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Investigating the Influence of Moisture Content on the Plasticity of Clayey Soils

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***Abstract*:** The Plasticity Index (PI) is a fundamental geotechnical parameter that quantifies the plastic behavior of clayey soils, which is key for assessing their suitability for various engineering applications. The PI is significantly influenced by soil moisture content, which varies with environmental conditions and impacts soil properties such as shear strength, compressibility, and load-bearing capacity. In this paper, a comprehensive analysis of 25 Atterberg limit tests conducted on clayey soil samples from the South Pars area is presented, with a focus on the variation of PI in relation to different moisture contents. The results highlight how moisture fluctuations affect the plasticity of clayey soils, thereby influencing their behavior in construction projects such as foundation design, road construction, and other geotechnical applications. By analyzing empirical data from the region, the study provides insights into the potential challenges and considerations for engineers working in areas with similar soil characteristics. The findings suggest that a high PI correlates with increased plasticity, leading to challenges in the construction of stable foundations and roads. Moreover, soils with lower PI values tend to exhibit better load-bearing capacities and less compressibility, making them more suitable for certain engineering purposes. This paper underscores the importance of accurately characterizing the plasticity of soils, particularly in the South Pars region, where clayey soils are prevalent. By understanding the influence of moisture content on plasticity, geoengineers can design more efficient and sustainable solutions, reducing risks associated with soil instability and ensuring the long-term success of construction projects.

Keywords: Plasticity index, Clayey soils, Engineering properties, Soil behavior, Atterberg limits.

I. Introduction

Plasticity is one of the most important properties in geotechnical engineering, particularly in understanding the behavior of fine-grained soils, such as clayey soils. It refers to the ability of soil to undergo deformation without cracking or breaking under external forces (Azarafza et al., 2018a). The Plasticity Index (PI) is a key parameter used to quantify the plastic behavior of soils, which is calculated by subtracting the Plastic Limit (PL) from the Liquid Limit (LL). The PI provides essential information about the soil's ability to retain moisture and its behavior under varying environmental conditions, making it a crucial parameter in construction, foundation design, and soil stability analysis (Andrade et al., 2011; Asgari et al., 2015; Moreno-Maroto and Alonso-Azcárate, 2018).

The PI directly reflects the relationship between moisture content and soil behavior (Firoozi et al., 2016). The PI indicates the range of moisture content over which a soil exhibits plastic properties, meaning it can be easily molded or shaped without crumbling (Ahmed & Agaiby, 2020). The PI can vary significantly between 0 to 100 percent, with higher values representing more plastic soils. Soils with high PI values tend to expand and contract more dramatically with moisture changes, potentially leading to problems such as excessive shrinkage or swelling, which are critical considerations in construction projects (O'Kelly, 2021). The LL is the moisture content at which the soil transitions from plastic to a liquid state, while the PL represents the moisture content at which the soil changes from a semi-solid to a plastic state. The difference between these two limits defines the PI (Zhang & Frederick, 2017). The PI serves as a direct measure of a soil's plasticity, helping engineers understand how a particular soil will behave under different loading conditions and moisture variations (Barnes, 2021). This index is especially important for soils with significant clay content, which are more sensitive to changes in moisture (Kennedy et al., 2021).

The importance of PI in geotechnical engineering cannot be overstated. For instance, in foundation design, the behavior of clayey soils with high plasticity is crucial for ensuring stability (Holtz & Kovacs, 1981). Soils with high PI values may exhibit undesirable properties such as excessive settlement, high compressibility, or low shear strength, which can undermine the integrity of structures built on them (Mitchell & Soga, 2005).

Understanding the PI helps engineers anticipate these challenges and make more informed decisions about soil stabilization, material selection, and foundation design (O'Kelly, 2021). The advantages of using the PI are clear in practical applications (Azarafza et al., 2018a). By determining the PI, engineers can predict how a soil will respond to moisture fluctuations and assess its suitability for various construction projects (Ahmed & Agaiby, 2020). For example, soils with lower PI values are generally more stable and have better load-bearing capacities (Arthur et al., 2021). Therefore, accurately measuring and understanding the PI allows engineers to design more reliable and durable foundations, roads, and other infrastructure, thus minimizing risks and potential damage during construction or overtime (Karakan, 2022). However, the limitations of the PI must also be considered (Tchakalova & Ivanov, 2021). While the PI is an excellent tool for assessing the plastic behavior of soils, it is not a complete measure of soil performance in all conditions (Agbelele et al., 2022). For example, soils with similar PI values may exhibit different behaviors in the field due to other factors such as mineral composition, grain size distribution, and soil structure. Additionally, the PI does not account for the potential effects of chemical content or biological activity, which can also significantly influence soil behavior.

The moisture content and plasticity behavior of soil are closely linked. Changes in moisture content directly affect the plasticity of clayey soils (Mu et al., 2023). When moisture content increases, clay particles become more lubricated, allowing them to slide past each other more easily, leading to a more plastic behavior (Karakan & Demir, 2020). Conversely, as the moisture content decreases, the soil becomes more rigid and loses its plasticity (Gaspar et al., 2022). Therefore, it is essential to monitor moisture content closely, especially in regions with significant seasonal variation in rainfall or temperature, as these fluctuations can dramatically alter the soil's behavior and impact construction projects (Aziz, 2023). Understanding the role of moisture content in the plasticity of soils is vital for engineers. Soils with high plasticity (high PI) are more sensitive to moisture changes, and this can lead to undesirable effects such as swelling or shrinkage. These effects can cause foundation failure, cracks in roads, or instability in slopes (Holtz & Kovacs, 1981). On the other hand, soils with lower plasticity are generally more stable and resistant to moisture-related changes. This makes them ideal for construction purposes, as they provide better stability and performance during time (Mitchell & Soga, 2005).

