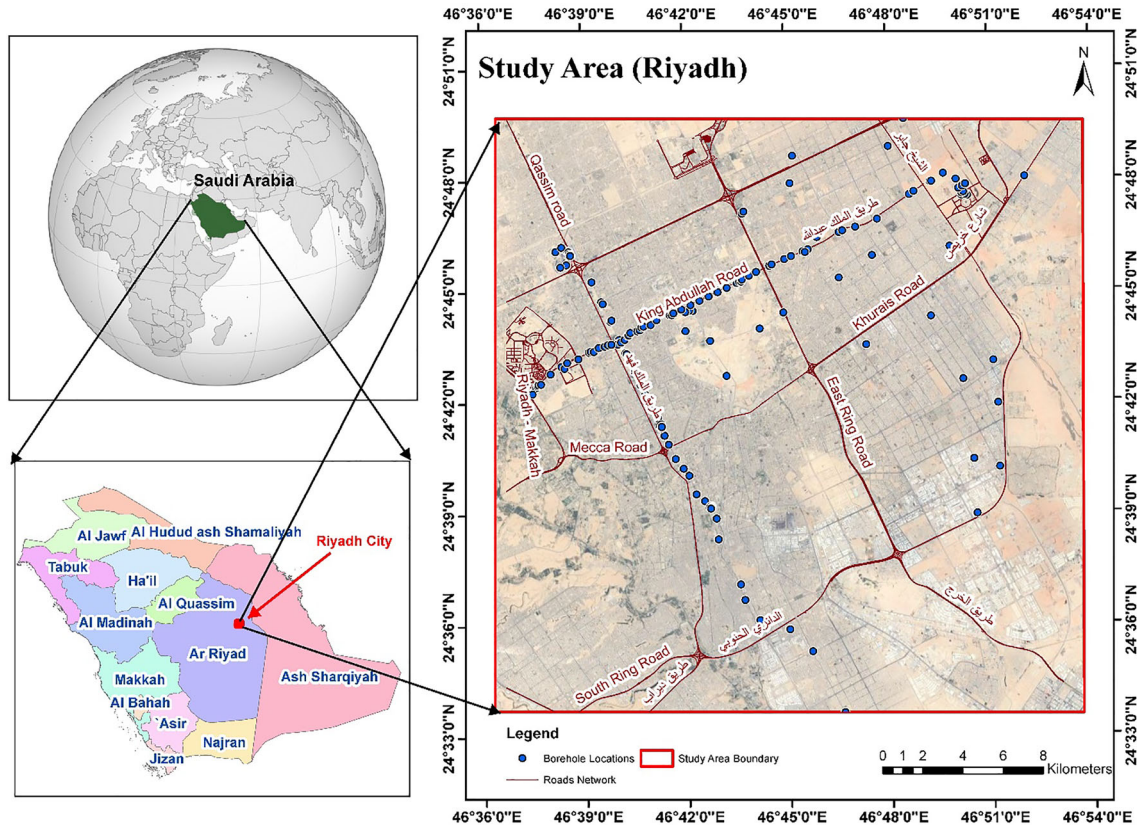


Fig. 1 Location and spatial coordinates of the study area and boreholes data points

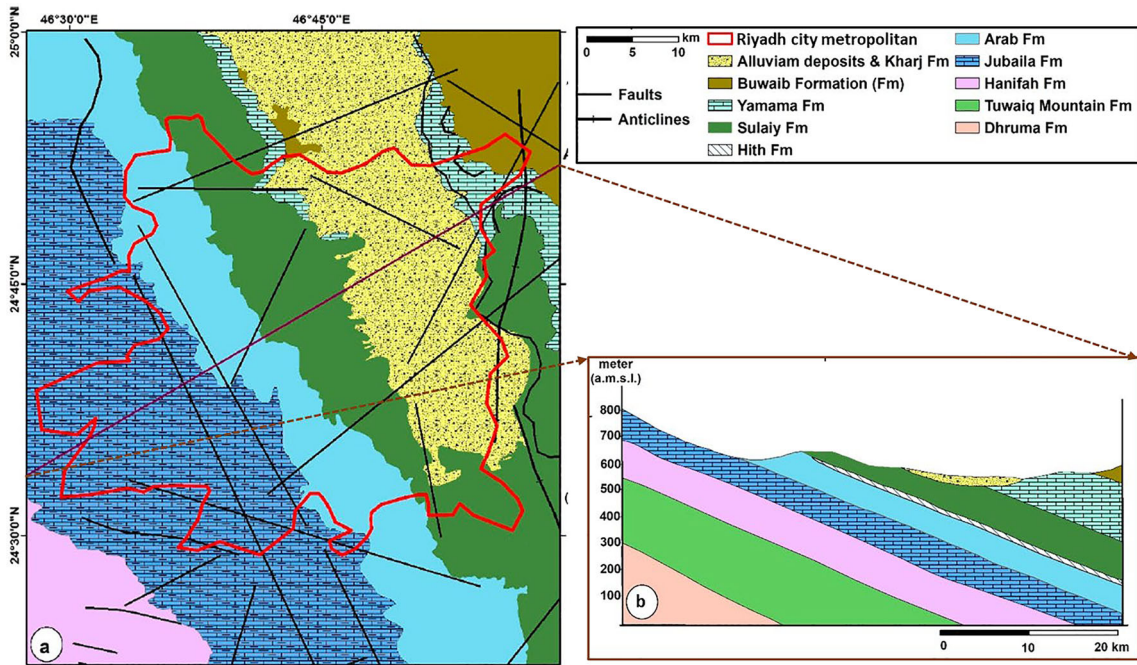


Fig. 2 Simplified geological map for Riyadh City and a typical cross section (Aljammaz et al. [38])

Table 1 Coding and classification of the geomaterials in the study area

Type	Code	Description
1	FM	Fill material/debris
2	G / WLS	Highly weathered limestone/gravel
3	LS	Limestone/limestone breccia
4	SD	Sand deposits
5	SCS	Silty/clayey sands, sandy/silty clays

3.1 Borehole Distribution and Database Description

Geotechnical data were collected from extensive geotechnical investigations carried out at 158 locations of the study area. The findings of the geotechnical investigations were available in the form of detailed reports and borehole logs. Based on the available database, the minimum and maximum depths of geotechnical explorations were 10 and 75 m, respectively, with the mean depth of exploration of about 31 m below EGL. The borehole logs were investigated to determine the lithology at each site. The description of each stratum, including the soil type, thickness of soil layer, the findings of in situ testing and laboratory testing such as the SPT-N values and RQD for the rock strata were collected for each borehole location.

