

# Engineering-Geological Characteristics of Quaternary Deposits in the Southern Caspian Sea Shelf

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## Abstract

This study characterises the engineering-geological properties of Quaternary deposits in the southern Caspian Sea to provide a reliable basis for offshore geotechnical design. A total of 300 core samples from 70 boreholes across 45 offshore sites in the Baku Archipelago, the Apsheron–Pre-Balkhan zone, and the Turkmenian and Iranian sectors were examined. Undisturbed samples collected during 1984–1996 and 2019–2022 were tested using standard geotechnical methods to determine their physical, mechanical and mineralogical characteristics. The deposits are dominated by clays and loams, with subordinate sands. Clay-rich units comprise up to 50% of the sequence, particularly in deeper basins. Fine fractions ( $<0.005$  mm) range from 32% to 93%, with hydromica and montmorillonite as the principal clay minerals. Carbonate contents vary from 0% to 39% and increase in areas influenced by mud volcanoes. Measured properties include natural moisture contents of 0.15–0.95, dry densities of 1.0–1.7 g/cm<sup>3</sup> and porosities of 35–70%. The soils show low to moderate plasticity and are generally normally consolidated. The angle of shearing resistance ranges from 7° to 29°, and cohesion from 0.005 to 0.175 MPa. The results support prediction of engineering parameters from limited data and strengthen seabed stability and foundation assessments for the Caspian shelf.

**Keywords:** Geotechnical, Quaternary Deposits, Lithology, Soil Composition, Physical and Mechanical Properties, South Caspian Basin, Engineering-Geological Properties.

## Introduction

Rocks have long been the subject of study as both the foundations and the host media for engineering structures, as well as sources of construction materials. The study of soils is conducted on a broad historical and geological basis, employing a variety of methods. Under natural conditions, soils are investigated using field techniques. However, laboratory methods are also of great importance. In the laboratory, the chemical, mineral, and granulometric composition, as well as the physicochemical, physical, hydro-physical, and mechanical properties of soils, are studied. These characteristics are essential both for the general engineering-geological assessment of soils and for the design and calculation of structures. The scope and relative significance of field and laboratory methods depend on the complexity of the engineering-geological conditions, the type of soils, and the nature of the structures being designed [1].

In recent decades, marine engineering geology has emerged as a key field within modern geoscience. This trend is driven by the rapid industrial development and exploitation of offshore oil and gas fields, as well as by the growing scale of construction on continental shelves.

The study of marine sediments has gained increasing importance for addressing fundamental engineering-geological and geotechnical challenges. As offshore development intensifies, the need to establish marine engineering geology as an independent and integrated research domain has become particularly evident.

Geological exploration across various parts of the Caspian Sea has revealed numerous oil and gas fields, along with indicators suggesting the potential for additional discoveries. The development of these offshore resources requires the construction of complex and costly hydraulic structures, whose reliability large-

ly depends on the engineering and geological conditions of the seabed.

In designing offshore oil and gas facilities, it is crucial to investigate the physical and mechanical properties of seabed sediments and to determine their geotechnical characteristics. Consequently, the principal objectives of marine engineering geology include understanding the formation and distribution of these properties, evaluating seabed sediments from an engineering-geological perspective, and developing a systematic classification of marine deposits.

Quaternary sediments are widespread throughout the hydrocarbon-bearing zones of the Caspian Sea, while Tertiary formations reach the seabed surface only in limited areas. Therefore, Quaternary deposits generally serve as the primary bearing strata for offshore oil and gas infrastructure.

Investigations of the engineering-geological properties of seabed sediments—together with analyses of their spatial and depth-related variability—enable the construction of engineering-geological maps and cross-sections for hydrocarbon-bearing regions of the Caspian Sea [2]. Establishing correlations between the principal physical and mechanical parameters of these sediments and determining their standard values enables the assessment of seabed conditions in advance. Such data are essential for engineering-geological evaluations and calculations at the design stage of offshore oil and gas facilities.

The main spatial regularities in the development of geological and engineering-geological processes on the shelf and coast of the Caspian Sea are formed under the influence of endogenous, exogenous, and anthropogenic factors.

The tectonic structure of the Caspian Depression and the adjacent land areas determines endogenous processes. Evidence of the region's high tectonic activity at the present stage includes data on seismicity, contemporary vertical crustal movements, and numerous manifestations of mud volcanism. Local endogenous processes occurring within the water area and along the coast of the Caspian Sea include the activity of mud volcanoes, the majority of which are concentrated within the South Caspian Depression. At present, 142 mud volcanoes have been identified in this region.

The surface of the outer shelf is characterized by the levelling of the relief under the influence of subaqueous exogenous processes. The edge of the shelf mainly belongs to the zone of stationary erosion. In this area, specific circulation movements of water masses develop, exhibiting high velocities within a thin near-bottom layer. The effects of bottom landslides and sus-

pension currents are most clearly manifested on the slopes of deep-water depressions.

Subaerial processes — erosional, gravitational, karst-suffosion, and aeolian — are actively developed within the coastal zone. Anthropogenic processes include the subsidence of the seabed and coastal surfaces associated with oil and gas extraction; the formation of sediment deficiency caused by the removal of construction materials and shell deposits from the coastal zone; and coastal erosion related to the construction of port facilities and the interception of longshore sediment transport. An additional anthropogenic factor is the rise in groundwater levels resulting from leakages from sewage and irrigation systems, leading to building damage and the waterlogging of coastal areas. These processes may also be intensified by the transgressive rise of water levels in the South Caspian Sea [3].

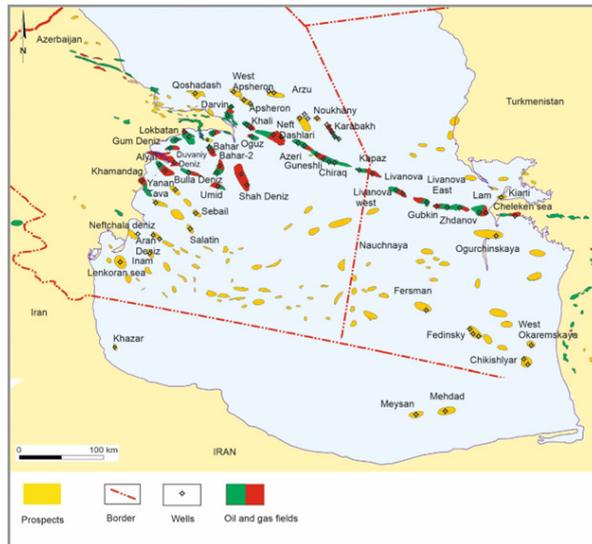
This study focuses on the engineering-geological characteristics of Quaternary deposits in the southern Caspian Sea and their suitability as foundation soils for offshore oil and gas structures. Note that as a general principle, for large tables font sizes can be reduced to make the table fit on a page or fit to the width of the text. If a table is divided into parts these should be labelled (a), (b), (c) etc but there should only be one caption for the whole table, not separate ones for each part [4].

The specific objectives of the research are to:

- Conduct a geological, lithological, and engineering-geological study of Quaternary deposits in the hydrocarbon-bearing areas of the Caspian Sea.
- Process and synthesize research results in the form of correlation relationships and tables of standard geotechnical parameters.
- Identify spatial patterns in the vertical and lateral distribution of Quaternary deposits.
- Develop an engineering-geological classification of these deposits, delineate lithogenesis zones, determine the controlling factors governing sediment properties, and assess the influence of geological conditions on their formation

## Materials and Methods

This study is based on data obtained from the investigation of soil samples collected from geotechnical boreholes drilled in the southern Caspian Sea. The author conducted these studies during two main research periods: 1984–1996 and 2019–2022. In total, 300 core samples from 70 boreholes across 45 offshore structures were analyzed. (Fig.1) The boreholes were located within the Baku Archipelago, the Apsheron archipelago, and the Iranian and Turkmen sectors of the southern Caspian Basin



**Figure 1:** South Caspian basin. Location of studied fields and structures

Between 1982 and 1997, the author was responsible for the sampling and analysis of core materials collected from boreholes in the Turkmen, Azerbaijani, and several Iranian sectors of the southern Caspian Basin. Furthermore, extensive published and archival materials were incorporated, including drilling logs, geophysical and hydrochemical data, and engineering–geological reports from Azerbaijani institutions such as Gipromorneft, the Marine Geological Exploration Office, and SOCAR. Additional materials included core columns from dozens of boreholes and several hundred laboratory test results on soil properties. Engineering–geological investigations were conducted to determine the lithological composition and physical–mechanical properties of seabed sediments within the proposed construction zones.

Drilling operations were performed using a specially equipped offshore drilling unit installed on a vessel outfitted with a 12 m-high drilling rig. This setup allowed boreholes to be drilled to depths of up to 100 m in waters up to 100 m deep, with borehole diameters ranging from 89 mm to 127 mm. Core samples were collected using specialized samplers, with recovery rates of 70–80% of the penetrated interval. In deeper areas of the southern Caspian Sea, a semi-submersible engineering–geological vessel was employed, enabling drilling to depths of up to 600 m below the seabed (in water depths up to 200 m within the shelf zone).