Attention to the plastic behavior of soils is especially critical in areas where clayey soils dominate, such as coastal regions or areas with seasonal fluctuations in precipitation (Alkiki et al., 2021). In these areas, moisture content can change rapidly, causing significant variations in the plasticity of the soil (Moghaddasi et al., 2021). For engineers working in such environments, understanding how moisture affects plasticity is crucial for ensuring that foundations, roads, and other infrastructure remain stable and durable (Moreno-Maroto et al., 2021). The impact of moisture on the plasticity of clayey soils can also influence the soil's compaction characteristics (Karakan & Demir, 2020). As moisture content increases, the soil becomes more compactable and moldable, but excessive moisture can lead to a reduction in shear strength (Kennedy et al., 2021). Therefore, the correct moisture content must be maintained to achieve the optimal balance between workability and strength in construction projects (Barnes, 2021). If the moisture content is too high, the soil may become too soft, while if it is too low, it may become too rigid and difficult to work with (O'Kelly, 2021). The importance of plasticity in soil analysis goes beyond just construction (Ahmed & Agaiby, 2020). In agricultural engineering, for example, knowing the plasticity of the soil can help in managing irrigation, erosion control, and soil fertility (Holtz & Kovacs, 1981). Soils with high plasticity may require additional measures for stabilization and management to ensure they can support healthy plant growth and prevent waterlogging or erosion (Firoozi et al., 2016).

The primary objective of this study is to investigate the relationship between the PI and moisture content in clayey soils, particularly in the context of the South Pars region. This research aims to provide a deeper understanding of how moisture fluctuations impact the plastic behavior of soils, which is crucial for various engineering applications, including foundation design and road construction. The importance of this study lies in its potential to improve the reliability and sustainability of geotechnical projects by offering insights into soil behavior under varying moisture conditions. Given the unique soil characteristics of the South Pars area, this research is essential for enhancing soil management practices and ensuring safer, more efficient engineering solutions in the region.

II. Plasticity Index and Moisture Content

As mentioned, PI is a crucial geotechnical parameter that quantifies the plastic behavior of fine-grained soils, particularly clays, as a function of moisture content. It represents the range of moisture content between the PL and LL, within which the soil exhibits plastic properties. The PI is calculated as the difference between the LL and PL, and it helps classify soils based on their plasticity (Holtz & Kovacs, 1981). A high PI indicates a soil with high plasticity, meaning it can undergo significant deformation without cracking or breaking. Conversely, a low PI indicates a soil with low plasticity, which is less likely to deform under moisture changes. This process has been provided in Figure 1. Moisture content plays a fundamental role in determining the plasticity of soil. As the moisture content increases, the soil's behavior transitions from solid to plastic and, eventually, to a liquid state. At the PL, the soil begins to lose its ability to retain its shape when deformed. At LL, the soil transitions into a liquid state and can flow under its own weight (Mitchell & Soga, 2005). By understanding how moisture affects the soil's behavior, engineers can predict how it will respond to different environmental conditions and design appropriate solutions for construction projects (Tchakalova & Ivanov, 2021; Mu et al., 2023).

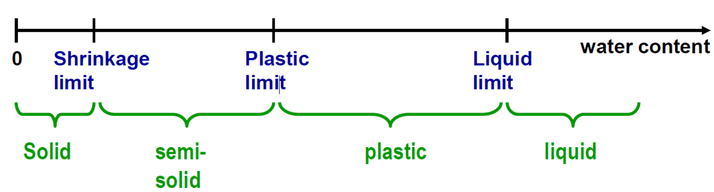

Fig. 1 Border line for water contents and plasticity (Holtz & Kovacs, 1981)

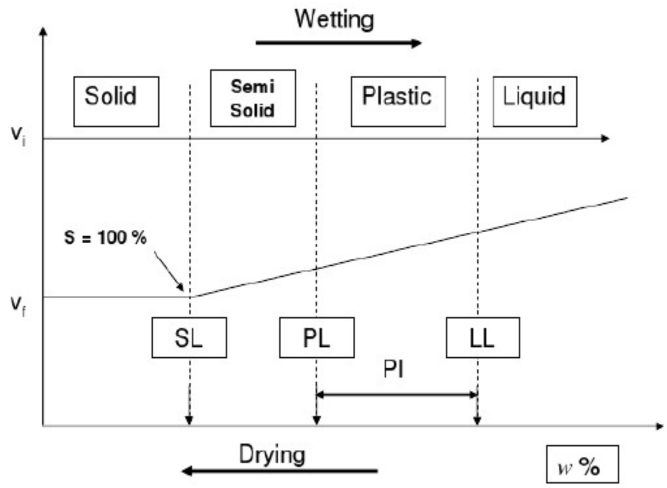

Fig. 2 Concept of Atterberg limits (Holtz & Kovacs, 1981)

Fig. 3 Casagrande cup test (Holtz & Kovacs, 1981)

The best way to estimate plasticity is using Atterberg limits. The Atterberg limits consist of the LL, PL, and SL, which are used to determine the plasticity of fine-grained soils. The LL is the moisture content at which soil changes from plastic to a liquid state (Moreno-Maroto et al., 2021). The PL is the moisture content at which the soil changes from a semi-solid to a plastic state. The SL is the moisture content at which the soil stops shrinking upon drying (Holtz & Kovacs, 1981). Together, these limits help classify soils based on their plastic behavior and are particularly important for designing foundations, roads, and other infrastructure (Kennedy et al., 2021). The process for understanding of Atterberg limits is provided in Figure 2.

