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Geological conditions and geotechnical characteristics of young shallow sediments of the southern shore of the Caspian Sea

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Abstract
Global warming and the consequent climate changes have significantly declined the precipitation level in Iran and increased domestic migration to the southern shores of the Caspian Sea. This issue has accelerated construction activities and led to rapid infrastructure development in these areas. The sustainable development requires a comprehensive understanding of geological and geotechnical conditions. The information on geological and engineering properties of shallow soils has wide applications in construction activities and the preparation of geotechnical hazard zoning maps. The study aims to investigate the geological and geotechnical characteristics of young coastal sediments of the southern Caspian Sea basin up to a depth of 30 m using borehole information. To this end, the available boreholes were superimposed on the map of the southern coast of the Caspian. Next, two-dimensional geological sections were drawn manually by correlating the homogeneous layers. The results showed that the coastal shallow soils are mainly Sandy and include four geological layers: poorly graded Sand (SP), Sand with fines (SC/SM), low-plasticity Clay (CL), and Gravel layer (G). Based on the obtained results, the grain size of the sediments shows a clear relationship with the width and slope of the coastal plain. In this respect, fine-grained sediments are often more abundant on the eastern coast than on the central-western coast. Finally, the geotechnical characteristics of each layer, including Atterberg limits (LL and PL), consolidation, undrained shear strength, and drained shear strength, were calculated by analyzing the results of the laboratory tests conducted on the samples obtained from different depths.

Keywords: South Caspian Coast; Geotechnical Properties; Geology; Strength Parameters.

Introduction

Due to global warming and the consequent changes in climatic patterns, Iran has faced long periods of drought and severe water stress. This issue has caused domestic migrations from the interior dry and southern areas of the Iranian plateau to the southern shores of the Caspian Sea. In addition, tourist attractions, including forests and Sand beaches, have intensified immigration to these areas (Mansouri Daneshvar et al., 2019). Accordingly, during recent decades, an unprecedented population increase has occurred due to the mentioned reasons in the urban areas on the southern shores of the Caspian Sea. Because of this population rise, the development of infrastructure and superstructures is growing. Performing such large construction projects requires studying their comprehensive effects over time. This issue has been the subject of intense research in terms of sustainable development.

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Determining the engineering characteristics of shallow soils and drawing basic engineering maps based on these data are among the important prerequisites for the sustainable development of urban areas. Geotechnical maps and models are among the basic tools for this purpose. These models are drawn and based on geographical, topographical, geological, and geotechnical information. These maps contain useful data about the physical strength of the earth and existing geotechnical hazards. Since superstructures impose large stresses on the surface layers of the earth, it is very important to have a correct understanding of the geotechnical characteristics of these layers when building such structures (Baecher, 2023).

Morgenstern and Cruden (1977) raised the first questions about using engineering information in geotechnical models. These authors stated that geotechnical complexities are due to genetic processes related to the initial formation of geological materials and epigenetic processes arising due to diagenesis, metamorphism, and weathering processes. According to these researchers, although process models lack the necessary accuracy, they can help engineers predict the observed hazards and explain how earth layers and materials are arranged.

Detailed studies of the geotechnical characteristics of an area involve identifying the area's geological history, including sedimentology, geological formations, geomorphology, and climate information (Fookes, 1997; Fookes et al., 2000). Sedimentological studies generally separate sediments formed under the same conditions. Therefore, it is possible to transform a sedimentological model into a geotechnical model by segregating similar sedimentary units, forming a sedimentological model in the study area, and determining engineering geological and geotechnical characteristics in each layer (Delgado et al., 2003; Aldiss et al., 2012). According to Delgado et al., (2003), such engineering information can provide a more accurate estimation of the strength characteristics of each subsoil layer. These models are confirmed and completed through site investigations. Also, each geotechnical layer's engineering parameters and hazards are similar in that layer. Hence, if information is lacking for a specific segment of a layer to estimate the engineering characteristics and risks of the layer, it can be predicted using the information of the engineering model.

In recent decades, several efforts have been made to study geology, determine regional geotechnical properties, and draw three-dimensional engineering models of surface soils (de Rienzo et al., 2008; Parry et al., 2014; Dong et al., 2015; Juang et al., 2018; Juang et al., 2019; Amanti et al., 2020; Chaminé et al., 2022; Petrone et al., 2023). Similar studies have also been conducted for coastal areas hosting urban and rural population centers regarding their geographic location (Goughlan et al., 2023; Goughlan et al., 2020; Horozal et al., 2021; Paul et al., 2022; Petrie et al., 2022; Chu et al., 2021; dos Santos & Coutinho, 2022; Krassakis et al., 2023). Most of these studies have used different methods to determine surface soil's geological and geotechnical properties.

Various studies have been conducted on the sediments of the southern coast of the Caspian Sea. In this respect, researchers have studied their various aspects from the geological to the engineering point of view. For instance, some studies have been done on the geological stratification of the shallow sediments of the southern coast of the Caspian Sea and different sedimentary environments in the coastline, especially in the western parts of the southern coast of the Caspian Sea (Hashemi et al., 2014; Yanina et al., 2021; Razmi et al., 2023). For example, Lahijani et al., (2019) focused on the sediment distribution pattern on the Caspian Sea's southern coast. The results showed a clear relationship between coastal currents and hydroclimatic characteristics with the sediment distribution pattern in this area. Also, several regional and case studies exist concerning the engineering geological, geotechnical, and dynamic properties of the shallow sediments of the southern shore of the Caspian Sea (Hashemi et al., 2013; Esfehanizadeh et al., 2015; Poorbehzadi et al., 2019; Fattahzadeh et al., 2022).

In the present study, the geological conditions and geotechnical characteristics of the shallow sediments of the coastal areas of the Caspian Sea (the north of Iran) are investigated to extract the information needed for use in urban planning and construction projects in these areas. For this purpose, first, the geological history of the Caspian Sea and its coastal areas are determined by analyzing the available geomorphology, sedimentology, seismicity, and geology data from the entire area. Next, surface layers of the soil are characterized by collecting information related to geotechnical exploratory boreholes drilled in the coastal areas and performing basic geotechnical tests on the extracted samples. In this regard, determining engineering characteristics will be a useful guide for development, planning, and construction in the studied area. Also, it will play a critical role in evaluating geotechnical risks such as excavation instability, bearing capacity, settlement, and liquefaction potential. In the early stages of construction projects, this information will help have a reasonable estimate of the likely geological conditions. Such information also helps find sensitive and critical areas during the decision-making stage for building urban infrastructure on the southern shores of the Caspian Sea.

Geology and Seismicity of the Caspian Coastal Areas

Caspian Lake, also known as the Caspian Sea because of its size, is the largest lake in the world. This sea is located between 5 different countries. The total length of its coastline is 5580 km (the south coastline is about 650 km), and the mean elevation is about 40 m below the level of the open seas. The area of this lake is 436,000 km^2, which contains 77,000 km^3 of water. South Caspian basin occupies the largest volume of this lake (i.e., 64%), and its deepest point (1025 m) is located in this area (Masteali et al., 2023). The South Caspian coast, which is the focus of this research, is located in the geographical coordinate range of 54 to 48° 52′ E and 38 to 36° 30′ N, neighboring a major part of the three northern provinces of Iran.