The recovered core samples were visually described, sealed, and transported to the laboratory, where the following analyses were conducted:

Soil composition parameters:

- Grain-size distribution
- Mineral composition

Chemical composition of water extracts

- Physical properties:
- Natural moisture content
- Bulk density
- Particle density
- Plasticity

Mechanical properties:

- Strength characteristics
- Deformation parameters

Grain-size distribution of clayey soils was determined by the areometric method, whereas for sandy soils it was determined by sieve analysis. The mineral composition of silt and sand fractions (0.1–0.01 mm) was examined using the immersion method under an Olympus BX53 microscope. The mineral composition of the pelitic fraction (< 0.001 mm) was analyzed using X-ray diffraction (XRD) with a DRON-2 diffractometer; particular attention was paid to identifying illite, montmorillonite, and kaolinite.

Determination of natural moisture content, bulk density, particle density, and plasticity limits followed standardized methodologies. Plasticity tests were performed on samples in their natural moisture state.

Derived indicators describing the physico-mechanical behavior of the soils were subsequently calculated based on the obtained parameters.

Dry density of the soil ( $\rho_d$ ) was determined using the formula:

$$\rho_d = \rho / (1 + W)$$

where:

$\rho$  — natural (bulk) density of the soil, g/cm<sup>3</sup>;

$W$  — natural moisture content of the soil, expressed as a decimal fraction.

Porosity ( $N$ ) and porosity coefficient in % ( $E$ ) were determined using the following equations:

$$n = 1 - \rho_d / \rho_s$$

$$e = n / (1 - n)$$

where:

$\rho_d$  — dry density of the soil, g/cm<sup>3</sup>;

$\rho_s$  — particle density of the soil, g/cm<sup>3</sup>.

Plasticity index ( $I_p$ ) was calculated from the natural moisture and plasticity limits using the formula:

$$I_p = W_L - W_p$$

where:

$W_L$  — liquid limit, %;

$W_p$  — plastic limit, %.

Consistency index ( $I_c$ ) of clayey soils was determined according to the formula proposed by V.A. Priklnskiy (1949):

$$I_c = (W_L - W) / (W_L - W_p)$$

where:

$W_L$  — liquid limit, %;

$W_p$  — plastic limit, %;

$W$  — natural moisture content of the soil, %.

The degree of moisture of clay soils was calculated using the formula:

$$S = w/w_L \times 100\%$$

where

$S$  — degree of moisture, %;

$W$  — natural (actual) moisture content of the soil, %;

$W_L$  — liquid limit moisture content, %.

The coefficient of porosity of sand in the loose state is determined by the formula:

$$e_0 = \rho_s / \rho_0 - 1,$$

where

$e_0$  — coefficient of porosity of sand in the loose state;

$\rho_s$  — density of soil particles (solid phase), g/cm<sup>3</sup>;

$\rho_0$  — density of sand in the loose state, g/cm<sup>3</sup>.

The coefficient of porosity of sand in the compacted state is calculated using the formula:

$$e_{\text{comp}} = \rho_s / \rho_{\text{comp}} - 1,$$

where

$e_{\text{comp}}$  — coefficient of porosity of sand in the compacted state;

$\rho_s$  — density of soil particles (solid phase), g/cm<sup>3</sup>;

$\rho_{\text{comp}}$  — density of sand in the compacted state, g/cm<sup>3</sup>.

The porosity of sand in the loose state is determined by the formula:

$$n_0 = 1 - \rho_0 / \rho_s,$$

where

$n_0$  — porosity of sand in the loose state (fraction or %);

$\rho_0$  — density of sand in the loose state, g/cm<sup>3</sup>;

$\rho_s$  — density of soil particles (solid phase), g/cm<sup>3</sup>.

In percentage form:

$$n_0 = (1 - \rho_0 / \rho_s) \times 100\%.$$

The porosity of sand in the compacted state is calculated using the formula:

$$e_{\text{comp}} = \rho_s / \rho_{\text{comp}} - 1,$$

where

$n_{\text{comp}}$  — porosity of sand in the compacted state (fraction or %);

$\rho_{\text{comp}}$  — density of sand in the compacted state, g/cm<sup>3</sup>;

$\rho_s$  — density of soil particles (solid phase), g/cm<sup>3</sup>.

In percentage form:

$$n_{\text{comp}} = (1 - \rho_{\text{comp}} / \rho_s) \times 100\%.$$

Different soil types were classified according to their plasticity and grain-size composition. It was established that soils with a liquidity index and a porosity coefficient for clays and for loams exhibit a high degree of water saturation and reduced structural stability.

To investigate the shear strength properties of the structurally significant deposits, a series of direct shear tests was performed using a slow-shear apparatus. The tests were conducted on normally consolidated clay soils that had undergone preliminary compaction. The main strength parameters—the angle of internal friction ( $\varphi$ ) and the cohesion ( $C$ )—were determined based on the relationship:

$$\tau = f(P),$$

where  $\tau$  is the shear stress and  $P$  is the normal stress.

The internal friction angle ( $\varphi$ ) was determined at three different levels of normal stress ( $P$ ) on soil specimens cut from a single, structurally uniform monolith of undisturbed soil.

To further examine the strength and deformation characteristics of stiff-plastic clay soils in an unconsolidated state, a series of triaxial compression tests was conducted using the consolidated–undrained (CU) method.

Based on these experiments, the undrained shear strength ( $C_u$ ) and angle of internal friction ( $\varphi$ ) of the soils were determined. Because the natural angle of repose of sands closely approximates their internal friction angle, for Quaternary sandy deposits, both the dry and submerged angles of repose were also measured.

The angle of internal friction ( $\varphi$ ) is a key soil property that represents the resistance of soil particles to sliding over each other. It's a measure of shear strength due to particle friction. Typical values: Clay: low (10–20°); Sand: higher (30–40°).

The angle of internal friction is typically found using shear strength tests, such as:

Direct shear test – A soil sample is placed in a shear box and subjected to a normal load. The shear force is gradually increased until failure.

Triaxial shear test – A cylindrical soil sample is subjected to controlled confining pressure and axial stress. The stress conditions at failure are used to calculate  $\varphi$ .

Unconfined compression test – Used mainly for cohesive soils (clays) where drainage is not allowed; this test helps determine cohesion rather than  $\varphi$  directly, but  $\varphi$  may still be estimated.

The angle of internal friction is one of the parameters in the Mohr–Coulomb failure criterion:

$$\tau = c + \sigma \tan \varphi$$

Where:

$\tau$  = shear strength of soil

$c$  = cohesion

$\sigma$  = normal stress

$\varphi$  = angle of internal friction

It helps engineers evaluate:

- Slope stability
- Bearing capacity of foundations
- Earth pressure on retaining walls

The investigation of both the lithological composition and the physical–mechanical properties of the soils was carried out on undisturbed core samples collected during the drilling of engineering–geological boreholes. A total of 558 soil samples were analyzed (Table 1), including:

- 182 samples from the Baku Archipelago,
- 231 from the Apsheron archipelago,
- 139 from the Turkmenian sector of the South Caspian Basin, and
- 6 from the Iranian sector of the South Caspian Basin

**Table 1:**The extent and quantity of geotechnical investigations in different oil and gas bearing sectors of the Southern Caspian Sea

area	name of soil	Coefficient of compressibility, $\alpha$ (1/kPa) under loading conditions.			
		0+0.1 MPa	0.1+0.2 Mpa	0.2+0.3 Mpa	0+0.3 Mpa
Baku archipelago	clayey silt	48.0	14.0	8.0	22.8
		22.0+78.0	10.0+22.0	4.0+14.0	
	silty loam	22.5	8.0	5.0	11.9
		13.0+40.0	5.0+14.0	3.0+7.0	
	clay	9.4	5.0	4.0	6.1
		2.0+24.0	1.0+11.0	1.0+6.0	
loam	7.9	3.9	3.0	5.0	
	1.8+19.0	1.0+8.0	1.0+6.0		
Apsheron archipelago	clayey silt	59.0	19	10	29.0
		19.0+80.0	10.0+28.0	4.0+11.0	
	silty loam	31.0	10.0	8.0	16.3
		12.4+43.0	5.0+16.0	4.2+11.0	
	clay	9.0	5.0	3.4	5.8
		2.0+25.0	1.0+14.0	0.8+5.5	
loam	8.0	3.8	2.3	4.7	
	1.0+15.0	0.7+6.0	0.4+5.0		
Turkmenian zone	clayey silt	21.0	7.0	5.8	11.0
		11.0+29.0	5.0+10.8	3.0+8.0	
	clay	5.4	3.4	2.2	4.0
		1.7+11.1	1.2+6.3	0.8+4.5	
	loam	4.2	2.9	1.9	3.0
0.7+10.7		0.4+5.5	0.3+4.0		

Following the determination of soil composition and physico-mechanical properties, all data were transmitted to specialized design and research institutes, where they were used in the calculation and design of offshore and oilfield engineering structures. Since detailed design calculations fall beyond the scope of this study, only the most relevant aspects are briefly noted here.