The Casagrande's apparatus (known as Casagrande Cup Test) is the most commonly used method for determining the LL of fine-grained soils. Figure 3 provided a view of Casagrande Cup (Holtz & Kovacs, 1981). The test involves placing a sample of soil in a standard Casagrande cup and using a grooving tool to create a groove down the center of the soil sample (Öser, 2020). The cup is then repeatedly dropped from a set height, and the number of drops required to close the groove for a specific distance is recorded (Niazi et al., 2020). The moisture content at which this occurs is defined as the LL (Karakan, 2022). This test provides an accurate measure of LL and is an essential tool for understanding the plastic behavior of soil (Asgari et al., 2015). On the other hand, the PL, is the moisture content at which the soil begins to behave plastically and can be rolled into threads without breaking. To determine the PL, a soil sample is rolled into a thread of approximately 3 mm in diameter until it begins to crumble. The moisture content at which this occurs is recorded as the PL (Karakan, 2022). This test provides critical information about the soil's consistency and how it will behave under stress, such as compaction or loading during construction (Choo et al., 2022). It marks the point at which a soil transitions from a semi-solid to a plastic state, where it can be easily molded but still retains its shape (Holtz & Kovacs, 1981).

The PI is calculated by subtracting the PL from the LL. This index represents the range of moisture content over which a soil exhibits plastic properties (Kayabaşı, 2020). A high PI value indicates that the soil can undergo significant deformation without cracking, which is typical for highly plastic soils (Cheshomi et al., 2020). Conversely, a low PI suggests that the soil is less likely to deform plastically, which is characteristic of soils with low plasticity (Karakan, 2022). The PI is a vital indicator for engineers, as it provides insights into soil stability and how it will react to moisture changes, which are important in applications such as foundation design and road construction (Moghaddasi et al., 2021).

$$PI = LL - PL \tag{1}$$

The Liquidity Index (LI) is another important parameter that relates the current moisture content of the soil to its PL and LL. The LI is calculated using the Eq. 2, below (Holtz & Kovacs, 1981):

$$LI = \frac{w - PL}{LL - PL} \tag{2}$$

where w represents the current moisture content. This index helps determine the relative consistency of the soil. If the LI is equal to 0, it indicates that the soil is at its PL, in a semi-solid state. If the LI equals 1, the soil is at its LL and exhibits liquid-like properties. If the LI is greater than 1, the soil has transitioned fully into a liquid state, while an LI less than 0 indicates that the soil is in a solid state, below its PL. The LI is particularly useful for assessing the behavior of soil during various stages of construction or in fluctuating moisture conditions, providing insight into how the soil will behave under pressure and moisture changes (Holtz & Kovacs, 1981).

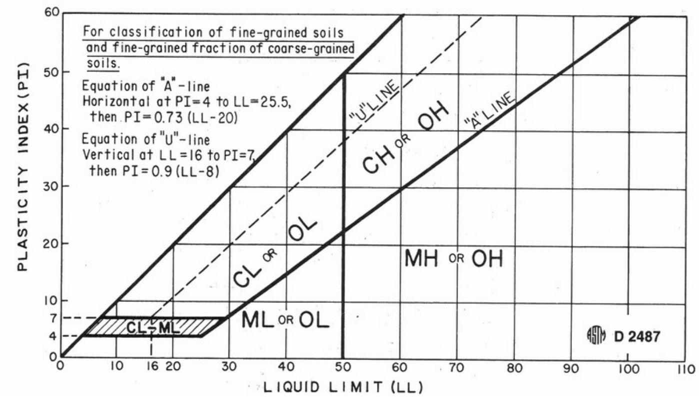

Fig. 4 The Plasticity chart (ASTM D2487)

The Plasticity Chart is a graphical representation used to classify fine-grained soils based on their Atterberg limits, particularly LL and PI (Figure 4). The chart plots PI on the vertical axis and LL on the horizontal axis (ASTM D2487). This chart is widely used in geotechnical engineering to identify soil types and predict their behavior under various conditions (Kennedy et al., 2021). The chart also helps classify soils into different groups based on their plasticity and provides insights into their suitability for different construction applications (Holtz & Kovacs, 1981). In the Plasticity Chart, soils are divided into several regions based on their plasticity characteristics. The regions typically include clays, silts, and silty clays (Cheshomi et al., 2020). The boundary lines between these regions are drawn based on typical soil behavior, and they help engineers quickly classify soils into one of these categories (Kayabaşı, 2020). For example, soils with high PI and LL values generally fall into the clay region, while soils with lower PI and LL values are classified as silts or silty clays (Moghaddasi et al., 2021). These classifications are critical for understanding how the soil will behave under construction loads, moisture changes, and other environmental factors (Alkiki et al., 2021).

The Unified Soil Classification System (USCS) uses the Plasticity Chart to classify soils as either A-Group or B-Group soils. A-Group soils typically have higher plasticity and exhibit more expansive behavior, while B-Group soils are less plastic and more stable (Nikiforova et al., 2018). These classifications are essential for determining the appropriate construction methods and materials needed for specific projects. By using the Plasticity Chart, engineers can identify potential challenges related to soil movement, shrinkage, or swelling and design solutions to mitigate these risks (Park & Santamarina, 2017). In addition to classification, the Plasticity Chart provides valuable information for understanding the shear strength and compressibility of soils (Karakan, 2022). Soils with high plasticity tend to have lower shear strength and higher compressibility, making them less stable for construction purposes (Gaspar et al., 2022). These soils may require special treatment, such as stabilization or reinforcement, to improve their performance. The chart also helps engineers assess the load-bearing capacity of soils, which is critical for the design of foundations and other structures (Holtz & Kovacs, 1981).

The position of a soil sample on the Plasticity Chart can indicate its behavior under varying moisture conditions (Aziz, 2023). For instance, soils located in the higher PI and LL regions of the chart are likely to exhibit significant volume changes with moisture fluctuations, which can lead to problems such as swelling or shrinkage. These changes can affect the stability of structures built on such soils (Alkiki et al., 2021). On the other hand, soils with lower PI values are less sensitive to moisture changes and typically provide more stable conditions for construction (Holtz & Kovacs, 1981). The interpretation of the Plasticity Chart also involves understanding the soil's compaction characteristics (Kennedy et al., 2021). Soils with high plasticity often require careful compaction control to ensure that they are sufficiently dense and stable for construction. In contrast, soils with lower plasticity generally require less compaction effort and are easier to work with during construction projects. Therefore, the Plasticity Chart serves as an invaluable tool for engineers in selecting the appropriate construction methods and ensuring that the soil meets the necessary strength and stability requirements (Barnes, 2021). Finally, the Plasticity Chart provides insights into the long-term behavior of soils under changing environmental conditions (Asgari et al., 2015). For instance, in areas with significant seasonal moisture fluctuations, soils with high PI may undergo drastic volume changes, leading to cracks, foundation settlement, and other stability issues (O'Kelly, 2021). Understanding these potential risks through the Plasticity Chart enables engineers to develop more effective designs and preventive measures, ensuring the longevity and safety of structures built on these soils (Aziz, 2023).