The bedrock of the southern Caspian coast consists of different geological formations. This bedrock has no outcrop and is covered with about 20 km of sediments. Since there is no reliable information about the border of bedrock and sediment, its tectonic history and geological age are not certain. However, an accepted scenario among researchers is that the south Caspian basin is a back-arc of the Neo-Tethyan Ocean (Brunet et al., 2003). The oldest layers identified in the south Caspian basin are Oligo-Miocene sediments. These sediments are fine-grained and located at a 10-12 km depth. These materials reach the surface as mud volcanoes abundantly seen in different regions, including Golestan province (Milkov, 2005). The younger layers, which have a significant spread in the shallower parts of the basin, are related to the Miocene evaporite deposits. Later, in the Late Miocene and Early Pliocene, the combination of fluvial-deltaic sediments created thick sedimentary layers with a thickness of about 5-7 km. These layers form the reservoir rock for many hydrocarbon sources in this area (Reynolds et al., 1998).

According to Fig. 1a, the coastal parts of the south Caspian basin are often covered with young Quaternary sediments, hosting most of the populated cities of the region. The southern border of the Caspian basin correlates to the Alborz mountain range with the Mesozoic-Cenozoic age. This range mainly includes intermediate igneous rocks and carbonate sediments comprising its peaks. In the western parts of the studied area, a magmatic arc with Jurassic to Cretaceous age forms the highlands. In the eastern areas, some outcrops of the Kope Dagh Formation are observed as sedimentary rocks.

From the tectonic point of view, the most important geological features in the study area are the Caspian fault and the Alborz mountain range. The Caspian fault, with a length of about 600 km, separates the southern Caspian basin and the Alborz mountain range. This range is located in the middle parts of the Alpine-Himalayan orogeny system, which is one of the most important seismic areas in the world. In this respect, about 15% of the world’s earthquakes have occurred in this range (Alavi, 1996).

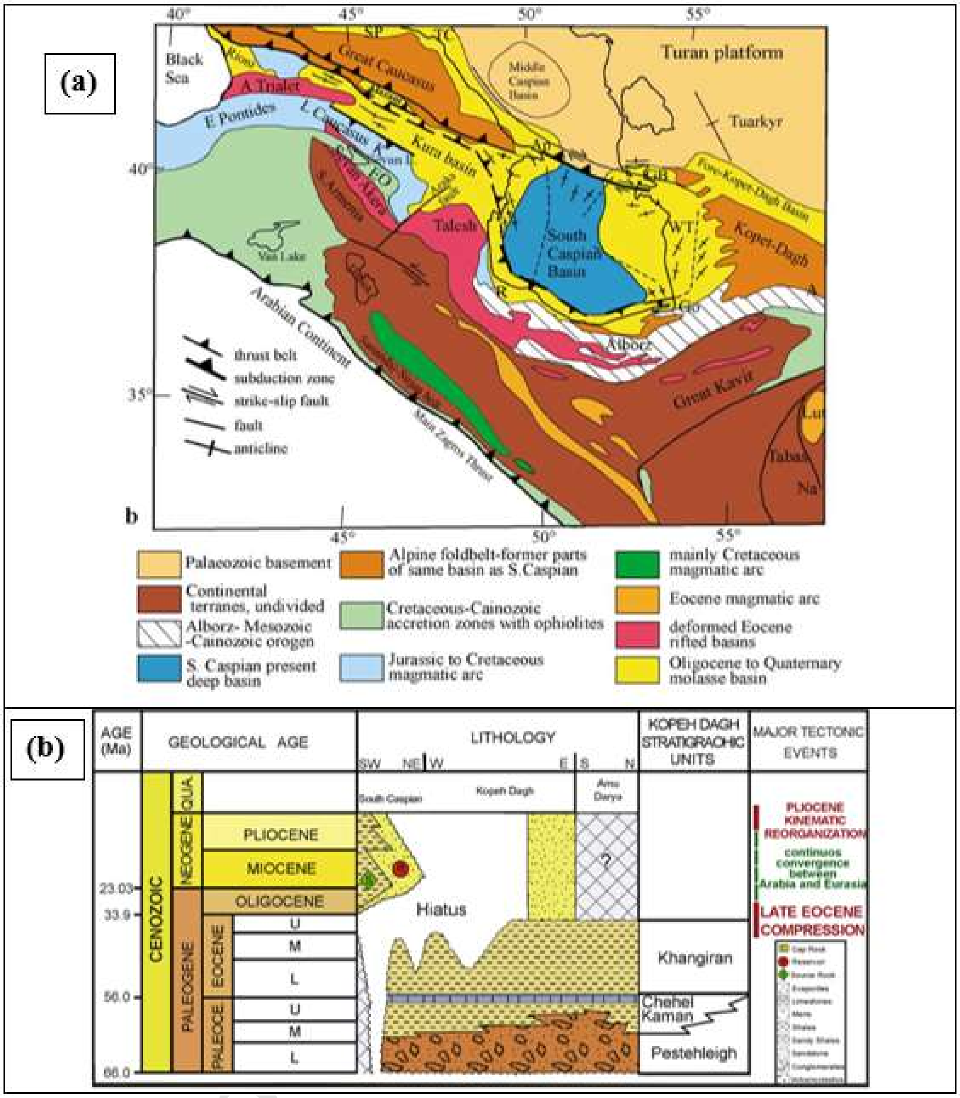

Figure 1. (a) Geological and tectonic map of the south Caspian basin (Brunet et al., 2003) and (b) Stratigraphic chart of the study area; major tectonic events shown on this stratigraphic chart can be correlated with the main regional observed hiatus (Slightly modified after Robert et al., 2014).

The Alborz mountain range is part of the Eurasia-Arabia collision zone, located 200-500 km north of the Neotethian rift (Axen et al., 2001). The main trends of the faults in the western part are in the Northeast-Southwest direction and the eastern parts in the Northwest-Southeast direction. Besides, this mountain range turns into the Kope Dagh fold belt in the east and the Talash thrust fault in the west (Jackson et al., 2001).

The surface sediments of the study area are mainly related to the Cenozoic geological period. The stratigraphic chart related to this time is shown in Fig. 1b. As can be seen, the surface sediments of the southern coast of the Caspian Sea are mainly sandy soil and fine-grained clayey soil.

In the Caspian coast, the strong motion of the earth on the main faults, including the Caspian fault, the Mazandaran fault, the Lahijan fault, and the Astara fault, has frequently caused strong earthquakes and significant damage. According to Khoshravan and Barimani (2012), the seismic hazard rate of this area is extremely high (Fig. 2a). Also, the south Caspian area shows high activity, especially in its eastern areas (i.e., Gorgan-Gamishan zone) with a very high risk of severe earthquakes.