In addition to static loads, piles and foundations are also subjected to dynamic loads, primarily resulting from wave and wind action. In the analysis of piles under dynamic loading, both the physical and mechanical parameters of the seabed soils are considered. The liquidity index and porosity coefficient are used to determine the proportionality coefficient in these calculations.

When assessing the stability of piles, the design values of the angle of internal friction, cohesion, and soil density are taken into account. In general, pile stability analyses employ both the liquidity indices and strength parameters of the soils [5].

In the design departments of engineering institutes, hydrotechnical calculations are performed to evaluate the influence of dynamic loads on piles and structural supports. These analyses consider the full range of soil physico-mechanical characteristics, as well as the wave and wind loads specific to each region, determined in accordance with the established engineering standards [6].

#### Lithological Features of Quaternary Deposits

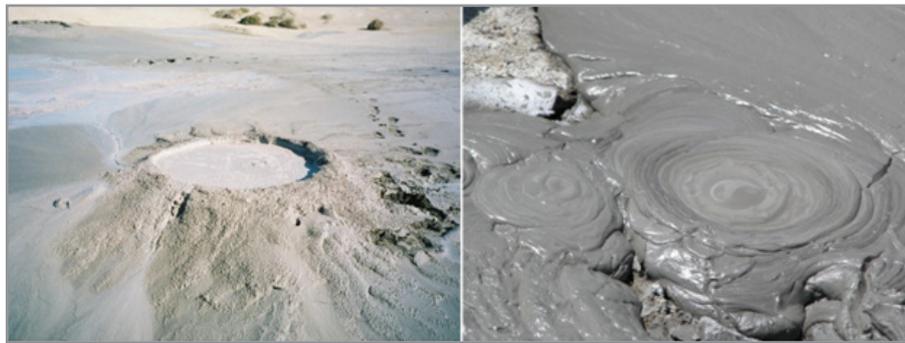
The study of the lithological features of Quaternary deposits plays a significant role in engineering-geological investigations

of these deposits, as the granulometric and mineral composition serves as a criterion for assessing the nature of the sedimentation process. Moreover, changes in particle size distribution and mineral composition have a substantial impact on the variation of the physical and mechanical properties of soils.

To characterize the lithological features of Quaternary deposits, their granulometric and mineral composition, as well as the chemical composition of water extracts from these soils, were used. The study primarily focused on clay varieties, as they constitute the main bulk of soils in the oil- and gas-bearing areas of the South Caspian Sea.

Macroscopically, the Quaternary deposits consist of light gray, gray, brownish-gray, greenish-gray, bluish-gray, grayish-brown, greenish-brown, and, less commonly, brown clays and loams, with thin and frequent interlayers or lenses of sand, and occasionally limestone. Shell fragments, sooty material, and small areas of iron staining are also encountered.

Among the Quaternary deposits of the Caspian region, mud volcano and bedded breccias are developed, which are products of both active and extinct mud volcanoes. The bedded breccia is represented by plastic, and in some places dense, clays containing fragments of sandstone and clays of varying density. The mud volcano breccia consists of mudflow material with inclusions of sand, gravel, and shell fragments. Photo 1.



**Photo 1:** Mud volcanoes from the Kobustan area (Azerbaijan), the coast of the South Caspian Sea

Clays are widespread and make up 50% of all Quaternary deposits. In the deep-water areas of the Baku Archipelago, as well as in the southern and eastern deep-water parts of the Pre-Apsheron subzone, the profiles of engineering-geological boreholes (to a depth of 50–100 meters below the seabed) consist almost entirely of clay. In the Turkmenian sector of the South Caspian Basin, the proportion of clay is lower, with loams and sands being more predominant.

As is well known, the hydrodynamic activity and seafloor topography of the basin control the mechanical differentiation of clastic material—that is, the degree of its fragmentation [7]. Thus, on the steeper western coast, clays accumulate relatively close to shore, whereas on the shallower eastern coast, loams and sandy formations are more common, and clays are of secondary significance. In percentage terms, loams account for 36% of all Quaternary deposits. Loams frequently alternate with clays in the vertical section. Sands and sandy loams of Quaternary deposits occur as interlayers and lenses. Sometimes, the thickness of these layers reaches 5 meters or more. Sandy loams make up 4% of all Quaternary deposits in the studied area of the Caspian Sea, while sands account for 10%.

### Granulometric Composition

Granulometric analysis of the Quaternary deposits shows that the content of the <0.005 mm fraction in Quaternary clays varies widely, ranging from 32.26% to 93.26%. The clays are generally highly silty.

In the Baku Archipelago region, clay content tends to increase slightly with greater sea depth and toward the south. However, fine-dispersed, well-washed clays are not observed in the Quaternary deposits of this archipelago.

In the Apsheron archipelago, the clay fraction content reaches high values in the southern and eastern deep-water parts (such as

the Shah-deniz field and the Chirag area), where in some cases the content of the <0.005 mm fraction exceeds 90%. However, this is localized within the subzone. In the central and western parts of the Apsheron archipelago, the clay fraction content decreases.

A predominance of loams and sands over clays characterizes the Turkmenian side. The clays in this subzone are also highly silty. Clay fraction content:

- In loams: ranges from 12.12% to 39.80%
- In sandy loams: from 4.26% to 19.14%
- In sands: from 0% to 10.71%

Loams of the South Caspian Sea have an average clay fraction content of 29%, classifying them as heavy varieties. Sands from both the Baku Archipelago and the Apsheron archipelago are mostly medium-grained, while coarse-grained sands dominate among modern coastal sediments. In relatively shallow-water areas and near-peninsula zones, the content of sandy-silty material slightly increases. As shown in Table 1, there are no significant changes in granulometric composition when transitioning from silt to clay and loam.

### Mineral Composition

The microstructure of the Quaternary deposits was examined using plane-parallel thin sections. Under a polarising microscope, the structure appears pelitic, and in some areas aleuropelitic. The texture is predominantly massive (disordered), and less frequently micro-layered. A distinctive "bubbly" texture is also observed in the Quaternary deposits of the Caspian Sea. According to L.I. Lebedev, this texture is associated with the influence of gases from mud volcanoes on the sediment. This texture is characteristic of clays from the Umid field [8].

In the light silty fraction of clay deposits from the Baku Archipelago, there is a significant presence of fragments of clay and carbonate rocks, as shown in Table 2.

**Table 2:** Mineral composition of the silt fraction of clay deposits of the Baku Archipelago

fraction in %	clay			loam		
	max	min	average	max	min	average
light fraction	100	95	96	100	95	97
quartz	31	1.5	14	45	9	17.5
feldspars	16	4	8	30	6	10
rock fragments	97	50	75	85	55	70
volcanic glass	1			single grains		
heavy fraction	4	0.01	1.5	2.5	0.01	3.3

magnetite,ilmenite	22	4	10	20	5	11
limonite	40		13	80		29
pyrite	80		15	95		15
leucoxene	16	2	7	20	3	7
zircon	9	1.3	4	7	single grains	3
apatite	single grains			1		
garnet	2			2		
rutile	3	single grains		4	single grains	1.5
tourmaline	1.5	single grains		2		1.2
titanite	1.5	single grains		1.7	single grains	
kyanite	single grains			single grains		
staurolite	single grains			single grains		
mica,	37	2.5	20	49	1	14
pyroxenes	25	1	5.4	11		4
hornblende	50	4	18	25	2	8
chlorite	6	single grains	2	3	single grains	1.2
glauconite	3			2.9		
epidote, zoisite	10		3	4		1.2
barite, anhydrite,	2			15		1
altered minerals	15		3	8		2

According to Table 3, a commonly occurring mineral association in the heavy fraction of Quaternary deposits in the Baku Archipelago region includes micas, pyroxenes, and ore minerals. Notably, the ore mineral content is higher in loams than in clays. In the Sangachal–Duvanny–Bulla Island areas, an increase

in quartz content in the light silty fraction is consistently associated with exposures of the productive formation or mud volcano ejections of large rock fragments from that formation. Further south of these areas, quartz content decreases, while feldspar content increases in the light silty fraction.

**Table 3:** Mineral composition of the silt fraction of clay deposits of the Apsheron archipelago

fraction in %	clay			loam		
	max	min	average	max	min	average
light fraction	97	90	97	97	96	97
quartz	68	10	35	65	8	35
feldspars	20		10	18	2	8
rock fragments	90	30	58	90	32	57
glauconite	2					
volcanic glass				9		
heavy fraction	10	0.01	1	3	0.01	0.03
magnetite,ilmenite	30		11	75	6	28
limonite	50		20	70		12
leucoxene	12		5	20		4.5
hematite	20		4	24		3
cuprite	6		1.5	1		
sphalerite	7					
goethite	1					
chalcopyrite	1.5					
pyrite	82	16		100		20
picotite	single grains			0.5		

hornblende	18	8		14		6
augite	12	4.5		6	single grains	3
micas	16	8.5		20		7
hypersthene	4					
glaucophane	2					
fluorite	2					
titanite	25		7	8	1	1
garnet	12		3	11	single grains	3
zircon	13		4	30	single grains	8
tourmaline	4		1	3		
monazite	2					
apatite	3			4		
sillimanite	1					
rutile	4			4		
epdote,zoisite	15		4	15		3
chlorite	6		2			
barite, anh drite,	5					
dolomite				10		1
altered minerals	8	1	2	13		2

In the deep-water part of the archipelago ( in Umid field), rock fragments dominate the light fraction. Quartz prevails over feldspars in these samples. In the Sangachal–Duvanny–Bulla Island areas and farther south (e.g., Sabail, Dashli structures), the heavy silty fraction of clays is dominated by limonite, micas, and pyroxenes. In the near-peninsula zones of the Baku Archipelago, the mineral composition of sediments is a mixture of material from the Kura River outwash and mud volcano breccia. Isolated grains of kyanite (likely referring to distene, an older term) are also found here, originating from older formations and transported by the Volga River.