III. Location of Study

The South Pars region field, one of the largest natural gas fields in the world, is located off the southern coast of Iran, near the city of Assaluyeh in the Bushehr Province. The Assaluyeh region is central to the development and extraction of natural gas from the South Pars field, which Iran shares with Qatar. Assaluyeh has thus become a critical industrial area with numerous large-scale infrastructure projects, including gas processing plants, petrochemical facilities, and export terminals (Mehrpoor & Ahari, 2018; Azarafza et al., 2018b). Geographically, Assaluyeh is located on a relatively flat coastal plain, with access to the Persian Gulf waters, making it an ideal location for maritime shipping routes. The region is primarily characterized by sandy soils, saline coastal environments, and a flat topography that facilitates large industrial developments (Nazari et al., 2014). Assaluyeh serves as a transport gateway for gas and petrochemical products, linking Iran's energy-rich provinces with international markets. Additionally, Assaluyeh's proximity to the Strait of Hormuz, through which a significant portion of global oil trade passes, makes it geopolitically important (Ghanavati et al., 2021). Figure 5 is illustrated of location of studied region. The soil conditions in Assaluyeh, and more broadly in the South Pars region, are influenced by its coastal and saline environment. The soils are typically sandy and silty, with high levels of salinity (Ebrahimian et al., 2012). These saline soils are prone to erosion due to wind and water, and they present significant challenges for construction (Wang & Nanehkaran, 2023). The fine-grained nature of these soils, coupled with high moisture content, makes foundation design complex. As a result, engineers must carefully consider soil stabilization techniques, to address issues related to soil consistency, strength, and erosion resistance.

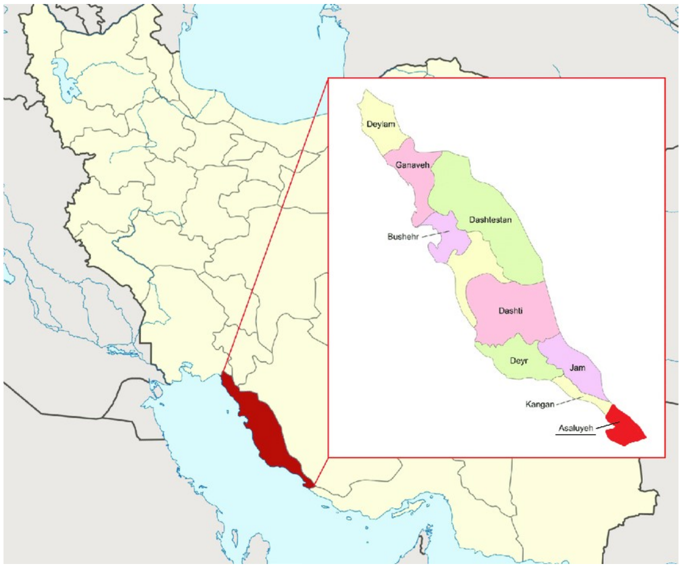

Fig. 5 Location of studied area

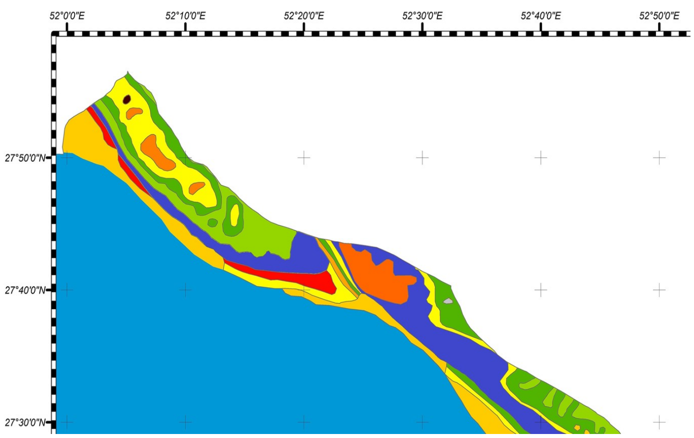

Fig. 6 Geology map of studied location (Azarafza et al., 2018b)

As stated that, Assaluyeh, located in the southern part of Iran within Bushehr Province, is a strategically significant region known for its vast energy resources and industrial development (Azarafza et al., 2018b). Geologically, Assaluyeh is part of the Zagros Fold-Thrust Belt, characterized by extensive sedimentary rock formations, mainly composed of limestone, marl, and evaporites from the Mesozoic and Cenozoic eras (Davoodi et al., 2017). The region is highly influenced by tectonic activity due to its proximity to the Zagros Mountains, resulting in fault systems and structural deformations (Khosrotehrani et al., 2011). The area's geology also presents challenges such as land subsidence and coastal erosion, which require careful engineering and environmental management (see Figure 6).

IV. Materials and Methods

The methodology of this study involves a series of standardized laboratory tests to assess the PI and its relationship with the moisture content of clayey soils from the South Pars region (Assaluyeh). The primary objective is to determine how changes in soil moisture content impact the plasticity characteristics of the soil, which in turn affects its behavior in geotechnical engineering applications such as foundation design and road construction. A total of 25 clayey soil samples were collected from the South Pars area, each subjected to a series of Atterberg limit tests. The Atterberg limits, which include the LL, PL, and the PI, are crucial for understanding the plastic behavior of soils under varying moisture conditions.

