Geoengineering characteristics modeling of Eocene limestone beds of the upper plateau of Mokattam area, Egypt using GIS techniques

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Abstract
This research paper is concerned with studying and evaluating the geoengineering characteristics and potential risks of the area under study with a view to safe urban expansion using GIS techniques. Different geotechnical laboratory tests such as Atterberg limits, free swelling test, swell potential and pressure tests, chemical analysis, unconfined compressive strength (UCS) and rock quality designation (RQD) were performed on 28 boreholes (95 samples). Furthermore, X-ray diffraction was used to examine clay minerals. The results indicate that the UCS values range from 47 to 72.2 kg/cm² and RQD from 21 to 45%. The free swell ratio ranges from 110 to 120%, and the plasticity index from 34 to 37%. In addition, GIS techniques have been utilized to produce the distribution layers of different geotechnical characteristics, then integrated to produce a geospatial urban model for delineating and defining safe and dangerous urban zones. This model is classified into four classes: low, moderate, high and very high hazard. Low and moderate hazards were detected in the major portion of the survey area. These portions are suitable for foundations at shallow depths. However, high to very high hazards were detected in the southeast portion of the study area. The reason for these areas is caused by the existence of heavily fractured limestone and highly swelling clay layers. This model would aid in the creation and discovery of the best areas of shallow base in the region under consideration.

Keywords Geospatial urban model · Geoengineering characteristics · GIS techniques · Unconfined compressive strength · Plasticity index

Introduction
In recent times, Egypt has witnessed a fast-growing population of over 90 million people. These numbers are below about 5% of Egypt’s territory. To stay up with the rapid increase in population, in recent years, the Egyptian government has encouraged the development of projects in the desert zones outside the Delta and Nile Valley. Hundreds of new cities, industrial zones and tourist villages have been established in the last 2 decades. Utmost of these regions have not been rigorously investigated in determining their suitability for these developments or even for determining geological hazards. Thus, there is a dire need to assess these zones for any development so as to bring down the numeral of risks as well as their catastrophic impact (Aly et al. 2005).

Limestone is a natural raw material of great importance as it is utilized in construction and decoration purposes, as well as in many industrial applications such as cement, chemical industries and fertilizers depending on its mechanical and physical properties (Harrison and Bloodworth 1994). From a geotechnical perspective, limestone has been studied in different regions of the world by several authors (e.g., Ben Salah et al. 2018; Dweirj et al. 2017; Pappalardo et al. 2016) and in Egypt (e.g., Roushdy et al. 2017; Ali and Yang 2014; Ahmed 2015; Abd El-Aal 2015; Abou Elmagd et al. 2020). Limestone fractures lead to serious damage to local infrastructure. Damage includes cracking and rupture of the paved main roads, the drinking water line, tipping of power and telephone lines, and cracking of adjacent buildings (Abdel Gowad et al. 2018). The Mokattam region has three plateaus: the upper plateau, the mid-plateau and the lower plateau. The current study focuses on the upper plateau, composed of successive layers of limestone, marl, and...
clay, having an average thickness of approximately 700 m, represented by Maadi Formation (Said 1962). The Mokattam plateau has serious problems, notably near the plateau’s boundaries, where several landslides have occurred owing to the cracking of the limestone, producing landslides that have devastated many houses and hotels. In addition, the fractured limestone is covered with a layer of clay that causes most of the engineering issues due to volume variations in the swelling clays resulting from human activities (Velde 1995). Soil swelling has been treated with numerous chemical additives and industrial wastes such as the waste marble powder to improve strength, durability, and reduce construction risks (Sakr et al. 2021).

Several studies took place in the study area, among others (Moustafa and Abdel Twaab 1985; Moustafa et al. 1985, 1991; Eid et al., 2003; EL-Sohby et al. 2004; Geological Survey of Egypt (EGSMA) 2004). Helmy et al. (2007) focused on the effect of using the vertical concrete wall to improve the stability of fractured sedimentary rock slopes on the Mokattam Plateau. Park and Shin (2009) supplied a commercial chemical consolidation agent using (Wacker OH 100) to fill the porous space and reinforce the jointed rock. Pore filling was confirmed by the reduced permeability and porosity of the rock samples as a result of the application of the consolidation product. Sultan (2010) used the geophysical survey to identify the geotechnical problems on the upper plateau. The shallow portion of the upper plateau is composed of moderate velocity and high-resistivity fractured limestone with a thickness of 2–5 m, and the top layer of limestone contains caves of various dimensions that can cause damage to buildings. The limestone covers a layer of clay, which has a detrimental effect on the buildings due to high swelling property. Yousif (2000) the inclines of the Middle Eocene rocks that form the edges of the central Mokattam plateau are unsteady and probably regions of rock collapse in various spots. Saad et al. (2020a, b) estimated the sub-surface soil east of G. Mokattam using geoelectrical and sedimentological studies. The study demonstrated the existence of clay with high fracture limestone. The dominant mineral in the clay samples investigated is montmorillonite. The old building damage is due to the presence of caves in the limestone layers and the swelling of the mud layers.

