Computational Research Progress in Applied Science & Engineering
©PEARL publication, 2017

ISSN 2423-4591

CRPASE Vol. 03(01), 7-18, February 2017

Observational-computational 3D Engineering Geological Model and Geotechnical Characteristics of Young Sediments of Golestan Province

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Keywords

Golestan province, Engineering geological model, Geotechnical characteristics, Geotechnical hazard.

Abstract

Recently, a number of subsurface investigations have increased as a result of infrastructure construction in Golestan province, north of Iran. Although there had been investigations on the geotechnical characteristics of the subsoils, understanding soil properties and 3D modelling of geological structures of the area subsoils have not yet been studied. This paper aims to conduct a 3D engineering geological modelling by means of boreholes data and computed geotechnical properties. Due to the lack of data and population concentration, geological model were drawn for Gorgan and Gonbad-e-Kavoos cities which are the biggest cities of the province. The result of these models showed that subsoil of both districts is mainly composed of low plasticity clay (CL) with interbed or lenses of coarse grain sandy and gravely soils. From sedimentological standpoint, it could be inferred that depositional environment of Gorgan city is alluvial fan created by Ziarat River and Gonbad-e-Kavoos is located on flood plain of Gharasoo River. Since the Golestan province subsoil is mostly consist of clayey soil, the geotechnical properties of the Golestan clay such as physical properties and engineering properties have been studied in this paper. Finally, geotechnical hazards associated with these sediments including excavation problems, low bearing capacity, settlement problems and liquefaction potential were reported.

1. Introduction

The eastern coasts of the Caspian Sea, due to the lack of appropriate development in the past years, experiencing a rapid change, construction and development at the moment. Golestan province has a high potential in different field of developments such as, agriculture, natural resources, tourism, export and import, transit and so on. Moreover, this province is experiencing an increasing developments in the urban and industrial regions, special economic zones, harbours and infrastructure constructions. Certainly, the sustainable development, especially in such regions with precious resources of soil, water and natural resources, needs a comprehensive understanding of the geological, geotechnical and geoenvironmental conditions. Therefore, such information results in identifying the appropriate regions and risks related to them.

Detailed study of the geotechnical aspects of a region, primitively is to investigate the geological history of the area, which includes aspects such as sedimentology, geological structures, geomorphologic and the weather [1, 2]. Sedimentological studies are, generally, separating the depositions, that are formed simultaneously with the same condition. Therefore, separation of similar sedimentary units, drawing of sedimentological model in the study area and determining the geological engineering and geotechnical properties in each layer, all can lead to the conversion of sedimentological model into geotechnical model [3, 4]. Based on the studies, such geotechnical models can result in more accurate estimation of the strength characteristics of each subsoil layer. If these models are drawn accurately, in addition to their efficiency in assessment of problems and geological hazards, the future site investigations would approve and complete its data [3]. Regarding the fact that the engineering parameters and the risks of each geotechnical layer are actually the same in that unit, to estimate the engineering properties and the risks of that unit, whenever the information of a part of a unit is unavailable, you can utilize the engineering model information.

One of the earliest discussions in the case of engineering geological models, was provided by [5]. They believed that the geotechnical complexity derived by three types of

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Received: 12 October 2016; Accepted: 15 December 2016

processes; firstly, genetic processes associated with the original formation of geological material, secondly epigenetic processes raised from diagenesis and deformation, and finally weathering processes.

In general, engineering geological model is defined as an approximation of the geological conditions, which are created with the aim of solving an engineering problem that includes models which are mainly according to geological features as well as models that are based on engineering features. In fact, the development of any specific engineering geological model will include a range of techniques, therefore, a restrictive and definite distinction is neither possible nor useful. Similarly, the engineering project parameters should be defined and factored into the engineering geological model, in order to evaluate the relevant geological information. If the engineering objectives of a project are understood, the assessment of the impact of the project on the ground will be possible both during construction and over the life time of the project, through utilizing the models, as well as the impact of the ground on the project.

In recent decades, more attention have been paid to the studies on the geotechnical properties and three-dimensional (3D) geological structures of the subsoils [6-12].

From geotechnical standpoint, two important facts to be considered are whether construction will cause excessive soil deformation and instability because of shear failure. Therefore, it is important to understand the compressibility and the shear strength behaviors of soil, regarding geotechnical analysis and design. To address these issues, a series of in situ tests included, field vane shear test (FV), standard penetration test (SPT), and cone penetration test (CPT), as well as laboratory tests such as consolidation test, unconfined compression test (UC), and direct shear box test (DSB) have been presented. Furthermore, in recent decades, in order to overcome the complex nature of the ground subsurface, many researches paid more attention to the discussions on subsurface stratigraphy using the framework of 3D geological modeling [13,14].

Recently, several researchers tried to explain subsurface layers and geological structures as well as analyze spatial inhomogeneity for geological features visually using 3D solid models [9, 15, 16]. In order to render 3D seismic ray-tracing and velocity inversion problems, [6] has presented a comprehensive introduction to the computer demonstration of complex geological objects. Some modeling approaches which were proposed to simulate stratified geological mediums derived by various types of data such as geological maps, contours, boreholes and cross sections [8, 9, 15, 17] continued to examine a 3D geological solid modeling and proposed a new approach associated with missing strata for sedimentary stratigraphic systems.

In this research, the engineering geological conditions of the shallow young sediments of Golestan province were evaluated to meet the engineering geological information needed for urban planning and development of the study area (Figure 1). To this end, two major cities of Golestan province including Gorgan and Gonbad-e-Kavoos adapted and a conceptual engineering geological model was developed by analyzing the available geomorphological, sedimentological, and geotechnical data across these areas. Finally, the main geotechnical hazards associated with the deposits of each unit including excavation instability, bearing capacity, settlement susceptibility, and liquefaction potential have been identified. The developed engineering geological model would be a useful guide for developing, planning, and constructing in the studied region. At the initial steps of civil projects, this model helps to anticipate what geological conditions are likely to be faced. This ability helping localize sensitive zones during the decision stage of the urban infrastructure projects to be conducted in Golestan province.

2. Topographic and Geological Settings

Golestan as one of the northern provinces of Iran, with Gorgan as its capital, located in the range of 36 30 to 38 8 N latitude and 53 51 to 56 22 E altitude (Figure 1). 1.3% of the country`s area is occupied by this province, with an area about 20438 Km2, which is the 21th province regarding the area [18]. Southern parts of the province have mountainous climate, while central and west southern areas haveMediterranean climate and northern regions have arid and semi-arid climate, which all of them represent the climate diversity. Golestan province, which is located in Alburz Mountains, could be divided into three mountainous, submontane and flat areas. The altitude of mountainous areas is about 400 to 3000 meters above the sea level, which is covered with forests and grass. Hills, mounds, and heights covered by green plants have constituted the submontane area. Plain and low land neighbors of the Caspian Sea and the Gorgan Gulf are located lower than the sea level and as you go to the east the height would increase [20].