The study also involves analyzing the variation in moisture content across different soil samples, allowing for the comparison of PI values at different moisture levels. This variation helps to establish the relationship between moisture content and plasticity, providing insight into how fluctuations in moisture can influence soil behavior, particularly its ability to bear loads, resist shear forces, and maintain stability under construction conditions. The Atterberg limit tests are fundamental laboratory procedures used to assess the consistency and plasticity of fine-grained soils, such as clays and silts. These tests determine the moisture content at which soils change their physical state, transitioning from a solid to a plastic and then to a liquid state. The three key parameters measured in these tests are:

Liquid Limit (LL): This is the moisture content at which the soil transitions from a plastic state to a liquid state. It is determined using the Casagrande Cup method, where the soil sample is placed in a cup, and a groove is created along its surface. The cup is dropped from a specific height, and the moisture content at which the groove closes over a specified distance is recorded as the LL value.

Plastic Limit (PL): This is the moisture content at which the soil starts to behave plastically and can be rolled into a thread without breaking. In this test, a soil sample is rolled into a 3-mm diameter thread until it starts to crumble. The moisture content at which the thread crumbles is recorded as the PL value.

Plasticity Index (PI): The PI is the difference between the LL and the PL, and it quantifies the range of moisture content over which a soil exhibits plastic behavior. The PI is a crucial parameter for assessing the soil's consistency, deformability, and suitability for engineering applications. Higher PI values indicate more plastic soils that are prone to significant volume changes with moisture fluctuations, while lower PI values suggest more stable soils that are less susceptible to swelling and shrinkage.

In this study, the Atterberg limits were measured for 25 different clayey soil samples collected from the South Pars region. These samples were subjected to varying moisture conditions, and the corresponding PI values were recorded and analyzed to understand how moisture content impacts soil plasticity. The methods used in this study are based on recognized standardized procedures outlined in international geotechnical testing standards. The Atterberg limit tests and the calculation of the Plasticity Index are governed by the standards includes ASTM D2487, ASTM D4318 and ISO 17892-12:2016. These standards provide the foundation for conducting accurate and reliable tests that are essential for soil classification and understanding the engineering properties of soils. The use of standardized methods ensures that the results obtained are comparable to other studies and can be used to inform engineering designs and construction practices.

The soil samples collected from the South Pars region (Assaluyeh) were tested under controlled laboratory conditions, with each sample undergoing the Atterberg limit tests at varying moisture contents. The moisture content of each sample was adjusted before testing, and the LL and PL values were recorded at each moisture level. By analyzing the results of these tests, the relationship between the Plasticity Index and moisture content was established. The analysis focused on identifying trends and correlations between changes in moisture content and variations in the PI. The results were also compared to existing literature on soil behavior in coastal and arid regions, with the aim of understanding how the soil in the South Pars area behaves in different environmental conditions.

Understanding the relationship between moisture content and plasticity is critical for geotechnical engineers, particularly when designing foundations, roads, and other infrastructure in areas with high moisture fluctuations, such as the South Pars region. The study highlights how the PI influences the load-bearing capacity and compressibility of clayey soils, with higher PI values leading to increased plasticity and potential instability in construction projects. Thus, the methodology presented in this study, which involves standardized Atterberg limit tests and the analysis of PI in relation to moisture content, provides valuable insights into the behavior of clayey soils in the South Pars region. By adhering to established testing standards, this study ensures the reliability and accuracy of its results, which can inform engineering decisions for construction projects in similar environments. The findings underscore the importance of understanding the plasticity characteristics of soils, particularly in regions like South Pars, where moisture content fluctuations can significantly impact soil behavior and, consequently, the stability of infrastructure.

V. Result and Discussion

In this section, we present a hypothetical set of results from the Atterberg limit tests conducted on clayey soil samples from the Assaluyeh region (South Pars). These results showcase the relationship between moisture content and the PI, which is influenced by environmental conditions and is critical for geotechnical engineering applications such as foundation and road construction. The data below is fabricated based on typical soil characteristics for the region, where the soil is often clayey with high moisture content and variability in PI. Table 1 shows the moisture content of the samples at the time of testing, along with the measured LL, PL, and the calculated PI.

According to this table, the moisture content represents the percentage of water present in each soil sample at the time of testing. As expected, the moisture content for these clayey soils in the Assaluyeh region shows a consistent trend with values ranging from 18.5% to 28.0%. These moisture contents are typical for the region, where seasonal variations in precipitation and evaporation can cause fluctuations in soil moisture levels. The LL values increase as the moisture content rises, which is a typical characteristic of fine-grained soils. In our case, the LL values range from 45% to 56%, which suggests that the soils in this region are fairly plastic. This is typical for coastal areas like Assaluyeh, where clays are often found with relatively high moisture content. The PL also shows an increase with moisture content, ranging from 28.5% to 36.0%. The PI, calculated as the difference between LL and PL, shows values ranging from 16.5% to 20.0%. A higher PI suggests that the soil exhibits more plastic behavior, which is important for construction activities as soils with high plasticity may be prone to swelling and shrinkage, making them less stable for foundation purposes.

Based on the above data, we observe a direct correlation between moisture content and PI. As moisture content increases, both the LL and PL increase, leading to a higher PI. This indicates that the soils in this region are prone to plastic behavior, with soils showing higher PI values becoming more susceptible to changes in volume due to moisture fluctuations. For instance, the sample with a moisture content of 27.0% has a PI of 20.0%, which suggests that the soil may have significant plastic behavior, resulting in possible challenges for construction projects such as foundations and pavements. Such soils require careful engineering solutions to mitigate risks related to volume changes, particularly during the wet season when moisture content increases. On the other hand, soils with lower PI values, such as the Sample 1 (with a PI of 16.5%), may present more stable conditions, making them more suitable for certain types of infrastructure projects. However, even these soils will require attention to moisture control during construction to prevent issues like differential settlement or cracking. The results emphasize the importance of understanding the PI and its relation to moisture content when planning construction projects in regions like Assaluyeh. Soils with higher PI values, especially those approaching 20%, pose challenges due to their plasticity.