3.2 Digitization of Geotechnical Data at Discrete Depth Intervals

For spatial analysis and interpolation of geological and geotechnical characteristics of Riyadh City, the borehole logs are interpreted to digitize the soil stratification at each 0.5 m depth. The spatial distribution of the borehole locations in the study area was plotted using longitudinal and latitudinal information, and each borehole location was digitized in a point data layer within ArcGIS. The natural surface level is used for vertical reference. The reason to plot the spatial distribution with respect to existing ground level is the simplicity in use of these spatial maps for practical applications [42, 43]. Given a consideration to wide variance in the soil types, both laterally and vertically, the soil description is reduced to five main classes (referred to as 1, 2, 3, 4, and 5) which are frequently encountered in most borehole logs. The soil class and its description and the code assigned for data processing are presented in Table 1. Some salient geological hazards (cavities in the limestones and groundwater table encountered during an excavation) along with the presence of the different soil classes at various depths are shown in Fig. 3. The soil class 3 (limestone / limestone breccia) dominates beyond 20 m depth of exploration in the study area. Considering these soil classes, the borehole logs were coded as inputs for ArcGIS to prepare the spatial maps and digital

subsoil profiles were created for all data stations. Each profile showed variations in the soil type at different depths. The variation in the engineering properties (RQD) with depth was also drawn on the same profile.

An ArcGIS geodatabase was developed to store the data collected from each data station. The geodatabase stores each data type in a separate table and connects the resulting tables using the station ID. It is imperative to mention that consideration of more data points would lead to more reliable spatial maps. In current research study, the actual field data is used as input to develop a framework for the spatial distribution of soil in Riyadh City at various depths for engineering applications. Hence, it is convenient to increase the ArcGIS geodatabase to further enhance the spatial distribution maps. The database for developing geotechnical zonation maps based on the soil type is shown in Table 2. The depth of each soil layer was recorded from the existing ground level (EGL). Similarly, the RQD values at various depths for each borehole were digitized for use as a database. The RQD database for the sample boreholes is presented in Table 3.

3.3 Interpolation of Data

ArcMap (ArcGIS 10.4) [44] was used as a tool for the development of spatial maps using spatial analyst and incorporating various interpolation methods, viz. inverse distance weighting (IDW), ordinary kriging and spline. Interpolation methods are used to predict the values of cells in a raster from a limited number of sample data points located in the neighborhood.

- The inverse distance-weighted (IDW) interpolation technique, which uses an interpolation method that estimates cell values by averaging the values of sample data points for each processing cell. IDW has been used in many precipitation mapping methods [45].
- The kriging technique generates an estimated surface from a scattered set of points with z-values. Natural neighbor technique determines the closest subset of input samples to a point where a value is required. Kriging technique has been employed by [46].
- The spline technique uses an interpolation method that estimates values using a mathematical function that minimizes the overall surface curvature, resulting in a smooth surface that passes exactly through input points. Spline technique has been used by [17].

It is imperative to mention that the accuracy of an interpolation method is affected by density and spatial distribution of input data, topography, and scale [43]. Hence, in the current study, the interpolated results from different techniques were compared with original real-time data observed at selected points and reveal that IDW was more effective to predict the



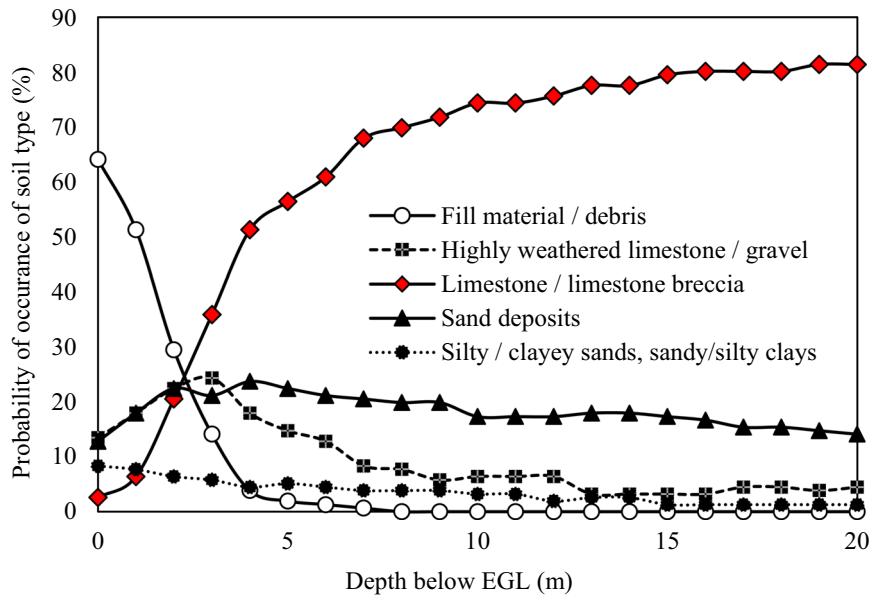


Fig. 3 Salient geological features and variation in geological profile in Riyadh City

Table 2 Digitization of the dataset based on soil type and its thickness

BH ID*	Easting	Northing	Explored depth (m)	Depth to GWT (m)	Soil layers (start of layer-type of layer-end of layer)
BH-01	668,980	2,735,243	40	27.5	(0-FM-2), (2-LS-4), (4-SCS-6), (6-LS-40)
BH-02	669,414	2,734,333	35	33.5	(0-FM-3), (3-LS-35)
BH-03	669,726	2,733,670	25	19.0	(0-FM-2.5), (2.5-LS-25)
BH-04	669,964	2,733,170	40	21.5	(0-FM-2), (2-LS-40)
BH-05	670,328	2,732,414	35	14.0	(0-FM-2.5), (2.5-LS-35)
-	-	-	-	-	-
-	-	-	-	-	-
BH-158	685,413	2,743,961	11	NA	(0-FM-1.5), (1.5-SD-11)

*The dataset pertains to a select few boreholes. The data for 158 boreholes were digitized in the similar manner

Table 3 Digitization of the dataset based on RQD values for each layer at the selected depth interval