In the deep-water part of the archipelago (Umid field), the heavy silty fraction is mainly composed of limonite and micas. The dominance of micas in this area is attributed to the low density of this mineral, which allows it to be transported into deep-water areas by currents. In the light silty fraction of clay soils from the Apsheron archipelago, rock fragments also predominate. The quartz content increases significantly, while feldspars are present in subordinate amounts or absent entirely in some samples.

In the Bahar field area, the light silty fraction is dominated by rock fragments. At the Guneshli field, where Quaternary deposits are mainly loams, the quartz and rock fragment contents in the light fraction are approximately equal. Feldspar content, represented by plagioclase, ranges between 2–7%. In the deep-water parts of the Apsheron archipelago (e.g., Chirag and Shahdeniz), the light silty fraction is also dominated by rock fragments, with plagioclase present in subordinate quantities or sometimes absent. In the heavy silty fraction of soils from the Apsheron archipelago, the common mineral association includes ore minerals, micas, and zircon. Some samples show pyrite content in the heavy fraction reaching up to 100% (notably at Bahar). At the Guneshli field, the heavy fraction of both clays and loams is dominated by magnetite and ilmenite, with contents ranging from 25% to 76%. In the upper parts of the stratigraphic section, limonite concentrations reach 32% in silty loams (depth: 0–4 m). In the lower parts, the limonite content decreases to 2–3%. In the deep-water parts of the South Caspian Pre-Apsheron subzone, ore minerals also dominate in the heavy fraction.

**Table 4:** Mineral composition of the silt fraction of clay deposits of the Turkmenia sector of South Caspian Sea

fraction in %	clay			loam		
	max	min	avarage	max	min	avarage
light fraction	100	97	97	100	97.5	97.5
quartz	50	single grains	15.1	60	14	33
feldspars	45	single grains	13	25	5	12
rock fragments	100	30	73	80	25	58
heavy fraction	0.08	0	0.03	0.1	0.01	0.05
magnetite,ilmenite	7	4	5	15	3	6
pyrite	40		9	100		8
limonite	18		8.5	11		4

leucoxene	17		7	8		5
zircon	8		3		single grains	2.9
apatite	single grains			single grains		
garnet	2		1	3		1
rutile	2		1	3		1
tourmaline	single grains		1.5	2		
titanite	single grains			1.5		
picotite	single grains			single grains		
kyanite	single grains			single grains		
staurolite	single grains					
micas	50		30	57	single grains	35
pyroxene,	13		7	18		6
hornblende	25		12	29		15
glaucophane	single grains			single grains		
chlorite	11		5	9		
glauconite	3			single grains		
epidote,zoisite	8		5	22		8
barite, anh drite,	15		3.4	17		3
altered minerals	7		3	9		3

The importance of mica increases. In the clay deposits of the subzone, the presence of small amounts of pyroxenes and amphiboles, along with the predominance of ore minerals, mica, and epidote, indicates the erosion of the bedrock in this area, which serves as the source of material for these sediments. In the light aleuritic fraction in the Turkmenian sector of the South Caspian Basin predominant majority is characterized by rock fragments, the quantity of which increases in the clays, sometimes reaching 100%. Quartz predominates over feldspars in all cases. (Table 4).

In the clays of the Livanov uplift, the percentage of quartz increases, while the content of hornblende decreases compared to other uplifts in this subzone. In the heavy aleuritic fraction of both clays and loams, mica predominates in all deposits. The heavy fraction of clay soils is also characterized by a predominance of ore minerals and pyroxenes. The content of barite and anhydrite significantly increases.

The mineral composition of the fine pelitic fraction (< 0.001 mm) of the Quaternary deposits of the Caspian Sea has been described in a number of studies devoted to the investigation of Caspian Sea sediments. This has been confirmed by research on marine clay deposits conducted in various regions by the following authors: Pashaly N.V. (1964, 1965), Kuprin P.N., Potapova I.L., Shatova A.S., and Shlykova V.G. (1974), Rateeva M.A., Pokidina A.K., Kheirov M.B. (1965), Panakhi Sh.A., Kheirov M.B., and Khalilov N.Yu. (1973), Alieva F.S. and Guseinov A.A. (1970), Polyakov et al, (1990), Aliyev, et al, (1970) among others. According to these authors, the clay minerals of the Quaternary deposits are mainly allothigenic. In the fine-pelitic fraction of clay soils in the Southern Caspian, hydromica predominates, making up 40-80% of the fraction [9- 15].

Montmorillonite is present in amounts of 20-30%. Kaolinite, chlorite, and others are also found. With an increase in the dura-

tion of transport under marine conditions and the depth of sediment deposition, the clay minerals undergo a process of coarsening, with the restoration of their crystalline forms. Among the authigenic formations are perfectly intact needle-like crystals of palygorskite and isometric, translucent particles of hydromica.

The hydromica in Quaternary deposits, unlike that in older deposits, is highly hydrated and its structure is less perfect. Compared to the hydromica in modern sediments, it is better crystallized. No significant change in the hydromica content is observed with depth. However, even within the same formation, sharp deviations from the average hydromica content are sometimes noted, which the authors associate with the products of mud volcano emissions.

A slight decrease in hydromica is observed from north to south, which is associated with its influx from the southern and southeastern slopes of the Greater Caucasus. From north to south and southeast, i.e., toward the area of tectonic subsidence and an increase in the thickness of Quaternary deposits, the content of montmorillonite increases. Montmorillonite also partially forms authigenically from volcanic glass in a weakly alkaline marine environment.

The content of kaolinite ranges from 15-20%, and it has an allochthonous origin. There is a direct relationship between the content of kaolinite and hydromica. Chlorite is also allochthonous and makes up 7%, increasing in the southern direction.

Studies of the mineral composition of the fine-pelitic fraction of clayey Quaternary deposits show that in the southern and southeastern deep-water parts of the South Caspian Pre-Apsheron subzone, where the sea depth reaches up to 200 meters and fine-grained material accumulates, an increase in the content of montmorillonite is observed in well cores, both in modern sediments represented by silts and in Quaternary deposits. This

is apparently related to the erosion products of bedrock in the western part of the Apsheron archipelago of various ages, predominantly from the productive strata, and the transport of this mineral by currents into the deep-water parts of the basin as the most dispersed mineral.

### Chemical Composition

For the studied Quaternary deposits of the southern Caspian region, no analyses of the chemical composition of water extracts were carried out. However, numerous published materials were reviewed, and their results are presented in a summarized form.

According to Rzaeva for both modern sediments and Quaternary deposits, the predominant composition of water-soluble salts is chloride-sodium. Furthermore, as one moves from modern sediments to Quaternary deposits and with an increase in the depth of deposition, slightly elevated values of  $\text{Ca}^{2+}$ ,  $\text{Na}^+$ , and  $\text{K}^+$  are observed. For the modern sediments of the Baku Archipelago, somewhat higher values of  $\text{SO}_4^{2-}$  and  $\text{Co}$  ions are typical compared to the Quaternary deposits. The values of  $\text{Mg}^{2+}$  increase slightly when transitioning from modern to Quaternary deposits. Modern sediments of the Apsheron archipelago are characterized by slightly elevated values of  $\text{H}^+$  and pH, as well as  $\text{CaCO}_3$ .

In the Turkmenian sector of the South Caspian Basin, among the anions,  $\text{Cl}^-$  predominates, and among the cations,  $\text{Na}^+$  and  $\text{K}^+$  dominate. The content of  $\text{CO}_3^{2-}$  is very low. The waters of the Caspian Sea are oversaturated with calcium carbonates, which precipitate during sedimentary differentiation. The carbonate content of Quaternary deposits in the Baku Archipelago ranges from 0-31%, with an average of 12-14%. Higher carbonate values are found in the areas of Bulla-More and the Umid area (12-31%). In some clay samples taken from the Umid area, an increase in  $\text{CaCO}_3$  content is observed, reaching up to 31%. This local increase in  $\text{CaCO}_3$  content is associated with the products of mud volcano emissions, among which both Tertiary and older rocks, rich in  $\text{CaCO}_3$ , are found. In the Apsheron archipelago, the carbonate content of clayey deposits ranges from 0-39%. The Quaternary deposits in this area are characterized by low carbonate values, but in modern sediments, which are rich in shell fragments, the carbonate content increases, reaching up to 39% in some cases. The carbonates in these sediments are mainly represented by the clastic component; chemogenic carbonate is subordinated to the clastic carbonate [16].