Nowadays, people need a greater understanding of critical environmental systems in order to help resource managers in taking suitable actions to prepare for future sustainability. Engineers and planners in geotechnical engineering utilize Geographic information systems (GIS) to locate boreholes because it allows them to conduct fresh research, particularly in newly developed regions (Wan-Mohamad and Abdul-Ghani 2011; Dong et al. 2018). GIS technology is utilized in the initial stage to determine the site planning and locations of residential areas and public facilities such as production facilities and highway networks. This technology is also used to interpolate values geographically and offer geotechnical data alongside the entire area rather than just boring points, where well data provide one-dimensional information on soil conditions along the depth that is subject to spatial ambiguity (Kim et al. 2020).

In this work, the integration approach of geotechnical characteristics and GIS is critical for building and providing digital maps and safety zones due to spatial correlation. GIS is an automated system for effectively storing, analyzing, and displaying geographic data (Dangermond 1984). The geospatial model is one of the important products of GIS uses in this study, and enables the representation or modeling of geographically referenced data graphically or geometrically, as the graphic form represents the location of the geographical phenomenon or its spatial distribution, while the geometric form describes its feature or characteristics. The map was considered a model in the 60s of the twentieth century, and then it was generally accepted by many cartographers later, considering that the map as a model reflects the actual surrounding world through personal understanding and awareness of the cartographer. Robinson et al. (1995) define the geospatial model in its simplest form as a composite map of a set of variables, derived from the aggregation of a number of one-variable maps. Geospatial models are especially suited to applications when time and cost constraints the necessary and predicted accuracy of the model (e.g., Risk assessments in areas lacking geotechnical testing). Therefore, there was an urgent need to integrate geotechnical data and GIS software efficiently by building a geospatial model by distinguishing spatial features (such as points and lines) from other non-spatial information.

These approaches have been utilized in a variety of research, including mineral exploration, environmental hazard, radiation hazard assessment, urbanization, and geotechnical modeling (Omar et al. 2016a, b, 2021; Arnous and Omar 2018; Saad et al. 2020a, b; Sakr et al. 2021; Omar 2021; Arnous et al. 2021; Aita and Omar 2021; Khan et al. 2021). All these recent publications demonstrated GIS’s potential to simplify data interpretation and produce superior outcomes.

Thus, an appropriate study was performed to evaluate the geotechnical characteristics to check the suitability of the study area to the urban extension using GIS techniques. Construct the geospatial urban extension model to choose the most suitable locations for safe urban expansion. In addition, identify hazardous locations and how they can be treated before various construction activities.

**Location and geological setting of study area**

The investigation zone is located on Cairo’s eastern outskirts, between northern latitude 29° 59’ 20” and 30° 00’ 50”, and eastern longitude 31°16’30” and 31° 19’ (Fig. 1).
The Mokattam area is a prominent plateau that borders Cairo from the southeast with its highest point at an altitude of 213 m a.s.l.

Geomorphologically, the investigated area has three plateaus. The high plateau is situated in the northern part, and its height ranges between 205 m in the southern part and 170 m in the northern part. A steep cliff separates it from the center plateau. As per NARSS (1997), the height of the central plateau reaches 110–150 m and the lower plateau reaches 50–80 m.

The geology of the examination region has been talked about by numerous authors (Said 1962, 1990; El-Shazly and Abdel-Hady 1976; Aboushook and Sherif 2000). Stratigraphically, this area is covered by a thick succession of carbonate rocks and less abundant argillaceous rocks ranging in age from Middle to Late Eocene, and they are distinguished into two main units, El Maadi and Gebel El Mokattam Formation (Fig. 2). El Maadi Formation is 45–60 m thick, and is composed of numerous yellowish brown dolomitic limestone that covers most of the surface of the Mokattam area. These incorporate shale and clayey marl layers alongside the essential limestone members. The El Mokattam Formation is essentially composed of white, medium-hard to hard limestone lying under El Maadi Formation. The upper member of the Mokattam Formation (Giushi) is 60 m long and made of thinly bedded white limestone. The structure of the investigation zone is principally determined by three main faults: NWN–SES, E–W and NW–SE trends (Fig. 2).

**Materials and methods**

The work was carried out in its different stages as described as the following (Fig. 3):

**Field investigations**

In the investigated region, 28 boreholes were drilled at depths ranging from 0 to 10 m below ground level. The scope of the field research was carried out using mechanical
rotary drilling rigs, and the field work was performed as per ASTM standards. A single core was used to obtain core samples from limestone rocks, and disturbed samples from backfill and loose soil from fractured limestone and clayey soil. After each core run, the retrieved sample was estimated to decide the total core recovery (Rec.% ) and the RQD. All samples were first graded in situ by a geologist and records were prepared (Fig. 4A–D). Samples were taken at depths of 1.0 m, 3.0 m and 6.0 m below the soil surface at each borehole. The depths chosen account for the shallow depth of most foundations as well as the expected depth of the active zone in the research region. No groundwater or leaching appeared until the end of the borehole, and leaching may appear due to human use or climatic conditions, etc. The field samples were stored in plastic bags and taken to the lab for analysis and classification purposes.

