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Engineering Geological Mapping of Al Jubail City, Kingdom of Saudi Arabia

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Abstract

Urban development and the expansion in the industrial areas are long faced with many geotechnical constraints, such as weak sabkha soils, mobile sand dunes, and saline groundwater. Site investigation and engineering geological mapping help in recognizing the importance of the geological conditions in the founding and growth stages of cities. The aim of this study is to conduct a detailed investigation to produce an engineering geological map and 3D soil profiles in Al Jubail Industrial complex to support urban planning, infrastructure design and hazard reduction. This was achieved by classifying the soil types, measuring the soil engineering properties and identifying the type of geological hazards within an area of 569 km^2. Huge construction works have still going on since the 80's which require an extra effort to match the week nature of the soil that may require foundation modification and/or soil improvement. The present investigation program starts with mapping the geological units in the area, followed by extensive in-situ testing (e.g., Standard Penetration Tests, SPT) and surface soil sampling at 23 surface points and 55 boreholes, following the American Association for Engineering Geologists (AAEG) standards. Several surface comprehensive engineering geological maps in addition to a number of soil profiles were prepared at different scales that can be used as multi-purpose. The maps took into consideration the surface modifications in the soil type and the new boundary between the various geological units. It was found that Al Jubail area is composed of sand dunes and sheets, and low laying sabkhas that pose several significant challenges for the planners and designers. The upper surface to 2 m is mainly loose poorly graded sand (SP) with low relative density, gradually changing to stronger poorly graded sand with silt (SP-SM) at greater depths, overlaid on sandy or clayey week sabkha flats. As a result, raising the ground level by landfill and rectifying the soil is performed on a large scale using either dune sand or dredged soil from the sea. The soil at the surface was divided into five engineering zones: Zone I (fine-medium sand over silty clay), Zone II (well-graded brown sand), Zone III (medium-coarse milky sand), Zone IV (sand with gravel), and Zone V (fine orange sand). SPT N-values at the upper 1.5 m ranged from 25 - 40 (moderately dense), improving noticeably below 6 m. Hazards include sand migration, sabkha corrosion and collapse, settlement in fat clay layers (CH) at 8 - 14 m, and shallow water tables (2 m near shore). 3D fence diagrams and profiles illustrate heterogeneous subsurface layers of marine origin, with relative densities from medium dense/medium stiff to very dense/very stiff. The detail in the produced engineering geological maps is proportional to their scale. The identified geological hazards include drifting sand and migrating dunes, the week and corrosive sabkhas, and the geotechnical problems of the fill materials in the form of settlement or vertical water percolation [1]. The engineering maps and the cross sections will provide general pictures of the material type and their engineering properties in Al Jubail. It is important to serve the developers, construction companies, consulting engineers, and the city residents to avoid problematic grounds or hazardous environment. These findings enhance engineering geological practices by providing a model for integrating satellite imagery, field data, and AAEG zoning in similar arid-industrial settings, enabling proactive soil improvement (e.g., compaction, deep foundations), risk avoidance for developers and residents, and sustainable infrastructure development to minimize settlement and environmental hazards.

Keywords

Al Jubail, Sabkha, Settlement, And 3D Soil Zonation Engineering Map

1. Introduction

Al Jubail is located along the Arabian Gulf in the Eastern Province of Saudi Arabia. (**Figure 1**) The area is nearly flat with an average elevation of 10 m above sea level. It is composed of weak, salty soil sabkha that surrounds a few hills, partially covered by sheet sand [2]. A massive industrial complex was built to the north in the early eighties, which includes about 160 industrial enterprises. The industrial complex spans an area of nearly 569 km^2, with a population of up to 375,000 people.

The investigated area is part of a broader geological region influenced by sedimentary processes dating back to the Paleozoic era ([4] [5] and DGMR, 1979). The bedrock beneath consists of Miocene limestone with marine fossils (Dam Formation), in addition to a Pliocene mixture of sandstone, limestone, shale, chert, and anhydrite (Hadrukh Formation). Steineke *et al.* [6] identified nine lithologic units for industrial mineral potential on a 1:500,000-scale geologic map, which was later expanded by a 1:100,000-scale industrial mineral map by Roger [7]. From the geological perspective, the upper surface is covered by Quaternary deposits, including unstable sabkha and mobile eolian sand. The sabkha can be described as an upper salt flat layer composed of soft-textured, silty, fine sand, with varying densities ranging from loose to very dense. The sabkha is covered by Quaternary deposits of unstable mobile eolian sand and raised coastal strips (**Fig-**

ure 2). This valuable industrial complex may be exposed to a variety of geological hazards. The eolian sand movement, weak soil, and shallow salty groundwater must be evaluated for safe infrastructure development. Soil slopes are not stable when excavated, and settlement is a common problem if they are not stabilized [8].

Figure 1. The geographical setting of Al Jubail City within the Eastern Province of Saudi Arabia, showing its position along the Arabian Gulf coastline. It identifies the industrial complex area and its surrounding topography. The map provides spatial context for the study area's hydrogeological and geomorphological framework (MPMR, 1986) [3].

