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Geological and engineering geological characteristics of surface alluviums in the Gorgan city

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Abstract

Engineering properties of soils and the 3D modeling of geological formations are widely used in site investigations and the preparation of geological hazard maps. The present study was conducted to characterize the engineering geological properties of the young surface alluviums of the Gorgan city (Iran) to a depth of 25 m and 3D modeling of their geology using boreholes data. To this end, after determining the location of the available boreholes on the aerial map of Gorgan, four hypothetical cross-sections were considered in the North-South and East-West directions. Then, the borehole data were marked on each section and their 2D geological cross-sections were manually drawn using correlation of the similar layers. In the next step, by expanding the information of these sections, a 3D geological model of Gorgan city was prepared using a conceptual-observational method. According to the evidence from the boreholes and field observations, the depositional environment of Gorgan alluviums was an alluvial fan created by the Ziarat River. Additionally, in terms of engineering characteristics of alluviums, the Gorgan subsurface soils can be divided into four engineering units, including upper clay unit (UCU), middle gravel unit (MGU), lower clay unit (LCU), and sandy unit (SU), which share the same engineering characteristics. Finally, the results of tests performed on samples from different depths were employed to calculate the engineering geological characteristics of each unit, including Atterberg limits, compressibility, undrained shear strength, and drained shear strength parameters.

Keywords: *Gorgan; Engineering geological characteristics; Depositional environment; Shear strength*

1. Introduction

Today, the need to build infrastructures and megastructures is increasing vastly regarding the increase in population and development of urban areas. The construction of such structures requires examining their full-scale impact over time, as an important objective of sustainable development.One of the requirements for sustainable development is the preparation of basic maps for the development of urban areas. One of these basic maps is the engineering geological models and maps. These models, which are based on geographic, topographic, geological, and geotechnical data, contain useful data about the physical strength of the ground and the existing potential geological hazards. Considering the big pressure induced by megastructures on the ground, a correct understanding of the strength parameters of the ground is of paramount importance in constructing such structures. In this respect, engineering geological models provide significant information to address this issue.In general, two methods are recommended to draw engineering geological models, namely conceptual and observational methods. In the first group of methods, a model is mapped based on understanding the relationships between engineering geology units and geometry and their probable spatial distribution. This method and the model derived from it are based on scientific and experimental concepts, with no connection with the real 3D state of space and time.

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These models are based mainly on geological concepts such as age, rock type, non-uniformity, and weathering.
On the other hand, in observational methods, models are plotted based on spatial distributions measured and observed by engineering geological units. Data in these engineering geology models are related to spatial and temporal distribution and are based on observations and assumptions (Parry et al. 2014). In both groups of methods, in addition to the general geological features, comprehensive and precise information on the engineering geological characteristics of soil-forming material is vital.
Morgenstern and Cruden (1977) were the pioneers in applying engineering information in engineering geological models. According to these authors, the complexity of geotechnical projects is due to genetic processes associated with the formation of primary geological materials, epigenetic processes caused by processes such as diagenesis and deformation, and finally weathering processes. These researchers stated that although process models do not necessarily have to be accurate and detailed, they might assist geologists in predicting rock facies and explaining how layers and materials are combined.
Among the first attempts to provide a method for the use of engineering geological data in such models, one can refer to the flowchart provided by Stapledon (1982). This researcher states that an engineering geological model should be based on a thorough understanding of regional geology, historical geology, and geology of the region studied. Also, such a model must express

engineering geology and quantitative characteristics such that to be understandable for both geologists and engineers. The idea that engineering geological models are more than a geological model was first expressed by Knill (2003). According to this scholar, geological models are inefficient for engineering purposes because they lack the proper definitions of the parameters of geotechnical engineering that are used by engineers and in design procedures. Therefore, such models need to be completed by adding engineering geological information to be used in subsequent engineering analyses. Sullivan (2010) also used engineering geological features in geological models. This author showed that only having a geological vision for developing these models is not enough for building geological models. According to Sullivan, a full understanding of the application of engineering data in geotechnical activities and encompassing the entire process from the beginning would be very difficult to gather important information.

Detailed studies of the geotechnical characteristics of a region are started by identifying the geological history of the region. This information includes features such as sedimentology, geological formations, geomorphology, and weather (Fookes, 1997; Fookes et al. 2000). In general, sedimentology studies separate alluviums formed simultaneously under the same conditions. Therefore, separating the same sedimentary units, creating a model of sedimentology in the area, and determining the engineering geological and geotechnical characteristics of each layer can lead to the transformation of the sedimentary model to the geotechnical model (Delgado et al. 2003; Aldiss et al. 2012; Liu et al. 2017; Sharifi Teshnizi et al. 2021).