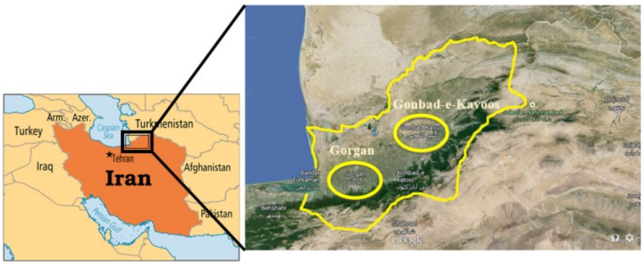

Figure 1. The location of studied area on the Iran map

The geological formations are mainly composed of rocks so it is not considered as the purpose of the current study. Small aeolian hills and badlands with fertile soils for agriculture, orchards and woods have composed the slopes area. Gorgan Plain (Dasht-e-Gorgan), is the third morphological part of Golestan, which includes lowlands and plains. This part is placed in the south starting from the mountain slopes and continue to north with flat and low slope areas and at the end finished in the lower height parts in the north. From the south to the north and from the west to the east, the overall slope of Golestan province gradually decreases (from 3000 meters to -27 meters at the side-lines of Gorgan Gulf). Through diverse geomorphology in these regions, different facies have been observed. Regular and irregular domain facies, erosional plain, alluvial fan, debris, landslides, alluvial bed, V-shaped valleys, micro-terrace, creep and slide scarps are different cases which have been reported in slope and plain areas [19].

The stratigraphy of Golestan province, in summary, is divided into three sections including formations and units of

Paleozoic, Mesozoic and Cenozoic. In Figure 2 the geological map of Golestan province is shown in detail. The first two sections contain rock formations and are not directly related to the purpose of the study. However, the formations and units of Cenozoic that had a rapid development in the province and mostly includes the quaternary deposits, which is the main focus of the paper [19].

The stratigraphy of quaternary deposits contains alluvial deposits, aeolian deposits (loess), fan cone and debris cone. Since the geological characteristics if these materials especially loess deposits have direct relation to the geotechnical properties of soil in the province, the definition and explanation regarding each deposits will be elaborated.

Thick loess deposits in Golestan Province cover an area of about 388,000 hectares, which is more than 17% of the province surface area [21]. Loess is an “Aeolian–glacial sediment” mostly composed of silt or silty loam and normally forms rich soils for agricultural purposes [22, 23]. Particle size is mostly in the range of silt (50-90%) with clay and sometimes sand-size grains [24]. Loess deposits are characterized by lack of layering and homogeneous sorting in the field. Also, they are generally composed of quartz, feldspar, calcite, dolomite, mica, iron and magnesium minerals with subordinate clay minerals as well. Color of loess deposits are generally yellow or brown due to chemical weathering and oxidation of iron minerals [25]. Loess deposits attracted lots of attentions because of their effect on some geological hazards such as collapse, subsidence, slope instability, and landslide.

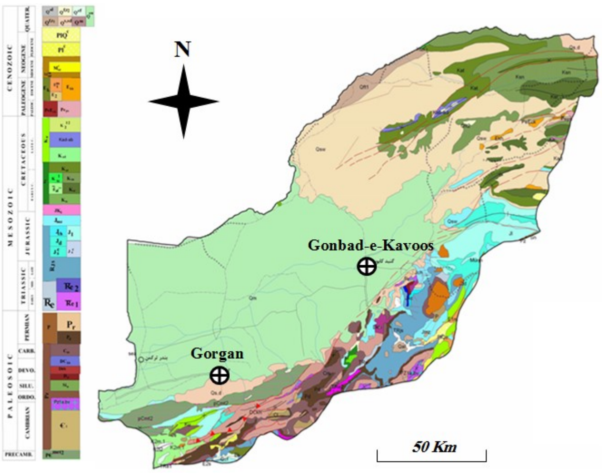

Figure 2. Geological map of Golestan province

As mentioned before, this area is subjected to rapid urbanization and development. More recently, growing population (with increasing tourism) has led to major constructions in this area, including the development of high height buildings, roads, sewer networks, railroads and related infrastructures. These civil engineering activities upon coastal and marine sediments having undesirable engineering geological conditions which have led to rising some engineering geological problems such as land settlement, excavation problems, and liquefaction susceptibility. As shown in Figure 3, fluctuations of underground water level has led to a collapse due to the presence of collapsible deposit of loess and bring about a sinkhole on which a lamppost fell over.

Figure 3. Subsidence of lamppost due to presence of collapsible soil in Gonbad-e-Kavoos

3. Data Collection and Methodology

The collected data, in the present study, are all derived from previous boreholes along with in-situ and laboratory test. The present data all deduced by two groups of previous researches done at the site of study and also borehole data, which given by Municipality of Gorgan and Gonbad-e-Kavoos cities (Table 1). 96 boreholes were examined in this research, among which 61 boreholes are located in city of Gorgan and 35 boreholes are sited in Gonbad-e-Kavoos, and none of them deep enough to touch the bedrock. The locations of boreholes used in this research, are illustrated in Figure 4.

The data of selected boreholes, in-situ tests and laboratory tests were collected in a common database. The database included the borehole number, easting, northing and elevation of the boreholes, soil type, depth to groundwater table, borehole depth, Standard Penetration Test (SPT) blow count (N), Atterberg limits, sieve and hydrometer analyses for all boreholes. Furthermore, available geophysical measurement data carried out by Municipality of Gorgan were evaluated. This database includes 6 geoelectrical profiling across the city of Gorgan. The locations of the geoelectrical measurements employed in the study are shown in Figure 5 along with one of their outputs as an example.

Two districts in Golestan province (Gorgan and Gonbad-e-Kavoos cities) were selected according to high population concentration and lack of available geotechnical data as presented in Figure 1. All the collected data and information regarding geology, groundwater and geotechnical characteristics of both superficial and subsurface, obtained from related government and private sectors. The data types and formats can be divided into two groups: first, digital maps data, and second, hardcopy of boring log data. The geological survey records are the major resource of geological information. As it cited before, this database include detailed drilling, sampling and measurement information, and 3D topology of soil boreholes.

The current study utilizes the manual approach for drawing the 3D models, since the performance of available software regarding the drawing of geological models and correlation of subsurface layers in small-scale and soil medium – with high diversity in changes of layering – is highly questionable. Accordingly, in the selected two cities, cross sections of east-west and north-south have been drawn based on the data and location of existing boreholes so that the most of the studied areas are covered (the sections are indicated in figure 4). Then, the information of the closest boreholes are plotted on each section and the geological layers with the same material are correlated with manual drawing approach. The figure 6 indicates two samples of the drawn cross-sections for cities of Gorgan and Gonbad-e-Kavoos. As it is shown in the Figure 6, the dominant material of the ground is the clay with low plasticity. It should be noted that the horizontal scale is much smaller and for this reason the incompatibility of scales, layer forms and the available lenses seem to be unreasonable.

Next, putting the drawn 2D sections together, a new conceptual-observational model of geology in the two studied areas was drawn separately in 3D format. With regard to the fact that the aim of the current study is drawing low-depth geological model and due to the limitation of data accessibility, the depth of the 3D models is limited to 25 meters. Also it is worth noting that in most of the construction and geotechnical projects the depth of the site investigation is lower than the mentioned depth.

While though numerous subsurface investigations have been carried out for different commercial projects in cities of Gorgan and Gonbad-e-Kavoos, no comprehensive study and attempt have been undertaken to centralize these activities. The analysis of boring log data could be used to provide a typical geological profile as well as the representative geotechnical characteristics. The resulting solid model is shown in Figure 7. The superficial soil distribution in some parts of the both region is mainly covered by made ground approximately 1.5 to 2m thick. It could be seen in the representative cross-sections of studied areas' subsoils that illustrated in Figure 6.