BH ID*	Easting	Northing	Explored depth (m)	Depth to GWT (m)	Soil layer (depth-RQD value)
BH-01	668,980	2,735,243	40	27.5	(5,10), (6.5,8), (8,0), (9.5,0), (10.5,20), (11.5,7), (13,14), (14,43), (15,21), (16.5,23), (18,10), (19,55), (20,21), (21,16), (22,42), (24,22), (25,42), (27,44), (28,24), (30.5,6), (32,26), (33.5,46), (35,41), (36.5,26), (38,26), (39,20), (40,32)
BH-02	669,414	2,734,333	35	33.5	(4,0), (5,0), (6,0), (11,18), (12,0), (15.5,11), (16.5,0), (17.5,40), (18.5,0), (19.5,25), (20.5,12), (21.5,0), (22.5,45), (23.5,53), (24.5,15), (25.5,43), (26.5,45), (27.5,0), (28.5,41), (29.5,47), (30,60), (31.5,36), (32.5,74), (33.5,32), (34.5,34)
BH-03	669,726	2,733,670	25	19.0	(3.5,0), (5,0), (6,0), (7,27), (8,22), (9,0), (10,0), (11,10), (12,10), (13,23), (14,10), (15,10), (16,10), (17,0), (18,11), (19,0), (2,41), (21,10), (22,0), (23,0), (24,15), (25,23)
BH-04	669,964	2,733,170	40	21.5	(3,10), (4,48), (5,56), (6,24), (7,51), (8,41), (9,5,58), (11,35), (12,0), (17,0), (18.5,37), (20,74), (21,27), (22,10), (23.5,49), (25,42), (26,10), (27,50), (28,10), (29,41), (30,22), (31,10), (32,25), (33,19), (34,16), (35,13), (36,20), (37,30), (38.5,39), (40,71)
BH-05	670,328	2,732,414	35	14.0	(3.5,37), (4.5,27), (5.5,75), (6.5,43), (7.5,53), (8.5,75), (9.5,58), (10.5,17), (11.5,17), (12.5,38), (13.5,47), (14.5,71), (15.5,54), (16.5,42), (17.5,22), (18.5,11), (19.5,30), (20.5,77), (21.5,0), (22.5,45), (23.5,34), (24.5,41), (25.5,45), (26.5,75), (27.5,4), (28.5,32), (29.5,40), (30.5,30), (31.5,13), (32.5,27), (33.5,57), (35,74)
–	–	–	–	–	–
BH-158	685,413	2,743,961	11	NA	No rock strata encountered up to the explored depth

*The dataset pertain to a select few boreholes. The data for 158 boreholes were digitized in the similar manner

real-time data; moreover, the finding is coherent with various pertinent studies [17, 47, 48]. This may be due to the fact that the IDW considers the effects of distance interpretation on interpolation, and the interpolated value is estimated using the weighted mean of the observations.

3.3.1 Inverse Distance Weighting (IDW) Interpolation

IDW is a global polynomial interpolation that fits a smooth surface defined by a mathematical function (polynomial) to the input sample points. The trend surface changed gradually and captured the coarse-scale patterns in the data. IDW assigns weights to neighboring observed values based on the distance to the interpolation location. The interpolated value was the weighted average of the observations [49]. IDW has been used by various researchers in different fields [45]; moreover, efficiency of IDW has been compared with other interpolation techniques [50]. Characteristically, in IDW interpolation method, the interpolated value is estimated using the weighted mean of the observations. The weights are proportional to the negative power of the geographical distance d_{α} between the point of interpolation and the considered observation points. Typically, not all observations t_{α} are considered in the estimation of the interpolating

value T_o but only k neighboring with that point of interpolation.

$$T_o = \frac{\sum_{\alpha=1}^k t_{\alpha} \omega_{\alpha}}{\sum_{\alpha=1}^k \omega_{\alpha}}$$

and the weights;

$$\omega_{\alpha} = 1/d_{\alpha}^{\lambda}$$

The power λ of distance has to be chosen appropriately depending on the interpolated variable. Generally, it is assumed that $\lambda = 2$ is a good choice, and the same value is used in this work. The sequence of all the activities in this study is listed in Fig. 4 as discussed in aforementioned sections.

3.4 Assumptions

The sole source of this geotechnical database was borehole logs from actual site investigation studies conducted by various organizations at several locations in Riyadh. Hence, it reveals the authenticity of the GIS-interpolated geotechnical zonation maps presented. Nonetheless, the zonation maps in the study area can be verified and improved with additional