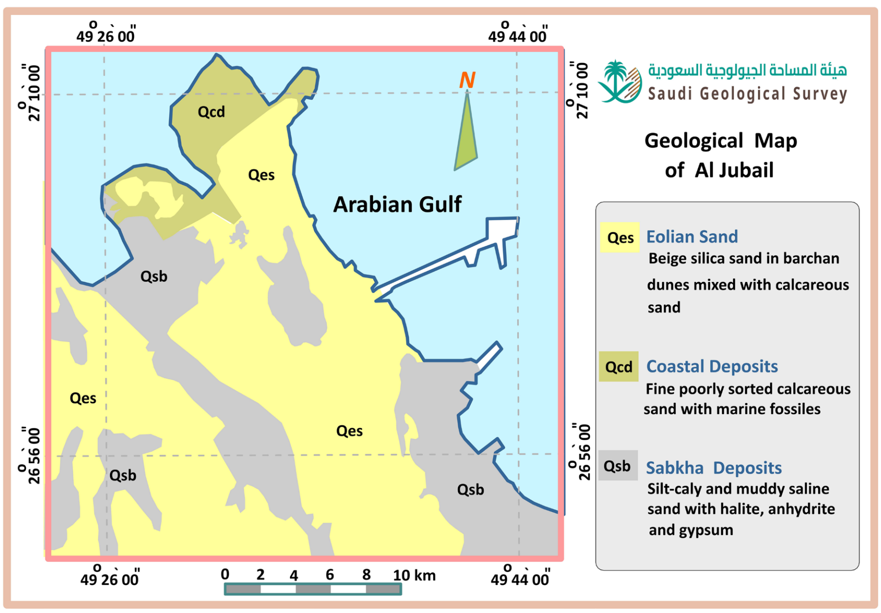

Figure 2. The regional geological formations covering Al Jubail, emphasizing Quaternary deposits such as sabkha flats, coastal dunes, and marine sediments. The map highlights the lateral variation in surface deposits and delineates the contact between sabkha, dune sand, and limestone outcrops, which directly influence the geotechnical properties and foundation behavior across the study area.

2. Methodology

The study conducted field tests (sand cone for density, SPT per ASTM D1586/D1586M-18e1 [9] for resistance) and sampled soils from 23 surface points and 55 boreholes (up to 20 m depth) using manual tools (spades, augers) and heavy equipment. Laboratory tests classified soils (e.g., SP, SP-SM) and estimated relative density from SPT values, integrating prior data [4]. Satellite imagery, aerial photos, borehole records, and field data were used to map 12 territorial units into five zones (e.g., Zone I: fine-medium sand over silty clay), adjusting for artificial fill (up to 2 m). Produced medium-scale maps showing SPT distributions, soil types, and water levels, supplemented by subsurface profiles. Soil profiles were created to 20 m depth and 3D fence diagrams to depict soil distribution and relative density, using SPT-based diagrams (e.g., **Figure 1**, **Figure 2** for 1.5 m and 3 m depths).

This approach provides actionable geotechnical insights for planning and construction, though specific statistical or GIS methods are not detailed.

3. Site Description

Al Jubail is in an arid coastal region characterized by extreme environmental conditions. Shallow, saline groundwater, extreme temperatures, and minimal rainfall shape the hydrogeological environment. The average annual rainfall is low (~100 mm), concentrated in December and January, with occasional heavy events that can result in flash floods and the formation of sabkha [10]. Rainwater rarely infiltrates due to surface sealing by sabkha crusts. Intense summer heat, high evaporation rates, shallow groundwater tables, and highly saline soil environments are factors that collectively affect the hydrogeological system and the design of engineering infrastructure in the area. The hydrogeological regime varies widely, particularly between dune zones and sabkha flats. It plays a central role in understanding construction suitability and groundwater. Seasonal fluctuations and salt crystallization processes define both the chemical behavior and structural limitations of the soils [2]. These dynamics are especially critical in sabkha zones, where engineering interventions must account for settlement risks, corrosion, and instability [11]. The insights gained from this hydrogeological analysis are crucial for designing safe and durable foundations and infrastructure in the region.

The site is adjacent to active dune fields influenced by prevailing northwesterly winds. These winds transport fine to medium sand particles, forming barchan dunes and sand sheets. The sand movement may accumulate over sabkha, roads, and infrastructure, and clog the air intakes of electronic systems.

Sabkha soil may collapse when cementation salts dissolve due to rainfall or irrigation [12]. It has a low bearing capacity, especially in clayey sabkha zones (e.g., west of an industrial city), which can cause corrosion of steel piles and rebars in foundations. The fluctuating, salty, shallow water table may percolate further up and break the crisp and delicate sabkha crust, causing soil hydro-compaction as surface crusts break down under changes in moisture. Naturally, loose dune sands are above capillary fringes. Pumping of shallow groundwater causes a zone of saturation within the top 1 to 2 meters of the aquifer. Excavations for trenches or basements may experience sidewall collapse, particularly during construction or when subjected to traffic vibrations. The overall structural soil strength of this environment is limited and cannot directly support the heavy industrial structures [12] [13].

4. Site Investigation

The data collection phase incorporated a comprehensive suite of field testing and laboratory procedures. Surface investigations included the sand cone test to determine in situ density and the Standard Penetration Test (SPT) to evaluate soil resistance [9]. The ASTM standard performed by the SPT. Soil sampling was executed using manual tools (spade and auger) for shallow profiles and heavy excavation equipment for deeper layers. The investigation included 23 surface points and 55 boreholes, with SPTs performed at various depths (1.5 m, 3 m, 4.5 m, 6 m, and deeper in some profiles). That means you had on the order of hundreds of SPT blows overall, distributed across the industrial and urban zones of Al Jubail. The industrial complex alone covers ~569 km^2. With 55 boreholes, this translates to roughly 1 borehole per 10 km^2. For regional mapping, this is acceptable for reconnaissance-level zoning to delineate sabkha, dune sands, and engineered fills. **Table 1** and **Table 2** describe the main soil types, distribution with depth and their properties.

Table 1. Soil types versus their depth and SPT values.

Soil Type	Depth	SPT N/Density
Sabkha (surface)	0 - 2	N < 10, very loose/soft
Sand dunes	0 - 3	N = 10 - 20, loose-medium
Silty sand	3 - 6	N = 20 - 30, moderately dense
Clay layers	6 - 9	N = 25 - 40, stiff
Fat clay (CH)	8 - 14	N = 20 - 30, medium-stiff
Dense marine sediments	9 - 20	N = 30 - 50+, dense-very dense

Table 2. Engineering description of the soil types.