While near the western coast, where the products of denudation from the Caucasus range are destroyed and washed into the sea, predominantly clastic material is deposited, as one approaches the eastern coast, the amount of clastic material decreases and is increasingly mixed with calcium carbonate. This is evident from the results of water extractions from the soils in the Turkmenian sector of the South Caspian Basin, where the content of  $\text{CaCO}_3$  is somewhat higher compared to the Baku Archipelago and Apsheron Archipelago. This corresponds to the idea that the precipitation of calcium carbonate occurs after the mechanical differentiation has almost fully completed, and the majority of mineral fragments, including clays, have finished their journey and fallen out of the migration paths [17, 18].

The distribution of organic matter is uneven. In terms of the content of  $\text{C}_{\text{org}}$  and  $\text{N}_{\text{opr}}$ , Quaternary deposits significantly lag

behind modern sediments. Higher values of  $\text{C}_{\text{org}}$  are found in clayey silts of the Baku Archipelago, where the average value of this component is 2.0. In the Turkmenian sector of the South Caspian Basin (Apsheron-Pre-Balkhan zone side), higher values of  $\text{C}_{\text{org}}$  are found in the clays of the Cheleken zone, where this component reaches up to 5.64 in some cases. In the soils of the Pre-Apsheron subzone, the content of  $\text{C}_{\text{org}}$  is significantly lower. In all cases, when moving from silts to clays and loams, the organic matter (OM) content decreases. This phenomenon is also observed when transitioning from clays to loams. The physicochemical indicators (the pH value) point to a weakly alkaline, occasionally weakly acidic environment.

### Physico-Mechanical Properties of Quaternary Deposits

If the lithological features of the Quaternary deposits allow us to infer the nature of the sedimentation process, then changes in the physicochemical properties of these deposits provide insight into the diagenetic transformations that occurred during the Quaternary period. 7.1 Physical Properties of Quaternary Deposits. In engineering-geological studies, the indicators of the physical properties of soils allow for a qualitative assessment of the strength and stability of soils as the foundation for the designed structures. They also provide an indirect way to judge the condition of the soils under their natural conditions of occurrence.

The plasticity of clay soils is characterized by the moisture content at the rolling yield point ( $W_p$ ) and by the plasticity index ( $I_p$ ).

The plasticity indices of clays and clayey silts vary between 0.17 and 0.44, with an average value of  $0.18 \pm 0.22$ . The relatively low plasticity of these clays is attributed to their high content of silt-sized particles. The proportion of clay particles exerts a strong influence on the plasticity characteristics of the studied sediments.

The liquid limit (WL) varies widely among different soil types, ranging from 0.18 to 0.95. The highest values were recorded in the montmorillonitic clays of the Apsheron archipelago zone (notably in the Shah Deniz and Chirag fields), where typically ranges from  $0.60 \pm 0.95$ . In the same areas, the plastic limit ( $I_p$ ) values are also high, usually reaching 0.62 and ranging from 0.40 to 0.62. The plasticity index ( $I_p$ ) in these regions varies from 0.25 to 0.44.

Based on plasticity index values, the Quaternary clays are generally classified as low-plasticity soils. Values of  $I_p$  are rare and are mainly associated with montmorillonitic clays of the Pre-Apsheron subzone.

Within the Baku Archipelago, the plasticity index of clays and clayey silts increases noticeably with the organic matter (OM) content. Higher OM content also correlates with greater values of both the liquid and plastic limits.

In the Turkmenian sector of the South Caspian basin, which is characterized by an increased proportion of sand and silt in the clays, plasticity indices are generally low. However, in certain clays rich in organic matter, the liquid limit (WL) reaches 0.78, the plastic limit ( $W_p$ ) reaches 0.52, and the plasticity index ( $I_p$ ) equals 0.29.

A gradual increase in the plasticity index and in the limits of plasticity is observed when transitioning from shallow-water clays and loams to deep-water deposits, which reflects the higher dispersity of sediments in deeper parts of the basin.

To characterize the soil consistency and to assess the bearing capacity of engineering structures, the liquidity index (IL) of Quaternary clayey soils was determined. Based on this index, Quaternary and modern marine sediments were classified into the following consistency types: hard, semi-hard, stiff-plastic, soft-plastic, and flowing. Most clays of modern sediments belong to the flowing type. With increasing depth and compaction, the liquidity index systematically decreases.

The majority of clay soils from the Baku Archipelago and the Apsheron archipelago exhibit stiff- to soft-plastic consistency, with mean liquidity indices of 0.50 and 0.48, respectively. For loams, the corresponding values are 0.43 and 0.42.

In contrast, the Turkmenian sector of South Caspian Basin is dominated by semi-hard clays, with an average liquidity index of 0.22 for clays and 0.25 for loams. In the Livanov field area, higher liquidity indices and the prevalence of stiff- and soft-plastic soils are observed.

From clayey silts to clays and loams, a sharp decrease in liquidity index values is evident, reflecting a reduction in soil fluidity. In the Baku Archipelago and Apsheron archipelago, the average liquidity index of clays is more than three times higher than that of loams, as confirmed by data presented in Tables 5–7. In the Cheleken subzone of the Turkmenian side, the mean liquidity index of clayey silts is approximately six times greater than that of loams, indicating pronounced variability in soil plasticity within the Quaternary section.

### Degree of Compaction (Kd)

In soil mechanics and geotechnical engineering, Kd (Degree of compaction (Kd) is defined as:

$$K_d = \rho_d / \rho_{(d,max)}$$

**Table 5:** Physical properties of Quaternary sediments of the Baku Archipelago

Physical property indicators	Clayey silt	Silt loam	clay	loam	sandy loam	sand
Moisture content (W) in fractions of a unit	0.60	0.45	0.35	0.28	0.23	
	0.50+0.72	0.35+0.60	0.20+0.55	0.17+0.45	0.18+0.35	
Density (P) in grams per centimeter	1.70	1.75	1.88	1.95	2.05	
	1.50+1.175	1.60+1.90	1.67+2.15	1.77+2.20	1.90+2.20	
Density of dry soil (Pd) in cubic centimeter						
Density in a loose state (Po) in grams per cubic centimeter						1.35
						1.16+1.58
Density in a compacted state (P comp) in grams per cubic centimetre						1.55
						1.20+1.80
Ps particle density of the soil in grams per cubic centimeter	2.75	2.70	2.75	2.70	2.67	2.65
	2.72+2.81	2.68+2.75	2.70+2.85	2.66+2.75	2.65+2.71	2.64+2.69

where:

- $\rho_d$  — dry density of the soil sample (g/cm<sup>3</sup> or t/m<sup>3</sup>),
- $\rho_{d,max}$  — maximum dry density from the Proctor test.

Thus,  $K_d$  shows how compacted a soil is compared to its maximum possible compaction. For example,  $K_d = 0.95$  means the soil is compacted to 95% of its maximum density. Compaction occurring under natural conditions due to the weight of overlying sediments represents one of the principal processes of diagenesis in clayey soils. As compaction progresses, the density of the clay soils increases. During this process, two characteristic states can be observed, each corresponding to significant changes in the physical properties of the clays: (1) the transition from liquid to plastic consistency and (2) from plastic to solid consistency.

From an engineering–geological perspective, it is essential to characterize the degree of compaction of clayey soils. The compaction coefficient (Kd) reflects both the current state of the soil and the extent to which its porosity has changed under natural conditions. This coefficient is evaluated with reference to the liquid and plastic limits of the soil.

Among modern and Quaternary marine sediments, three main types of compaction states are distinguished:

- Undercompacted soils ( $K_d < 1$ ),
- Normally compacted soils ( $K_d \approx 1$ ), and
- Overcompacted soils ( $K_d > 1$ ).

Most Quaternary clayey soils of the Caspian Sea are normally compacted. Undercompacted soils include nearly all types of modern sediments and the upper horizons of Quaternary deposits, as well as zones affected by mud-volcanic processes. Overcompacted soils are comparatively rare within Quaternary sequences and are represented by hard clays found in the Karadag-Deniz and Lok-Katan-Deniz areas of the western Pre-Caspian subzone, as well as at the Zhdanov Bank, Gubkin Bank, and Lam Bank fields of the Cheleken subzone. Within the Baku Archipelago, hard (overcompacted) Quaternary clays occur only locally and in isolated cases.