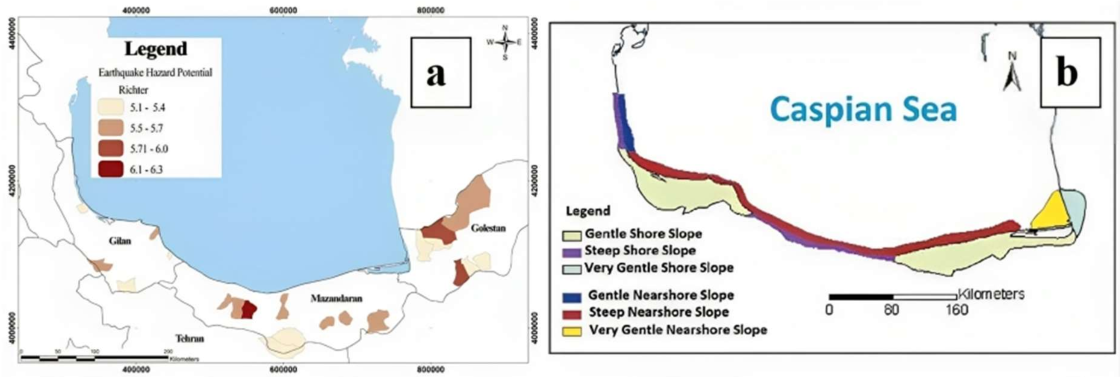

Figure 2. (a) Earthquake hazard potential map of the South Caspian basin (Khoshravan & Barimani, 2012) and (b) Slope morphology map for the South Caspian basin (Firoozfar et al., 2012)

Morphologically, the southern coast of the Caspian Sea is narrow, and the slope of the coastal front is mostly steep and rough. In addition, the coastal plain has a small width and a gentle slope in the south-north direction (Fig. 2b). In the land, the southern shore of the Caspian Sea can be divided into three different morphological regions. From south to north, these regions include 1) steep rocky slopes that generally form the border of the Alborz mountains, 2) the foothill facies, mainly including alluvial sediments and in-situ soil, and 3) coastal plains with a slope of less than 5°, which are mostly composed of Quaternary sediments (Firoozfar et al., 2012).

According to Fig. 1a, the geology of the south Caspian basin is mainly divided into two sections: 1) Mesozoic and Cenozoic rock formations and units and 2) Quaternary sediments. The first section includes rocky parts and is not directly related to the purpose of this paper, i.e., the young surface sediments of the area. Instead, this study aims to examine Quaternary deposits in the coastal parts, where Cenozoic formations and units have developed significantly. The stratigraphy of Quaternary sediments includes coastal sediments, river and delta alluvium, aeolian sediments (loess), alluvial fans, and alluvial sediments (Jackson et al., 2001). Since the geological characteristics of these materials, especially the coastal sediments, are directly related to the geotechnical characteristics of the soil in the study area, each sediment type is defined and explained in the following:

The coastal sediments of the Caspian Sea in the southern part reflect its diverse geology and mineralogically. As can be seen, these sediments mainly include fragments of carbonate minerals, Feldspars, Plagioclase, and Microcline. A closer look at the gathered hand samples indicates significant mineralogical changes in the sea's coastal sediments from the west to the east. Based on the results, coastal sediments on the west coast and the central part (Gilan and Mazandaran provinces) are mostly composed of heavy fragments, Pyroxene minerals, iron-bearing minerals, and different carbonates, chert, and quartz. Meanwhile, when moving to the east of the coast, the dominant type of sediments changes to light fragments, Quartz, Calcite, and Clay minerals (Lahijani & Tavakoli, 2012). In terms of grain size, most of these sediments are in the sand-size category. Therefore, in coastal areas, these soils can also be seen in all kinds of geotechnical hazards, i.e., subsidence, settlement, liquefaction, and landslides (Leroy et al., 2022).

This study aims to investigate and determine the geotechnical properties of the surface sediments of the coast of the south Caspian basin. To this end, the data related to the geotechnical boreholes drilled in these soils and different parts of the coast are collected. Then, the soil layers and their engineering properties were characterized by extracting soil samples from these excavations and performing various geotechnical tests. In general, the results of this study can be used to determine the geological and geotechnical changes of the southern Caspian coastal sediments up to a depth of 30 m. This depth was chosen because most engineering structures induce changes in the subsoil up to this depth. Therefore, most of the construction identification studies are limited to this depth. Second, the engineering data available up to this depth is more abundant and accurate.

Methodology and data collection

The data used in this paper are all obtained from existing drilled boreholes along with their field and laboratory tests. The boreholes are related to the geotechnical identification studies of construction projects, which private consulting engineering companies collected. Also, these data include borehole specifications collected by the public sector, such as municipalities, governorates, and the crisis management center (Table 1). A total of 35 boreholes were examined in this research, located in different parts of the coastline and close to it. Notably, none of the boreholes were deep enough to reach the bedrock. Fig. 3 presents the location of the boreholes used in this study on the map of the main and minor faults of the south Caspian basin.

Table 1. Various experiments performed in this article

Test name	Test type		Number of tests	Standard
	In situ	Laboratory		
Uniaxial compressive strength	-	✓	82	ASTM D7012
Direct shear test	-	✓	129	ASTM D3080-90
Soil gradation test	-	✓	157	ASTM D422-63
SPT	✓	-	654	ASTM D1586
Microtremor array measurements	✓	-	21-site	-
Odometer test	-	✓	72	ASTM D2435

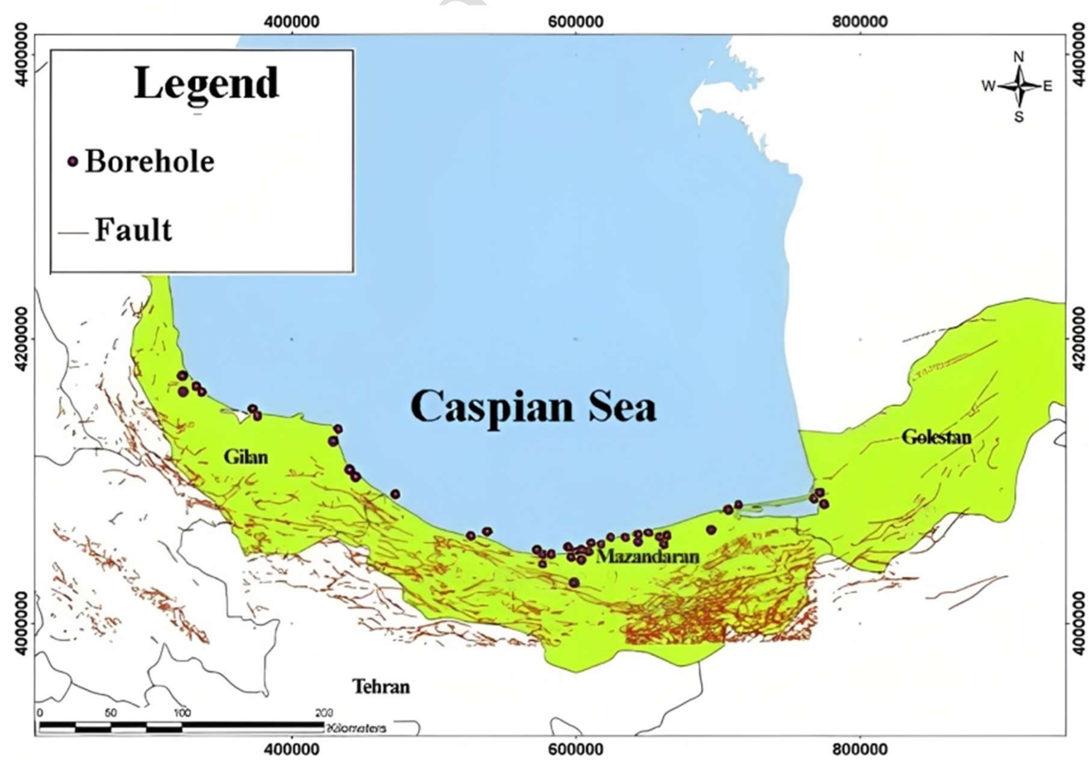

Figure 3. Location of the studied boreholes on the map of main and minor faults

In the next step, the data from the selected boreholes, in-situ tests, and laboratory tests were imported into a common database. The database includes borehole number, coordinate data (latitude and longitude), borehole depth, geological material type, groundwater level, number of blows of Standard Penetration Test (N_{SPT}), Atterberg limits (LL and PL), sieve test (grain size gradation), and hydrometry for all boreholes. In addition, the results of geotechnical tests performed on soil samples at different depths, including standard compaction tests, UCS, direct shear, and consolidation tests, were collected.