According to Delgado et al. (2003), such engineering geological information can provide a more accurate estimate of the strength properties of each soil layer. If these models are carefully prepared, in addition to their capability in assessing geological problems and hazards, site investigations will subsequently validate and complete their data. Moreover, because the engineering parameters and the risks of each geotechnical layer on that layer are similar, engineering model information can be used to estimate the engineering characteristics and the risks of the layer, whenever the information of a part of a layer is not available.

In recent decades, more attention has been paid to the characteristics of engineering geological and 3D geotechnical structures of bed soil (Dassargues et al. 1991; Jones and Wright 1993; Lemon and Jones 2003; de Rienzo et al. 2008; Tonini et al. 2008; Hettiarachchi and Brown 2009; Marache et al. 2009; Vatcher et al. 2016; Wang et al. 2017; Bina et al. 2020). In the present study, the engineering geological characteristics of the young surface alluviums of Gorgan city (Iran) are evaluated based on the information needed for urban planning and development of this area. For this purpose, the conceptual engineering geological model was developed with the analysis of geomorphology, sedimentology, and geology data from all over the region. Determining the engineering geological characteristics is a useful guide for development, planning, and construction in the study area. Besides, it plays a key role in assessing geotechnical hazards such as excavation instability, bearing capacity, settlement, and liquefaction potential (Panzera et al. 2018; Sharifi Teshnizi et al. 2021). In the early stages of construction projects, this information will help to make a reasonable estimate of geological conditions. This ability will help to find problematic and critical areas during the decision-making process for constructing urban infrastructure in Gorgan city, Iran.

2.Geomorphology and general geology

Gorgan region is comprised of a vast plain between 51-54° 30′ E and 36 to 37′ N in the north of Iran and the east of the Caspian Sea. From the geological point of view, it is located in the north of the eastern Alborz area, the west of the Kopet Dagh area, and the eastern area of the Caspian Sea. According to the structural-sedimentary units' map of Iran, the study area is located in the Gorgan-Rasht zone. The zone consists of areas that cover the Caspian Sea margin and is located in the north of the Alborz fault. Also, most of the study area is covered by rivers, delta, and coastal alluviums and its appearance is a product of tectonic activities of the Precambrian era. The combined performance of constructive forces (e.g., orogeny and earthquake) and destructive forces (e.g., weathering and erosion) continuously reduce the heights and fill the depressions. The continuation of these forces has caused various morphological forms in this area. In this respect, geology (bedrock and tectonic) and climatic conditions are some of the factors influencing the morphology of the region. Among the tectonic processes that have been effective in shaping the geomorphology of this region, faults have played a major role. The type of faults has also been a major factor in the early formation of geomorphology in this region. The slope and direction of movement of the thrust faults have a special effect on the ground. Morphology of the study area follows the structures of folds and faults with a NE-SW to EW trend. Fig. 1 illustrates the general geological map of the city of Gorgan.

According to Fig. 1, the geology of the Gorgan area is divided into two parts: i) Mesozoic and Cenozoic rock formations and ii) Quaternary alluviums. The first part consists of rock formations and is not directly related to the purpose of this paper. But the second part, i.e., Cenozoic formations and units, have significant extension in this area, of which Quaternary deposits are the focus of this paper. Stratigraphy of Quaternary alluviums includes an alluvial fan and eolian (loess), alluvial, and talus deposits (Jackson et al. 2002). Since the geological characteristics of these materials (especially the loess deposits) have a direct relationship with the geotechnical properties of the studied soil, the definition and explanation of each of these alluviums will be described in more detail as follows.

Thick loess deposits cover about 388,000 ha (17%) of Golestan province (Frechen et al. 2009). Loess is a "glacial-aeolian sediment" composed mainly of silty or silty loam that provides fertile soils for agricultural purposes (Kehl et al. 2009). Particle size is mainly in the range of silt (50-90%) with clay and sometimes with the size of the sand particles (Hao et al. 2010). Loess alluviums are classified as non-layered and heterogeneous soils. These deposits generally are composed of quartz, feldspar, calcite, dolomite, mica, iron, and magnesium minerals, as well as clay minerals. The color of loess alluviums due to chemical weathering and iron oxidation is generally yellow or light brown (Kuster et al. 2006). Loess alluviums have been the subject of intense research regarding their effects on geological risks such as ground subsidence, settlement, soil slope instability, and landslides.