**Laboratory work**

Several laboratory tests have been carried out on soil samples to investigate the physical and mechanical properties of the soil, including free swelling (FS), mineralogical identification, Atterberg limits, swell potential (S), swelling pressure (SP) and (UCS) on rock samples. Noting that the Atterberg limits comprise the plastic limit (PL) and liquid limit (LL) of fine-grained soils, which pass through sieve No.40, these limits were implemented in accordance with ASTM D-4318 (2010). The SP was implemented as per ASTM D-2435 (2011). Clay soil X-ray diffraction has been performed using a Philips diffractometer (9 type PW 3710) and a Ni-filter cake radiation. The samples were run from 2 to 50 at 40 mA and 40 kV. In addition, the testing program comprised the determination of the pH, chloride content (Cl−), sulfate content (SO32−) and the total dissolved salts (TDS). Cl− and SO32− were analyzed by ion chromatography. The instrument used was the Dionex IC model ICS 1100 equipped with high capacity columns (AS9) for anion (Cl and SO3). Rock samples of almost cylindrical shape were tested using the UCS apparatus. The test was conducted as per the International Society of Rock Mechanics. (ISRM) and as per ASTM D-2938-95 (2002). These samples were tested in dry condition. Both diametral (D) and axial (A) test types were conducted on samples extracted from boreholes.

**Spatial data analysis and geospatial modeling (GM) of the geoengineering properties**

A geoengineering data integration approach and the development of a geospatial model for geoengineering hazards have been proposed in an attempt to help decision makers and the state in planning the safe urbanization of new urban areas. Geoengineering data collected must be entered into a database so as to model and evaluate the geoengineering properties of the studied region. The acquired data are then subjected to geospatial interpolation technology utilizing GIS for statistical analysis of the entire region and the integration of geoengineering data into a digital map with high spatial resolution. The goal of spatial interpolation is to identify and give soil information along the entire region instead of at a particular point that may be used for designing safe construction regions. Geospatial interpolation methods are broadly classified into two techniques: deterministic and geostatistical. The deterministic technique, which is based on basic empirical or preset mathematical equations, does not take into account the influence of spatial variation with distance forecasting values at unknown places (Kim et al. 2020). The geostatistical techniques, such as the kriging algorithm and its variants, are highly successful at interpolating spatial data over a large range of areas. The geostatistical techniques are considered more accurate than deterministic methods for geoengineering characteristic interpolation because of their better ambiguity integration (Arshid and Kamal 2020). In this work, this approach uses the kriging method to perform geostatistical analysis of geoengineering parameters. Spatial analyses contain a wide range of data, especially geoengineering measurement points. The geographic locations (X, Y) of these points are imported as geographical points in the grid into ArcGIS; however, the Z values can be defined using interpolation techniques. The kriging approach makes allowance for the influence of distance and direction.

The geospatial approach entails the creation of geo-databases, as well as the integration and analysis of geoengineering data. Using ArcGIS tools, a geospatial model
of geotechnical hazards is created by creating geo-data sets and statistical weighting for each geotechnology indicator. The current work employs geospatial analysis to create a geo-database of several themed maps highlighting the most promising areas for safe urban development. The geotechnical data are integrated and assessed in this study using two ways: the first method is based on the weight of the indicator, while the second method is based on collaboration experiences.

Several software tools were utilized to finish the modeling procedure, including ERDAS imagines 9.2, Arc map 10.5, and surfer v 12. Assessed loads appointed to these layers as demonstrated by the Egyptian code 2001. This model will be helpful in the development and discover

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**Legend**
- Fossilized pieces of silty clay with breaks of limestone
- Fine to medium breaks of limestone
- Yellowish white hard massive limestone
- Large size of limestone breaks with dark yellow of silty clay
- C.R. = Core Recovery
- R.Q.D = Rock Quality Designation

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### Table A

| Lithofacies | Lithology | Thickness (m) | Sample No. | Depth (m) | C.R. % | R.Q.D % |
|-------------|-----------|---------------|------------|-----------|--------|---------|
| Eocene      |           | 2             | 17-1       |           |        |         |
|             |           | 3             | 17-2       | 4         | 85     | 21      |
|             |           | 5             |            |           |        |         |

### Table B

| Lithofacies | Lithology | Thickness (m) | Sample No. | Depth (m) | C.R. % | R.Q.D % |
|-------------|-----------|---------------|------------|-----------|--------|---------|
| Eocene      |           | 3             | 18-1       |           |        |         |
|             |           | 1             |            | 1         |        |         |
|             |           | 1             |            | 1         |        |         |
|             |           | 1             |            | 1         |        |         |
|             |           | 1             |            | 10        | 74     | 34      |

### Table C

| Lithofacies | Lithology | Thickness (m) | Sample No. | Depth (m) | C.R. % | R.Q.D % |
|-------------|-----------|---------------|------------|-----------|--------|---------|
| Eocene      |           | 3             | 19-1       |           |        |         |
|             |           | 1             |            | 1         |        |         |
|             |           | 1             |            | 1         |        |         |
|             |           | 1             |            | 3         |        |         |
|             |           | 1             |            | 10        | 82     | 45      |

### Table D

| Lithofacies | Lithology | Thickness (m) | Sample No. | Depth (m) | C.R. % | R.Q.D % |
|-------------|-----------|---------------|------------|-----------|--------|---------|
| Eocene      |           | 4             | 20-1       |           |        |         |
|             |           | 1             |            | 1         |        |         |
|             |           | 2             |            | 2         |        |         |
|             |           | 1             |            | 1         |        |         |
|             |           | 1             |            | 1         |        |         |
|             |           | 1             |            | 7         | 80     | 34      |
|             |           | 1             |            | 9         | 85     | 36      |

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Fig. 4  Idealized soil profile of the upper plateau, El Mokattam area
the ideal areas of shallow foundation of the zone under examination.