One of the applications of the existing computer programs is to correlate geological subsurface layers and build large-scale geological models. However, their capability in soil environments with great diversity in stratification is open to question (Buccianti et al., 2006). In this respect, a manual method was used to correlate the data of the adjacent boreholes. Accordingly, the subsurface layering of the ground was drawn for the coastal areas, and the engineering characteristics of each layer were determined separately. Regarding the large scale of the study, small local layers and small intermediate layers were ignored for the sake of simplification.

Some 2D cross-sections drawn with commercially available software at RockWorks (version 16.0) were also modeled to ensure the correctness of the manual correlation of geological layers. Fig. 4 provides an example of a 2D cross-section drawn manually and the output obtained from the software for the same cross-section.

Fig. 4 provides an example of two-dimensional sections of local geology in the east part of the Southern Caspian Sea. As can be seen, the dominant material of the ground is low-plasticity clay (CL). The horizontal scale is much smaller than the vertical scale, which seems unreasonable due to the incompatibility of the scales, the form of the layers, and the existing lenses.

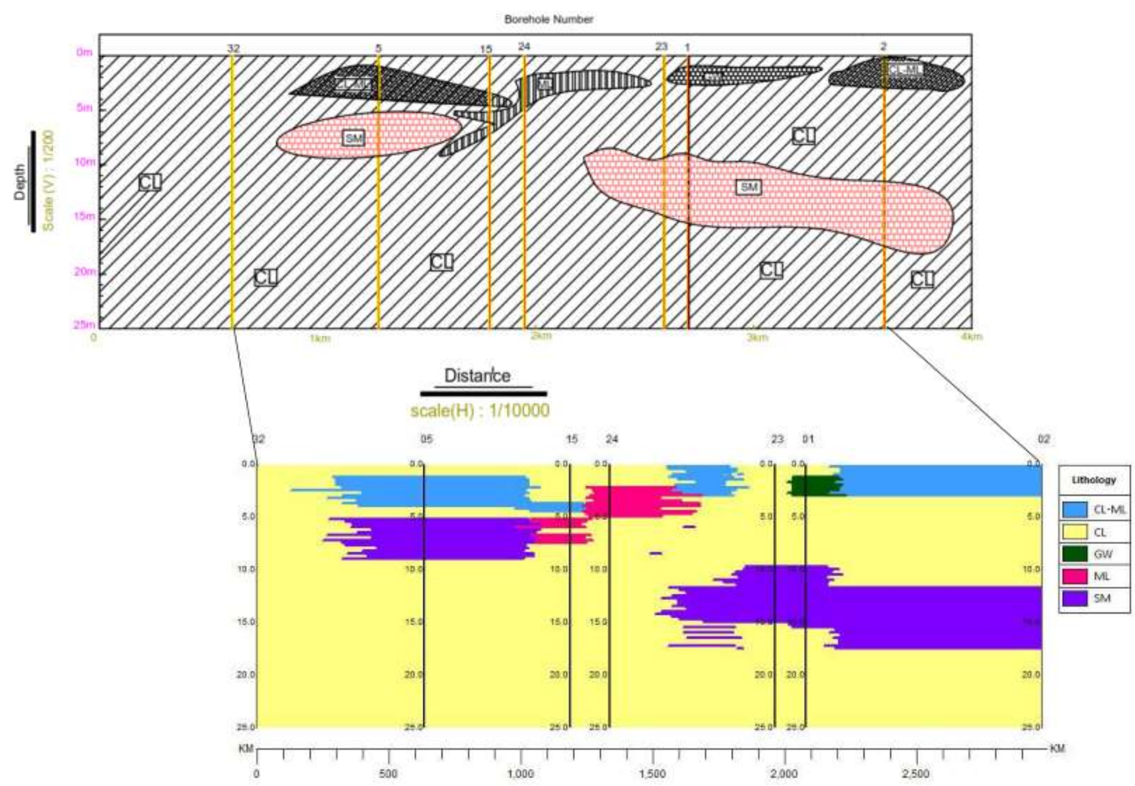

Fig. 4. An example of two-dimensional geological cross-sections drawn using the manual approach and RockWorks (version 16.0)

Then, a 3-D conceptual-observational geological model was prepared for the study area by overlaying two-dimensional cross-sections. Examining the geological type of the samples obtained from the exploratory boreholes shows that the changes of the layers in the Caspian coast area are very extensive such that it is not possible to consider a single geological model for it. Examining the boreholes shows that the dominant geological type of the coastal soils is sand, although there are significant changes in the grain size and thickness of the layers. The fine content in the sediments has increased in the eastern part of the Caspian coast, i.e., around Bandar Turkman to Bandar Amirabad. As a result, the ground surface is composed of clayey Sand (SC) with a depth of about 5 m. Moreover, by going to the depth of a layer of Clay, the lean Clay (CL) layer can be recognized with a thickness of 4 m, underlying layered Sand (SM) to a depth of 30 m.

Sandy sediments form the major part of the surface soil in the middle parts of the Caspian coast. This material is poorly graded Sand (SP) on the surface of the ground up to a depth of about 10 m, underlying a layer of lean Clay (CL) with a thickness of 3 m and the Sand layer (SM). Notably, in some parts of the shore, a layer of poorly graded Gravel (GP) is observed in the surface soils of the shore with a limited horizontal expansion. Generally, this layer is limited to the shores of Ramsar and Tonekabon cities. In the western parts of the Caspian coast, which occupies a major part of the coast of Gilan province, the coastal sediments are influenced by the large Sefidroud delta. This section has a specific sequence of marine sediments (coarse-grained sediments) and deltaic sediments (fine-grained sediments) created during periods of increased and decreased activity of the Sefidroud River. Generally, in this area, layered Sand (SM) can be seen up to a depth of 10 m, underlying a lean Clay layer (CL) with a 6-9 m thickness. As can be seen, the thickness of this layer decreases when moving west. Below this layer, a silty Sand layer (SM) is seen with a thickness between 10 and 20 m, whose thickness increases by moving toward the west. Notably, Clay interlayers with high plasticity (CH) are also seen in this area. These interlayers are considered among the facies related to deltaic environments.

From the sedimentology perspective, several sedimentary environments can be seen on the Caspian coast, including the coastal, river, floodplain, and alluvial fan environments. These environments have led to the geological diversity of the study area. Studies have shown (Holland & Elmore, 2008; Pradhan et al., 2022; Zhou et al., 2022) that fine Sand-size sediments have the best sorting among sediments, which is also the case in the coastal sediments of the Caspian Sea. Besides, in Sandy soils, there is an inverse relationship between grain size and sorting (Bjorlykke, 1974). This issue is also seen in the Caspian coast sediments. Examining the collected Sand samples shows that in the central and western parts of the Caspian coast, these sediments have good sorting and negative skewness, suggesting that the origin of these sediments is from dunes formed by Sea currents and the action of waves. Sea currents and wind have been the factor active in their transportation and sedimentation. It should be noted that the Sands deposited by the rivers on the coastline have poor sorting (Folk, 1980).