Porosity ratio (N), in %	In natural state (N)	62	56	50	43.5	38	
		2.75+2.80	50.5+65	35+60	33+58	24.5+42	
	in a loose state (N loose)						50.2
Porosity ratio (N), in %	in the compacted state (N comp)						41+57
							42
							35+52
Porosity ratio (E), in %	In natural state (E)	1.62	1.25	1.00	0.76	0.60	
		1.50+2.15	1.00+1.80	0.45+1.50	0.50+1.18	0.89+1.00	
	in a loose state (E loose)						50.2
Soil moisture content	in the compacted state (E comp)						41+57
							42
							35+52
Soil moisture content		1.00	1.00	1.00	0.99	0.99	
		0.98+1.02	0.97+1.00	0.93+1.00	0.90+1.00	0.87+1.00	
yield limit Wl		0.50	0.40	0.44	0.34	0.23	
		0.39+0.85	0.27+0.48	0.35+0.96	0.25+0.40	0.20+0.28	
rolling limit Wp		0.27	0.27	0.25	0.22	0.19	
		0.20+0.37	0.18+0.30	0.18+0.55	0.15+0.33	0.15+0.25	
plasticity number Ip		0.60	0.14	0.20	0.12	0.05	
		0.18+0.33	0.09+0.17	0.17+0.45	0.07+0.17	0.04+0.07	
flow index		1.60	1.50	0.48	0.42	0.40	
		1.00+9.19	1.00+3.00	(-0.35)+ 1.56	(-0.40)+ 1.29	(-0.17)+ 1.40	
degree of compaction		-0.61	-0.33	0.55	0.63		
		(-0.03)+(- 8.09)	(-0.02)+(- 1.93)	1.40+(-0.40)	1.38+(-0.31)		

**Table 6:** Physical properties of Quaternary sediments of the Apsheron Archipelago

Physical property indicators	Clayey silt	Silt loam	clay	loam	sandy loam	sand
Moisture content (W) in fractions of a unit	0.65	0.44	0.33	0.27	0.20	
	0.50+3.21	0.37+0.75	0.17+0.55	0.15+0.45	0.15+0.28	
Density (P) in grams per centimeter	1.65	1.80	1.90	1.97	2.1	
	1.16+1.75	1.64+1.88	1.68+2.18	1.80+2.19	1.96+2.20	
Density of dry soil (Pd) in cubic centimeter	1.02	1.25	1.45	1.55	1.73	
	0.28+1.20	0.95+1.38	1.11+1.85	1.25+1.90	1.54+2.00	
Density in a loose state (Po) in grams per cubic centimeter						1.41
						1.16+1.60
Density in a compacted state (P comp) in grams per cubic centimetre						1.65
						1.50+1.90
Ps particle density of the soil in grams per cubic centimetre	2.75	2.71	2.74	2.70	2.67	2.65
	2.70+2.981	2.68+2.73	2.71+2.83	2.65+2.70	2.65+2.70	2.63+2.67
In natural state (N)	70.00	55.0	48.0	42.3	35.2	
	60.1+83.5	50.0+64.0	31.1+63.0	32.2+54.5	29.0+40.8	
Porosity ratio (N), in %	in a loose state (N loose)					45.5
						40.5+55.5
in the compacted state (N comp)						38.0
						30.5+44.5

Porosity ratio (N),in %	In natural state (N)	1.70	1.20	0.95	0.75	0.55	
		1.60+5.05	1.00+1.80	0.44+1.70	0.48+1.20	0.40+0.70	
	in a loose state(N loose)						0.88
							0.70+1.30
in the compacted state (N comp)						0.60	
						0.42+0.80	
Soil moisture content		1.00	1.00	0.99	0.99	0.99	
		0.98+1.00	0.97+1.00	0.95+1.00	0.89+1.00	0.90+1.00	
	yield limit Wl	0.48	0.40	0.45	0.35	0.20	
		0.41+0.60	0.30+0.50	0.35+0.68	0.25+0.45	0.12+0.21	
	rolling limit Wp	0.28	0.25	0.25	0.22	0.05	
		0.20+0.40	0.15+0.30	0.18+0.45	0.14+0.33	0.03+0.08	
	plasticity number Ip	0.,20	0.15	0.20	0.15	0.50	
		0.18+0.30	0.08+0.18	0.17+0.30	0.07+0.17	(-0.06)+2.0	
flow index		1.52	1.57	0.50	0.43	0.5	
		1.00+2.35	1.00+2.75	(-0.25)+1.66	(-0.20)+1.25	(-0.06)+2.0	
degree of compaction		-0.56	-0.55	-0.50	-0.60		
		(-0.02)+(-1.30)	(-0.01)+(-1.70)	1.25+(-0.48)	1.23+(-0.15)		

**Table 7:** Physical properties of Quaternary sediments of the Turkmenian sector of South Caspian

Physical property indicators		Silt loam	clay	loam	sandy loam	sand
Moisture content (W) in fractions of a unit		0.40	0.30	0.25	0.20	
		0.36+0.55	0.18+0.50	0.15+0.38	0.15+0.25	
Density (P) in grams per centimeter		1.81	1.95	2.00	2.06	
		1.75+1.90	1.70+2.15	1.76+2.19	1.95+2.17	
Density of dry soil (Pd) in cubic centimeter		1.29	1.50	1.60	1.73	
		1.12+1.40	1.14+1.80	1.28+1.90	1.54+1.90	
Density in a loose state (Po) in grams per cubic centimeter						1.40
						1.18+1.65
Density in a compacted state (P comp) in grams per cubic centimeter						1.65
						1.42+1.90
Ps particle density of the soil in grams per cubic centimeter		2.70	2.75	2.70	2.70	2.65
		2.67+2.70	2.71+2.80	2.63+2.70	2.63+2.70	
Porosity ratio (N),in %	In natural state (N)	52.0	45.3	41	35.2	
		50.4+58.2	36.1+59.0	29.0+t52.0	27.7+44.2	
	in a loose state(N loose)					50.0
						40.2+52.8
in the compacted state (N comp)					41.00	
					32.00+43.8	
Porosity ratio (N),in %	In natural state (N)	1.09	0.83	0.70	0.55	
		1.00+1.40	0.57+1.43	0.41+1.08	0.38+0.80	
	in a loose state(N loose)					0.90
						0.65+1.01
in the compacted state (N comp)					0.69	
					0.44+0.78	

Soil moisture content		1.00	0.99	0.98	0.99	
		0.95+1.00	0.94+1.00	0.91+1.00	0.87+1.00	
Plasticity as a decimal fraction	yield limit Wl	0.34	0.44	0.35	0.25	
		0.26+0.40	0.36+0.78	0.23+0.43	0.16+0.28	
	rolling limit Wp	0.24	0.26	0.22	0.18	
		0.18+0.28	0.18+0.53	0.12+0.33	0.10+0.22	
	plasticity number Ip	0.10	0.18	0.12	0.08	
0.07+0.17		0.17+0.29	0.07+0.17	0.02+0.07		
flow index		1.60	0.23	0.25	0.33	
		1.00+2.90	0.34+0.92	(-0.47)+1.28	(-0.35)+1.08	
degree of compaction		-0.66	0.77	0.75		
		(-0.01)+(-1.90)	1.63+0.07	1.50+(-0.24)		

### Strength Properties of Quaternary Deposits

In geotechnical and engineering–geological studies, the strength properties of Quaternary sediments are commonly expressed by the angle of internal friction ( $\phi$ ), cohesion (C), modulus of deformation (E), and the dependence of strength on the degree of compaction and moisture content.

Test results show that the angle of internal friction in Quaternary deposits varies from  $7^{\circ}06'$  to  $29^{\circ}54'$ , and cohesion ranges from 0.005 to 0.175 MPa, depending on the degree of dehydration and compaction. For silty and fluid clays, tests were conducted using the unconsolidated–undrained (UU) method, which reflects their undercompacted state. Under these conditions, the undrained shear strength ( $C_u$ ) was determined, and the angle of internal friction ( $\phi$ ) was assumed to be zero. Due to their high porosity and hydration, these soils generally exhibit low cohesion values; however, with increasing compaction, the cohesion increases.

As depth and degree of compaction increase, both the internal friction angle and cohesion also increase, indicating an improvement in the strength characteristics of the soils with burial depth. Strength parameters depend strongly on soil type and composition: as the sand and gravel content increases, the internal friction angle rises while cohesion decreases. Conversely, higher silt and clay content enhances cohesion but reduces the internal friction angle. Even within the same area, clays and loams exhibit notable variability in strength properties, influenced by soil consistency and degree of compaction. A reduction in density and an increase in liquidity index correspond to lower values of both  $\phi$  and C for clays and loams alike. Hard soils with semi-hard to hard consistency exhibit the highest strength values.

In the Baku Archipelago, particularly in the Sangachal–Duvanly–Bulla area, semi-hard and hard clays of low natural moisture display high internal friction angles, ranging from  $17^{\circ}13'$  to

$21^{\circ}48'$ . For stiff-plastic clays in the Bulla–Deniz–Umid–Dashly uplifts,  $\phi$  values range from  $10^{\circ}19'$  to  $20^{\circ}23'$ , depending on their consistency and deformation modulus. Plastic silty clays of deep-water zones in the Baku Archipelago are characterized by lower internal friction angles ( $7^{\circ}06'$ – $15^{\circ}42'$ ) and cohesion values of 0.005–0.016 MPa. In stiff-plastic clays, cohesion increases to 0.005–0.035 MPa, and in hard-plastic clays it ranges from 0.010 to 0.090 MPa, reaching up to 0.175 MPa in semi-hard and hard clays. The internal friction angles of loams in this region are generally higher than those of clays.