Results and discussion

Geoengineering characteristics of clayey soil

PI is the basic parameter used for grading fine-grained soils. The following values from Table 1 were suggested by Chen (1988) to establish a relationship between soil expansion and PI. The clay soils investigated are high-plastic soils, with PI values ranging from 37 to 39% (Table 2 and Fig. 5A). The geospatial distribution map values of PI show that the highest values occur in the northeastern and northwestern portions of the examined area represented by the red color. The low IP values are located in the southern area represented by the green color. The investigated soil’s FS ratios vary from 110 to 120% Table 2 and Fig. 5B. The FS geospatial distribution map values show that the highest values are in the eastern portion represented by the red color, while the low values are situated in the south with the green color. This means that the soil may swell and problems with the building are expected, under the Egyptian Code 2001.

Seed et al. (1962) and Geraid (1974) presented an expansive soil classification based on S and SP values, as shown in Tables 3 and 4. Obviously, all soil classification methods are in agreement that the soil samples examined have a high degree of expansion, where S values range from 11.87 to 17.6% and SP from 692 to 816 kN/m² (Table 2 and Fig. 5C).

| Sample no. | Initial water content (WC%) | Liquid limit (LL%) | Plastic limit (PL%) | Plasticity index (PI%) | Free swell (FS%) | Swelling pressure (SpkN/m²) | Swelling potential (S%) |
|------------|-----------------------------|-------------------|--------------------|-----------------------|-----------------|---------------------------|------------------------|
| 17-1       | 20.5                        | 72                | 35                 | 37                    | 110             | 755                       | 11.87                  |
| 18-1       | 26.5                        | 75                | 36                 | 39                    | 120             | 692                       | 14.1                   |
| 20-1       | 25.3                        | 73                | 34                 | 39                    | 115             | 816                       | 17.6                   |

Fig. 5 Geospatial distribution map of PI (A), FS (B), SP (C) and S (D)
D). The geospatial distribution map values of SP (Fig. 5C) show that the highest values occur in the northeastern part with the red color, while the low values are in the western part with the green color. The geospatial distribution map values of $S$ (Fig. 5D) indicate that the highest values are situated in the northeastern portion with the red color, while the low values are situated in the southern portion with the green color. The variation of swelling percent and applied pressure is illustrated in Fig. 6. The percent swell versus time of the studied sample no. 1 at boreholes 17, 18 and 20 (Fig. 7A–C).

Soil classification is an important factor in laboratory testing that indicates the properties of the soil in question. Laboratory determinations of LL and IP for the soil sample make it possible to assign fine grain soils to the appropriate group using the plasticity diagram. The plasticity diagram showed that the clay specimens studied fall into high-grade plastic soil (Fig. 8).

The mineralogical and chemical composition of clay deposits varies considerably according to the type of relative proportions of their clay and non-clay minerals. As for the crystalline structure of clayey minerals, they are usually categorized in two groups; the type of two-layer structure, e.g., kaolinite group and the type of three-layer structure, (e.g., illite and montmorillonite groups). The network structure of these groups varies depending on the combination of tetrahedral silica layers $[\text{Si}_2\text{O}_5]^{2-}$ attached to the corners with octahedral layers of alumina $[\text{Al}_2(\text{OH})_4]^{2+}$. Mineralogical studies of the X-ray diffraction (XRD) analysis of the collected samples indicate that the sediments are comprised of montmorillonite and kaolinite (Fig. 9A–C). The important constituent of the clay minerals investigated was montmorillonite. Clay minerals such as montmorillonite in land clearly indicate the potential to expand. Thus, this kind of soil is not permitted to direct the foundation over them due to its high swelling property, which dangerously affects the constructions.

### Geoengineering characteristics of limestone rock

The (RQD) is the relationship between the total length of rock samples 10 cm or greater and the length of the core. The RQD described as excellent, good, fair, poor and very poor as per the Egyptian code 2001 (Table 5). The RQD values of the examined rock samples are considered very poor to poor, with values ranging between 21 and 45% (Table 6). The geospatial distribution map values of RQD (Fig. 10A) showed that the highest values are distributed in some parts of the study area. These parts are distributed in the northeastern, southwestern and central parts represented by the red color. The lower values are distributed in the southern and western parts represented by the green color. Table 6 and Fig. 10B show the UCS values of the studied rock samples.

| Degree of expansion | Swelling potential $S$ (%) |
|---------------------|---------------------------|
| Low                 | 0–1.5                     |
| Medium              | 1.5–5                     |
| High                | 5–25                      |
| Very high           | > 25                      |

| Degree of expansion | Swelling pressure SP (kPa) |
|---------------------|-----------------------------|
| Low                 | < 196                       |
| Medium              | 196–392                     |
| High                | 392–687                     |
| Very high           | > 687                       |

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**Table 3** Soil classification according to swelling potential (after Seed et al. 1962)

**Table 4** Classification of expansive soil according to the swelling pressure (after Geraid 1974)

**Fig. 6** Variations of swelling percent and applied pressure
which ranged from 47 to 72.2 kg/cm². This figure shows that the highest UCS values are concentrated in the western and southwestern parts represented by the red color. The lowest values are concentrated in the central part represented by the green color. These values refer to the limestone samples under study are highly fractured, as these values indicate low strength and weak to medium weak based upon Egyptian code 2001, Deere and Miller (1966) (Tables 7 and 8). The limestone of the upper plateau contains caves which may cause some damage to construction.