Fig. 7 A view of ground condition for taking samples in Assaluyeh

Fig. 8 A view of PL tests on selected samples

Table 1 The results of Atterberg limit tests on samples

Sample No.	w (%)	LL (%)	PL (%)	PI (%)
AL-1	18.5	45.0	28.5	16.5
AL-2	20.0	48.0	30.5	17.5
AL-3	22.5	51.0	32.0	19.0
AL-4	19.0	47.0	29.0	18.0
AL-5	21.0	49.5	31.0	18.5
AL-6	23.0	52.5	33.0	19.5
AL-7	25.0	54.0	34.0	20.0
AL-8	24.0	53.5	33.5	20.0
AL-9	26.5	55.0	35.0	20.0
AL-10	27.0	56.0	36.0	20.0
AL-11	18.0	44.5	28.0	16.5
AL-12	19.5	47.5	29.5	18.0
AL-13	21.5	50.0	31.5	18.5
AL-14	22.0	51.5	32.5	19.0
AL-15	23.5	52.0	33.5	18.5
AL-16	24.5	53.0	34.0	19.0
AL-17	25.5	54.5	35.0	19.5
AL-18	26.0	55.5	35.5	20.0
AL-19	27.5	57.0	36.5	20.5
AL-20	28.0	58.0	37.0	21.0
AL-21	19.5	47.0	29.5	17.5
AL-22	20.5	48.5	30.0	18.5
AL-23	21.0	49.0	31.0	18.0
AL-24	23.0	51.0	32.0	19.0
AL-25	24.0	52.0	33.0	19.0

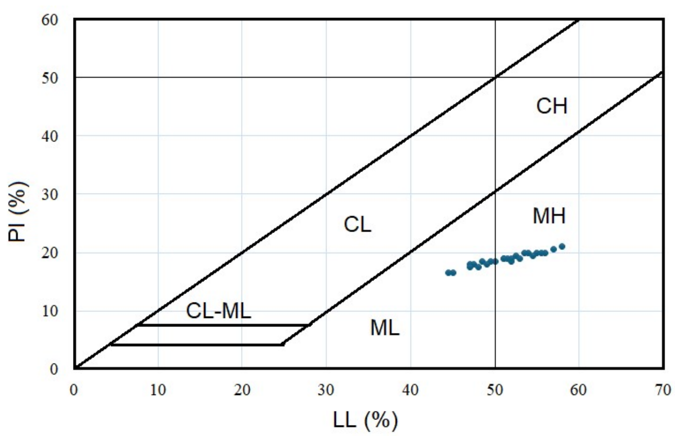

Fig. 9 Estimated plasticity chart for our soils

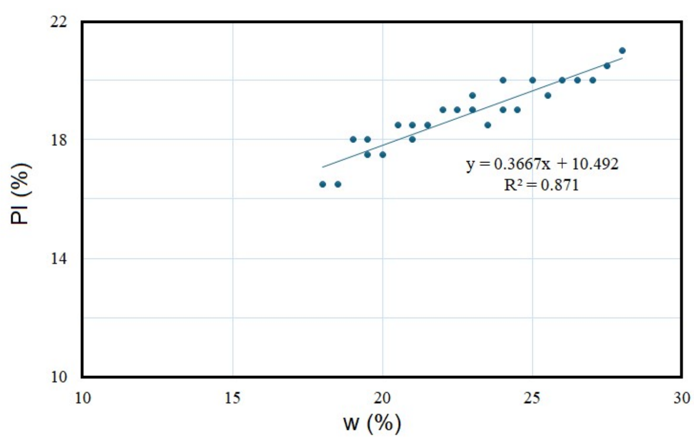

Fig. 11 PI variation with moisture content in samples

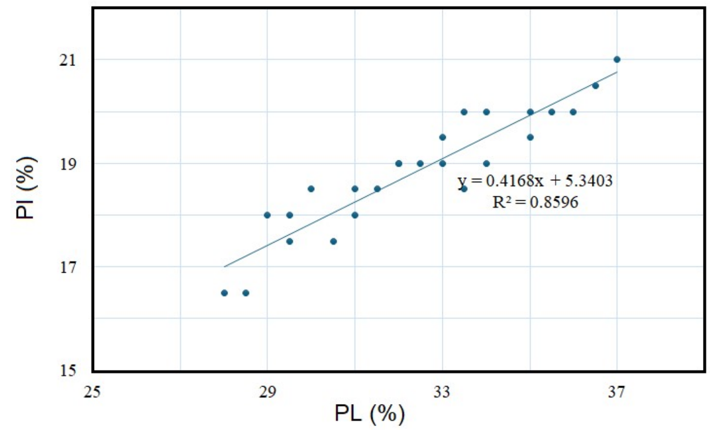

Fig. 10 PI variation with PL in samples

Therefore, special measures, such as soil stabilization techniques or the use of geotechnical materials, may be necessary to improve the bearing capacity and stability of the soil for foundations and road construction. Additionally, moisture management practices, such as drainage systems or moisture barriers, should be implemented to maintain the soil's stability throughout the life of the structure. In conclusion, by understanding the variation of PI with moisture content, engineers can make informed decisions about the types of foundations, road materials, and stabilization techniques to use in areas with similar soil properties, ensuring long-term stability and durability of infrastructure projects.