In the Apsheron archipelago, clayey silts exhibit very low cohesion values, averaging 0.006 MPa. In shallow-water areas such as Lokbatan–Deniz and Karadag–Deniz, semi-hard and hard clays demonstrate high internal friction angles ( $17^{\circ}03'$ – $26^{\circ}34'$ ). The corresponding cohesion values also increase, ranging from 0.015–0.075 MPa for loams and 0.025–0.125 MPa for clays, reflecting the transition from deep-water to shallow-water environments. The stiff-plastic clays, which form the dominant part of the Quaternary section, have internal friction angles of  $12^{\circ}25'$ – $19^{\circ}15'$  and cohesion values of 0.015–0.085 MPa. For stiff-plastic loams, the respective ranges are  $13^{\circ}30'$ – $29^{\circ}20'$  and 0.010–0.080 MPa.

In the Turkmenian sector of the South Caspian Basin, where semi-hard clays are predominant, the strength parameters are relatively high. The undrained cohesion of clayey silts in this area ranges from 0.005 to 0.012 MPa, increasing significantly with the transition to clays and loams. The observed variability in the strength properties of clayey soils results from differences in composition, physical properties, and structural–textural features. Since the internal friction angle of sands closely approximates their natural angle of repose, both dry and submerged angles of repose were determined for these sediments; the results are also presented in Table 8.

**Table 8:** Results of density tests of Quaternary deposit soils in the South Caspian

area	name of soil	shear strength of soil under undrained conditions	angle of internal friction ( $\phi$ ) in degree	specific cohesion (in MPa)	Soil density in a dry state, ( $\rho$ dry)	
					Soil density in a dry state, ( $\rho$ dry)	Soil under water ( $\rho$ water)

Baku arhchipel-ago	clayey silt	0.008					
		0.005+0.017					
	silty loam	0.006					
		0.005+0.010					
	clay		15°28'	0.033			
			7°06'+21°48'	0.005+0.176			
	loam		16°47'	0.029			
			9°05'+26°34'	0.005+0.100			
sand				32°16'	29°18'		
				29°11'+39°07'	24°02'+35°11'		
Apsheron archi-pelago	clayey silt	0.006					
		0.004+0.012					
	silty loam	0.006					
		0.005+0.011					
	clay		15°46'	0.035			
			8°57'+27°35'	0.005+0.126			
	loam		17°28'	0.028			
			10°10'+29°54'	0.010+0.075			
sand				31°05'	28°07'		
				29°57'+34°13'	24°25'+29°17'		
Turkmenian zone	silty loam	0.005					
		0.004+0.011					
	clay		15°55'	0.038			
			11°02'+26°35'	0.020+0.140			
	loam		18°31'	0.036			
			12°25'+28°18'	0.010+0.125			
	sand				32°31'	26°20'	
					31°00'+33°55'	25°17'+27°45'	

### Deformation Properties of Quaternary Deposits

Compression tests provide important insight into the settlement behavior of foundation soils underlying engineering structures. Based on the values of the compression coefficient ( $a$ ) within the pressure range of 0–0.3 MPa, the soils forming the seabed in the hydrocarbon-bearing areas of the Caspian Sea were classified into three groups:

- Highly compressible soils, for which ;
- Moderately compressible soils, for which ;

- Low-compressibility soils were not identified within the Quaternary clay deposits down to depths of 100 m at applied loads of 0–0.3 MPa.

All silty and soft (fluid) soils, representing undercompacted sediments, belong to the highly compressible category. For clayey silts, the compression coefficient under loads of 0–0.3 MPa ranges from 40.0 to  $13.0 \times 10^{-3} \text{ MPa}^{-1}$ , whereas for silty loams, it varies from 18.3 to  $10.2 \times 10^{-3} \text{ MPa}^{-1}$  (Table 9).

**Table 9:** Deformation properties of clay soils of Quaternary deposits

area	name of soil	Deformation modulus E (MPa) under loading conditions		
		0+0.1 MPa	0.1+0.2 Mpa	0.2+0.3 Mpa
Baku archipelago	clayey silt	1.14	1.75	3.13
		0.38+1.80	0.88+2.28	1.28+5.02
	silty loam	1.18	2.19	3.86
		0.49+1.65	1.33+3.25	2.53+4.57
	clay	3.75	4.61	6.28
		1.16+9.12	2.18+12.44	3.20+14.82
	loam	4.03	5.40	7.25
		0.97+11.80	1.99+12.85	3.05+14.20

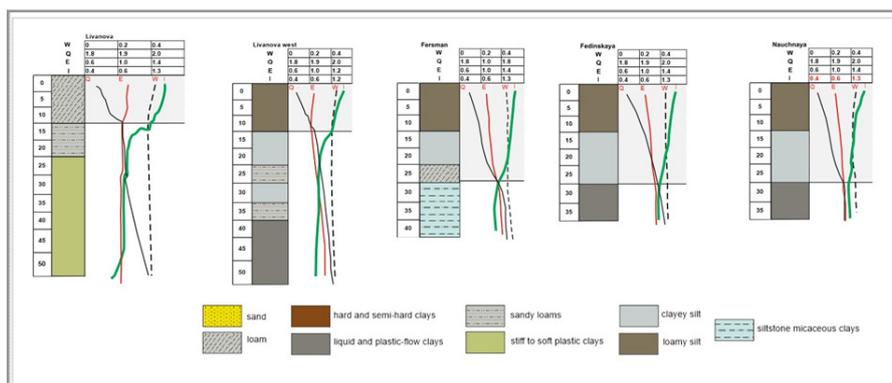
Apsheeron archipelago	clayey silt	0.93	1.56	2.20
		0.30+1.35	12.85	1.20+6.30
	silty loam	0.98	1.63	2.47
		0.45+2.17	0.94+2.28	1.27+3.15
	clay	4.67	5.98	7.36
		11.95	1.56+13.80	2.06+16.20
loam	4.86	6.00	7.68	
	1.04+12.90	2.04+13.30	2.38+14.20	
Turkmenian zone	clayey silt	1.25	2.07	3.75
		0.53+2.09	1.15+3.02	1.84+4.99
	clay	4.49	6.73	9.20
		1.69+10.67	2.90+15.01	3.73+30.13
	loam	5.95	8.09	11.65
		1.24+19.28	3.10+37.90	4.69+39.65

Highly saturated (silty) sediments are characterized by very low moduli of deformation (E). During the initial loading stages, these soils lose a substantial portion of the pore water, indicating weak structural and pore strength. The active expulsion of free water during compression is accompanied by significant changes in porosity, as observed in the consolidation process.

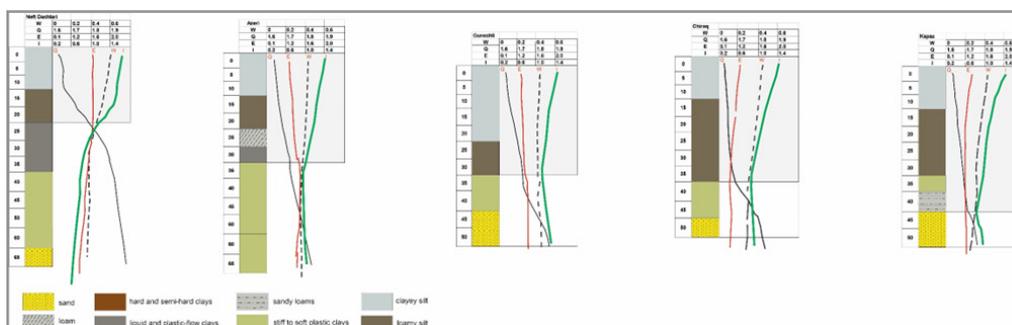
With the transition from silts to clays and loams, the modulus of deformation (E) increases while the compression coefficient ( $\alpha$ )

decreases, reflecting progressive dewatering and compaction of the sediments (Fig. 2, 3 and 4).

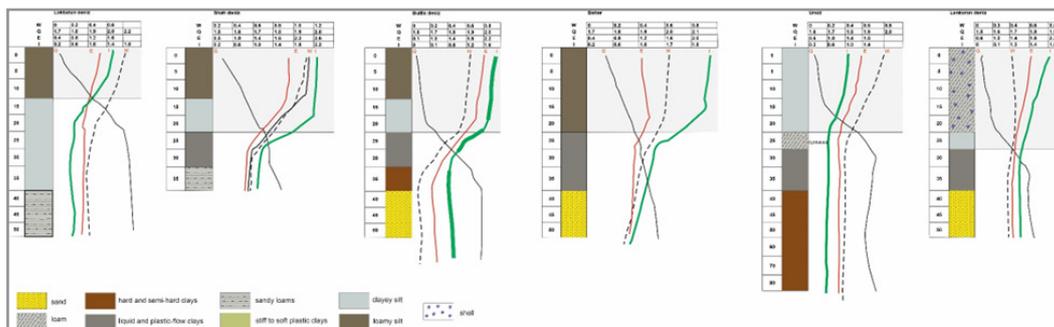
Consequently, soils evolve from highly to moderately compressible types. As shown in Figs. 2, 3, and 4, which illustrate the variation in deformation properties of Quaternary clays with depth across representative Caspian Sea fields, the rate of compression within Quaternary strata is less pronounced than in modern silty deposits.