Since the distance between two cities is significant each geological model interpreted separately. Based on the 3D geological model of Gorgan city, the stratigraphic framework of studied areas can be categorized into one single subsoil conditions, in another word, stratigraphic framework of the city is almost similar. Underneath the made ground, medium stiff clay approximately 6–7m thick is presented. The soil layer is followed by medium to very dense coarse-grained soil mainly poorly graded gravel and sand (GP and SP) up to a level of 15m. Beneath these layers there is again a layer composed of very stiff low-plasticity clay (CL) to 25m deep. Based on field investigation it is found that these deposits are all in red color showed that deposited in oxygen rich condition. Also coarse-grained part of the sediments are composed of poorly graded rounded rock debris. Field observation showed that these deposits are unsorted and without any sharp stratifications. From sedimentological standpoint it could be concluded that depositional environment of Gorgan city is alluvial fan. This conclusion can supported with the fact that Gorgan city located in areas with a steep gradient (North Slope of Alborz Mountain) from a drainage catchment (Ziarat River) to the basin floor whereas wadis in valleys form where the gradients are much lower.

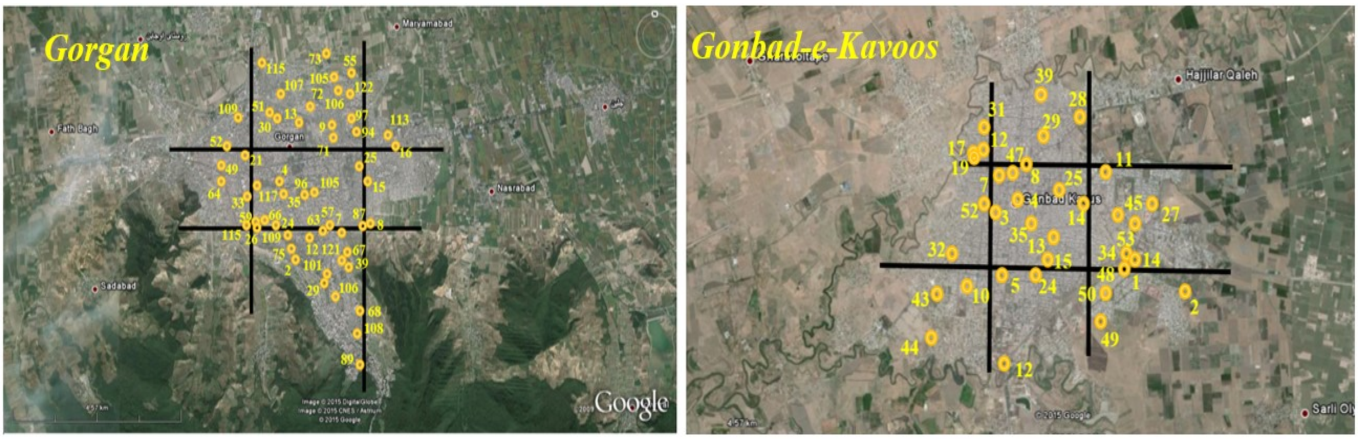

Figure 4. Aerial map of Gorgan and Gonbad-e-Kavoos with location of boreholes and drawn cross-sections

Table 1. List of conducted tests in the survey

Test name	Test type		Number of tests	Standard
	In-situ	Laboratory		
Triaxial test	-	✓	35	ASTMD4767-95
Uniaxial test	-	✓	49	ASTM D7012
Direct shear test	-	✓	56	ASTM D3080-90
grain size distribution	-	✓	192	ASTM: D422-63
SPT	✓	-	96	ASTM-D1586
In situ density	✓	-	148	ASTM D1556
Oedometer test	-	✓	72	ASTM D2435

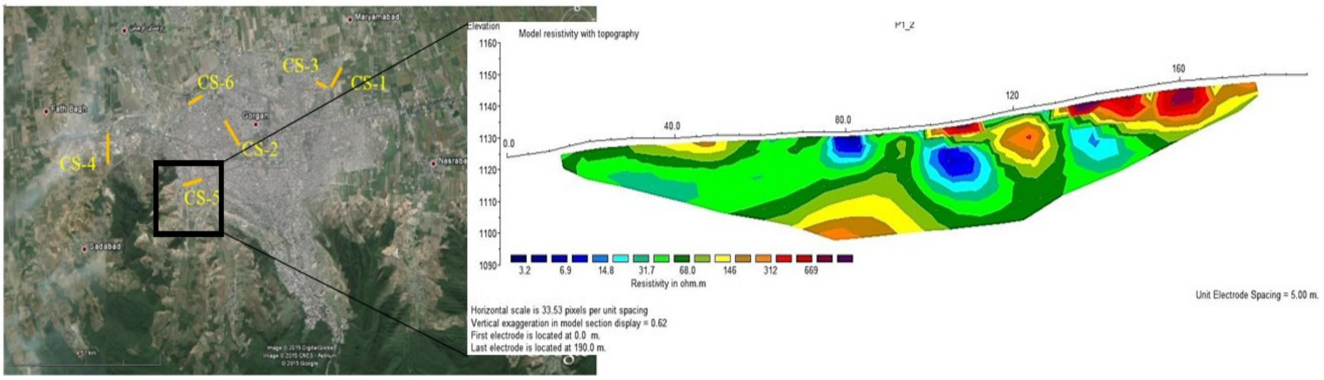

Figure 5. An example of the result of geoelectrical survey conducted in Gorgan city

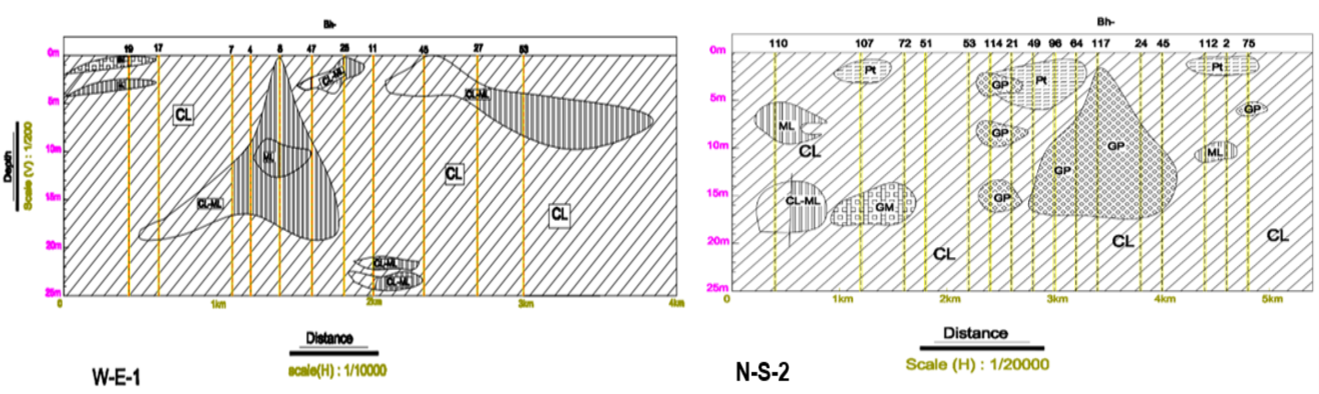

Figure 6. A drawn sample of 2D sections, west-east section of Gonbad-E-Kavoos city (left) and north-south section of Gorgan city (right)