A closer look at Fig. 2b indicates a clear relationship between the slope and the width of the shore with the grain size distribution of its surface soil. The main part of the western coast, which is within the delta of the Sefidroud River, forms a wide and shallow coast, while the central part has a shallow and steep coast. In the eastern part, which has the shallowest shore, the shore is wide and gentle. As can be observed, the grain size distribution of surface soils depends on the width of the shore (sediment transport distance) and the shore slope. Consequently, fine-grained sediments dominate the east coast, where the transport distance is long and the slope angle is low. On the other hand, in the central and western areas of the coast, coarse-grained sediments with low sorting are dominant. For instance, the shore of Ramsar City, located in the narrowest coastal area, is mostly Sandy and has weak grading. Other studies in sedimentary areas have similar observations and confirm the results obtained in this article (Lahijani & Tavakoli, 2012; Naderi Beni et al., 2013; Lahijani et al., 2023).

Geotechnical characteristics of sediments

The coastal surface soils of south Caspian were subjected to geotechnical characterization through an observational approach. As explained in this approach, soil engineering characteristics are determined in a simplified manner based on mean real observations (Peck, 1969). For this purpose, the study area was divided into layers or separate engineering units based on the prepared geological model. For this purpose, the results of the geotechnical tests were plotted on the borehole logs according to the test's depth. Regarding the number of tests and the variety of their types, the obtained strength parameters were averaged through engineering judgment. Then, regardless of the geological type, layers with similar engineering characteristics, especially the SPT number, were considered an engineering layer or unit.
Regarding the large area of the studied region, it is not possible to draw a 3D geological model. However, using the data from geotechnical boreholes, several 3D geological models were drawn locally to determine the relationship between the layers more precisely and to validate the data of the adjacent boreholes. Fig. 5 presents two three-dimensional geological models drawn as examples.

In Fig. 5, the model on the left is related to Chalus City in the central area of the southern shores of the Caspian Sea. Meanwhile, the model on the right is for the city of Rezvanshahr on the west coast of the studied area. In general, the geological model is prepared to solve an engineering problem. Such a model is an approximation of the geological conditions made according to the geological characteristics and based on the engineering characteristics. As shown in these examples, the thickness and sequence of geological layers vary throughout the studied area.

According to the information on the boreholes, 4 engineering layers can be distinguished up to a depth of 30 m in the coastal area of the south Caspian. These layers include a unit of poorly graded Sand (SP), a lean Clay unit (CL), a Silty/Clay Sand unit (SC/SM), and a Gravel unit (G) (Fig. 6a). It is of note that significant changes are seen in the sequence and thickness of these layers due to the massive size of the study area. In addition, as mentioned earlier, layers and lenses with other geological materials, such as high plasticity or sensitive Clay (CH), are also observed in different areas. However, this research did not investigate these materials due to their limited expansion. Another noteworthy point is that the geological layers closely follow the engineering layers.

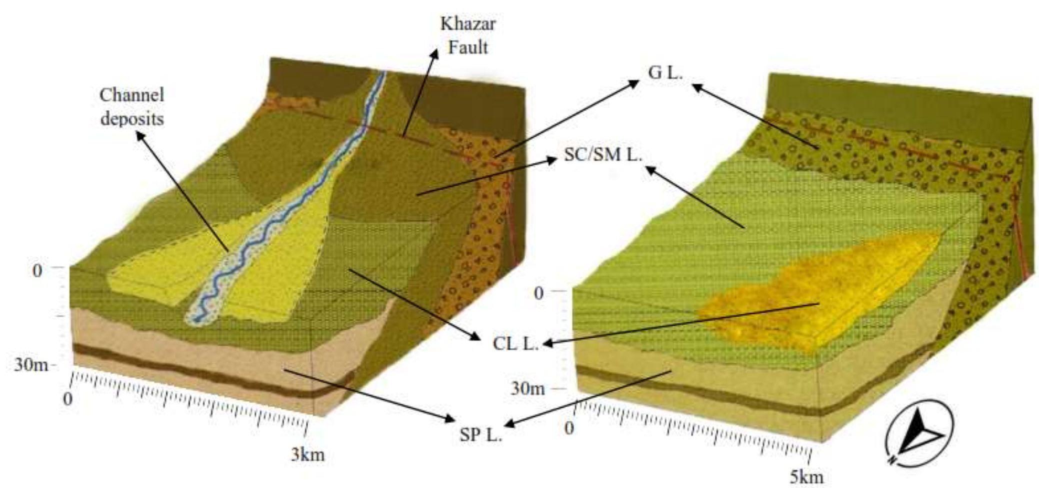

Figure 5. An example of three-dimensional geological models for flood plain depositional environment in studied area (slightly modified after Hashemi et al., 2014)

As the surface layer in most areas, the SP layer is mainly composed of sand sediments. This layer has special importance since it is the foundation of most structures built in the study area. The thickness of this layer varies between 9 and 25 m, and its SPT number is in the range of 16-41. The expansion of low-plasticity or lean Clay unit (CL) with a thickness of 2-8 m increases almost from the west to the east of the Caspian coast. In some eastern parts, it even forms the surface layer. Based on the samples obtained from boreholes and field observations in the location of natural trenches in the coastal areas, this layer is largely uniform in grain size and contains Clay minerals. From the consistency perspective, the manual examination of the samples shows that it is weak to moderate. As a result, the SPT number in this unit is 6 to 21 for this unit. The next engineering unit is Sandy soil with fines content. According to the unified soil classification system (USCS), this unit contains SC and SM soil. Also, it is hard to medium granular soil in terms of strength. The thickness of this unit varies between 4 and 12 m, and its lateral expansion increases from south to north and east to west. The grain size of this layer is highly heterogeneous and contains rounded grains consisting of hard minerals such as Quartz and Feldspar.

The SPT number in this layer varies between 19 and 46. The Gravel unit (G), with a thickness between 3 and 7 m, is mostly seen in the central and western regions of the Caspian. Also, its lateral expansion shows an increase from east to west. The grain size of this layer is highly heterogeneous and has semi-rounded grains mainly containing rock fragments and tough minerals such as Quartz and Feldspar. The soils of this unit are classified as GP to GC, according to the USCS. The SPT number of this unit varies between 38 and more than 50, sometimes showing a noticeable increase with depth. Also, plugging the sampler tip into the rubble is a common phenomenon in this unit. In the following, some geotechnical features of each layer are presented separately.

At the end of this section, it is worth mentioning that the 4 identified engineering layers are only the most abundant layers observed throughout the southern coast of the Caspian Sea, and there are layers of different geological types with local extent. The thickness and sequence of these 4 layers are very variable regarding the vastness of the studied area. These characteristics are selected based on frequency, borehole data, and engineering judgment. For instance, in some geotechnical boreholes, the entire depth of 30 m is composed of fine Clay soil or Sandy soil. As a result, all 4 detected soil types are expected to be seen in all depths, but they were more frequent in the mentioned depths. In addition, although the name of these layers is chosen similar to the soil unified classification, it is only one name that refers to the most frequent geological type of the layer and does not necessarily match the unified classification.

Atterberg limits

Fig. 6 shows the plasticity index (PI) graph versus liquid limit (LL) for fine-grained soil samples collected from different depths up to 30 m from the southern Caspian coast (Fig. 6b and 6f). Due to the extent of fine-grained soil on the east coast and the large scale of the study, this diagram is drawn separately for the east coast and the central-west coast. In this diagram, the A-line separates Clays and Silts. Also, the U-line is a line above which no soil plasticity data can actually exist. Figs. 7a and 7b summarize the results of the Atterberg test of fine-grained soils for the two eastern and central-western areas of the south Caspian coast, respectively.