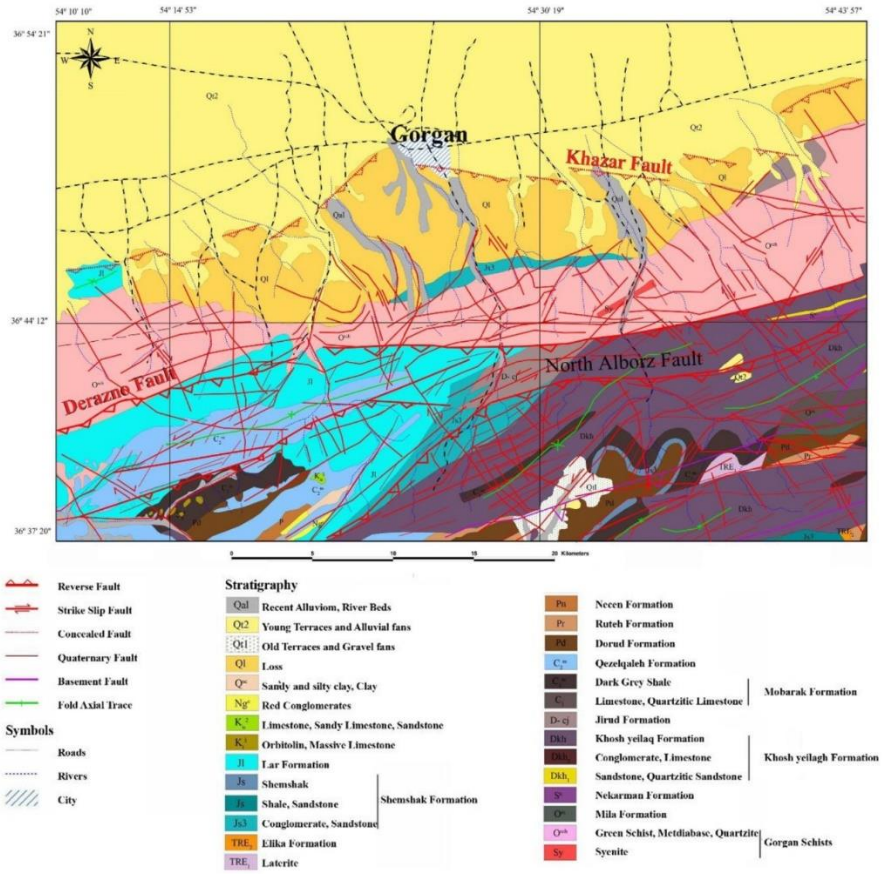

Fig 1. Geological map of the study area

3. Methodology and data collection

All data used in this paper were extracted from drilled boreholes and their in-situ and laboratory tests. Available data are from two groups of geotechnical investigations carried out in the study area by private consulting engineers companies, as well as data on boreholes provided by the public sector such as Gorgan Municipality, Golestan Governorate, and Crisis Management Center (Table 1). Overall, 53 boreholes were collected in this study. These boreholes were located in different parts of Gorgan city, and none of them was so deep that to reach the bedrock. The locations of the boreholes used in this paper are marked in Fig 2 on Gorgan aerial map.

In the next step, the data of selected boreholes, in-situ tests, and laboratory tests were collected in a common database. The database includes boreholes number, geographical coordinates, boreholes depth, soil type, groundwater level, number of SPT blow counts (Nspt), Atterberg limits, sieve analysis (grading), and hydrometer tests for all boreholes. Based on their type and format, these data can be divided into two groups of digital maps and printed versions of boreholes reports. Geological reports are the main source of geological information. As previously mentioned, the database prepared in this study contains detailed drilling, sampling, and measurement data and a 3D topology of soil boreholes.

Table 1. Specifications of various tests used in this paper

Test Title	Type of test		Number of tests	Standard
	laboratory	In situ		
Unconfined Compression Strength Test	✓	-	21	ASTM D7012
Direct Shear Test	✓	-	29	ASTM D3080-90
Particle-Size Analysis	✓	-	87	ASTM D422-63
SPT	-	✓	53	ASTM D1586
Relative density	-	✓	74	ASTM D1556
Odometer test	✓	-	34	ASTM D2435

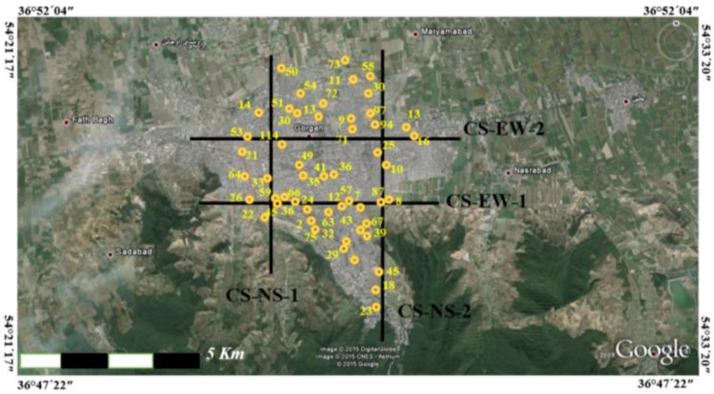

Fig 2. Location of the collected boreholes along with the hypothetical cross-sections