Table 9 presents the chemistry of the limestone samples examined to detect the pH, Cl⁻, SO₄²⁻ and TDS salts. The

\[ \begin{array}{|c|c|}
\hline
\text{RQD}\% & \text{Rock quality} \\
\hline
< 25 & \text{Very poor} \\
25–50 & \text{Poor} \\
50–75 & \text{Fair} \\
75–90 & \text{Good} \\
90–100 & \text{Excellent} \\
\hline
\end{array} \]

Fig. 7 Percent swell versus time of the studied clay samples

Fig. 8 Plasticity chart of the studied clayey soil

Fig. 9 X-ray diffraction of the studied clay minerals

Table 5 Rock classification according to RQD in Egyptian code

strength and weak to medium weak based upon Egyptian code 2001, Deere and Miller (1966) (Tables 7 and 8). The limestone of the upper plateau contains caves which may cause some damage to construction.

Table 9 presents the chemistry of the limestone samples examined to detect the pH, Cl⁻, SO₄²⁻ and TDS salts. The
TDS values from 100 to 1050 (Fig. 11A), where higher values of TDS are distributed in the most of the examined area, which appear with the red color. The lower values are distributed in some localities represented by southwestern, eastern and northeastern areas, which appear with the green color. The high estimations of TDS are coming about because of high filtering and/or dissipation of salts which solidified in soil, where the filtering may prompt a subsidence of soil under the structures. The Cl− values from 320 ppm (moderately aggressive) to 480 ppm (moderately aggressive) (Fig. 11B). The high values of Cl− salts are distributed in the southeastern part shown as red, while the low values are distributed in the southern part shown as green. The SO2−3 ranges from 160 ppm (non aggressive) to 260 ppm (moderately aggressive) (Fig. 11C). Many localities have higher values of SO2−3 salts distributed in some parts of the study area. These parts are distributed in the northeastern, southeastern and southwestern portions, which appear with the red color. The lower values are found in two northern and northeastern parts, which appear with the green color. The pH values range from 7 to 8.2 (Fig. 11D), where high pH values are distributed in the southeastern and southwestern portions depicted with the red color. Lower pH values are spread across the north of the study area represented by the green color. The pH is an important agent that is utilized to transform the SO4, Cl and TDS into ions. The high rates of these particles in the soil detrimentally affect the foundations, as per Egyptian code 2001. Components of chemical investigation could be utilized to estimate the kind of utilized concrete. The geospatial distribution maps of pH, Cl−, SO2−3 and TDS are illustrated in Fig. 11A–D, respectively.

### Geospatial modeling of geoengineering characteristics

The construction, fitting to shallow establishments with the end goal of urbanization in the investigation area is resolved using GIS techniques in the modeling process. Where, this model will be helpful in the development and discovery of the ideal areas of shallow foundation of the zone under examination. In the current work, we incorporate all the parameters and properties that control and help secure construction, inhabitants, and norms that are utilized.
to investigate the suitability of sites. The geospatial urban model in the examination area (Fig. 12) was constructed by integration of physical, mechanical, and chemical analysis of soil and rocks (Figs. 5, 10 and 11). The constructed geospatial urban model within the study area is broken down into four areas: low, moderate, high and very high, with mid blue, mid green, yellow and red colors, respectively. Most of the regions in the investigated zone were found to have low and moderate hazard zones. These areas are ideal for shallow foundations. The high and very high zones were observed in some small areas in the southeast of the investigation area. Appropriate care must be taken in these areas (high and very high zones) before designing the foundations. Based on geotechnical rock and soil research results of the field region, appropriate caution should be needed in many locations, such as demands for using sulfate-resistant cement in all sub-surface concrete works.

**Remediation and mitigation**

From the results shown above, the Mokattam area suffers from the existence of any problems represented by high fractured limestone and clay layers that have high swelling properties. Another major problem is the infiltration of water. Water leakage and runoff into cavities and cracks are due to natural causes such as precipitation accumulation and as a result of human activities such as irrigation and breakdown of sanitation facilities. The accumulation of rain over time occurs in deeper strata in contact with limestone and shale. Later, urban development has increased water consumption without improvements to the sanitation system. Typically, ducts are subjected to joint opening, cracking, and increased leakage, leading piping and internal erosion of the surrounding soil. This is normally unattended. As a result, infiltration moves downhill or weak areas of shale and marl, causing softening, saturation, and deterioration of the geomechanical states of those clay layers. Consequently, the subsequent degradation of the bearing condition occurs and collapses due to bending and fracture of the overlying layers (EL-Sohby et al. 2004).

The limestone in the Mokattam area is mostly porous and sensitive to chemical reactions with water rich in sulfates and chlorides. The pores make it possible to store water in the rock formation, creating a good environment for chemical reactions. A portion of the soluble carbonate constituents dissolves in the stored water, which results in a continuous process of creating voids and expanding existing voids. This process goes on and eventually leads to the formation of large pores, pits, and cavities, finally reducing the rock to a low porous formation with remarkably low resistance. Therefore, subsidence, flexion and fracture occur in the overlying strata. Fractured parts of the bedrock are further separated from the parent rock. Near the cliff, instability erupts and rocks fall. In addition, down the cliff, the degradation of the geomechanical state of the clay strata caused by the seepage of water affects the limestone complex which covers it, in order for tensile and existing fractures to determine the conditions conducive to failure.