According to Figs. 7a and 7b, up to a depth of 30 m, the young fine-grained sediments of both parts of the Caspian coast show different PL behavior against the LL. As can be seen, the LL and PI values are in the range of 14 to 40.5% and 3 to 12.5%, respectively, for the Clay of the eastern region. Meanwhile, for the Clay of the central-western region, the LL and PI values are 29 to 53.5% and 6.5 to 27.5%, respectively. Overall, it is inferred that there is an ascending linear relationship between PI and the LL for the fine-grained soils of the central-west coast, while such a relationship is not seen on the east coast.

Figure 6. (a) an example of different soil types, (b) Atterberg limit tests procedure, (c) direct shear test instrument, (d) unconfined uniaxial compressive test, (e) consolidation test procedure, and (f) hydrometer test procedure

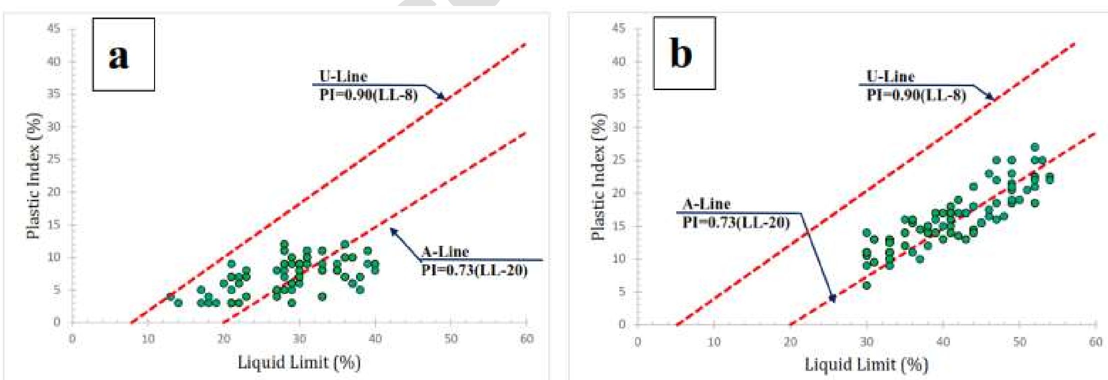

Figure 7. The graph of the changes in the plasticity limit according to the liquid limit of the fine-grained soil of the southern coast of the Caspian Sea: (a) fine-grained soil of the east coast and (b) fine-grained soil of the central-west coast

According to the above data, most of the PI-LL values of the central-west coast samples tend to be located near the A-line. Therefore, it can be concluded that fine-grained soils on the central-western coast have higher plasticity than on the eastern coast.

According to Fig. 7, since the LL of most of the samples in both regions of the southern shore of the Caspian is less than 50%, the Clay is of the low-plasticity type (CL) or lean Clay. Finally, it can be said that the data points of the fine-grained soil samples of the eastern coast are quite close to the A-line. This closeness suggests the presence of more Silty particles in these sediments than on the Central-Western Coast. This data can be explained based on the geological situation of the southern Caspian coast. According to Fig. 1, which shows the geological map of the Caspian coast, the central-western coast has been mostly affected by the river and deltaic sediments (especially the Sefidroud delta). These deposits originated from igneous rocks of the Alborz mountain range. On the other hand, the eastern coast is more affected by the sedimentary rocks (often carbonate) of Kope Dagh. To our knowledge, weathered soils from igneous rocks mostly contain sensitive Clay minerals such as montmorillonite, while soils from sedimentary rocks contain lighter Clay minerals such as illite (Wilson, 2004; Spagnoli & Shimobe, 2022). Therefore, the plasticity of the fine-grained soils of the central-western coast of the Caspian is more than that of the eastern coast.

Consolidation

Fig. 8 presents the consolidation potential of soils of the study area up to a depth of 30 m. These results are obtained through the data of the one-dimensional (oedometer) consolidation test on the fine-grained soils of the southern Caspian coast (Fig. 6e). In-situ effective stress σ´v (KPa) and past maximum stress (σ´pc, KPa), pre-consolidation ratio (OCR) along with compression index (Cc) and swelling index (Cs) versus depth are displayed in Figs. 8a to 8c. In Fig. 8a, the vertical effective stress for each sample is calculated in terms of the unit weight of the soil volume multiplied by its sampling depth. Besides, the maximum experienced stress is calculated based on the oedometer test results. In this study, the plotted data are average values obtained from the fine-grained soil section of Caspian coastal soils, taking into account only the type of soil rather than the geographic location of the collected sample.

Examining the trend of changes in effective stress against depth along with the maximum stress experienced by the soil (Fig. 8a) shows that these two parameters significantly differ at shallow depths, although converging with depth. OCR (Fig. 8b) is a geotechnical parameter related to the change in the stress level of the soil compared to the maximum stress tolerated over time.

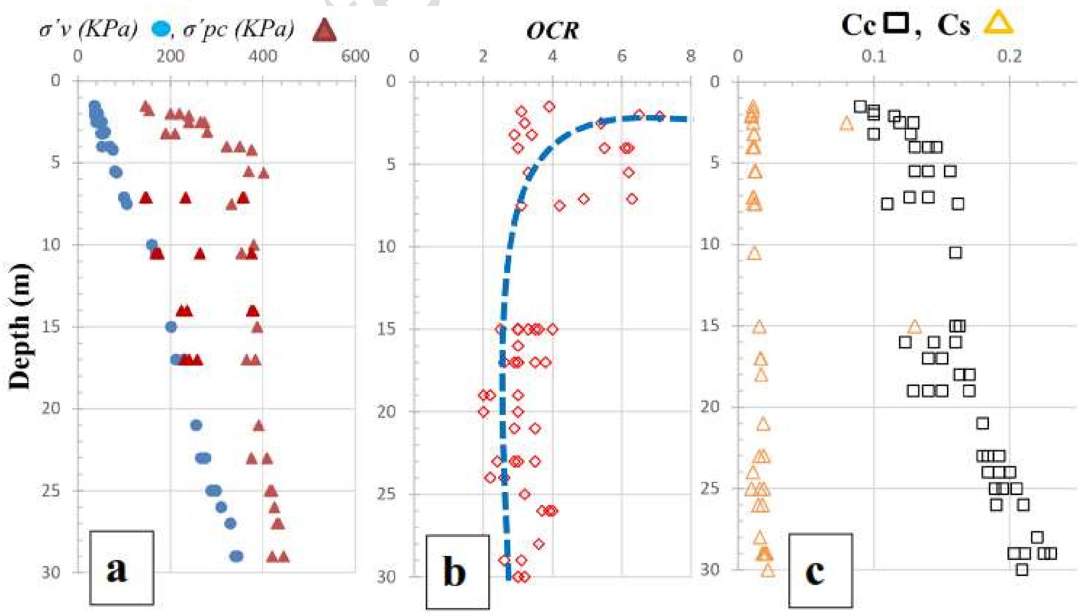

Figure 8. Consolidation of fine-grained soils of the southern coast of the Caspian Sea: (a) effective in situ stress (σ´v) and maximum experienced stress (σ´pc) versus depth, (b) overconsolidation ratio (OCR) versus depth, and (c) compression index (Cc) and swelling index (Cs) versus depth

OCR is estimated by analyzing the graphs obtained from the oedometer test using a graphical method proposed by Casagrande (1936). According to Fig. 8b, as the depth increases, the OCR decreases. The OCR seems independent of depth at 9 to 30 m depths, where the OCR value is almost constant. Therefore, it is inferred that the fine-grained soil of the studied area is pre-consolidated at shallow depths and normally consolidated at greater depths. This geotechnical observation can be explained based on the geological nature of the Caspian coast and the presence of Sand dunes. These dunes are created by strong winds and are moved along the coastline, leading to over-consolidation of surface sediments due to accumulating these dunes. Also, Cc and Sc are calculated using the consolidation test results (Fig. 8c). Cc and Cs are, respectively, the slope of the normal consolidation line and the loading line in the logarithmic drawing of the effective vertical stress against the void ratio. According to Fig. 8c, Cc increases with depth. Up to a depth of 30 m, Cc varies from 0.090 to 0.230 and Cs from 0.011 to 0.097, with an average value of 0.160 and 0.054, respectively.