Geological reports are the main source of geological information. As previously mentioned, the database prepared in this study contains detailed drilling, sampling, and measurement data and a 3D topology of soil boreholes. Regarding the questionable capability of available commercial software in correlating the subsurface layers and drawing of geological models in small scale and soil environments (with a great variety in layering change), the present study employs a manual method to draw 2D profiles and 3D models. Accordingly, in the city of Gorgan, the EW and NW cross-sections were selected based on the information and location of the existing boreholes to cover most of the studied areas (these sections are shown in Fig 2). Then, the borehole information was depicted in each section and the geological layers with similar materials were correlated manually. Fig. 3 depicts one example of cross-sections drawn for Gorgan city. As shown in Fig 3, the dominant material of the ground is clay with low plasticity (CL). It is noteworthy that the horizontal scale is much smaller than the vertical scale. Therefore, the form of layers and existing lenses seems illogical due to the incompatibility of the scales. Then, by considering 2D sections together, a 3D conceptual-observational geological model was drawn for the study area. Since the purpose of the present study is to map the surface geological model and due to limited access to data, the depth of the 3D model is limited to 25 m. Nevertheless, in most construction and geotechnical projects, the depth of site investigation is less than this depth.

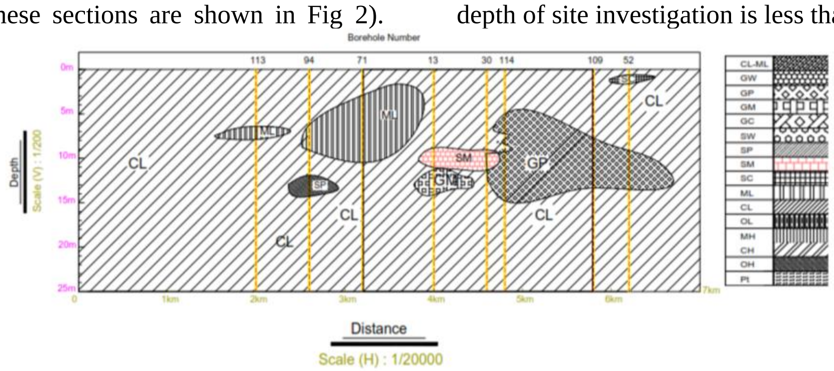

Fig 3. A drawn sample of 2D sections (EW cross-section No. 2 in Gorgan)

Although several subsurface studies have been carried out for various commercial projects in Gorgan, there has been no comprehensive study and effort to gather these activities and their data. The borehole log analysis can be used to provide a simple geological profile and to introduce geotechnical properties. The obtained 3D geological model is shown in Fig 4.

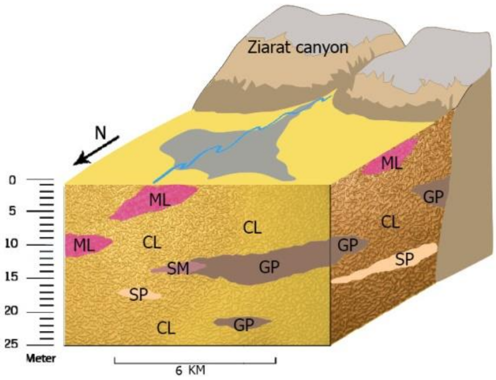

Fig 4. The three-dimensional (3D) geological model of subsurface soil in Gorgan city

Due to the poor distribution of manmade soils in the study area (mainly less than 1-m thick in some areas), this layer is not shown in the model. According to the geological model of Gorgan, the stratigraphic framework of the studied area can be categorized as the same subsoil; i.e., the stratigraphic framework of the Gorgan is almost similar. Below this limitedly expanded manmade soil, there is a medium-stiff clay with a thickness of 6-7 m. This soil layer is followed by a coarse-grained soil layer with a medium to very dense, mainly from poorly-graded sand, to a depth of 15 m. Beneath these layers, there is again a layer made up of low plasticity clay (CL) to a depth of 25 m. According to field observations, these alluviums are often red, indicating their depiction in rich oxygen (continental) conditions. Also, the coarse-grained part of the alluviums is composed of non-uniform, rounded, poorly-graded rocky pieces. Field observations indicate that these deposits are unsorted and heterogenetic. From the sedimentology point of view, it can be concluded that the sedimentary environment of Gorgan is an alluvial fan. This conclusion can be verified by studying the surface topography of the city of Gorgan (which is convex) and the fact that Gorgan is located in the watershed basin of the Ziarat River and the low amplitude of the Ziarat valley.