To solve these problems, it is preferable using a mat foundation rather than a spread foundation to repair subsidence or failure of buildings. Fractured limestone is, therefore, considered a suitable base layer for light engineering structures. In the case of heavy structures and

| Table 7 | Rock classification according to unconfined compressive strength in Egyptian Code |
|---------|--------------------------------------------------------------------------------|
| UCS (kg/cm²) | Rock type |
| > 2000 | Extremely hard |
| 2000–1000 | Very hard |
| 1000–500 | Hard |
| 500–125 | Medium hard |
| 125–50 | Medium weak |
| 50–12.5 | Weak |
| ≤ 12.5 | Very weak |

| Table 8 | Rock classification according to unconfined compressive strength (after Deere and Miller 1966) |
|---------|--------------------------------------------------------------------------------|
| UCS (MPa) | Description |
| > 200 | Very high strength |
| 110–220 | High strength |
| 55–110 | Medium strength |
| 27.5–55 | Low strength |
| < 27.5 | Very low strength |

| Table 9 | Chemical analysis of the studied rock samples |
|---------|-----------------------------------------------|
| Sample no. | pH | SO₃ (ppm) | Cl (ppm) | TDS | Type of soil |
| 1-2 | 7.4 | 210 | 450 | 950 | Limestone |
| 2-2 | 7.5 | 190 | 435 | 1050 | Limestone |
| 3-2 | 7.2 | 200 | 360 | 100 | Limestone |
| 4-2 | 8.1 | 250 | 480 | 885 | Limestone |
| 5-2 | 7.2 | 176 | 380 | 890 | Limestone |
| 6-2 | 7.4 | 210 | 410 | 950 | Limestone |
| 7-2 | 7.2 | 190 | 435 | 1040 | Limestone |
| 8-2 | 8.2 | 260 | 360 | 100 | Limestone |
| 9-2 | 7.6 | 160 | 400 | 885 | Limestone |
| 10-2 | 7.5 | 190 | 380 | 990 | Limestone |
| 11-2 | 7.2 | 176 | 380 | 890 | Limestone |
| 12-2 | 7.6 | 210 | 410 | 950 | Limestone |
| 13-2 | 7.4 | 190 | 435 | 1040 | Limestone |
| 14-2 | 7.9 | 260 | 360 | 100 | Limestone |
| 15-2 | 7 | 160 | 400 | 885 | Limestone |
| 16-2 | 7.3 | 190 | 380 | 990 | Limestone |
| 19-2 | 7.8 | 200 | 320 | 990 | Limestone |
| 26-2 | 7.9 | 210 | 330 | 890 | Limestone |
construction, grout is essential to enhance the resistance of the bedrock to the desired level. Consolidation grout is an accepted measure for sealing open joints and fractures and improving weak areas in foundation rock. The most commonly used materials for grouting are cement, asphalt, clay, and hot bitumen. Grout mixes made from cement are commonly used in recent grout practices. Cement typically consists of > 95% of the grout mixture, and other components include bentonite, various chemical additives, polyurethane, and artificial sponges. The stable clay-cement grout mixture utilizes clay as the base component along with cement and bentonite as additional components (Abd El-Aal and Masoud 2017). The other way around, to reduce soil swelling and prevent buildings from moving upwards, it is recommended that they be replaced and/or stabilized with chemical additives.

**Summary and conclusion**

The current study succeeded in identifying the geoengineering characteristics of the upper plateau of the Mokattam region for its evaluation of the safe urban extension. The geoengineering investigation described in this article indicated the presence of several engineering problems confronting Mokattam civil engineers. According to the Egyptian Code, these problems are distinguished by badly fractured limestone and the presence of clay layers with substantial swelling, the value of which exceeds 100% and has an adverse influence over the building.

The current work demonstrates the efficacy of GIS approaches in the construction of geospatial urban models in the context of safe regional development. In this work, we integrate and exploit multivariate data by overlaying geoengineering layers to generate an integrated geoengineering hazard model that delineates safe and dangerous building regions for the study area. The produced model is categorized into four zones as low, moderate, high, and very high hazard zones to assess the suitability of the study area for the safe urban extension. The geospatial model shows the low and moderate hazard zones cover the majority of the study area. These regions are ideal for foundations with shallow...
depths. The high hazard zone is represented by a tiny region in the research area’s center, but the very high hazard zone was not detected in the study area. In addition, this model will be used as an information base in the future to reduce the risk impact of buildings.

**Recommendations**

The current study is recommended for geophysical studies, including shallow seismic refraction tomography and multi-channel analysis to detect subsoil condition and p-wave velocity distribution, which is important in the evaluation of fracture and geological units, and also to visualize the fractures extent in the underground strata. For heavy structures and buildings, it is necessary to inject cement, grout and mat foundations to prevent future engineering hazards.