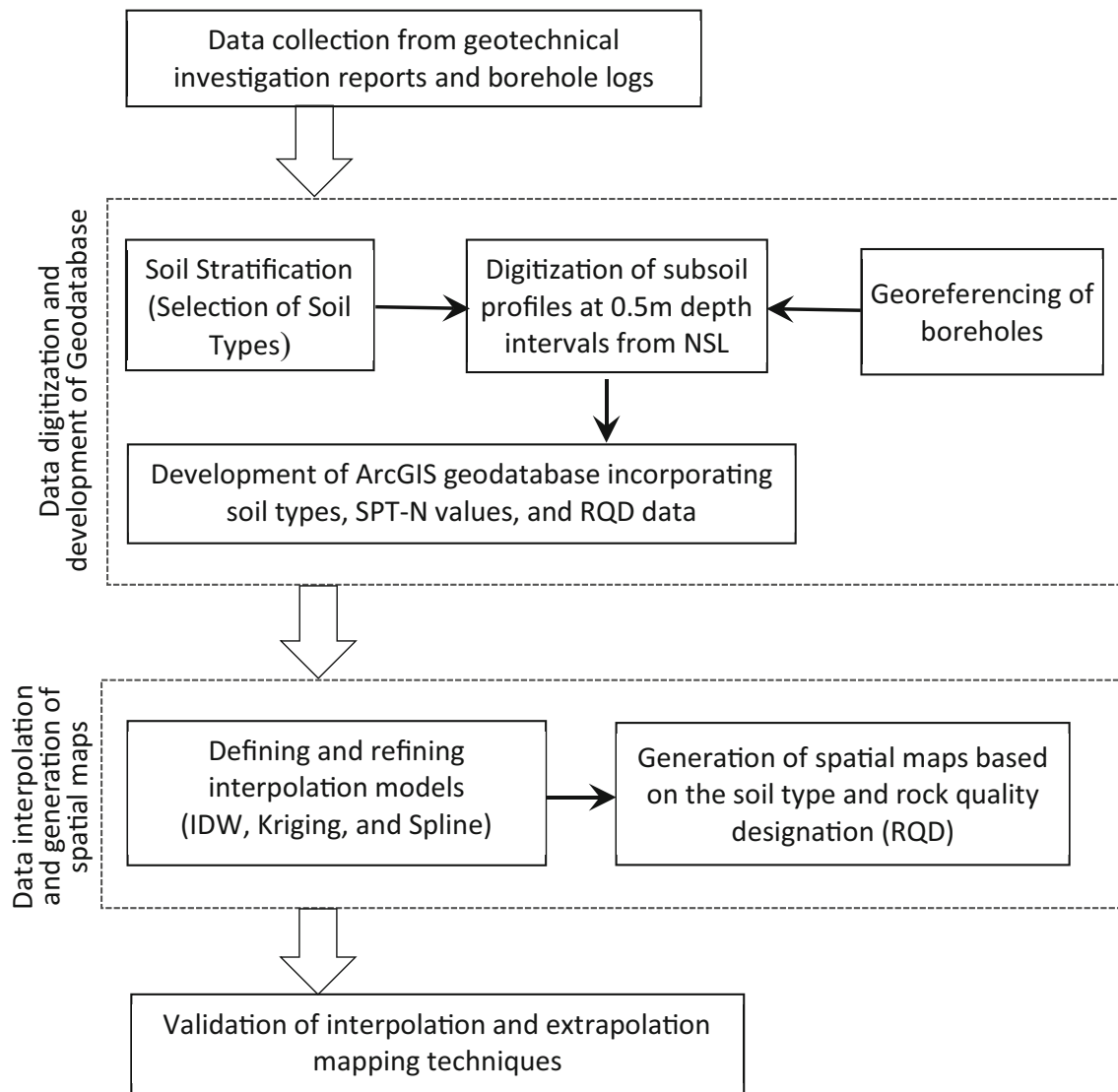


Fig. 4 The process adopted to collect, digitize and interpolate geospatial data

geotechnical investigations in the future. Interpolation and extrapolation were used to continuously map the geotechnical properties of the soil in the study area using discretely collected borehole data. Based on the available data and information, the following assumptions were made.

- The conditions at the unsampled locations were predicted based on information from the nearest available measured points.
- Spatial interpolation was employed for the predictions made within the spatial extent of the measured point locations.
- Spatial extrapolation was used for predictions made outside of spatial extent of measured locations.
- The value at an unsampled location is the distance-weighted average of the values from the surrounding data

points within a specified window. The points closest to the prediction location were assumed to have a greater influence on the predicted value than those farther away, such that the weight attached to each point was an inverse function of its distance from the target location.

4 Development of GIS-Based Interpolated Geotechnical Zonation Maps

The geotechnical zonation maps based on the soil type and RQD values were developed using the database discussed earlier. These maps were generated at depths of 0, 1, 2, 3, 4, 5, 7.5, 10, 15, 30, and 60 m below the NSL. Although this range was selected arbitrarily, it encompasses the likely

Table 4 Statistics of the database for soil profiles in the study area

Number of boreholes	158
Min. depth	6 m
Max. depth	75 m
Depth increment used to assess soil type	0.5 m
Total number of data points considered	23,750
Frequency of soil types across the study area	
Type-1	2%
Type-2	4%
Type-3	78%
Type-4	15%
Type-5	1%

depths of excavations and foundations of the infrastructure developed in the study area. The interval extends to 30 m toward the end because no significant variation in RQD was noted in the dataset examined up to a depth of 60 m. To keep the figures-to-text ratio to a minimum in the manuscript, the zonation maps have been presented at depths of 0, 5, 10, 15, 30, and 60 m below existing ground level (EGL).

Spatial maps were generated using the ArcMap software, which is an important component of the ArcGIS 10.4 suite. ArcMap was used for geospatial processing, including viewing, evaluating, forming, and amending geospatial data. Geostatistical Wizard was used to define and refine the interpolation models. In current study, IDW, ordinary kriging and spline were compared. For inverse distance weighting, power of λ and number of points to be considered in interpolating are two important parameters that influence the results. Power of λ can vary between 1 and 100. The effects of changing the power by examining the preview surface were inspected, and power 2 was found to be a good choice. The optimization evaluates several models and selects the power value that provides the model with the lowest root mean square error. Moreover, the goodness of fit of the model was assessed using the predicted and error graphs. Once satisfactory results were obtained from the model, the final surface showing zonation maps at a particular depth was generated.

5 Results and Discussions

5.1 Zonation Maps Based on Soil Type

Based upon the digitalization of the subsurface profile, as shown in Table 2, the summary of the profile and soils is presented in Table 4. There exists an evident variation in soil type near the ground surface, whereas almost the same soil type, i.e., limestone, is encountered at greater depths. This stratigraphic distribution of the soil types is in accordance

with the geology of Riyadh City. A typical soil profile of Riyadh City is shown in Fig. 5. The fill material is localized mostly in Riyadh's central region, which reduces with increasing depth and becomes insignificant at a depth of 5 m. The fill material denotes soil deposits that contain a combination of construction and/or municipal solid wastes and highly weathered limestone that spatially does not extend beyond a depth of approximately 13 m. With further increase in depth, the sandy/silty sand/clayey sand region starts shrinking. At the depth of 60 m, the spatial distribution of soil substantially consists of limestone. It is also important to mention that there is a little change in stratigraphy after 15 m depth. The geotechnical zonation maps based on soil types are then prepared for 30 and 60 m from existing ground level (EGL). The maps as shown in Fig. 5 have been drawn at a scale of 1:300,000.

5.2 Zonation Maps Based on RQD Values

RQD-based geotechnical zonation maps were prepared at similar depths, that is, 0, 1, 2, 3, 4, 5, 7.5, 10, 15, 30, and 60 m from the existing ground level (EGL), based on the summary of the soil profile results presented in Table 5. Figure 6 shows the variation in the RQD with depth. The measured RQD values varied between 0 and 75%. The average values of RQD for each depth interval are plotted in Fig. 7b. A summary of the RQD results based on the total data points is shown in Fig. 7a, where it is evident that a substantial stratum is composed of RQD < 25%. However, the plot does not elaborate the depth relationship with the RQD. To correlate the depth factor with the RQD, the data point percentages were plotted against the RQD at varying depths.