Soil Type	Engineering Notes
Sabkha (surface)	Weak, collapsible, saline, corrosion risk
Sand dunes	Mobile by wind, low density, improves with compaction
Silty sand	Better strength, but heterogeneous, moderate compressibility
Clay layers	Good bearing but variable, settlement if saturated
Fat clay (CH)	High settlement potential, critical for heavy loads
Dense marine sediments	Competent stratum, suitable for piles

It should be mentioned that the purpose of this study does not include detailed engineering design (e.g., foundation design for individual plants, towers, or infrastructure). No statistical assessments of the collected data were used. Data from in-situ tests (e.g., Standard Penetration Test or SPT N-values) and laboratory analyses used directly or through standard geotechnical derivations. For instance:

- SPT N-values are reported as ranges (e.g., 25 - 40 at 1.5 m depth, indicating moderately dense soil) without statistical processing described.
- Relative densities (Dr) for soil layers are "approximated from the recorded SPT values" using established correlations, a common practice in geotechnical engineering where Dr is estimated via empirical formulas like those based on N-values for sands (e.g., $\mathrm{Dr} \approx \sqrt{N/\left(A+B*e_{\min}\right)}$), though no specific formula is cited in the report). This derivation is qualitative rather than statistically rigorous, focusing on categorization (e.g., loose to medium-dense for dune sands, stiff or dense for deeper layers). Laboratory tests determined soil classification and engineering properties, following the AAEG system [14]. The results were integrated into medium-scale engineering geological maps, subsurface profiles up to 20 m depth, and 3D fence diagrams. Based on these, 12 soil units were zoned into five main engineering zones, highlighting sabkha and dune sands as the most problematic areas.

The compiled knowledge from previous investigations was used to produce:

- Several engineering maps for the surface distribution of SPT values, soil type, and water levels.
- Soil profiles that show the soil lateral and vertical distribution to a depth of 20 m, the soil type, and layer shape and thickness are also indicated concerning depth.
- A detailed fence diagram in the form of 3D profiles.

5. The Engineering Geological Mapping

The aim of the engineering geological maps of this research is to bridge the gap between traditional geological maps and the actual needs of engineers, planners, and construction professionals. While standard geological maps focus on stratigraphy, lithology, and formation ages, they lack detailed, site-specific information on geotechnical parameters such as soil density, water table variability, strength, rock discontinuities, and weathering. The maps are based in part on zoning standards provided by the International Association for Engineering Geology and the Environment (IAEG, 1976) [15]. The maps produced can be used for future construction and urban development decisions (**Figure 3**). The area under investigation spans approximately 569 square kilometers and comprises various geological units, including sabkha, dunes, artificial fill, and limited limestone outcrops. A combination of satellite imagery, aerial photos, borehole records, laboratory test data, and field investigations was utilized to create maps and soil profiles. They are comprehensive, medium-scale maps that provide information applicable to a wide range of engineering and planning activities.

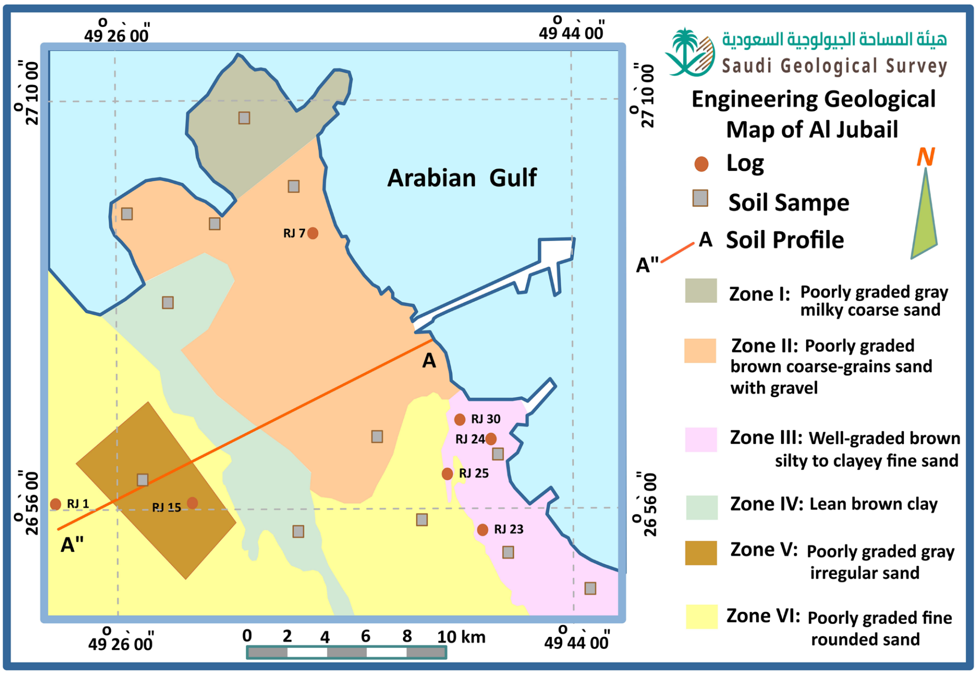

Figure 3. The integration of borehole data, SPT results, and surface observations to define five engineering zones differing in soil composition and density. It shows the spatial distribution of sabkha, dune sand, artificial fill, and gravelly zones. The map supports urban and industrial planning by identifying suitable foundation zones and areas requiring soil improvement.

A total of 12 territorial units (zones) were Identified and evaluated based on the uniformity of their engineering properties and conditions. Each unit was classified and described using standardized terminology and grouped into five zones with their hazard level as follows:

- Zone I (NW of the city, medium risk): Fine to medium poorly graded sand overlying silty clay.
- Zone II (SE of the city, low risk): Well-graded brown fine to medium sand.
- Zone III (Al Fanatir, medium risk): Medium to coarse, poorly graded milky sand with subangular grains.
- Zone VI (Port and industrial area, high risk): Brown poorly graded sand with gravel.
- Zone V (Southwest industrial city, high risk): Fine orange sand, poorly graded.

The boundaries of some zones are unnaturally straight due to artificial intervention, including large-scale soil modifications performed by the Royal Commission, such as the application of fill material up to 2 m thick to stabilize construction zones.

The map was supplemented with subsurface profiles and SPT-based diagrams to describe variations in soil resistance and relative density. SPT N-values at 1.5 m depth generally ranged between 25 and 40, indicating moderately dense to dense soil, just below the standard foundation level in many regions (Figure 4). The N-values from depths 3 m to 4.5 m remained stable or slightly improved (Figure 5 and Figure 6).