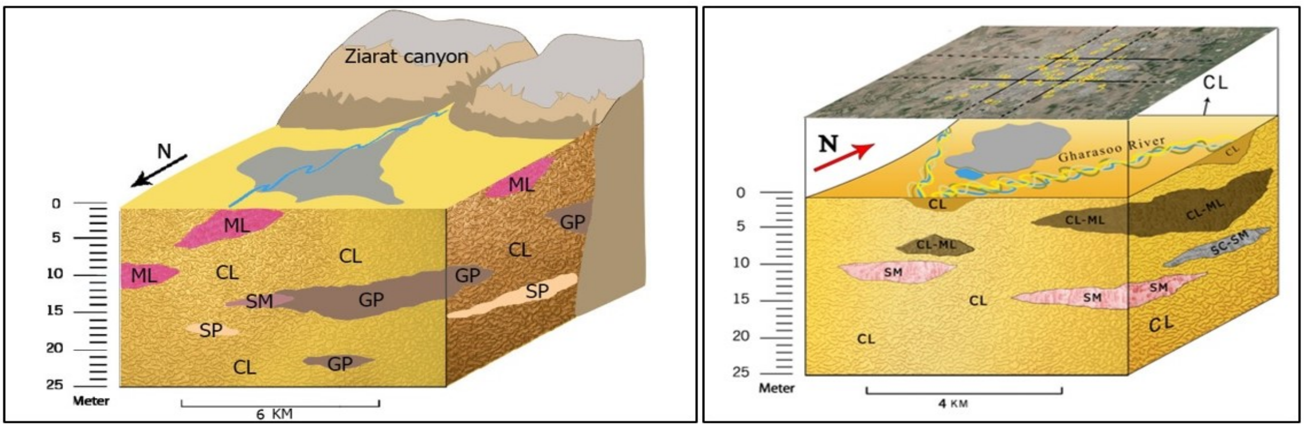

Figure 7. 3D geological model of Gorgan (left) and Gonbad-e-Kavoos (right) subsoils in oblique view with vertical exaggeration

According to the 3D geological model of Gonbad-e-Kavoos city, the subsoil is mainly composed of low-plasticity clay (CL) and silty clay (CL-ML). As it could be seen in the model the occurrence of CL-ML is much less than the occurrence of CL. Man-made ground is rare in this city because of even surface of the ground. As it can be seen in the model as well, there are several coarse-grained soil lenses mostly consist of silty sand (SM). Some evidence such as red color of deposit, rounded grains and the shape of the lenses proved that depositional environment of Gonbad-e-Kavoos city is a flood plain. As it can be seen in the 3D geological model there are two rivers around the city which they originate from the same source (Gharasoo River).

These two rivers are meandered type (as shown in the model) and they have many turns and windings. Through time, these two rivers have changed their path for many times that is a reason of many abounded channels around Gonbad-e-Kavoos city. Because of change in the river channel's position, coarse grained lenses remained in different parts of city which are the sediments inside the river channel. A notable point in this 3D model is that based on field studies, the fine-grained clayey sediments are very similar to the loess sediments covering most parts of Golestan province. In fact, the source of this much clayey sediments is the loess which is eroded by river activity and deposited again so although the sediments are similar to loess in appearance, but due to their layering, they are called pseudo-loess.

4. Engineering Properties of Subsoils

In this stage of study, the 3D engineering geological model for the two studied regions was provided based on the geological 3D models and using experimental and in situ test's results. To develop the model, the results from experimental and in situ tests were assigned to their respective soil and layers, with or without the same type of soil. Then, the parts with same or almost same engineering parameters were assumed as one engineering geological (or geotechnical) layer. Afterward, the engineering geological model modified according to undrained shear strength which obtained from the in situ tests and field observations. Finally, with gathering all data and applying engineering judgments on them the final 3D model for the studied regions were prepared. It worth to note that the number of in situ tests were significantly less than experimental tests, consequently the results rely more on laboratory tests and in situ tests play role as complementary data for engineering judgment.

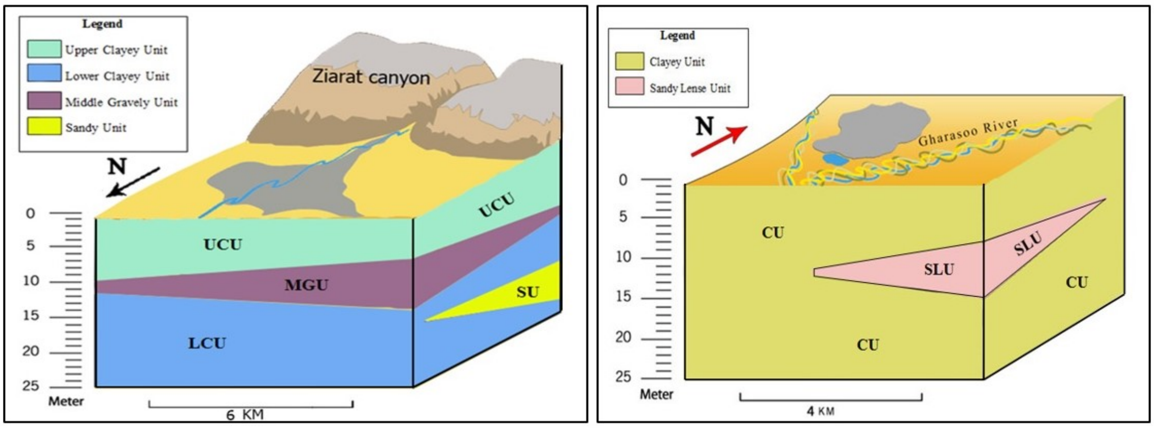

Figure 8. Observational-computational 3D geotechnical profiles of Gorgan (left) and Gonbad-e-Kavoos (right) subsoils in oblique view with vertical exaggeration

Table 2. Main computed engineering properties of the soils of geotechnical units

Soil parameters		Gorgan city				Gonbad-e-Kavoos city	
		UCU	MGU	LCU	SU	CU	SLU
Grain size distribution	Gravel (%)	0	40-60	0	0-10	0	0-10
	Sand (%)	0	20-30	0-10	85-95	0	75-90
	Silt and Clay (%)	100	0-10	90-100	0-5	100	5-15
Natural moisture content (%)		24.1-29.1	5-16	20-23.5	14-18.5	26.1-31.2	15.2-17
Liquid limit (%)		33-54	NA	22-29	NA	29-52	17-24
Plasticity index (%)		15-21.5	NA	8-18.5	NA	7.9-27.4	2.8-4.6
Specific gravity		2.54-2.91	2.61-2.78	2.76-2.91	2.17-2.49	2.42-2.89	2.14-2.40
Unit weight (KN/m3)		15.3-17.4	16.32-18.02	16.0-18.1	17.2-18.8	15.2-17.8	17.21-18.24
SPT blow count		8-37	24->50	9-34	14->50	7-22	16-41
Strength parameters	Cohesion (KPa)	11-64	0-0.9	16-41	1.1-5.2	32-73	2.8-4.6
	Friction angle (degree)	19-24.5	27-36	23-29	23-31	17-21.5	25-31
	Unconfined shear strength (KPa)	73-223	NA	47-357	NA	63.5-190	NA