The RQD values varied considerably near the ground surface and were more consistent at deeper depths. The rock quality at the top surface was minimal and tended to improve with the depth. The rate of improvement can be measured using two approaches: (a) a decrease in the lowest RQD group, that is, < 25%, and (b) an increase in the values of RQD groups representing better quality rocks. The latter is simplified using the average of the groups, except for the first group of RQD < 25%. Applying the above approaches, the reduction rate in the lowest RQD group was approximately 6% of the total data points with each meter interval in depth. Similarly, approach (b) showed an increase of 2% in the total data points with each meter depth interval. Approach (b) can further be divided into two groups: (i) the average percentage of data points increases for depths ≤ 7.5 m, and (ii) the average percentage of data points increases with depths ≥ 10 m. Both groups exhibited a unique pattern, as shown in Fig. 7. The increase in average data points for group (i) is notably higher than that for group (ii), representing a higher quality improvement, even at shallow depths. This rock quality improvement continues at a trivial pace with increasing

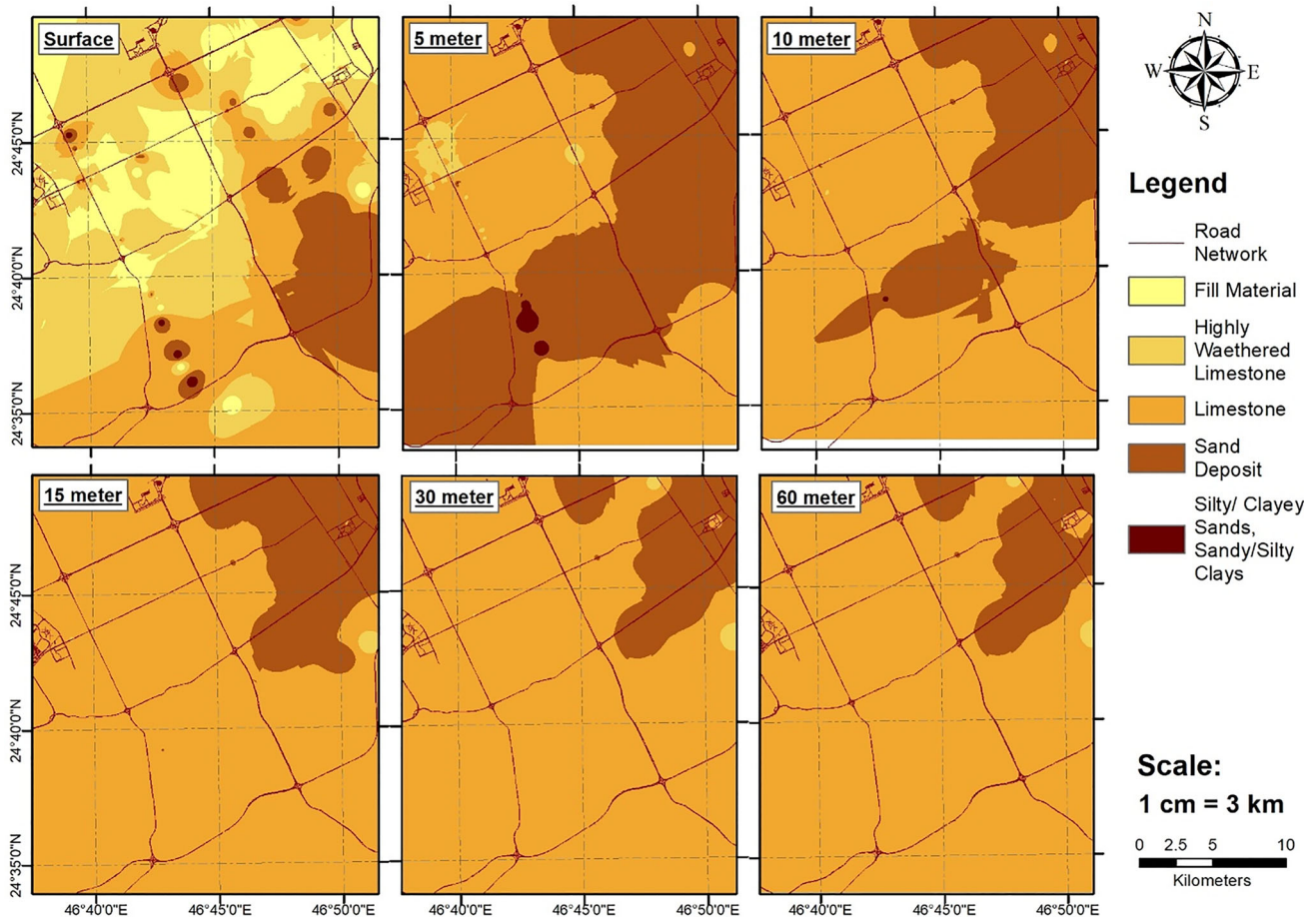


Fig. 5 Geotechnical zonation map of Riyadh City at various depths

depth until it approaches uniform rock quality. It can be concluded that at deeper depths, there is a uniform distribution of rock quality over Riyadh City. Hence, it is anticipated that these RQD maps could be a supportive geodatabase for the available geological and geotechnical information on Riyadh City. Group (i), with RQD < 25%, was mainly dominant near the top surface and gradually decreased with increasing depth. Such low RQD values suggest that the surface and surroundings in Riyadh are composed mainly of soils rather than rocks, which is also evident from the geotechnical zonation map in Fig. 5. The GIS-based RQD zonation map is plotted in Fig. 8 with subsets at varying depths. The corresponding RQD values are shown as the numerical values outside each zone. As discussed earlier, because the top surface is mainly composed of fill material and soil, no RQD value is shown for the surface plot. With increasing depth, the effective zones for highly weathered limestone and sandy/silty deposits reduce up to depths of ≤ 30 m. Beyond this depth, no significant variation was noticed in the rock classification, and most of the Riyadh City area is considered to be composed of limestone deposits. Hence, the RQD map in Fig. 8 provides useful

Table 5 Statistics of the database for RQD profiles in the study area

Number of boreholes	158
Min. depth	6 m
Max. depth	75 m
Depth increment used to assess RQD	0.5 m
Total number of data points considered	23,750
RQD and in situ rock quality (Peck et al. 1974)	Frequency of RQD values across the study area
Very Poor (RQD < 25%)	2%
Poor (RQD = 25–50%)	4%
Fair (RQD = 50–75%)	78%
Good (RQD = 75–90%)	15%
Excellent (RQD = 90–100%)	1%

and essential information about the nature and quality of the rock in relation to the depth under the surface.