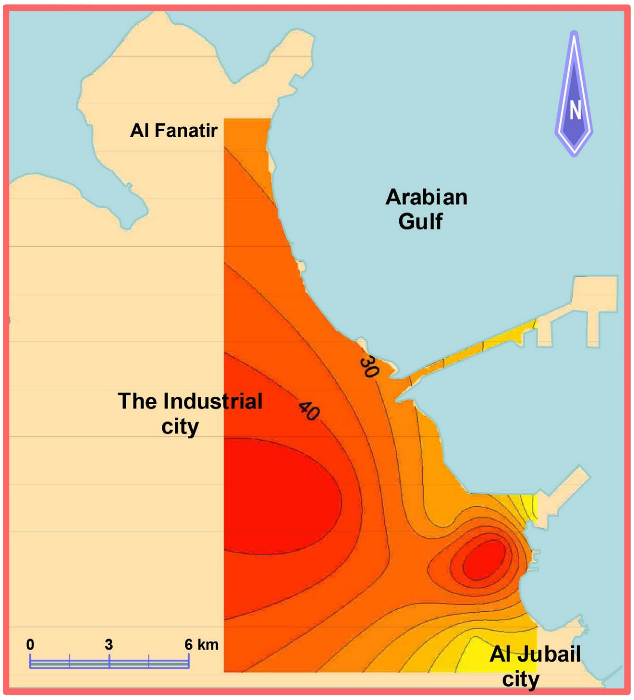

Figure 4. An analytical map illustrating the Standard Penetration Test (SPT) N-values across the upper 1.5 m of soil. It identifies moderately dense to dense sand near reclaimed areas and weaker sabkha zones close to the shoreline. These results are used to assess surface soil strength for shallow foundations.

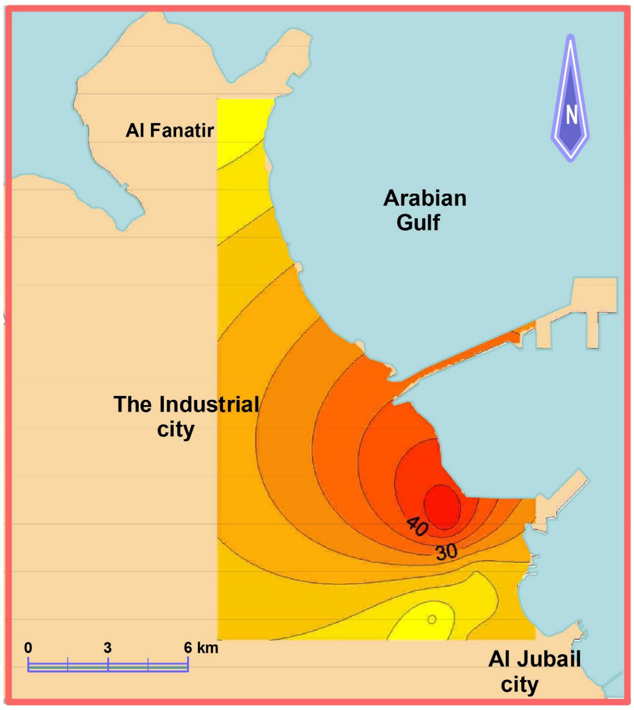

Figure 5. The interpolated SPT values at 3 m depth, showing lateral variation in subsurface density. Denser soils appear toward artificially filled industrial zones, while low-N-value regions correspond to sabkha flats prone to settlement. The map helps delineate subgrade improvement requirements.

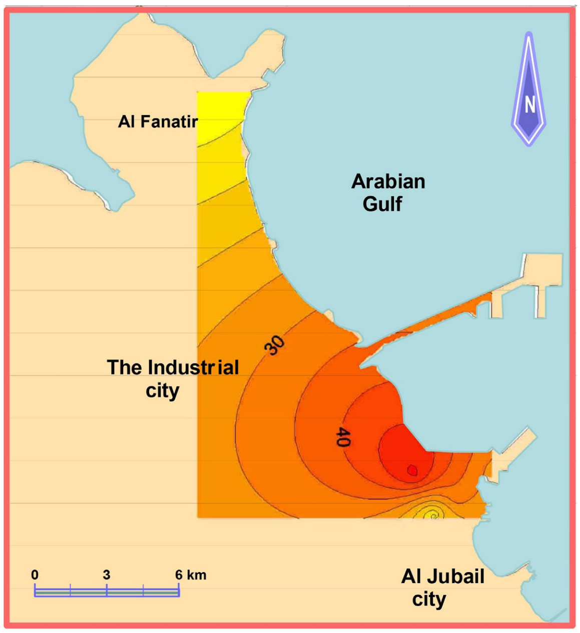

Figure 6. This map depicts continued improvement in soil density with depth, revealing a trend toward denser sandy layers. It is useful for evaluating the transition from loose surface sand to more competent strata suitable for mid-depth foundations.

However, a significant improvement was achieved in the soil relative density at a depth of 6 m, especially in reclaimed or engineered areas, marking the transition to competent soil layers suitable for structural foundations (Figure 7). The water level is 2 m deep near the shoreline and increases in depth further west (Figure 8).

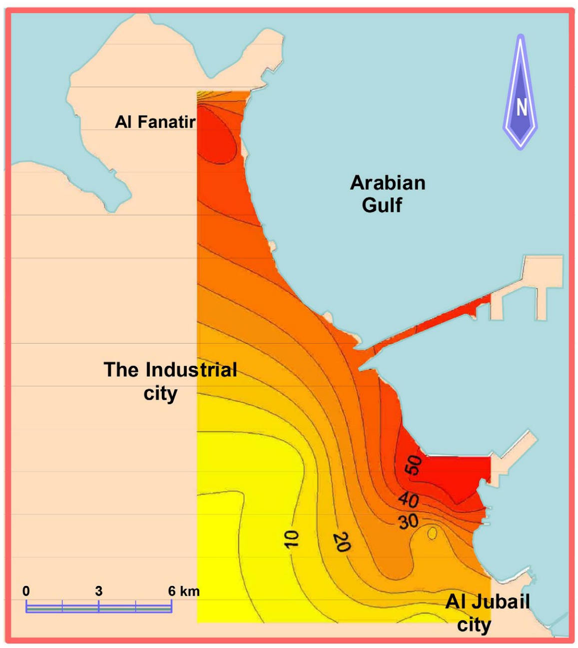

Figure 7. The significant improvement in relative density at around 6 m, particularly in reclaimed or compacted fill areas. These competent layers mark the recommended bearing depth for heavy structural foundations.