4. Engineering geological characteristics of alluviums

The geological characteristics of alluviums in Gorgan were investigated through an observational approach. As explained in this approach, the geological features and structures are simplified based on the average of actual observations. For this purpose, based on the geological model, the study area was divided into separate engineering layers. To this end, the results of geotechnical tests carried out on the boreholes were plotted against the depth of the tests on the geological model. It is noteworthy that due to the number of tests and their variation, the values of strength parameters obtained by engineering judgment were averaged. Then, regardless of the geological type, each layer that was closely related to the engineering specifications (especially the SPT number) was considered as an engineering unit or layer.

With regard to subsurface conditions, down to 25 m of the city, 4 layers of engineering geology are detected. These layers include the upper clay unit (UCU), middle gravel unit (MGU), lower clay unit (LCU), and sandy unit (SU). Another noteworthy point is that the engineering layers are very similar to the geological layers.

The UCU layer is a superficial layer composed mainly of fine-grained deposits. The layer is of great importance as it hosts the foundation of most structures constructed. The thickness and SPT number of this layer are in the range of 4-10 and 8-37, respectively. The thickness of MGU is 2-5 m, which increases from about north to south. Based on the samples obtained from exploratory drilling and field observations from natural trenches of the city, the soil of this layer is highly non-uniform and has rounded grain particles. According to the Unified Soil Classification System (USCS), this unit contains GP and GP-GM soil and it is a hard to medium dense soil in terms of strength. The number of SPT in this layer varies from 34 to more than 50. It should be noted that clogging the SPT sampler head is a common phenomenon in this unit.

The lower clay unit or LCU has a thickness of 8-13 m and indicates a lateral extension from south to north and from east to west. This unit is composed of almost uniformly dark brown clay with a good to moderate strength and it is classified as CL in the unified classification. The SPT number of this unit varies from 26 to 34, locally increasing dramatically with depth. The study area has a 2-5-m thick SU that extends from south to north and its thickness decreases from west to east. Based on the samples obtained from the depths by exploratory drilling, this layer is composed of a relatively coarse poorly graded sand (SP). The SPT count (N) values range from 17 to over 50. In the following, some geotechnical features of each of these layers are presented separately.

4.1. Atterberg limits

Fig 5 shows the plasticity index (PI) against the liquid limit (LL) for fine-grained soil samples collected from different depths (up to 25 m) of the city. In this figure, Line-A marks the boundary between clay and silt and Line-U is the upper limiting line, above which the plasticity data of no soil cannot lie. Figs 5A and 5B present a summary of the results of the Atterberg limits of fine-grained soils for the two engineering layers of UCU and LCU in Gorgan, respectively.

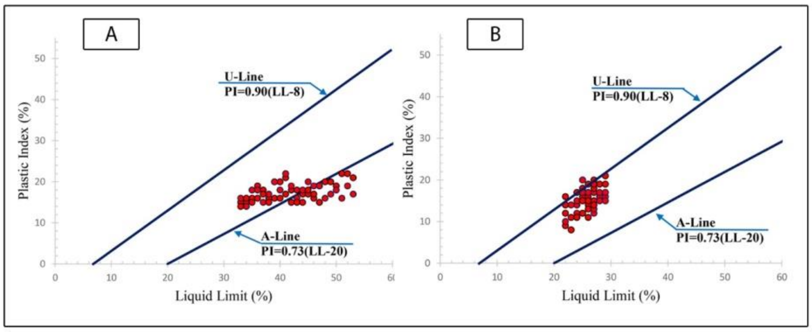

Fig 5. Correlations between plasticity index and liquid limit of fine-grained soil in Gorgan: (A) low-plasticity clay related to the UCU engineering layer and (B) low-plasticity clay related to the LCU engineering layer

According to Figs. 5-A and 5-B, down to a depth of 25 m, the young alluviums of both engineering layers show the same behavior. As can be seen, the LL and PI values range from 33 to 54% and from 15 to 21.5% for the UCU, respectively. For the LCU, the LL and PI values range from 22% to 29% and from 8% to 18.5%, respectively. Therefore, it can be concluded that clay at a shallow depth has more plasticity compared to greater depths. According to these data, most PI-LL values of the UCU samples tend to be placed close to line A. According to Figs. 5-A and 5-B, the effect of the LL on the PI is sharp such that with increasing the LL, the PI also increases. Based on Fig. 5, since the liquid limit of most samples of both engineering layers is less than 50%, the clay is of a low-plasticity type. Finally, it can be stated that the data points of Gorgan fine-grained topsoil samples are close to line A, suggesting the presence of more silty particles in these alluviums compared to the LCU.