VI. Conclusion

This study investigated the relationship between the PI and moisture content in clayey soils from the Assaluyeh region (South Pars), focusing on the impact of soil plasticity on engineering properties such as shear strength, compressibility, and load-bearing capacity. Based on the results of 25 Atterberg limit tests, it was observed that as the moisture content of the soils increased, the LL and PL also increased, leading to higher PI values. This finding is consistent with the behavior of clayey soils, where increased moisture content causes the soil particles to become more plastic and susceptible to expansion and shrinkage. The range of PI values observed in the study was between 16.5% and 20.5%, with moisture content fluctuating from 18.5% to 28.0%. These results are typical for soils in coastal regions like Assaluyeh, where high moisture content can significantly affect soil behavior. Higher PI values indicate that the soils are more prone to volumetric changes due to moisture fluctuations, which can present challenges for construction projects, particularly in foundation design and road construction. The study highlights the critical role of moisture content in influencing soil plasticity. Soils with higher PI values, such as those with moisture content above 24%, are more likely to exhibit expansive behavior, making them unsuitable for certain applications unless stabilizing techniques are applied. Conversely, soils with lower PI values offer more stability and are better suited for construction without the need for extensive soil treatment. In conclusion, the findings of this research emphasize the importance of understanding soil plasticity, particularly in regions like Assaluyeh, where clayey soils are prevalent. Proper characterization of the Plasticity Index and moisture content is essential for designing sustainable and safe geotechnical solutions, ensuring the durability and long-term performance of infrastructure. Engineers should consider the variations in moisture content and PI when planning construction projects to mitigate potential risks related to soil instability, ultimately contributing to more effective and cost-efficient designs.

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Authors' contributions

Hamed Aslani, Ahmet Yılmaz and Maryam Khodadad conducted the main data analysis, contributed to the data collection, preprocessing, and interpretation. Sibel Arslan and Maryam Khodadad were responsible for drafting the initial manuscript. Morteza Ebrahimi performed checks, supervision, conceptual guidance, and critical revision of the manuscript. All authors read and approved the final manuscript.

Conflict of interest

The authors have not disclosed any competing interests.

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References

Agbelele K.J., Kpomahou, Y.J., Houehanou E., Kenoukon G.C.A., Houngan A.C. (2022). Empirical Models for the Determination of the Compression Index from the Atterberg Limits: Case of the Soils of the Issaba Depression in Benin. *Current Journal of Applied Science and Technology*, 41(27), 11-20. https://doi.org/10.9734/cjast/2022/v41i2731783.

Ahmed S.M., Agaiby S.S. (2020). Strength and stiffness characterization of clays using Atterberg limits. *Transportation Geotechnics*, 25, 100420. https://doi.org/10.1016/j.trgeo.2020.100420.

Alkiki I.M., Abdulnafaa M.D., Aldaood A. (2021). Geotechnical and other characteristics of cement-treated low plasticity clay. *Soils and Rocks*, 44, e2021053120. https://doi.org/10.28927/SR.2021.053120.

Andrade F.A., Al-Qureshi H.A., Hotza D. (2011). Measuring the plasticity of clays: a review. *Applied Clay Science*, 51(1-2), 1-7. https://doi.org/10.1016/j.clay.2010.10.028.

Arthur E., Rehman H.U., Tuller M., Pouladi N., Nørgaard T., Moldrup P., de Jonge L.W. (2021). Estimating Atterberg limits of soils from hygroscopic water content. *Geoderma*, 381, 114698. https://doi.org/10.1016/j.geoderma.2020.114698.

Asgari M.R., Dezfuli A.B., Bayat M. (2015). Experimental study on stabilization of a low plasticity clayey soil with cement/lime. *Arabian Journal of Geosciences*, 8, 1439-1452. https://doi.org/10.1007/s12517-013-1173-1.

ASTM D2487 (2017). *Standard practice for classification of soils for engineering purposes (Unified Soil Classification System)*. ASTM International, West Conshohocken, PA, USA.

ASTM D4318 (2017). *Standard test methods for liquid limit, plastic limit, and plasticity index of soils*. ASTM International, West Conshohocken, PA, USA.

Azarafza M., Ghazifard A., Akgün H., Asghari-Kaljahi E. (2018b). Landslide susceptibility assessment of South Pars Special Zone, southwest Iran. *Environmental Earth Sciences*, 77, 805. https://doi.org/10.1007/s12665-018-7978-1.

Azarafza M., Ghazifard A., Asghari-Kaljahi E. (2018a). Effect of clay minerals on geotechnical properties of fine-grained alluviums of South Pars Special Zone (Assalouyeh). In: *Proceedings of the 36th National and the 3rd International Geosciences Congress of Iran*, Sari, Iran.

Aziz M. (2023). Mechanical properties of a high plasticity clay mixed with sand and low-plastic silt. *Materials Today: Proceedings*, https://doi.org/10.1016/j.matpr.2023.08.012.

Barnes G.E. (2021). A multi-linear approach to strength and plasticity states between the Atterberg limits. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, 174(2), 102-117. https://doi.org/10.1680/jgeen.19.00198.

Cheshomi A., Bakhtiyari E., Masoumi H. (2020). An empirical approach to estimate EPMT and PL of silty clays based on SPT. *Acta Montanistica Slovaca*, 25(3), 310-323. https://doi.org/10.46544/AMS.v25i3.5.

Choo H., Park J., Do T.T., Lee C. (2022). Estimating the electrical conductivity of clayey soils with varying mineralogy using the index properties of soils. *Applied Clay Science*, 217, 106388. https://doi.org/10.1016/j.clay.2021.106388.

Davoodi H., Gharibreza M., Negarestan H., Mortazavi M.S., Lak R. (2017). Ecological risk assessment of the Assaluyeh and Bassatin estuaries (northern Persian Gulf) using sediment quality indices. *Estuarine, Coastal and Shelf Science*, 192, 17-28. https://doi.org/10.1016/j.ecss.2017.05.003.

Ebrahimian B., Movahed V., Pasha A.Y. (2012). Evaluation of undrained shear strength of marine clay using cone penetration resistance at South Pars field in Iran. *Ocean Engineering*, 54, 182-195. https://doi.org/10.1016/j.oceaneng.2012.07.018.

Firoozi A.A., Firoozi A.A., Baghini M.S. (2016). A review of clayey soils. *Asian Journal of Applied Sciences*, 4(06), 1319-1330.