Figure 8 illustrates the studied areas 3D engineering geological models separately which drawn using computed geotechnical data. As it can be seen in Figure 8a Gorgan city subsoil can divided into four different units include upper clayey unit (UCU), middle gravely unit (MGU), lower clayey unit (LCU) and sandy unit (SU). The main geotechnical properties of these units are summarized in table 2. UCU that corresponds to the youngest sediments of the city is the upper unit in our model (Figure 8a), and the foundation of any structure in the city of Gorgan is directly located on this zone. The thickness of this unit ranges from 5 to 7m and increases from the south to the north and also from the east to the west. Based on the field observations and drillings the groundwater table is detected in depth 3-5m, and affects the behavior of clayey soils of this unit. This unit is predominantly composed of fine brownish loose to medium stiff clayey soils that are approximately uniform in size and structure. The clayey soils are low plasticity and silty clay as CL and CL-ML according to the unified soils classification. The occurrence of CL-ML is much less than the occurrence of CL. The SPT "N" values range from 12 to over 19 showing a general increasing trend with depth (the confining effect has been considered). Increasing of SPT N values with depth indicates that the density of the soil generally increases with depth too.

The MGU has thickness of about 3 to 5 m and increases from the north to the south of Gorgan city. According to the sample recovered from drillings and field observations of natural trenches around the city it is inferred that the unit has rounded grains and was very heterogenic. This unit is mainly composed of coarse reddish medium to very dense gravely soils that are not uniform in size. The gravely soils are poorly graded gravel and silty gravel as GP and GP-GM according to the unified soils classification. The occurrence of GP-GM is much less than the occurrence of GP. The SPT "N" values range from 34 to over 50 showing a general increasing trend with depth again(the confining effect has been considered). Plugging the SPT sampler in this unit is common due to existence of the big debris or boulders.

The thickness of LCU ranges from 8 to 13m and increases from the south to the north and from the east to the west. This unit is predominantly composed of fine dark brownish medium to very stiff clayey soils that are approximately uniform in size. The clayey soils are low plasticity clay as CL according to the unified soils classification. The SPT "N" values range from 26 to over 34 showing a general increasing trend with depth (with taking into account the confining effect). Increasing of SPT N values with depth indicates that the density of the soil generally increases with depth too.

The SU has thickness of about 2 to 5m and increases from the north to the south of the Gorgan city. According to the sample recovered from drillings it is seen that the unit has rounded grains and was almost uniform in grain size. This unit is mainly composed of coarse medium dense sandy soils that are approximately uniform in size. The sandy soils are poorly graded sand as SP according to the unified soils classification. The SPT "N" values range from 17 to over 50 showing a general increasing trend with depth again (the confining effect has been considered). It is worth mentioning that the SPT number over 50 is perhaps due to existence of boulders with causes plugging of instrument sampler.

Based on the 3D geological model of Gonbad-e-Kavoos city, the subsoil is mainly composed of low-plasticity clay (CL) and silty clay (CL-ML). Form geotechnical standpoint, these two types of soils do not have any significant difference expect their plastic index. So these two type of soils could be assumed as a single geotechnical unit namely clayey unit (CU). CU that corresponds to the youngest sediments of the city is the upper unit in our model, and therefore the foundation of any structure in the city of Gonbad-e-Kavoos is directly located on this zone. The thickness of this unit ranges from surface to over 25m and increases from the south to the north. According to the field observations and drillings the groundwater table is detected in depth 2-3m, and affects the behavior of clayey soils of this unit significantly. As it is said this unit is predominantly composed of fine light brownish loose to medium stiff clayey soils that are approximately uniform in size. The SPT "N" values range from 10 to over 31 showing an ascending trend with depth (the confining effect has been considered). Increasing of SPT N values with depth shows that the in-situ density of the soil generally increases with depth too.

In addition to this unit one more geotechnical unit can be recognized in the city. This unit is not a consistence layer and actually composed of some coarse-grained lenses named as sandy lens unit (SLU). The SLU has thickness of about 2 to 5m and increases from the north to the south and west to east of Gonbad-e-Kavoos city. According to the sample recovered from drillings and field observations of river cuts around the city it is inferred that the unit has rounded grains and is very heterogenic. This unit is mainly composed of coarse reddish medium to very dense silty sand soils that are not uniform in size. The silty sand soils are well graded sand with silt particles as SM according to the unified soils classification. The SPT "N" values range from 26 to over 38 showing a general increasing trend with depth again (the confining effect has been considered).

4.1. Atterberg Limits

Figure 9 has illustrated a typical plot of plasticity index (PI) and liquid limit (LL) of fine-grained soil samples that have been collected from different depths up to 25 m from Gorgan and Gonbad-e-Kavoos, two district areas, in Golestan province. The line which demonstrates delineation of boundaries between clays (above the line) is the A-line , and the line that illustrates the limiting line above which PI-LL data of any soil cannot fall , is the U-line. The summary of the test outputs of Atterberg limits of fine-grained soils in mentioned cities, has been indicated in figures 9a and 9b, respectively.

According to the Figures 9a and 9b, this young clay shows similar plasticity index-liquid limit behavior in both district areas, at the depth up to 22m. This figure has shown LL values ranging from 21.1% to 56.6%, and PI values varying from 4.1 to 26.7% for Gorgan district, while for Gonbad-e-Kavoos city the LL values ranging from 18.2% to 55.3% and PI values varying from 2.65 to 24.5%. It can be concluded that the Golestan clay, at shallow depths, has low to high plasticity. Based on mentioned statements, most of the PI-LL values of the samples tend to lie close to the A-line. As indicated in figures 9a and 9b, LL influence on the PI is obvious. With the PI increasing, LL increases. It is important to note the different PI-LL behaviors for Gorgan clay at deeper depths, as shown in the figure. Test results shown in Figure 9b are close to the test results illustrated in Figure 9a, which is more scattered. Based on Figure 9a, since LL being less than 40%, its clay is of low plasticity. Finally, it can be stated that totally the data point of Gorgan clay is near to A-line, which means that there is more silty-sized particle in this sediment comparing to Gonbad-e-Kavoos clay.