4.2. Compressibility

Fig. 6 shows the compressibility graphs of Gorgan fine-grained soils up to a depth of 25 m. The compression index (Cc) and swelling index (Cs), and over-consolidation ratio (OCR) versus depth are shown in Figs. 6-A and 6-B, respectively. As can be seen from Fig. 6-A, the Cc, Cs, and maximum effective vertical stress in each depth can be calculated by analyzing the odometer test data. In this figure, the marked data are average values obtained from the fine-grained subsoil of the city of Gorgan. Thus, at some depths, due to the presence of coarse-grained soil, no information is available on these graphs.

The Cc and Cs were calculated using the consolidation testing outputs and presented in Fig. 6-A. In this graph, Cc and Cs are respectively the slopes of the normal consolidation line and the unloading line, in the logarithmic graph of the effective stress versus the void ratio. According to this figure, the Cc values increase with depth such that to a depth of 25 m, Cc ranges from

0.095 to 0.091 and Cs varies from 0.018 to 0.090, having mean values of 0.142 and 0.054, respectively. Besides, Fig 6-B presents the calculated OCR values by analyzing the graphs obtained from the odometer test using the graphic method proposed by Casagrande. It is of note that OCR is a geotechnical parameter related to the change in the stress level in the soil relative to the maximum stress tolerated over time (Casagrande 1936).

According to Fig 6-B, OCR decreases with increasing depth. It seems that the trend of OCR in depths of 7 to 25 m is independent of depth as it shows an almost constant OCR. Therefore, it can be concluded that the fine-grained soil of the study area is over-consolidated in shallower depths while they are normally consolidated in more depths.

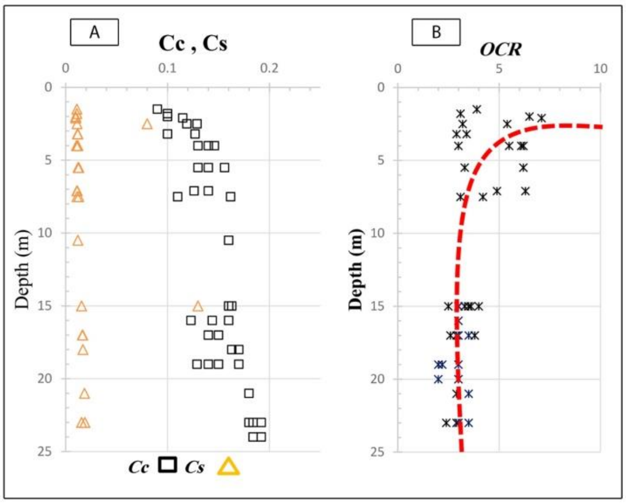

Fig 6. Compressibility of fine-grained soil in the Gorgan: (A) Compression index (Cc) and swelling index (Cs) versus depth and (B) over-consolidation ratio (OCR) versus depth

4.3. Undrained shear strength

Fig 7 presents undrained shear strength (Su) data of the fine-grained soil of UCU and LCU. These values were obtained according to laboratory and field tests, especially the unconfined compression test (UC). Su and Su normalized with effective vertical stress versus depth are shown in Fig. 7-A and 7-B, respectively. Despite some dispersions, the results of the test clearly show that Su increases with increasing depth.

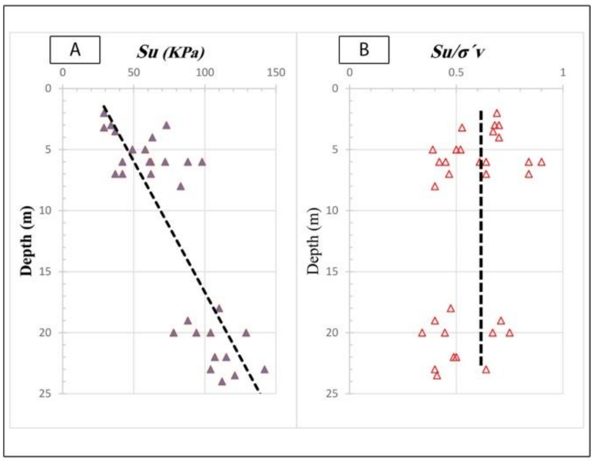

Fig 7. Undrained shear strength (Su) from unconfined compression test (UC): (A) Su versus depth and (B) Normalized values of undrained shear strength relative to effective stress versus depth

According to the results, undrained shear strength values range from 31 to 146 kPa. Also, Fig. 7-B shows that for the unconfined compression test, by normalizing the values relative to the effective stress in each depth, a mean Su value of 0.63 was obtained.