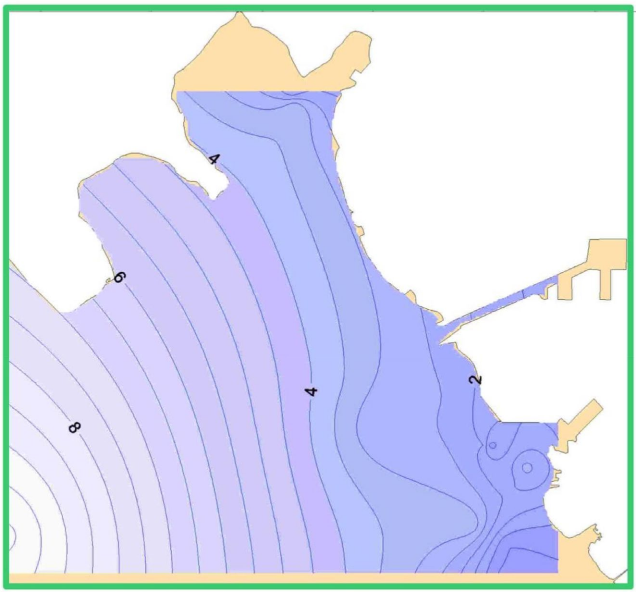

Figure 8. A contour map showing groundwater depths ranging from approximately 2 m near the coast to more than 5 m inland. The shallow water table indicates high corrosion potential in sabkha zones and informs the selection of appropriate foundation and drainage designs.

Figure 9. This map identifies surface and near-surface soil types—primarily poorly graded sand (SP) and silty sand (SP-SM). It delineates early foundation zones that require densification or replacement before construction.

A soil profile demonstrates the following soil types:

- The upper 0 - 3 m is predominantly sand (SP and SP-SM) (Figure 9).
- From 3 m to 6 m, the soil is silty sands (SM) with occasional clay lenses (CL) (Figure 10).

- The soil from 6 m to 9 m is interbedded layers of stiff clays and sand clays (Figure 11). Below a depth of 9 m is a transition to more stable and dense soil conditions.

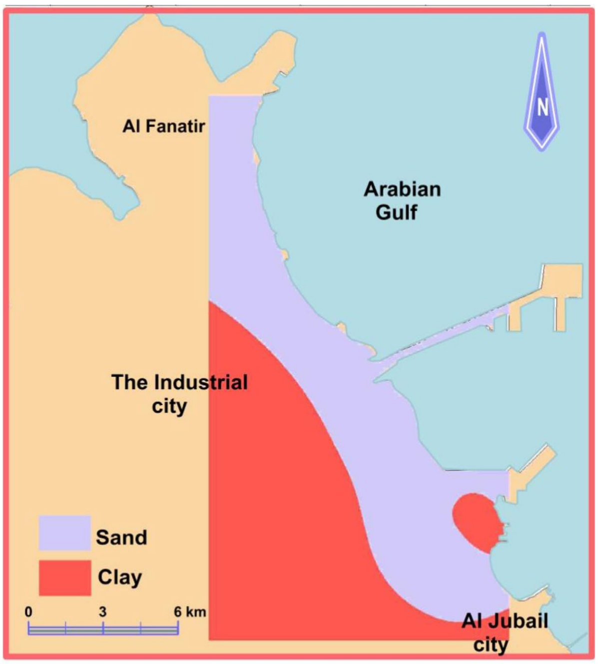

Figure 10. The subsurface variation dominated by silty sand (SM) and occasional clay (CL) lenses. These layers represent intermediate strata where moisture and salinity may influence settlement behavior.

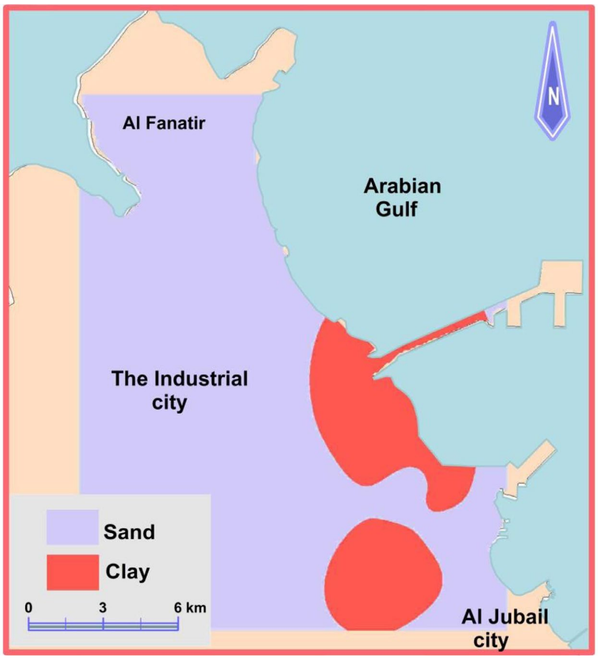

Figure 11. The occurrence of stiff clay (CL-CH) interbedded with sand, marking the transition to more stable and dense conditions. This information helps predict long-term settlement risks for deep foundations.

Figure 12 and Figure 13 illustrate the soil layers along a line extending across the industrial city in two different directions: NE-SW and NW-SE. The main soil types to a depth of about 20 meters are of two types.