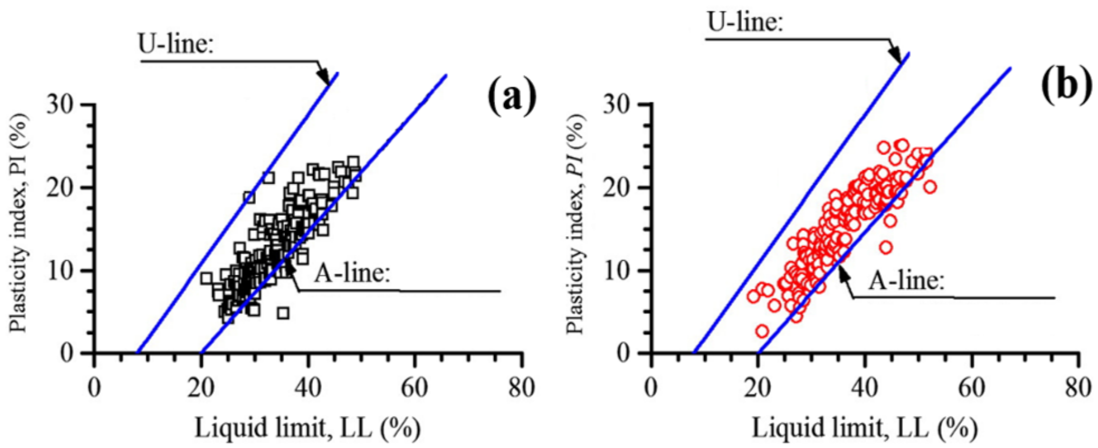

Figure 9. Correlations between plasticity index and liquid limit of Golestan province subsoils. (a) low-plasticity clay of Gorgan city, (b) low-plasticity clay of Gonbad-e-Kavoos city

4.2. Compressibility

Figure 10 shown the compressibility of the Golestan clay up to depth of 20m. The in-situ and preconsolidation pressure and overconsolidation ratio (OCR) as well as compression and swelling index (Cc and Cs) are respectively specified against depth in Figure 10a-c. As it is indicated in Figure 10a, the in-situ vertical effective stress was computed as effective unit weight, at any depth, while multiplied by corresponding depth, and the preconsolidation pressure was calculated by the oedometer test analysis. It is important to mention that the specified data are mean values derived from clayey part of both district`s subsoil profile.

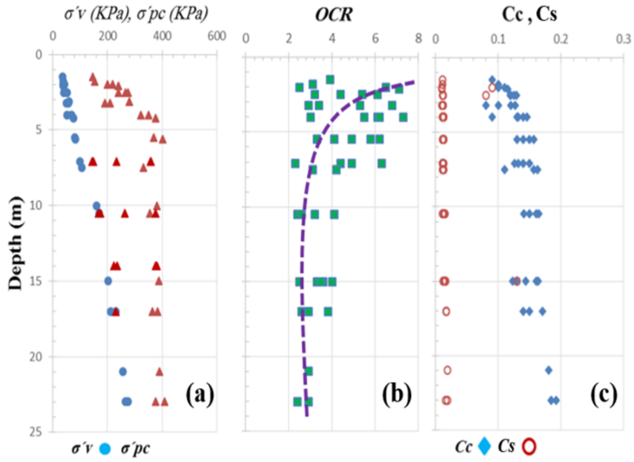

Figure 10. Compressibility of the Golestan clay. (a) In situ vertical effective stress (σv′) and preconsolidation pressure (σ′pc) versus depth, (b) overconsolidation ratio (OCR) versus depth and (c) compression index (Cc) and swelling index (Cs) versus depth

According to figure 10a the σ′pc is significantly higher than the σ′v. Also, σ′pc are largely scattered and at shallow depth it is less than 7m before reaching a similar value at a deeper depth. Figure 10b has illustrated the overconsolidation ratio (OCR), a geotechnical parameter related to historical changes in the case of the existence of stress in the subsoils [26], which was computed as the ratio of σ′pc versus σ′v. Based on Figure 10b as depth increases, the OCR decreases. It seems that the trend of OCR is independent of depth at the depths varying from 9 to 25m, while the OCR value is nearly constant and fixed. Hence, it can be inferred that the clay of the studied areas is subjected to overconsolidation, at shallow depths and to normally consolidated clay at deeper depths. In addition, the compression and swelling indices computed by the consolidation test outputs, have been shown in Figure 10c. It is important to note that these compression and swelling indices (Cc and Cs) are the slope of the normal consolidation line (NCL) and unloading line in a plot of the logarithm of vertical effective stress against void ratio, respectively. Furthermore, obviously test results of compression indices (Cc) are increasing with the depth. Cc ranging from 0.092 to 0.198 and Cs from 0.015 to 0.096, at depths up to 25m, which are followed by the average value of 0.145 and 0.055, respectively.

4.3. Undrained Shear Strength

Figure 11 has shown the estimation of the undrained shear strength of the Golestan clay (Su) which is according to laboratory and field tests and especially the unconfined compression (UC) test. In the following, the undrained shear strength (Su), and the undrained shear strength normalized by in-situ vertical effective stress against depth, have been demonstrated respectively in Figure 11a and 11b. Although there are some scatterings, the test results obviously indicate that with the depth increasing the (Su) increases (Figure 11a). Accordingly, it can be seen in Figure 11b that the Su/σ′v differs from 0.156 to 0.924 with an average of 0.54 for the UC tests.

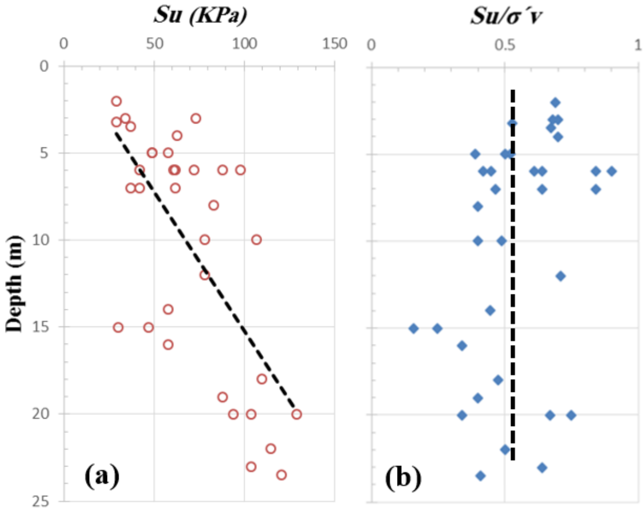

Figure 11. Undrained shear strength from unconfined compression (UC) test. (a) undrained shear strength versus depth and (b) normalized undrained shear strength versus depth

4.4. Drained Shear Strength Parameters

The direct shear box test have been accomplished under plane strain condition. In this way, the failure plane is defined on the horizontal direction which has been particularly utilized in many geotechnical engineering projects. Two main advantages of this test are the simplicity of sample preparation and testing procedure. According to Mohr-Coulomb failure criterion, the shear strength from direct shear test can be obtained as follows:

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

While $\sigma'v$, φ' and c' express respectively the vertical effective stress, the effective internal friction angle of soil and the effective cohesion. The shear stress at peak state was considered as the failure point. As indicated in Figure 12, the results of the test about effective cohesions and effective internal friction angles have been obtained from the direct shear test on intact samples at district points with depth up to 25m. The clay specimens were trimmed to the dimension of 6 cm diameter and 2 cm height, by using a cylindrical cutting ring and a wire saw. Tests in, which four various vertical effective stresses of 50,100, 200 and 300 KPa were used, determined each pair of c' and φ' the shearing rate of 0.01 mm/min was also applied. At the end of the primary consolidation stage, the samples were sheared. Test results show that the average values of c′ and φ′ are respectively close to 33KPa and 21° (Figure (12a)).