4.4. Drained Shear Strength Parameters

The direct shear test has been performed under plane strain conditions. In this method, the surface of failure is defined in the horizontal direction. The output of this test is specially used in geotechnical engineering projects. The two main advantages of this test are the simplicity of sample preparation and the testing procedure. According to the Mohr-Coulomb failure criterion, the shear strength of the direct shear test is obtained as follows:

$$\tau = c + \sigma'v \tan\varphi \quad (1)$$

where φ, σ'v, and c are effective vertical stress, internal friction angle of the soil, and cohesion under effective stress conditions, respectively. Shear stress is considered in the maximum state as a point of fracture. The cohesion values and the friction angle obtained from the direct shear test were analyzed on the undisturbed and disturbed samples at different depths of the soil up to 25 m. In Fig. 8, the values of the internal friction angle obtained from the shear test carried out in different depths of the subsurface soil of the Gorgan city are presented for each engineering layer. As can be observed from the average values of these graphs, the highest angle of friction is related to the MGU due to the coarse-grained and frictional nature of this unit. Although the values of the internal friction angle of the two fine-grained units are approximately equal, it is slightly more in LCU compared to UCU due to its moderate depth. Notably, undisturbed clay samples with a diameter of 6 cm and a height of 2 cm were trimmed using a cylindrical cutting ring and a wire saw. Also, in these tests, four effective vertical stresses of 50, 100, 200, and 300 kPa were applied and the shear rate was 0.01 mm/min. The cohesion values obtained from the shear tests carried out in different depths of subsurface soil in Gorgan city are presented in Fig. 9 for each engineering layer separately. As expected and clearly visible in these graphs, the highest cohesion value is for the UCU. As shown previously, the UCU had a higher clay content than the LCU. Moreover, the results of the analysis of the odometer test data showed that the clay soils of the study area are over-consolidated in the shallow depths, both confirming the higher cohesion of UCU than LCU. In Table 2, the values of different engineering-geological parameters of young alluviums of Gorgan city up to the depth of 25 m are summarized. According to the engineering characteristics of subsurface soils of Gorgan (Table 2), there are four separate engineering units.

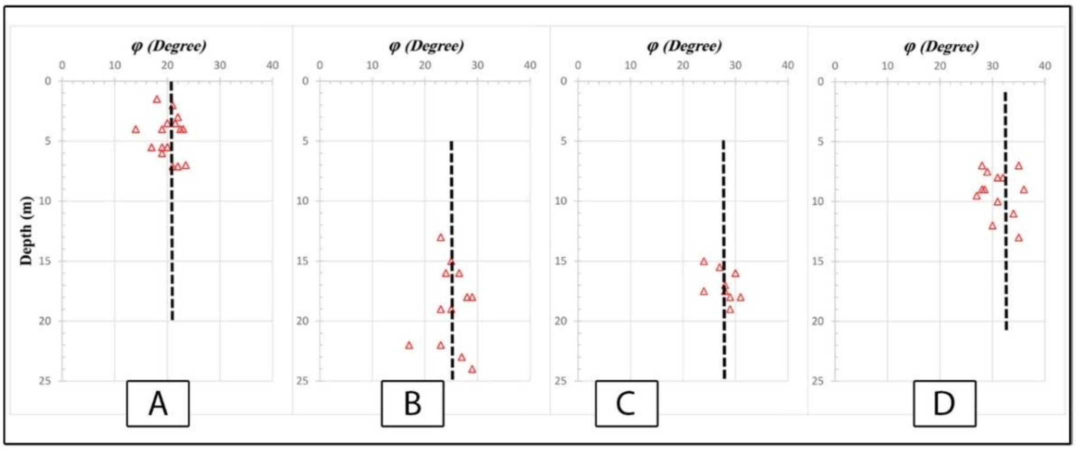

Fig. 8. Variation of internal friction angle obtained from direct shear test versus depth: (A) the data for the UCU, (B) the data for the MGU, (C) the data for the LCU, and (D) data relating to the SU