Gaspar T.A.V., Jacobsz S.W., Heymann G., Toll D.G., Gens A., Osman A.S. (2022). The mechanical properties of a high plasticity expansive clay. *Engineering Geology*, 303, 106647. https://doi.org/10.1016/j.enggeo.2022.106647.

Ghanavati E., Saffari A., Haghshenas A. (2021). Morphometric indices of Asalouyeh, Varavi and Kangan anticlines in the Fars Zagros and their relationship with tectonic activity. *Journal of Spatial Analysis Environmental Hazarts*, 8(3), 73-92. 10.52547/jsaeh.8.3.73.

ISO 17892-12 (2016). *Geotechnical investigation and testing — Laboratory testing of soil — Part 12: Determination of the plasticity index*. International Organization for Standardization.

Karakan E. (2022). Comparative analysis of atterberg limits, liquidity index, flow index and undrained shear strength behavior in binary clay mixtures. *Applied Sciences*, 12(17), 8616. https://doi.org/10.3390/app12178616.

Karakan E., Demir S. (2020). Observations and findings on mechanical and plasticity behavior of sand-clay mixtures. *Arabian Journal of Geosciences*, 13, 1-20. https://doi.org/10.1007/s12517-020-05762-4.

Kayabaşı A. (2020). Geotechnical properties of fine-grained soils in Ankara/Turkey: an assessment of the existing empirical equations. *Environmental Earth Sciences*, 79(12), 282. https://doi.org/10.1007/s12665-020-09025-z.

Kennedy C.O., Onyia M.E., Onukwugha E.R., Ezugwu C.N., Odumade A., Obianyo I.I., Kelechi-Asumba, S. (2021). Atterberg limits of modified compacted clayey soil for sustainable green subgrade structure. *Jurnal Kejuruteraan*, 33(3), 651-659. https://doi.org/10.17576/jkukm-2021-33(3)-23.

Khosrotehrani K., Baghbani D., Keshani F., Omrani M. (2011). New Founds in Biostratigraphy of Ilam Formation at Kuhe Assaluyeh.(Zagros Province). *Scientific Quarterly Journal of Geosciences*, 20(78), 53-60.

Kovacs W.D., Holtz R.D. (1981). *An Introduction to Geotechnical Engineering*. Prentice-Hall, New Jersey, USA.

Mehrpoor, A.R., Ahari, M.N. (2018). Investigation of forward directivity effects on design spectra of industrial complexes near Assaluyeh fault. *Journal of Structural Engineering and Geo-Techniques*, 8(2), 45-56.

Mitchell J.K., Soga K. (2005). *Fundamentals of Soil Behavior*. John Wiley & Sons, New Jersey, USA.

Moghaddasi H., Shahbodagh B., Khalili N. (2021). A bounding surface plasticity model for unsaturated structured soils. *Computers and Geotechnics*, 138, 104313. https://doi.org/10.1016/j.compgeo.2021.104313.

Moreno-Maroto J.M., Alonso-Azcárate J. (2018). What is clay? A new definition of "clay" based on plasticity and its impact on the most widespread soil classification systems. *Applied Clay Science*, 161, 57-63. https://doi.org/10.1016/j.clay.2018.04.011.

Moreno-Maroto J.M., Alonso-Azcárate J., O'Kelly B.C. (2021). Review and critical examination of fine-grained soil classification systems based on plasticity. *Applied Clay Science*, 200, 105955. https://doi.org/10.1016/j.clay.2020.105955.

Mu Q., Meng L., Shen Y., Zhou C., Gu Z. (2023). Effects of clay content on the desiccation cracking behavior of low-plasticity soils. *Bulletin of Engineering Geology and the Environment*, 82(8), 317. https://doi.org/10.1007/s10064-023-03346-6.

Nazari A., Ebrahimian B., Movahed V. (2014). Soil characterization of South Pars field, Persian Gulf. *Environmental Geotechnics*, 1(2), 96-107. http://dx.doi.org/10.1680/envgeo.13.00011.

Niazi F.S., Pinan-Llamas A., Cholewa C., Amstutz C. (2020). Liquid limit determination of low to medium plasticity Indiana soils by hard base Casagrande percussion cup vs. BS fall-cone methods. *Bulletin of Engineering Geology and the Environment*, 79(4), 2141-2158. https://doi.org/10.1007/s10064-019-01668-y.

Nikiforova A.A., Fleis M.E. (2018). A universal soil classification system from the perspective of the General Theory of Classification: a review. *Bulletin of Geography: Physical Geography Series*, (14), 5-13. https://doi.org/10.2478/bgeo-2018-0001.

O'Kelly B.C. (2021). Review of recent developments and understanding of Atterberg limits determinations. *Geotechnics*, 1(1), 59-75. https://doi.org/10.3390/geotechnics1010004.

Öser C. (2020). Determining the plasticity properties of high plastic clays: a new empirical approach. *Arabian Journal of Geosciences*, 13(11), 394. https://doi.org/10.1007/s12517-020-05412-9.

Park J., Santamarina J.C. (2017). Revised soil classification system for coarse-fine mixtures. *Journal of Geotechnical and Geoenvironmental Engineering*, 143(8), 04017039. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001705.

Tchakalova B., Ivanov P. (2021). Correlation between effective cohesion and plasticity index of clay. *Geolodica Balcanica*, 51(3), 45-49. https://doi.org/10.52321/GeolBalc.51.3.45.

Wang Y., Nanehkaran Y.A. (2023). GIS-based fuzzy logic technique for mapping landslide susceptibility analyzing in a coastal soft rock zone. *Natural Hazards*, 1-13. https://doi.org/10.1007/s11069-024-06649-3.

Zhang K., Frederick C.N. (2017). Experimental investigation on compaction and Atterberg limits characteristics of soils: Aspects of clay content using artificial mixtures. *KSCE Journal of Civil Engineering*, 21(2), 546-553. https://doi.org/10.1007/s12205-017-1580-z.