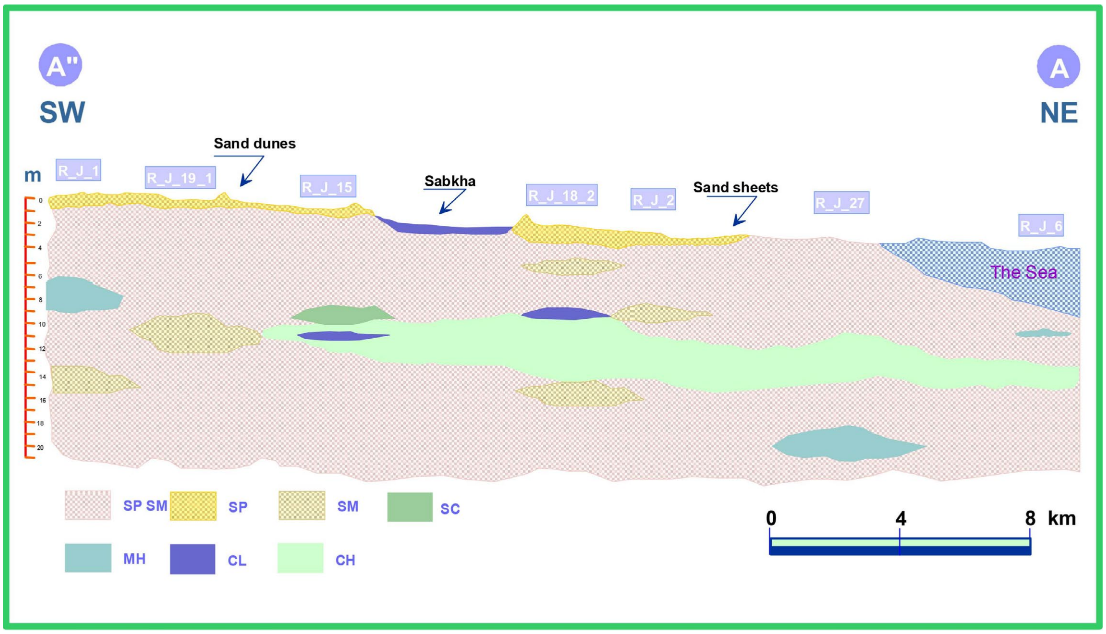

Figure 12. A cross-section illustrating the stratigraphic layering and lithologic transitions to a depth of ~20 m. The section reveals alternating silty sand and clay layers, reflecting marine deposition and highlighting the continuity of the "fat clay" (CH) horizon associated with potential settlement.

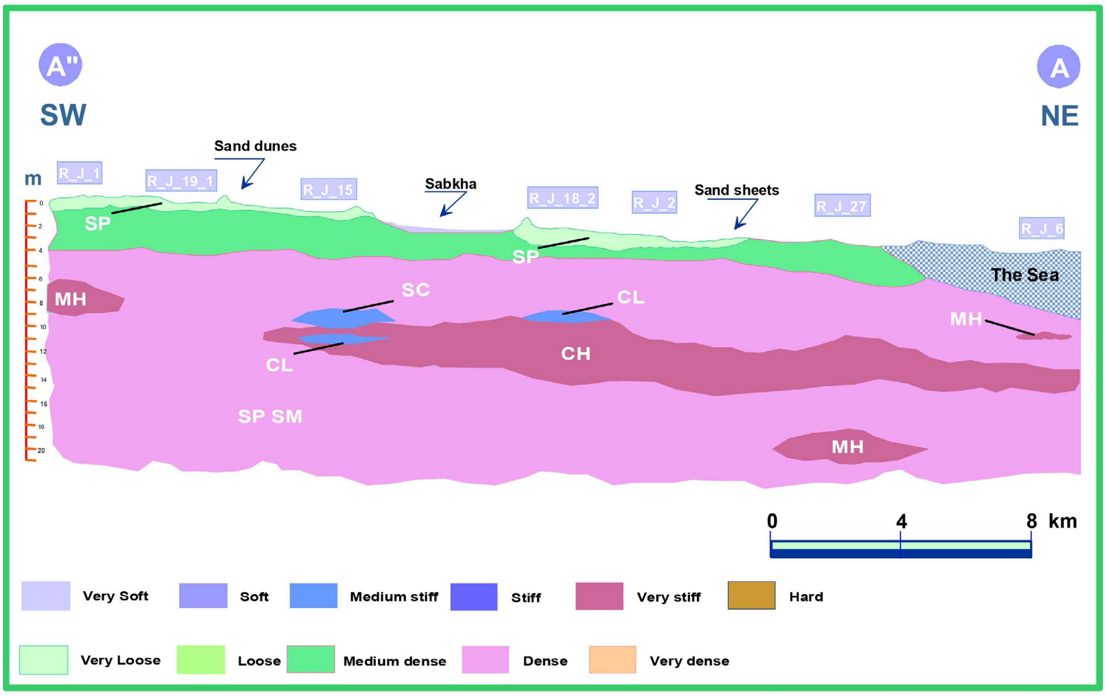

Figure 13. This cross-section complements Figure 12, emphasizing lateral variation in sabkha and sandy deposits. It depicts the depth and extent of soft, compressible layers and their correlation with surface zones identified in the engineering geological map.

a) silty sand (SM) along the shoreline that includes Al Jubail city and the marine base, and

b) poorly graded sand with silt (SP-SM) that occupies most of Al Jubail area.

These soil types are believed to have been deposited in a marine environment. As marine conditions change over time, the main soils at depths include lenses and small layers of other varieties of sand (SP and SC), silt (ML and MH), and clay (CL and CH). The relative densities (Dr) of the soil layers along selected lines were approximated from the recorded SPT values. The obtained relative densities of the coarse and fine soils along the two profiles are generally moderately dense/medium stiff to very dense/very stiff. The fat clay layer (CH) might be a source of significant settlement if the structural load reached a depth of 8 to 14 m. That layer is approximately 4 to 8 m thick, and its main extension is in the NE-SW direction for about 20 km.