Undrained shear strength

The undrained shear strength (Su) is one of the most widely used indices for determining the consistency of fine-grained soils. Su is obtained using laboratory and field tests, especially the unconfined uniaxial compressive test (Fig 6d). The undrained shear strength (Su) and normalized values by effective vertical stress versus depth are plotted and shown in Figs. 9a and 9b, respectively. Although some fluctuations can be seen in Fig. 9a, the test results demonstrate that Su increases with depth. Based on these results, the Su values of the southern Caspian coast's fine-grained soils are 18 to 192 kPa. Moreover, the diagram in Fig. 9b was drawn to nondimensionalize the UCS results by normalizing the Su values with respect to the effective vertical stress at each depth. As can be seen, the data are scattered up to a depth of about 9 m, but with increasing depth, the results are in a specific range with an average value of 0.37. In other words, this graph shows that the stiffness of fine-grained soils is similar except for the surface depths. Here, the increase in soil consistency with depth is due to the increase in confining stress. Also, the dispersion of data up to 9 m depth can be attributed to the overconsolidation of the soil at these depths.

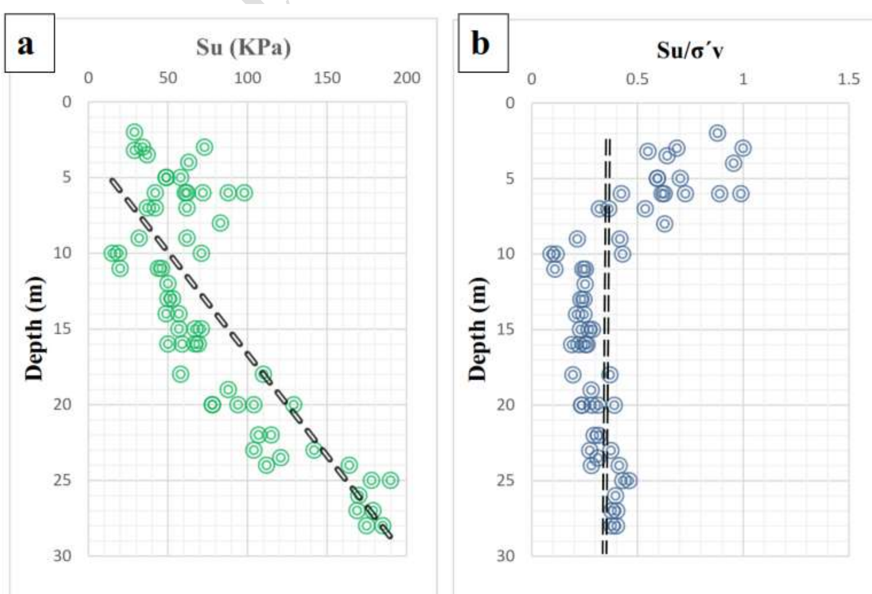

Figure 9. Undrained shear strength (Su) obtained from unconfined compression (UC) test: (a) undrained shear strength versus depth and (b) normalized Su values versus effective stress versus depth

Drained shear strength parameters

The direct shear test is one of the most widely used tests to determine the shear strength parameters of all soils (Fig 6c). This test is performed under plane strain conditions. In this method, the failure plane is defined in the horizontal direction and is especially used in geotechnical engineering projects. Two main advantages of this test are the convenience of sample preparation and the test method. According to the Mohr-Coulomb failure criterion, the shear strength of the direct shear test is obtained as follows:

$$\tau = c + \sigma'v \tan\varphi \tag{1}$$

Where σ'v, φ, and C are the vertical effective stress, soil internal friction angle, and cohesion in the effective stress state, respectively. The maximum shear stress is considered the failure point. The values of C and φ obtained from the direct shear test on intact and failed samples were analyzed at different soil depths up to 30 m. Fig. 10 illustrates the values of φ obtained from the direct shear test carried out at different subsurface soil depths of the south Caspian coast for the engineering unit. There is no data in the graphs regarding the limited expansion of some layers in some depths. According to the mean values of these graphs, the largest φ is related to the Gravel layer (G) with an average value of 33°, which is due to the coarse grain and gravel nature of this layer. Moreover, the φ values of the Clay layer with low plasticity (CL) were the lowest, with an average of 18°. Finally, the average values of φ for the Sand layer with fines (SC/SM) and poorly graded Sand (SP) are 22.5 and 25.5°, respectively. In this study, undisturbed samples with a diameter of 6 cm and a height of 2 cm were prepared for the fine-grained soil samples using a cylindrical cutting ring and a smooth saw. Also, four different vertical effective stresses of 50, 100, 200, and 300 kPa were used in the experiments, and the shearing rate was considered to be 0.01 mm/min.

Fig. 11 shows the cohesion values obtained from the direct shear test performed at different depths of the subsurface soils of the south Caspian coast for each engineering unit. As expected and visible in these graphs, the largest cohesion (C) is related to the low-plasticity or lean Clay layer (CL) with an average value of 24.5 kPa. The other three layers have small C due to their coarse-grained nature, as it is less than 10 kPa for most of the samples. Based on the direct shear test results, the average C for the Gravel layer, Sand layer with fines, and poorly graded Sand is equal to 5, 10.5, and 3 kPa, respectively.

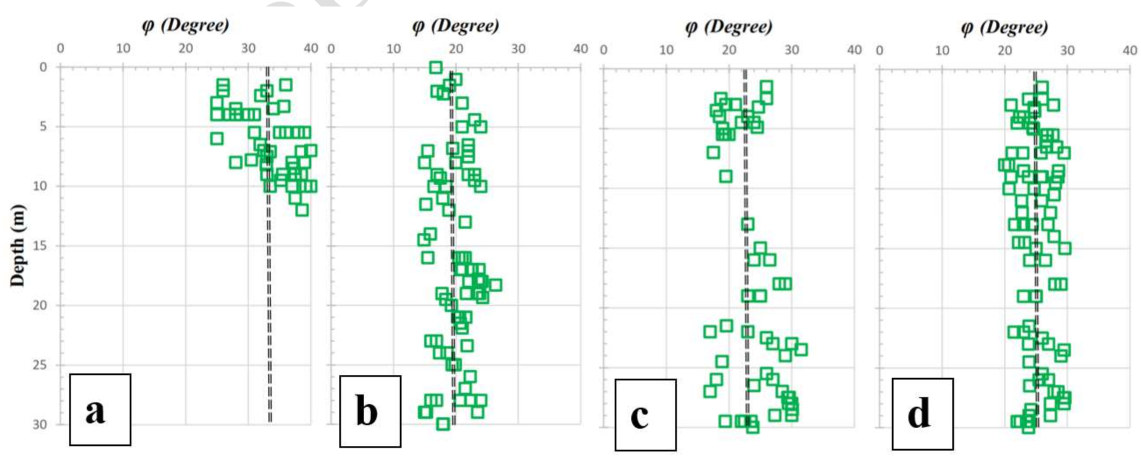

Figure 10. Diagram of the φ obtained from the direct shear test against depth: (a) Gravel layer, (b) low plasticity Clay layer, (c) Sand layer with fine content, and (d) poorly graded Sand layer

Table 2 presents the values of various geotechnical parameters for young coastal sediments of the southern Caspian Sea basin up to a depth of 30 m. Based on the engineering characteristics of the subsurface soils of the south Caspian coast, these materials are divided into 4 dominant geological types. The characteristics of each layer are given separately in Table 2. It is noteworthy that the data presented in Table 2 include the minimum and maximum values of the studied quantity. These values were obtained from the results of geotechnical tests conducted in the laboratory.