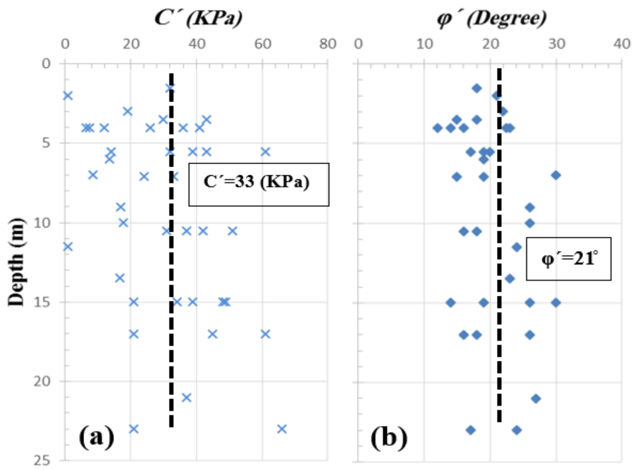

Figure 12. (a) Effective cohesion and (b) effective internal friction angle from direct shear box test.

4.5. Comparison of Compressibility and Strength Properties

Table 3 have indicated the summary of geotechnical characteristics of the Golestan clay in comparing to Tehran, Bangkok, Singapore clay and Hong Kong marine clay at depth up to 25m. From sedimentological standpoint, these soils include similar Quaternary residual deposits. Based on the test observations shown in Table 3, the Golestan clay is less compressible than Tehran clay, Bangkok clay and Hong Kong marine clay. While the overconsolidation ratios of Golestan clay is lower than Tehran clay, but it is quiet similar to the clay of Bangkok. Regarding the undrained strength features, the average *Su/σ'v* of Golestan clay is equal to 0.54, which comparing to that of Bangkok is 38% higher and 62% more than that of Hong Kong. Furthermore, Golestan and Bangkok clay represent mostly similar internal friction angle of 21 and 24 degree, while Tehran clay shows higher friction angle of 28̊. Regarding the case of cohesion, Golestan, Tehran and Bangkok clays are of similar values.

5. Geotechnical Hazard With the Sediments

Saturated young sediments of Golestan area with generally weak geotechnical properties like low shear strength and low density are accompanied with some problems including excavation instability, low bearing capacity, large settlement susceptibility, and liquefaction potential.

5.1. Excavation Problems

Loose sandy soils and low strength clayey soils associated with shallow water table cause rising many problems during the excavations in both Gorgan and Gonbad-e-Kavoos cities. The groundwater table in the city of Gorgan lies between 3 and 5 m and for Gonbad-e-Kavoos is about higher level of 2-3m. During the rainy seasons, the water table is higher than 1.0m in both districts. Construction activities, hence, sometimes involve excavations of considerable depth underwater. The development of surface and underground civil constructions in Gorgan city is mostly in UCU that below the water table requires rigorous and careful planning. If the depth of excavation reaches to MGU unit, there would be a need to severe stabilization. This is due to the fact that this unit is mainly composed of coarse-grained rounded particles with low cohesion.

Also the unforeseen events during the excavation works in saturated loose to medium dense soils of MGU can lead to serious problems, posing at risk the surrounding buildings. Some examples of soil-related failures of excavation built below the water table in MGU including the financial and life loss is reported by Gorgan municipality. Since excavations lead to unstable situations, it is often imperative to adopt bracing systems and lowered the groundwater table. Most of the constructions in Gonbad-e-Kavoos city such as excavation are done in CU unit. As stated earlier, this unit has weak engineering properties that has made the excavation dangerous, particularly because of the high level of groundwater level which decreasing the safety factor of excavations. Another dangerous problem during excavation is the existence of sand lenses with low cohesionless soil. The saturation of these lenses would cause quick sand and failure as the excavation does not use appropriate retaining structures, Therefore, it is recommended, with regard to unpredictable position of the lenses, to do geotechnical drilling if there is deep excavation.

5.2. Bearing Capacity Problem

Low bearing capacity is an issue that mainly affects the UCU and CU in both cities. Building foundations in these zones must take into account the low shear strength of sediments and probable foundation problems in the future.

Table 3. Summary of geotechnical engineering properties of Golestan clay, Tehran clay, Bangkok clay and Hong Kong marine clay at depth up to 25m.

Soil properties	parameters	Golestan clay	Tehran clay	Bangkok clay	Hong Kong marine clay
Compressibility and stress history	Cc	0.092-0.198	0.223-0.308[a]	0.691-0.1682[b]	0.308-1.315[f]
	Cs	0.015-0.096	0.018-0.027[a]	0.069-0.184[b]	0.0198-0.1241[f]
	OCR	1.2	1.7[a]	1.3[c]	-
Normalized undrained shear strength	Su/σ´v	0.54	-	0.33[d]	0.20[f]
Drained shear strength	C´ (KPa)	33	35[a]	38[e]	-
	φ´ (Degree)	21	28[a]	24[e]	-

[a][27]; [b][28]; [c][29]; [d][30]; [e][31]; [f][32].

This problem could be solved by using a suitable foundation type based on the nature of the sediments. Superficial (up to 5m in depth) clayey soils of UCU and CU are not competent and have weak nature and low bearing capacity. As mentioned previously in section (4.2), low compressibility and swelling coefficient which is in agreement with low SPT N values show low shear strength and low density of these soils. This fact, in turn, demonstrates low bearing capacity of such soils. Many buildings in the city of Gorgan and Gonbad-e-Kavoos are low-rise buildings (one to four-story residential buildings) that impose small loads to the ground. Various types of shallow foundations embedded in UCU and CU are suitable for these loading conditions. The heavy loads are not bearable by both UCU and CU soils, since foundations involving heavy loads and high-rise buildings with more than five-story should be founded on the competent soils, which have a high bearing capacity (for example in Gorgan city on MGU). Under these conditions, mat-pile foundations supported principally by the end bearing would be needed. Regarding the depth of MGU, the length of piles varies between 7 and 12m. Since CU soils in city of Gonbad-e-Kavoos are very soft and have low bearing capacity, any structure with more than four stories on these soils (especially in the south and southeast of the city) should be founded on mat-pile foundations. Depth of competent sandy lenses are relatively variable in this area, so pile foundations with the maximum of 15m length would be required based on geotechnical investigations. Using shallow foundations up on CU will pose serious foundation problems such as shear failure and large settlement.

5.3. Settlement Susceptibility

Settlement susceptibility is mostly dependent on compressible nature of the clayey soils of UCU in Gorgan district and CU in Gonbad-e-Kavoos city. Evaluation of compressibility of UCU and CU soils was made based on the results of oedometer tests. As it mentioned in section (4.2) according to the test results insignificant overconsolidation observed at the clayey soils of the studied area which decreases by increasing depth slightly. Moreover, natural moisture contents in comparison with liquid limits of the clayey soils of UCU and CU indicate that these soils are almost normally consolidated. The relatively high Cc values (Table 3) are attributed to high in-situ void ratios and moisture contents and partially to the presence of organic materials. These values are indicative of their vulnerability to excessive settlements under applied loads. In the city of Gorgan, where MGU occurs in the depths less than 10m, light loads cannot cause excessive settlement of the ground due to consolidation settlement of MGU; however, heavy loads can cause this problem. In these situations, mat-pile foundations could be used to prevent excessive settlement problem. In Gonbad-e-Kavoos city the presence of thick clayey unit with high compressibility potential causes more serious settlement problems. Also due to rivers activity around the city there is higher organic materials in this sediments as well as higher ground water table result in bigger settlement in this area. Therefore any construction loads may cause settlement problems that would be prohibited by applying deep or mat foundations.