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**References**

Abd El-Aal AK (2015) Engineering evaluation of some lower Eocene carbonate rocks as raw materials, Sohag governorate, Egypt. In: Eighth international conference on the geology of Africa. P:PI-3-I-50

Abd El-Aal AK, Masoud AA (2017) Impacts of karst phenomena on engineering properties of limestone foundation bed, Ar Riyadh, Saudi Arabia. Arab J Geosci 10:347. https://doi.org/10.1007/s12517-017-3089-7

Abdel Gowad AM, Punzo M, Di Fiore V, Tarallo D, El-Haddad A, Al-Akraby AH (2018) Shallow seismic refraction tomography and MASW survey for investigating the fractures along Qena-Safaga Road, South of Egypt. In: International congress and exhibition “Sustainable civil infrastructures: innovative infrastructure geo-technology”. Springer, p 165–190. https://doi.org/10.1007/978-3-319-61648-3_12

Abou Elmagd K, Emam A, Hazem M (2020) Geotechnical properties of Lower Eocene limestones, Sinn El-Kaddab Plateau, southwest of Aswan, Egypt. Arab J Geosci 13:293. https://doi.org/10.1007/s12517-020-5275-2

Aboushokk MI, Sherif A (2000) Analysis and reinforcement of fissured large roof of a cavern in Mokattam hill at the suburb of Cairo. In: Proceeding of ISRM symposium Eurock 2001, Espoo, Finland, p 401–408

Ahmed HT (2015) Physical and mechanical characteristics of Helwan limestone: for conservation treatment of ancient Egyptian limestone monuments. J Am Sci 11(2):136–151

Aita SK, Omar AE (2021) Exploration of uranium and mineral depositing remote sensing data and GIS applications, Serbal area, Southwestern Sinai, Egypt. Arab J Geosci

Ali MAM, Yang HS (2014) A study of some Egyptian carbonate rocks for the building construction industry. Int J Min Sci Technol 24:467–470. https://doi.org/10.1016/j.ijmst.2014.05.008

Aly MH, Giardino JR, Klwin AG (2005) Suitability assessment for new Minia City, Egypt, a GIS approach to engineering geology. Environ Eng Geosci 11:259–269. https://doi.org/10.2113/11.3.259

Arnous MO, Omar AE (2018) Hydrometeorological hazards assessment of some basins in Southwestern Sinai area, Egypt. J Coastal Conserv 22:721–743. https://doi.org/10.1007/s11852-018-0604-2

Arnous MO, ElMowafy AA, Azzaz SA, Omar AE, Abdel Hafeez WM (2021) Exploration radioactive mineralization using mapable data integration approach: example from Wadi Dahab area, Southeastern Sinai, Egypt. Arab J Geosci 14:599. https://doi.org/10.1007/s12517-021-06781-5

Arshid MU, Kamal MA (2020) Regional geotechnical mapping employing kriging on electronic geodatabase. Appl Sci 10:7625

ASTM D-2435 (2011) Standard test methods for liquid limit, plastic limit, and plasticity index of soils. American Society for Testing and Materials, West Conshohocken

ASTM D-2938-95 (2002) Standard test method for unconfined compressive strength of intact rock core specimens. American Society for Testing and Materials, West Conshohocken

ASTM D-4318 (2010) Standard test methods for liquid limit, plastic limit, and plasticity index of soils. American Society for Testing and Materials, West Conshohocken

Ben Salah I, Ben M’Barek M, Mezza S, Boughdiri M (2018) Geotechnical study of the Aptian limestone of the kef region, Northwestern Tunisia: evaluation for industrial use. Open J Geol 8:1084–1101. https://doi.org/10.4236/ojg.2018.812066

Chen FH (1988) Foundations on expansive soils. Elsevier, Amsterdam

Dangermond J (1984) Review and synthesis of problems and directions for large scale geographic information system development. In: Proceedings of the international symposium on spatial data handling, Zurich, vol 1, p 19–25

Deere DU, Miller RP (1966) Engineering classification and index properties for intact rock. Technical Report Air Force Weapons Lab, New Mexico, pp 65–116

Dong M, Hu H, Xu R, Gong X (2018) A GIS-based quantitative geoenvironmental evaluation for land-use development in an urban area: Shunyi New City, Beijing, China. Bull Eng Geol Environ 77:1203–1215. https://doi.org/10.1007/s10064-017-1069-5

Dweirj M, Fraige F, Alnawafleh H, Titi A (2017) Geotechnical characterization of Jordanian limestone. Geomaterials 7:1–12. https://doi.org/10.4236/gm.2017.7110

Egyptian Code (2001) Soil mechanics & foundations design & construction, ECP 2025-issue 2001. Foundations on problematic soils, Part 5, Cairo. National Center for Housing & Construction Research (2009)

Eid MM, Fattah EA, Zaghloul EA, Elbeih SF (2003) Measurement of surface lateral ground movements in the vicinity of the southwestern scarp, El-Mokattam Plateau, Cairo, Egypt. J Egypt Geotech Soc 14:1–22

El-Shazly EM, Abdel-Hady MA (1976) Geological investigations on Gebel El-Mokattam. Report. Academy Sci Res Techno, Egypt vol 1, p 25