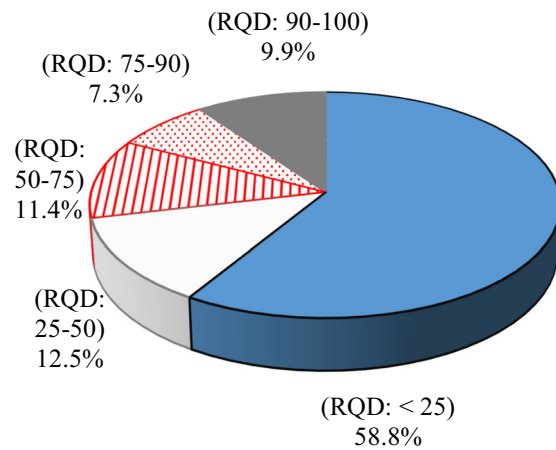
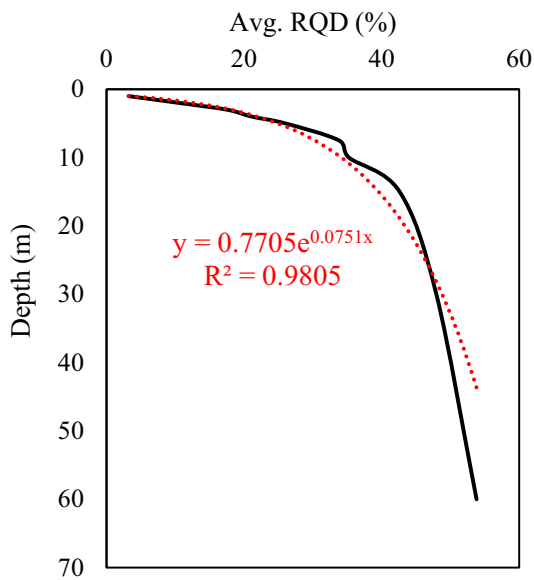
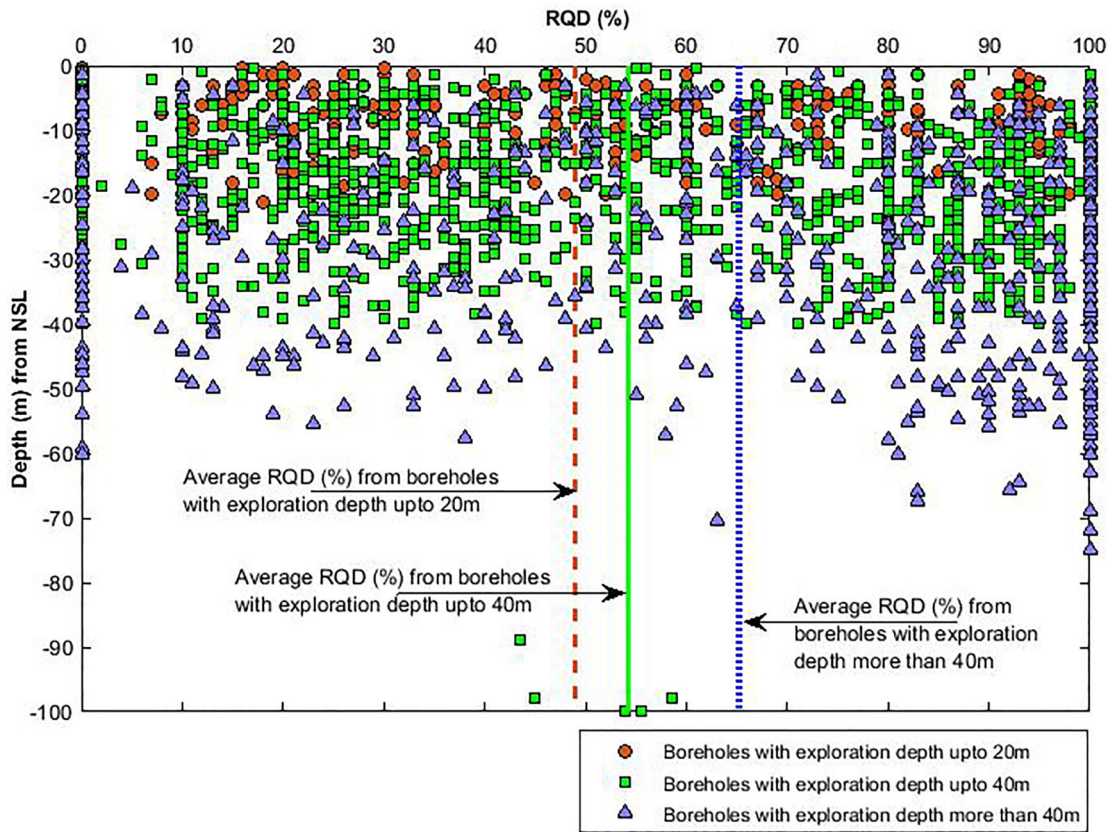
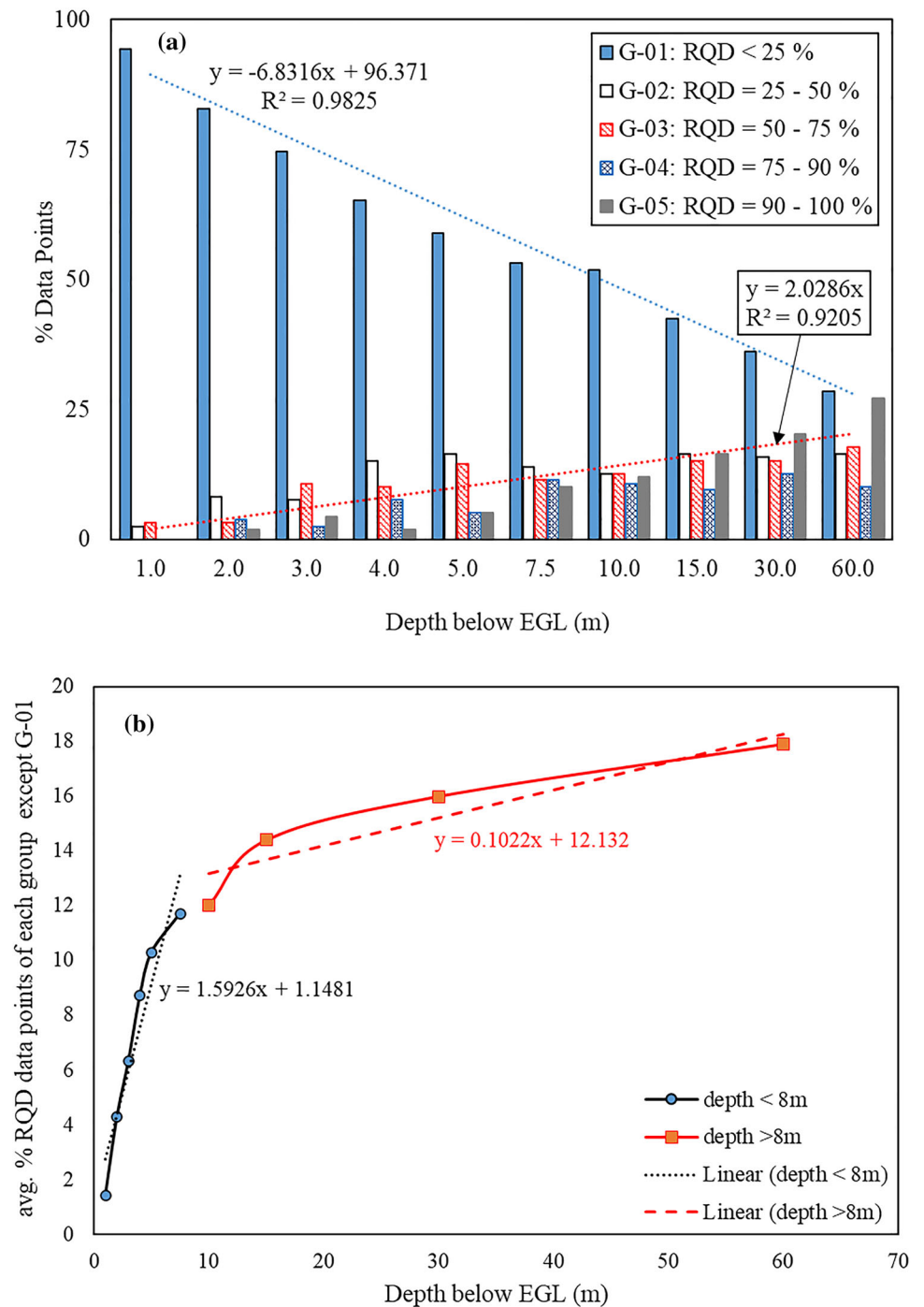