**Figure 2:** The change in strength and deformation properties of Quaternary deposits with increasing depth of occurrence in the Turkmenia sector of the South Caspian basin



**Figure 3:** The change in strength and deformation properties of Quaternary deposits with increasing depth of occurrence in the Absheron Archipelago



**Figure 4:** The change in strength and deformation properties of Quaternary deposits with increasing depth of occurrence in the Baku Archipelago.

Consequently, soils evolve from highly to moderately compressible types. As shown in Figs. 2, 3, and 4, which illustrate the variation in deformation properties of Quaternary clays with depth across representative Caspian Sea fields, the rate of compression within Quaternary strata is less pronounced than in modern silty deposits.

With increasing burial depth, the structural strength of the soils rises; however, they generally remain moderately compressible, characterized by moderate deformation moduli and relatively high compression coefficients. This is attributed to the persistent presence of free pore water in these sediments.

In the lower parts of the profiles, where semi-hard and hard clays ( $I_L \approx 0$ ) occur in a densely compacted state ( $K_d \approx 1.0$ ), the structural strength exceeds the in situ effective stress, resulting in high deformation moduli and low compression coefficients. An increase in clay particle content corresponds to a decrease in the compression coefficient and an increase in the modulus of deformation shown in Table 9.

Values of and vary both vertically and laterally, as shown in the graphs in Fig. 2;3 and 4. These parameters differ markedly between shallow-water and deep-water regions of the basin. In shallow-water areas (e.g., Zhdanov Bank), high values and low values are observed even at shallow depths, while in deep-water zones (e.g., Shah Deniz and Gyuneshli fields), high and low values persist throughout the entire Quaternary section.

Clayey soils of the Turkmenian sector of South Caspian Basin are distinguished by high moduli of deformation and low compression coefficients, reflecting their compacted state and semi-hard consistency.

### Discussion

The comprehensive investigation of Quaternary deposits in the oil- and gas-bearing regions of the Southern Caspian Sea has revealed significant patterns in their lithological, mineralogical, and geotechnical characteristics, reflecting both depositional conditions and subsequent diagenetic transformations. The predominance of fine-grained clayey sediments, which constitute up to half of all Quaternary deposits, corresponds to the low hydrodynamic energy of the basin and the continuous supply of terrigenous material from surrounding uplifts and river systems. Vertical and lateral variations in grain size and mineral composition indicate the progressive transformation of these sediments from soft, water-saturated silts into denser, low-porosity clays

as burial depth and compaction increase. The physical and mechanical data confirm these evolutionary trends. With greater depth and consolidation, soil density rises, while porosity and natural moisture content decrease, leading to a marked increase in strength parameters. The angle of internal friction varies between  $7^\circ$  and  $29^\circ$ , and cohesion ranges from 0.005 to 0.175 MPa. These variations are closely linked to the degree of compaction, the montmorillonite–illite ratio, and the content of organic and carbonate components. The increase in strength parameters with depth corresponds to the diagenetic evolution of marine clays, where dehydration and structural rearrangement gradually enhance their load-bearing capacity. These findings are consistent with observations from other enclosed basins such as the Black Sea, indicating a regional pattern in the lithification of marine Quaternary sediments.

The present research provides new scientific insights into the engineering–geological characteristics of the Southern Caspian shelf. For the first time, correlations between the physical, mechanical, and lithological properties of Quaternary deposits were developed using a large and representative dataset derived from 70 boreholes and 300 core samples.

On the basis of these relationships, normative tables of strength and deformation characteristics were compiled, which make it possible to estimate soil parameters in areas where direct testing is limited. The construction of generalized engineering–geological cross sections for the Baku, Apsheron–Pre-Balkhan, and Turkmenian sectors allowed the identification of four lithogenetic zones that reflect different stages of compaction and diagenesis. This classification not only refines the understanding of sediment consolidation but also provides a coherent geological framework for future offshore development.

From an engineering perspective, the findings have direct practical value. The established geotechnical typification of Quaternary deposits enables accurate evaluation of seabed stability and bearing capacity, which is crucial for the safe and cost-effective design of offshore oil and gas structures. The ability to predict strength parameters from basic physical indices such as moisture, porosity, and plasticity provides engineers with a powerful tool for preliminary assessments, particularly during the early stages of feasibility studies and economic planning. The developed normative data and correlations also help reduce the scope and cost of field and laboratory investigations, ensuring efficiency in offshore geotechnical exploration.

The results have broader implications beyond the Caspian region. The identified dependencies between lithological composition, mineralogy, and mechanical behavior can be applied to similar marine basins, offering a methodological basis for predicting soil performance in foundation engineering. Moreover, the comprehensive dataset obtained in this study enhances regional geotechnical mapping, assists in determining optimal areas for detailed investigations, and supports the safe installation of pile foundations and other offshore support systems.

In summary, this research provides a new understanding of the engineering-geological framework of the Southern Caspian Sea, combining both scientific and practical advances. The established relationships between mineral composition, lithological variability, and mechanical strength allow for reliable prediction of geotechnical conditions, significantly improving the accuracy of seabed modeling and the safety of offshore construction. The integration of extensive historical and recent data has produced a robust foundation for further studies and practical applications. Continued investigations, including in-situ testing and numerical modeling of stress-strain behavior under cyclic loads, will deepen the understanding of seabed dynamics and ensure the stability of future offshore infrastructure in the Caspian region.

### Conclusions

Studies of the lithological composition of the Quaternary deposits indicate that the examined strata represent terrigenous facies composed of weakly carbonated sediments formed under arid climatic conditions and deposited during periods of elevated sediment accumulation rates. Lithologically, clayey varieties dominate in all sections, while silty and sandy facies play a subordinate role. The clays are notably silty, and the proportion of clay-sized particles increases with sea depth and within synclinal zones.

The mineralogical composition of the aleuritic and pelitic fractions of the Quaternary deposits reflects a predominance of allochthonous material, whereas authigenic mineral formation is minor. Among the identified authigenic minerals are pyrite, limonite, glauconite, and anhydrite, with their concentrations decreasing with depth.

The presence of pyrite in several sections indicates reducing depositional conditions, likely associated with bacterial activity enhanced by mud-volcanic processes. In the Bahar area, high pyrite contents (up to 100% in the heavy fraction) indicate zones of low pH during sedimentation. However, in other localities, the increase in glauconite content suggests a neutral to weakly oxidizing environment in near-surface layers. Elevated limonite concentrations in some areas reflect periodic shifts between reducing and oxidizing geochemical conditions. Anhydrite is another common authigenic mineral. Its highest concentrations in the Turkmenian sector of the South Caspian Basin are likely related to increased salinity of pore waters, supported by extraction data showing elevated Na and Cl contents and by the higher temperature of seawater in that region.

The results of the physical-mechanical investigations show that the properties of the Quaternary soils vary widely both laterally and vertically. With increasing clay content, the values of moisture, porosity, consistency index, and compression coefficient

increase, whereas density, internal friction angle, and deformation modulus decrease.

With increasing depth, a regular trend is observed: moisture content decreases, while density increases. As moisture ( $W$ ) decreases, the liquidity index, porosity, and void ratio also decrease, while the compaction coefficient, strength parameters, and deformation modulus increase. No systematic variation in the plasticity limits or plasticity index with depth was observed.

Silty sediments are characterized by high porosity and strong water saturation. Their liquidity indices are very high, and by their compaction coefficients, they belong to the undercompacted category. A sharp change in physical-mechanical properties occurs in the transition from silts to clays and loams: moisture and porosity decrease, while density, compaction coefficient, internal friction angle, cohesion, and deformation modulus increase. Figures 2;3, and 4 illustrate these abrupt transitions, after which the changes continue more gradually with depth.

The deep-water clayey soils differ significantly from shallow-water clays. Shallow-water clays, enriched in sand and silt, exhibit lower moisture, porosity, liquidity, and plasticity, but higher density and compaction coefficients. Consequently, they possess greater strength and higher deformation moduli. In contrast, deep-water, more finely dispersed clays, particularly those rich in montmorillonite, display higher moisture, porosity, plasticity, and liquidity indices, as well as higher hydrophilicity and lower cohesion.

The wide range of strength parameter values observed in the Quaternary deposits reflects their heterogeneous composition, variable physical properties, and distinct structural-textural features. With increasing particle dispersion, the strength properties of the bottom sediments decline. Since the composition of exchangeable cations affects the degree of aggregation of clay and colloidal particles, it also influences soil strength. The chloride-sodium composition of the water-soluble salts enhances the soil's resistance to external loads.

According to their deformation characteristics, silts and fluid clays are highly compressible, corresponding to undercompacted or weakly compacted soils, while normally compacted Quaternary clays are classified as moderately compressible.

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## Declaration of Competing Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

## Data Availability

The datasets generated and/or analysed during the current study are not publicly available due to their proprietary and archival nature but are available from the corresponding author upon reasonable request.

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