EL-Sohby M, Aboushokk M, Mazen O (2004) Slope degradation and analysis of Mokattam plateau, Egypt. In: 2nd international
conference on geotechnical site characterization (ISC-2), Porto, Portugal, p 1081–1887
Geological Survey of Egypt (EGSMA) (2004) Geological and geo-
physical studies for Mokattam area (Phase II), Cairo Government, internal report (in Arabic)
Gerald J (1974) Review of expansive soils. ASCD J Geotech Eng 100(6):667–687
Harrison DJ, Bloodworth AJ (1994) Industrial minerals laboratory manual: construction materials. British geological survey technical report WG/94/12
Helmy HM, El-Nahhas FM, Tawfik MM (2007) Stabilization of jointed sedimentary rock slopes using anchored wall. In: Proceeding of the sixth international conference on structural and geotechnical engineering, Alexandria University, Egypt, p 1011–1018
Khan MS, Park J, Seo J (2021) Geotechnical property modeling and construction safety zoning based on GIS and BIM integration. Appl Sci 11:4004. https://doi.org/10.3390/app11094004
Kim M, Kim HS, Chung CK (2020) A three-dimensional geotechnical spatial modeling method for borehole dataset using optimization of geostatistical approaches. KSCE J Civ Eng 24:778–793
Moustafa AR, Abdel Twaab S (1985) Morphostructures and non-tectonic of Gebel Mokattam. Middle East Res Center Ain Shams Univ Sci Res Ser 5:68–78
Moustafa AR, Yehia A, Abdel Twaab S (1985) Structural setting of the area east Cairo, Maadi and Helwan. Middle East Res Center Ain Shams Univ Sci Res Ser 5:40–64
Moustafa AR, El-Nahhas F, Abdel Twaab S (1991) Engineering geology of Mokattam city and vicinity, eastern Greater Cairo, Egypt. J Eng Geol 31:327–344
NARSS (1997) Geological and geomorphological studies of the Mokattam plateau. Geol Surv Egypt, internal report in Arabic.
Omar AE (2021) Application of geospatial approaches to prospect radioactive minerals in the Um Bogma Younger Granites, Southwestern Sinai, Egypt. Arab J Geosci. https://doi.org/10.1007/s12517-021-06684-5
Omar AE, Arnous MO, El-Ghawaby MA, Ashami AS, El Zalaki MA (2016a) Seismotectonic hazards assessment in Southwestern Sinai area using remote sensing and GIS. Sinai J Appl Sci 5:427–442. https://doi.org/10.21608/sinars.2016.78664
Omar AE, Arnous MO, El-Ghawaby MA, Ashami AS, El Zalaki MA (2016b) Flash flood hazard mapping of wadi Baba basin Southwestern Sinai, Egypt. Sinai J Appl Sci 5:409–426. https://doi.org/10.21608/sinars.2016.78663
Omar AE, Korany AK, Abdel-Halim KA (2021) Calculation of natural external radiation dose rate for environmental impact assessment, case study: Abu Zenima area, Southwestern Sinai, Egypt. Int J Environ Anal Chem. https://doi.org/10.1080/03067319.2021.1895133
Pappalardo G, Mineo S, Monaco C (2016) Geotechnical characterization of limestones employed for the reconstruction of a UNESCO world heritage baroque monument in southeastern Sicily (Italy). Eng Geol 212:86–97. https://doi.org/10.1016/j.enggeo.2016.08.004
Park HD, Shin GH (2009) Geotechnical and geological properties of Mokattam limestones: implications for conservation strategies for ancient Egyptian stone monuments. Eng Geol 104:190–199. https://doi.org/10.1016/j.enggeo.2008.10.009
Robinson AH, Joel LM, Muehrcke PC, Kimerling AJ, Guptill SC (1995) Elements of cartography, 6th edn. Wiley, New York, p 674
Roushdy M, Hammed MS, Abdel-Moteleib A (2017) Geotechnical properties of Galala limestone tiles, Eocene rocks, Ain El Sukhna, Red Sea Coast, Egypt. Int J ChemTech Res 10(5):368–378
Saad AM, Mohamed AKh, Sakr MAH, Selim MSh (2020b) Application of geoelectrical and sedimentological studies to evaluate the subsurface soil of the road supporting for the ring road between El-Mosheer axis and El-Maadi carrefour tunnel, Cairo, Egypt. Sed Egypt 25:1–14
Saad AM, Sakr MAH, Omar AE, Temsah YA (2020a) Assessment of radioactivity and geotechnical characteristics of soil foundation for suitability of safe urban extension using geospatial technology. New Sahl Hasheesh Marin Port, Eastern Desert, Egypt. Int J Environ Anal Chem. https://doi.org/10.1080/03067319.2020.1802444
Said R (1962) The geology of Egypt. Elsevier, New York
Said R (1990) The geology of Egypt. A.A. Balkema, Roterdam
Sakr MAH, Omar AE, Saad AM, Moayedi H (2021) Geotechnical parameters modelling and the radiation safety of expansive clayey soil treated with waste marble powder: a case study at west Gulf of Suez, Egypt. Environ Earth Sci 80:263. https://doi.org/10.1007/s12665-021-09573-y
Seed HB, Woodward RJ, Lundgren R (1962) Predication of swelling potential for compacted clays. J Soil Mech Found Eng Div 88(SM4):53–87
Sultan SA (2010) Geophysical investigation for shallow subsurface geotechnical problems of Mokattam area, Cairo, Egypt. Environ Earth Sci 59:1195–1207. https://doi.org/10.1007/s12665-009-0109-2
Velde B (1995) Composition and mineralogy of clay minerals, origin and mineralogy of clays. Springer, New York, pp 8–42
Wan-Mohamad WNS, Abdul-Ghani AN (2011) The use of geographic information system (GIS) for geotechnical data processing and presentation. Procedia Eng 20:397–406. https://doi.org/10.1016/j.proeng.2011.11.182
Yousif MSM (2000) Slope stability of the middle Eocene rocks of Gebel Mokattam, ICEHM. Cairo University, Egypt, pp 14–22
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