Fig. 6 The RQD dataset and its variation in the study area

Fig. 7 a Statistical insight on the rock quality **b** grouping of the average data points



5.3 Groundwater Conditions in the Study Area

The water level in Riyadh exhibits heterogeneity, influenced by seasonal variations and urban activities. Several aquifers are identified within the subsoil of Riyadh such as shallow aquifers located in the wadi channels, karst aquifers found in carbonate-sulfate formations and sandstone aquifers. For many years, the inhabitants of Riyadh have relied on Wadi Hanifa for their water supply. Only in the past two decades

have the other water sources begun to contribute to Riyadh’s water supply system. As surface water resources are scarce in Riyadh, the city predominantly relies on groundwater [19]. Considering its importance, data on the groundwater table (GWT) depth from the borehole database was retrieved and are visualized in Fig. 9a. The figure illustrates that the GWT is either situated within the bedrock (limestones) or within the surface soils. Similarly, through a statistical analysis, Fig. 9b depicts a higher frequency of GWT occurrence in the bedrock

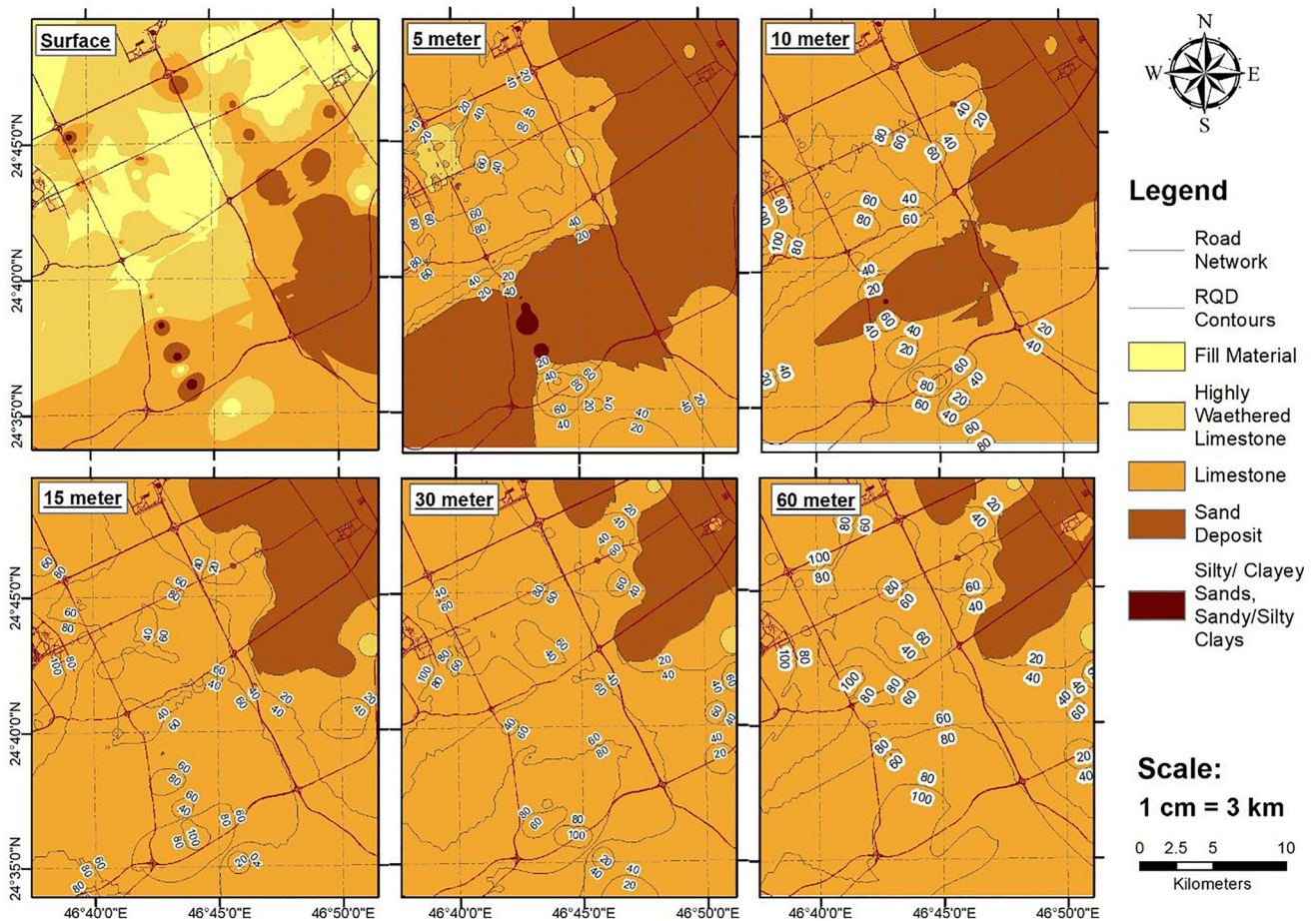


Fig. 8 RQD-based geotechnical zonation map of Riyadh City at various depths

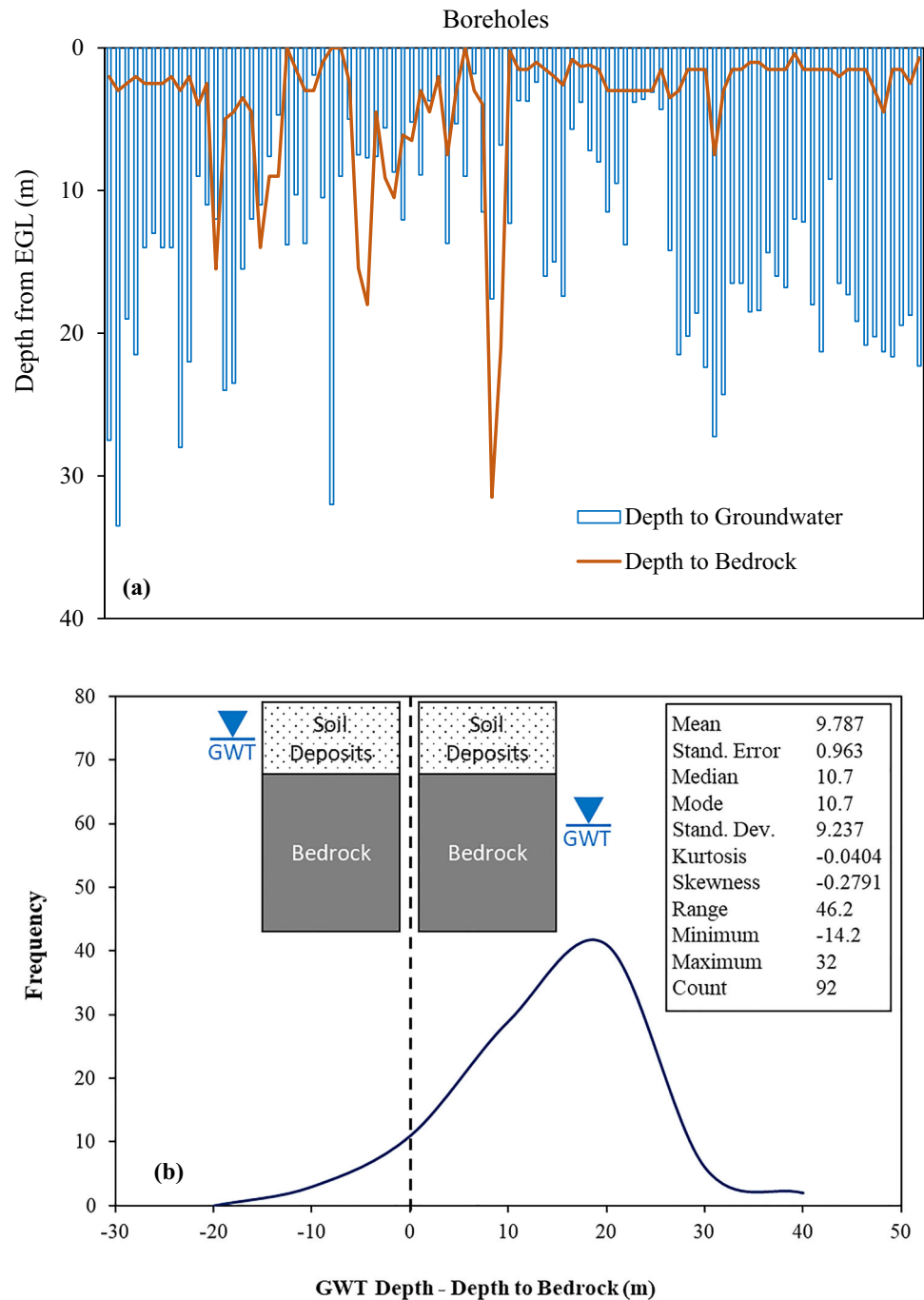
compared to soil deposits. This insight can be instrumental in strategizing groundwater pumping for water supply and designing dewatering systems for potential excavations in the study area.

6 Conclusions

The main objective of this study was to build comprehensive GIS-based geodata regarding soil description and engineering properties of soils in Riyadh City (as a case study) through the collection of available geotechnical investigation reports. Using a subset of data stations in the geodatabase, various