Table 2. The main engineering characteristics of the geological layers of the South Caspian coast

Soil parameters		**Layer name**			
		CL	**G**	**SC/SM**	**SP**
Grain size distribution	**Gravel (%)**	0	40-60	0-5	0
	Sand (%)	0	20-30	45-65	85-95
	Silt and Clay (%)	100	0-10	30-15	0-5
Natural moisture content (%)		14.1-26.7	4-17.5	7.8-20.5	14-18.5
Liquid limit (LL, %)		14-53.5	NA	NA	NA
Plasticity index (Ip, %)		3-27.5	NA	NA	NA
Specific gravity		2.24-2.98	2.51-2.88	1.96-2.67	2.15-2.44
Unit weight (KN/m3)		15.1-17.9	16.3-18.8	16.0-18.6	17.1-18.9
SPT blow count		6-21	38->50	19-46	16-41
Strength parameters	**Cohesion (kPa)**	14.5-32	0.9-8.0	5-21	0-3.3
	Friction angle (°)	15-24.5	24-39.5	17-30	21-29
	Unconfined shear strength (kPa)	21-197	NA	73-276	NA

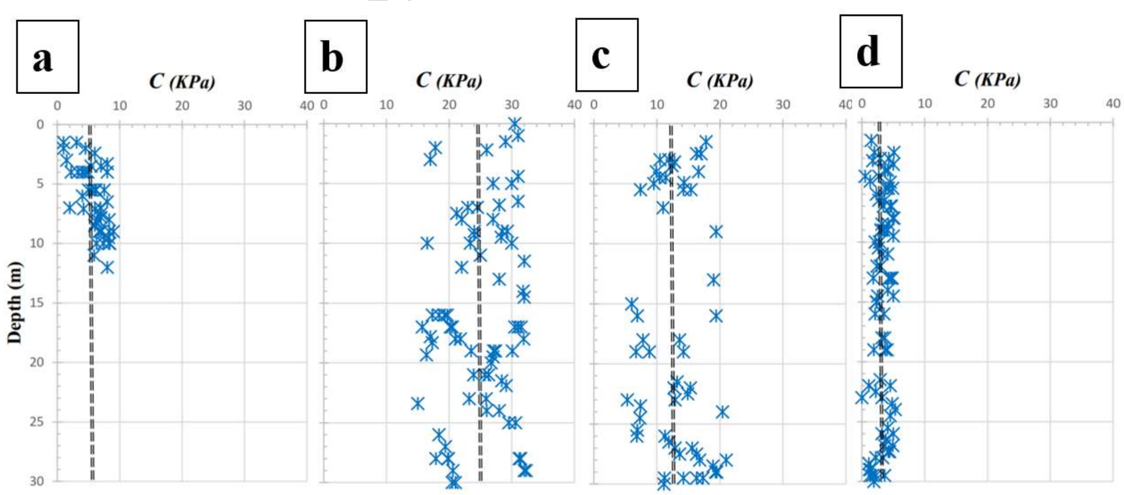

Figure 11. The graph of changes in cohesion values obtained from the direct shear test against depth: (a) Gravel layer, (b) Clay layer with low plasticity, (c) Sand layer with fine content, and (d) poorly graded Sand layer

Conclusion

In this study, the geological conditions and the geotechnical properties of young coastal sediments of the southern Caspian Sea basin are investigated based on geological and sedimentological studies and the results of laboratory and field geotechnical tests conducted in the study area. Based on the geological and geotechnical characteristics of these sediments, the soils of the study area are classified into four specific geological units: low plasticity Clay unit (CL), Gravel unit (GP), Sand with fine content unit (SC/SM), and poorly graded Sand unit (SP). The Caspian coasts were identified and introduced up to a depth of 30 m. After analyzing the geotechnical characteristics of these geological layers, the main results can be summarized as follows:

Examining the boreholes cores revealed that the subsoil of the south Caspian basin is mainly composed of Sandy soil. The origin of these Sandy soils is resistant minerals eroded from the geological formations of the Alborz mountain range in the south of this basin. A closer examination of the Sand sediments showed an inverse relationship between the grain size and their sorting, suggesting the distance of their transportation. This result has also been reported in other studies on coastal soils.

The data obtained from the boreholes showed that up to a depth of 30 m, despite the geological diversity of Caspian coastal soils, 4 separate geological types can be recognized. These four layers include low plasticity Clay (CL), Gravel layer (GP), Sand layer with fine content (SC/SM), and poorly graded Sand layer (SP). Besides, due to the vastness of the studied area, the spatial expansion and thickness of these layers are highly variable. Therefore, some other layers with local expansion were ignored in this study.

Examining the soil type shows a clear relationship between the width of the coastal plain and the land slope with the grain size. For instance, since the coastal plain is wide and the land slope is low, the coastal sediments are finer-grained on the east coast. On the other hand, in the central coast parts, the coastal sediments are coarser due to the narrow coastal plain and steep slope.

From the sedimentology perspective and according to some evidence such as the topography of the land, red sediments, rounded grains, and non-uniformity of the sediments, it is inferred that sea currents more influenced the sedimentary environment in the eastern and central parts of the coast. In comparison, on the western coast, the Sefidroud delta has played a major role in the evolution of coastal sediments.

The Atterberge test results showed that the fine-grained soils on the central-western coast have more plasticity properties than the eastern coast. Also, since the LL of most of the samples in both regions of the southern Caspian coast is less than 50%, the Clay is of low plasticity (CL) type or lean Clay. The difference in their plasticity is attributed to the origin of sediments: The soils of the central-western coast originate from igneous rocks of the Alborz mountain range, while those on the east coast mainly originate from sedimentary rocks (often carbonate) of Kope Dagh.

The analysis of the results of oedometer tests revealed that the coastal soils of the southern Caspian Sea were subjected to slight pre-consolidation at shallow depths and consolidated at more normal depths. This difference could result from surface over-consolidation caused by the loading of coastal Sand dunes.

According to UCS test results on fine-grained soil samples, the Su of the samples has an ascending trend with increasing depth. However, by normalizing these values with respect to the effective vertical stress at the desired depth, the Su changes become linear and show an average value of 0.37.

Analyzing the results obtained from the direct shear tests conducted at different depths indicated that the Gravely layer has the highest value of the internal friction angle. Also, the cohesion (C) values of the lean Clay layer (CL) were the highest, while the C values of the poorly graded Sand layer (SP) were almost zero. Overall, examining shear resistance parameters of different layers revealed that Caspian coastal sediments have a weak to medium strength.

Declarations

Competing interest: the authors declare no competing interests.

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