These profiles were visualized more clearly using fence diagrams, which illustrated the distribution, depth, and thickness of different soil types across (Figure 14). Also included were relative density diagrams (Dr), derived from SPT correlations, showing that dune sands tend to be loose to medium-dense. At the same time, deeper marine sediments and artificially compacted fill are generally stiff or dense, as confirmed by borehole drilling (Figure 15).

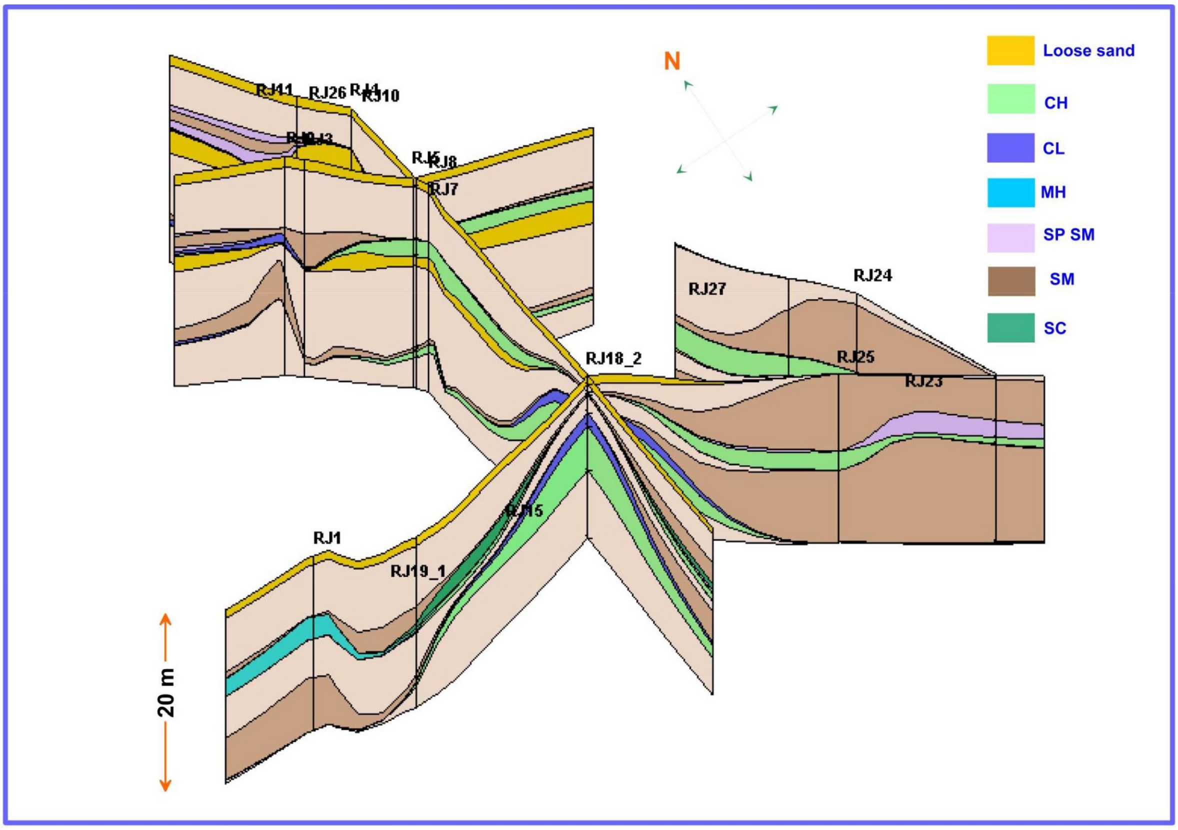

Figure 14. The fence diagram visualizes the spatial variability of soil units in three dimensions. It demonstrates the relationship between sabkha flats, dune sands, and artificial fill materials, clarifying the heterogeneity and interbedding pattern across the study area.