interpolation and extrapolation techniques were used in ArcMap to prepare zonification maps for the study area at the surface and at various depth intervals, based on the engineering properties of soils. The results of the interpolation and extrapolation techniques were compared, and the applicable technique was utilized to conclude the following:

- This stratigraphic distribution of the soil types found through GIS-based maps is in accordance with the geology of Riyadh, as presented in the literature.
- The inverse distance weighting (IDW) method in the spatial analysis showed better representation of these zonation maps based on both soil type and RQD.
- Based on the developed GIS-based geotechnical zonation maps, considerable savings in the exploration program can be realized by reviewing existing information regarding subsoil conditions at the site under consideration.
- Limited work has been conducted on the preparation of geotechnical maps for various regions of Saudi Arabia. Developing detailed geotechnical maps for quick and comprehensive geotechnical characterization of subsoils for different regions across the Kingdom could be useful in generating geohazard maps for problematic soils, rocks, and karstic zones.

Fig. 9 a Groundwater level and depth to bedrock distribution
b frequency of occurrence of groundwater in soil and bedrock



Acknowledgements The authors would like to acknowledge the support and resources provided by King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia. The borehole database extracted from geotechnical investigations for various projects in the study area conducted by Gulf Engineering House, Riyadh Geotechnique & Foundations, Dar Al Riyadh, GTC Engineering, and Soil & Foundation Company are also gratefully acknowledged.

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