5.4. Liquefaction Potential

Because of increased water pressure in saturated soil, which is derived by cyclic stress, liquefaction results in diminished ground strength. Liquefaction is one of the most common hazardous phenomena in coastal areas which is more occur as a consequence of earthquakes [33]. Three primary factors in the case of the development of cyclic mobility or liquefaction are stated as ground motion properties, soil type and in-situ stress state as well as geological features [33, 34]. These features include the type of soil, relative density (Dr) [35], the grain size of soil [36], the history and condition of the depositional environment [37]. Golestan province as one of the southern Caspian Sea region, is seismically active based on many historical and instrumental earthquakes records [19]. The most significant tectonic feature in this area is the Fault of Khazar, which has caused main changes in the region morphology. The surface trace of this fault is about 454 km in length which plays the role of a border between the mountain and its neighbor plain. Frequent occurrence of mid-range to large-scale earthquakes is one of the seismotectonic properties of this area. Based on fulfilled seismic efforts in this region, the maximum horizontal acceleration of mentioned area is equal to 0.3g with a moment magnitude of 7.5.

By comparing the cyclic stress ratio (CSR) with the cyclic resistance ratio (CRR), we can calculate the liquefaction potential of the sediments. With using Eq. (2), it can be deduced that the cyclic stress ratio resulted from a strong ground motion, which is known as the seismic stress ratio [38] and can be obtained at various depths of the boreholes. Table 4 has illustrated some of the calculated results of samples.

$$CSR = 0.65 r_d(\sigma v_0/\sigma' v_0)(\alpha_{max}/g) \quad (2)$$

Table 4. Summary of the results of calculations relating to liquefaction potential in different depths of selected boreholes

Depth (m)	N (SPT)	γ_d (gr.cm^{-3})	γ_{sat} (gr.cm^{-3})	Gs	r_d	CSR	CRR	FS	Liquefaction possibility
3	10	1.36	1.84	2.66	0.996	0.305	0.188	0.62	possible
6	4	1.31	1.85	2.69	0.956	0.296	0.240	0.81	possible
6	22	1.34	1.85	2.79	0.956	0.290	0.225	0.78	possible
15	14	1.36	1.88	2.74	0.776	0.310	0.182	0.77	possible
20	38	1.52	1.98	2.67	0.937	0.289	0.558	2.03	impossible
12	36	1.48	1.90	2.65	0.906	0.315	0.207	0.73	possible
6	20	1.32	1.84	2.66	0.953	0.155	0.195	0.67	possible
8	44	1.52	1.84	2.71	0.954	0.171	0.426	1.42	impossible
9	47	1.56	1.90	2.67	0.934	0.257	0.669	2.31	impossible
16	22	1.42	1.85	2.55	0.906	0.291	0.197	0.68	possible

3	51	1.4	1.84	2.70	0.974	0.080	0.205	0.68	possible
19	35	1.46	1.96	2.65	0.934	0.243	0.476	1.63	impossible
12	23	1.46	1.84	2.69	0.937	0.312	0.191	0.63	possible
18	12	1.42	1.84	2.71	0.934	0.341	0.408	1.87	impossible
24	16	1.50	1.87	2.64	0.745	0.374	0.674	4.02	impossible
9	>50	1.45	1.87	2.74	0.931	0.237	0.208	0.73	possible
5	18	1.38	1.79	2.67	0.887	0.312	0.187	0.77	possible
8	29	1.43	1.87	2.68	0.947	0.082	0.200	0.65	possible

For analyzing the results of in-situ tests, different methods of calculating the CRR are exist [39]. The three scale factors of earthquake magnitude, effective overburden stresses and ground slope are effective on the CRR [35]. In addition, the outputs of standard penetration tests (SPT) were used for this region. According to [36], in a condition which the percent of fine grains of the soil exceeds 35%, the CRR can be obtained from the following equation

$$CRR = 0.065-0.234\, PI^{0.5} + 0.057\, PI + 0.34[e_0/N]^{-0.028} \quad (3)$$

By examining the ratio of CRR to CSR, we can obtain the factor of safety. In limit equilibrium conditions, the quantity of liquefaction factor of safety is equal to 1 and in depths which the safety factor quantity is less than 1, there would be a potential for liquefaction (Table 4).

Golestan province soils are young and consist of sandy material with low relative density that occurs in saturated conditions. Moreover, as it said the region is seismically active. Considering the above mentioned conditions, it can be deduced that the sandy soils of SU of Gorgan and SLU of Gonbad-e-Kavoos have high liquefaction potential. As shown in Table 4, in many cases, these two soils have high liquefaction potential considering the factor of safety against liquefaction less than 1. It is worth mentioning that those sandy soils in some depths having SPT N values more than 30 were treated as non-liquefiable and a factor of safety of max more than 2 were assigned to them. So the high liquefaction potential of SU and SLU sediments would be taken in to account in engineering practice, and improvement techniques should be taken before construction of any infrastructure up on these soils in Golestan area.

6. Conclusion

In this paper, the engineering geological conditions of young sediments of Golestan province were investigated based on geological and sedimentological studies, SPT test results and the geotechnical data collected over the study area. Based on the sedimentological and geotechnical properties of these sediments, four engineering geological units (UCU, MGU, LCU and SU) in Gorgan city and two unit (CU and SLU) in Gonbad-e-Kavoos city were identified and introduced in the form of an geotechnical model up to depth of 25m. The geotechnical characteristics of units of the model were analyzed and their main hazard were identified. The main conclusions can be summarized as follows

1) Based on 3D geological models of the both cities it has been found that subsoil of these areas mainly composed of fine-grained clayey soils (CL). The origin of these clayey soils is loess that covered more than 40% of the Golestan province surface.

2) From sedimentological standpoint and according to some evidences such as topography of the ground, red color sediments, rounded grains and heterogeneity of the sediments it is found that depositional environment of the Gorgan city was a alluvial fan which is formed by Ziarat River.

3) Gonbad-e-Kavoos depositional environment based on geological type of the sediments and field observation and also the presence of two branch of Gharasoo River around the city found that is a flood plain.

4) The results of Atterberg tests showed that the Golestan clay (data collected from the both districts) at shallow depth can be considered as low to medium plasticity clay.

5) The geotechnical tests results revealed that the Golestan clay undergoes light overconsolidation at shallow depth and normal consolidation at deeper depth.

6) Analysis of gathered data showed that drained shear strength of Golestan clay is low (C'=33 KPa and φ'=21°) and this cause to serious excavation problems especially if the excavation face meets low-cohesion coarse-grained units (MGU in Gorgan and SLU in Gonbad-e-Kavoos).

7) Based on the results of laboratory tests including oedometer and uniaxial tests it is obtained that compressibility of UCU and CU are high which result in large settlements and low bearing capacity in both cities especially in CU because of its collapsible nature.

8) Liquefaction potential assessment of the sediments showed that due to the presence of normally consolidated saturated coarse-grained sediments and seismicity of the region, Golestan province is susceptible to liquefaction. Also according to the results it has been found that the SU in Gorgan city is most liquefiable unit.

Finally it is worth mentioning the analysis results are useful for further research and study on subsurface condition in Golestan province as well as civil engineering practices. Clearly, developing the applied aspects of geological classification could be an extremely useful for engineers in the construction of civil structures. This study is considered as the first research document on Golestan subsoils engineering characteristics which could be used in small civil projects and as a first stage of site investigation in large civil projects or building infrastructures in the region.

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