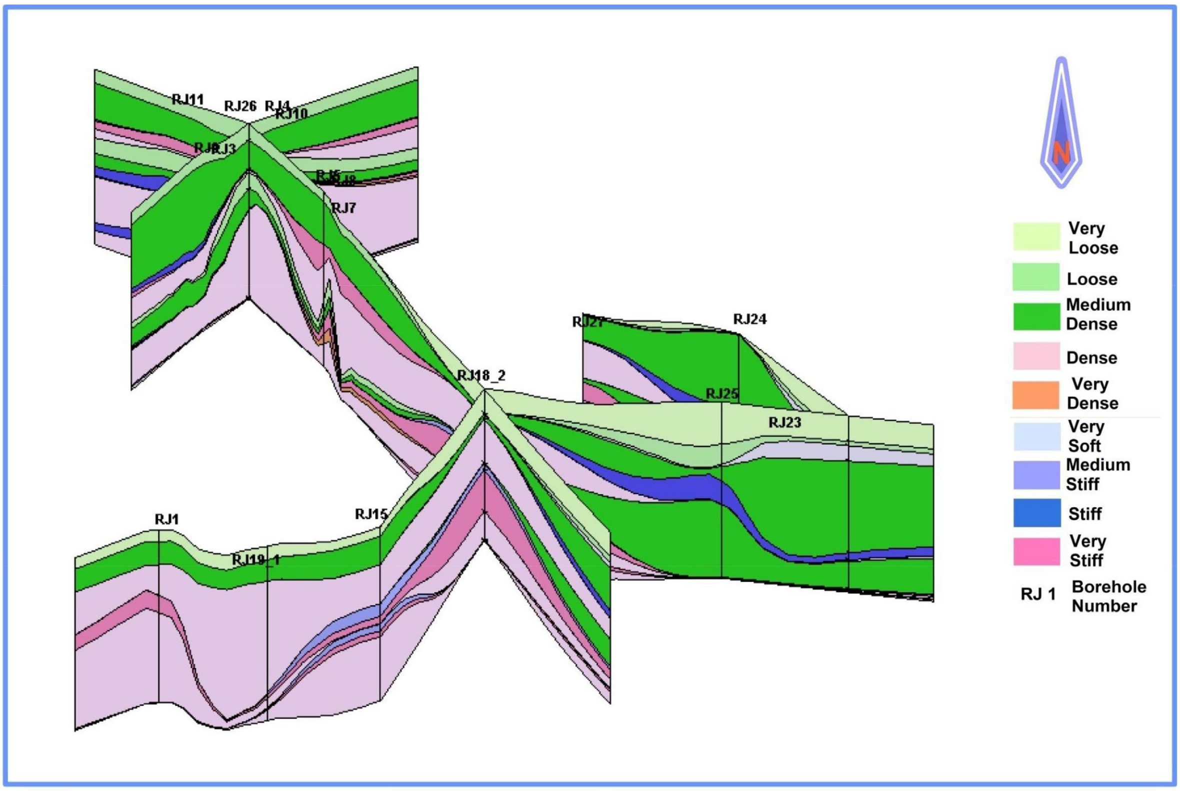

Figure 15. This 3D representation shows the relative density variation derived from SPT correlations. It reveals loose to medium-dense dune sands near the surface, transitioning into dense to very dense marine sediments and engineered fills at depth—critical for defining load-bearing capacities and identifying areas prone to settlement.

The results of this mapping effort have some key implications for design and development. Identifies suitable zones that require soil improvement before foundation installation. The low-lying sabkha zones are vulnerable to waterlogging. The SPT N-values represent a preliminary estimation of load-supporting ability. The foundation selection, whether shallow or deep, is based on subsurface layering and material strength.

6. Discussion

The stability of structures in Al Jubail is influenced by a complex interplay of several factors related to soil type, its salinity, and the type of urban development in coastal arid environments. Sabkha extent and thickness affect the stability of the primary structure. Major geotechnical problems are expected at depths 8 to 14 m due to the presence of "fat clay" that extends in the northeast-southwest profile. It is likely a deposit from a marine environment. Among the challenges of this soil type are low strength, swelling and shrinkage, permeability, and settlement. Fat clay is characterized by low undrained shear strength when molded or saturated and requires a special foundation to avoid bearing capacity failure. Seasonal fluctuations in groundwater levels may lead to soil volumetric changes, which are another factor contributing to additional internal loading in all directions. Moisture change may cause hydrocompaction during construction or dewatering activities.

Shallow saline groundwater in Al Jubail sabkha soils compromises foundation stability through collapse, settlement, and uplift effects, while also accelerating corrosion of steel and concrete materials [5]. Effective foundation design must combine deep foundations, durable construction materials, and soil/groundwater treatment to ensure long-term performance. The very low permeability will slow the drainage rate and extend the consolidation time even further. The soil thickness may affect the design of deep foundations, particularly under long-term loading that can cause differential movement of foundations and pavements. Petrochemical installations are more susceptible to tilting or cracking due to uneven settlement. These conditions reflect the case in the study area, which may affect the ongoing and future maintenance demands and potential significant structural distress. Proper mitigation includes preloading, soil stabilization methods, and the use of deep foundations.

On the other hand, lightweight structures, including roads and pavements, can be supported by compacted infill material made from imported soil. The sources of the fill material used in the study area are dunes and dredged sea soil. The dune grain size and texture, gradation, initial moisture content, negligible salt content, workability, strength when compacted, and cost are significant properties that favor dunes. To understand the general behavior of sabkha soil under the influence of these multiple contributing factors in a specific location, an engineering geological map was produced, supported by several three-dimensional profiles.

A comparative analysis between Al Jubail and three representative areas—Jeddah coastal plain, Ras Al-Khair industrial zone, and Yanbu coastal area can be done. The SPT ranges and sabkha properties in Al Jubail are consistent with those reported in several articles [13] for other Gulf sabkhas, confirming a pattern of loose upper sand (SP, SP-SM) over medium-stiff to stiff clayey sabkha at 6 - 14 m. The presence of marine-origin "fat clay" horizons is recurrent across all coastal industrial zones (Ras Al-Khair, Jubail, Yanbu), reflecting paleo-lagoonal deposition. Settlement, corrosion, and collapse risks under shallow saline water tables are comparable Kingdom-wide; however, Jubail's industrial reclamation (landfill up to 2 m) slightly improves surface density relative to the more natural sabkhas in Jeddah or Yanbu.

7. Conclusions

Based on the outcome of this study, the following can be concluded:

- The subsurface soil is heterogeneous, with various sources: sabkha, dunes, and artificial fill, each of which may create different geotechnical constraints.
- The saline and low relative density, poorly graded sand (SP, SP-SM) requires engineering treatment, especially in the upper 3 meters, prior to infrastructure development.
- The Sabkha zone is geotechnically problematic. The concentrated soluble salts (halite and gypsum) and a shallow water table can easily cause dissolution and collapse after heavy rain, leading to soil settlement. Shallow saline groundwater weakens soil and accelerates corrosion.

- Pile foundations should be used for heavy structures, as the soil strength is gradually improved beyond 6 meters, as identified from the borehole data.
- The unstable dune sands may move due to wind and accumulate near critical structures, potentially eroding exposed surfaces.
- Variable subsurface layers create uneven load-bearing capacity and settlement risks.
- The engineering geological map of Al Jubail was achieved by integrating satellite imagery, field surveys, and laboratory analyses, utilizing the classification schemes of AAEG [14]. It stands as a model for similar urban-industrial environments.
- Future Research.
- Long-term monitoring of soil settlement, groundwater, and salt effects.
- Foundation performance and corrosion studies.
- Evaluation of soil improvement and stabilization methods.
- Hydrogeological dynamics and climate change impacts.
- Advanced modeling, geophysics, and remote sensing for hazard mapping.

8. Recommendations

The document highlights several areas for future research to address Al Jubail's geotechnical challenges. These include conducting more detailed, site-specific investigations for construction projects, and specifically studying the settlement behavior of the identified fat clay layer at 8-14m depth. Further research should also focus on testing the effectiveness of different soil improvement and stabilization techniques for the local sabkha and sand soils, as well as developing better methods to mitigate the corrosion risks from saline groundwater. Another area is researching methods to control sand movement and migrating dunes, which pose a hazard to infrastructure.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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