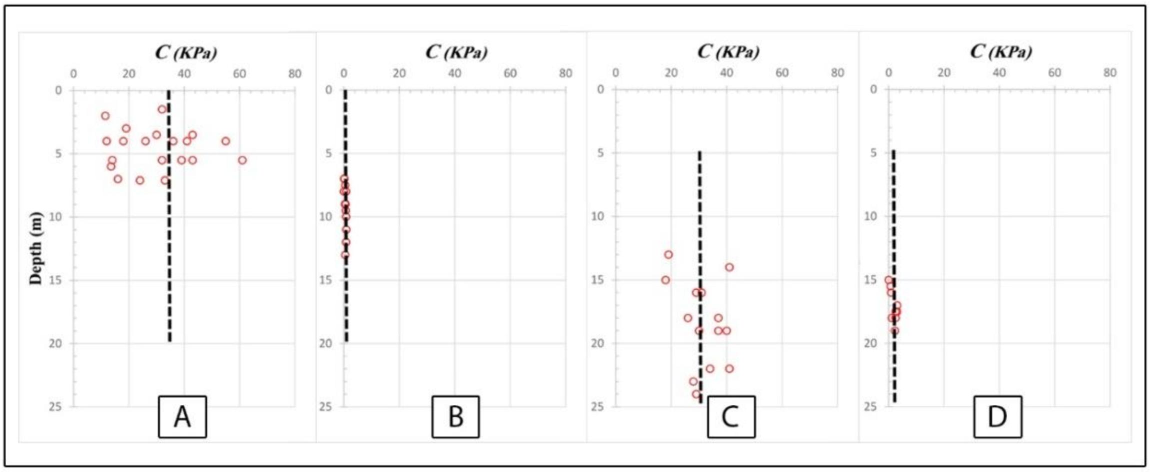

Fig. 9. Variation of cohesion values obtained from direct shear test versus depth: (A) the data for the UCU, (B) the data for the MGU, (C) the data for the LCU, and (D) data relating to the SU

Table 2. Main characteristics of engineering geological units in Gorgan

Soil parameters		Gorgan city			
		UCU	MGU	LCU	SU
Grain size distribution	Gravel (%)	0	40-60	0	0-10
	Sand (%)	0	20-30	0-10	85-95
	Silt and Clay (%)	100	0-10	90-100	0-5
Natural moisture content (%)		24.1-29.1	5-16	20-23.5	14-18.5
Liquid limit (%)		33-54	NA	22-29	NA
Plasticity index (%)		15-21.5	NA	8-18.5	NA
Specific gravity		2.54-2.91	2.61-2.78	2.76-2.91	2.17-2.49
Unit weight (KN/m3)		15.3-17.4	16.32-18.02	16.0-18.1	17.2-18.8
SPT blow count		8-37	24->50	9-34	14->50
Strength parameters	Cohesion (kPa)	11-64	0-0.9	16-41	0-3.1
	Friction angle (degree)	19-24.5	27-36	23-29	23-31
	Unconfined shear strength (kPa)	31-98	NA	73-146	NA

5. Conclusion

In this paper, the engineering geological characteristics of the young alluviums of Gorgan city, Iran, were investigated based on geological and sedimentological studies, SPT test results, and geotechnical data collected in the study area. Based on the sedimentological and geotechnical characteristics of these alluviums, four engineering geological units were identified and introduced up to a depth of 25 m. These units are the upper clay unit (UCU), middle gravel unit (MGU), lower clay unit (LCU), and sandy unit (SU). Analysis of the geotechnical characteristics of these engineering units showed that:

1. Based on the 3D geological model of Gorgan city, the subsoil of these areas is mainly composed of fine-grained low plasticity clayey soil (CL). The origin of these clay soils is loess deposits, which cover more than 40% of the Golestan province.

2. From the sedimentology viewpoint and according to some evidence such as the topography of the ground, the red color of alluviums, rounded grains, and non-uniformity of alluviums, the sedimentary environment of the city of Gorgan was an alluvial fan formed by the Ziartar River.

3. The results of the Atterberg test (data collected from Gorgan) showed that the fine-grained soil in the UCU contains more clay content than the LCU and therefore has higher plasticity.

4. Analysis of the odometer results showed that the fine-grained soils of the city of Gorgan have a slight over-consolidation in the shallow depths while they are normally consolidated in greater depths.

5. The results of the unconfined compression strength test on fine-grained soil samples showed that the Su of samples increases with increasing depth. However, by normalizing these values relative to the effective vertical

stress at the desired depth, the undrained shear stress variations are linear and represent a mean value of 0.63.
6. By analyzing the results of direct shear tests carried out at different depths revealed that the MGU has the highest internal friction angle. Also, the cohesion values of the middle coarse-grained gravel unit and sand unit were almost zero. Furthermore, the cohesion of the UCU was higher compared to LCU due to the higher clay content and more over-consolidation.

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