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Predicting the Compression Index of Marine Soft Carbonate Clays Using Geotechnical Index Properties: A Case Study

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Abstract

Carbonate-rich marine clays along the northern Persian Gulf and Oman Sea exhibit complex compression behavior due to their unique fabric, crushability, and cementation. However, no reliable empirical correlation exists to estimate the compression index (C_c) of these marine carbonate clay using conventional index properties. This study investigates the relationships between C_c and index properties (liquid limit, natural water content, and initial void ratio) for Bushehr and Jask carbonate clays. A total of 237 oedometer tests on undisturbed samples were analyzed, along with Atterberg limits, XRD, and SEM analyses. Results show that carbonate content governs compressibility. Bushehr samples (50% carbonate) exhibit lower C_c due to cementation, while Jask samples (25% less carbonate) show higher C_c with larger voids. Conventional correlations for non-carbonate soils are not applicable. A new $C_c - LL$ equation for Persian Gulf marine carbonate clays is proposed. The combined dataset falls to the left of the compression liquid limit line, defining an "Iran marine soft carbonate clay zone" where carbonate cementation moderates compressibility.

Keywords: Carbonate; Marine clay, Liquid limit, Compression index.

1. Introduction

Marine and coastal soils, especially in shallow waters such as the northern Persian Gulf, contain considerable amounts of carbonate compounds and often form carbonate clay mixture (Pilkey and Nobel 1966; Winoto et al., 2022; Barem and Bayesteh, 2026; Tun and Zeng, 2026). Carbonate rich clay, which are common features of coastal sediments, have complex compositions. Their carbonate fraction is present as discrete skeletal or detrital grains, micritic pellets, or authigenic cements (Le Tirant and Nauroy 1994). This diversity in origin and form creates a unique fabric with highly variable particle morphology, intra-particle porosity, and bonding in stark contrast to the behavior of purely siliceous clays (Fookes 1988). Carbonate minerals can exist as discrete grains or as cementing agents that bind fine particles and sand together. They are usually identified by simple field tests (e.g., effervescence with dilute HCl), XRD analyses, and thermal/chemical methods (Yong and Warkentin 1975; Mitchell, Soga, and O'Sullivan 2025). The behavior in these sediments is controlled by a combination of factors beyond simple carbonate form (grain or cement), particle morphology, and the nature of cementation after deposition (Le Tirant and Nauroy 1994; Fookes 1988). As a result of this and diagenetic variation, a wide range of behavior is observed from highly compressible and crushable behavior that is not compatible with the common non-carbonate clays (Mitchell, Soga, and O'Sullivan 2025). Therefore, it is essential to use the suitable correlation to predict the geotechnical properties of carbonate clay during engineering projects. In coastal projects, especially those constructed on tidal flats, the high compressibility of soft marine deposits can lead to considerable settlements, partly because of the penetration of granular materials into the underlying weak seabed (Bayesteh and Mansouriboroujeni 2020).

Accordingly, even when the basic index properties appear similar, the consolidation behavior of carbonate clays can diverge significantly from that of typical silicate clays. This divergence arises from fundamental micromechanical controls–fabric, particle crushability, and cementation–that fundamentally govern how stress is transferred and accommodated within the sediment (Le Tirant and Nauroy 1994; Bayesteh and Bayat 2021). Studies on Persian Gulf coastal materials further emphasize this point. Farshbaf Aghajani and Salehzadeh (2015) indicated inherent fabric anisotropy and fragile

grain geometries that produce directional mechanical behavior. Furthermore, direct comparisons show that, despite equivalent grading and similar initial states, carbonate soils exhibit greater compressibility, distinct pore pressure responses relative to ordinary marine clays (Hassanlourad, Rasouli, and Salehzadeh 2014). Studies specific to the Persian Gulf show that local factors–such as mineral composition and pore water chemistry–influence the volume change behavior of these clays (Bayesteh and Bayat 2021). This means that index parameters-compressibility relationships must consider these specific regional conditions (Pilkey and Noble 1966). Therefore, conventional empirical correlations that successfully relate index parameters (LL, PI, w_n, e_0) to compression index (C_c) for silicate clays may not be directly applicable to carbonate marine clays. Their reliable application requires regional calibration and explicit consideration of fabric and diagenetic status (Le Tirant and Nauroy 1994).

The prediction of settlement in fine-grained soils depends primarily on C_c, obtained from oedometer testing (Shimobe and Spagnoli 2021). Although direct laboratory determination of the compression index using oedometer testing provides the most reliable measure of compressibility, this method is intrinsically time-consuming for the preliminary design of the practical projects (Giasi, Cherubini, and Paccapelo 2003). As a result, researchers have long sought empirical correlations to estimate compression index from more easily obtainable index properties (Skempton 1944; Lo and Lovell 1982; Cepero and Valeria 2014). However, it is noteworthy that the compressibility index of marine carbonate clays–particularly from the Persian Gulf and the Oman Sea–has not been systematically correlated with conventional index properties. While regional studies have extensively documented shear behavior and structure (e.g., Hassanlourad, Salehzadeh, and Shahnazari 2008; Farshbaf Aghajani and Salehzadeh 2015), comprehensive datasets that relate index parameters to compression index are mostly calibrated on non-carbonate soils (Shimobe and Spagnoli 2021; Fan et al. 2021).

Despite this, global studies that highlight single parameter C_c regressions also underscore their fundamental limitations (Abdrabbo and Mahmoud 1990). In contrast, regional datasets show that local controls–such as fabric, carbonate content, and depositional history–govern and reshape correlation trends. This situation highlights the limited predictive power of existing correlations for these soils, a limitation noted since early reviews (Poulos 1980). To overcome this, the present study

develops definitive C_c-index parameters correlations for the carbonate rich coastal deposits of the Persian Gulf and Oman Sea based on the several boreholes and laboratory tests, providing a region-specific correlation for consolidation settlement prediction of Persian Gulf's marine carbonate clays.

2. Technical Background

The compressibility of clayey soils is primarily investigated using a one-dimensional consolidation test. The results are presented as a consolidation curve that plots the void ratio (e) against the logarithm of effective vertical stress (σ'_v). This curve typically shows a flatter recompression slope at lower stresses and a steeper virgin compression slope at higher stresses. The slope of the virgin compression line is defined as the C_c, a fundamental measure of soil compressibility (Yong and Warkentin 1975). The C_c is often estimated using empirical correlations with determined index properties (Azzouz, Krizek, and Corotis 1976). The most commonly used parameters are the liquid limit (LL), the natural water content (w_n), and the initial void ratio (e_0) (Tiwari and Ajmera 2012). For reconstituted clays, the intrinsic compression index (C_c^*) shows a strong correlation with the void ratio at the liquid limit (e_L), which is itself a function of LL and specific gravity (G_s) (Burland 1990). Establishing reliable empirical correlation for parameters such as C_c often requires complex analysis of large datasets. Recently, advanced statistical methods and regression analysis have been used on a comprehensive database of oedometer tests of coastal clay soils to regional relationships (Gao, Chen, and Airey 2019).

The LL is a measure of the specific surface area and activity of the clay; higher LL values indicate more active clays (e.g., smectites), which are strongly correlated with greater compressibility (Bayesteh and Hoseini 2021). Moreover, the active clays have more potential for compression due to the large distance between their diffuse double layer (DDL) and their sensitivity during changing the pore fluid chemistry (Van Olphen 1991). The dependence of the compression behavior of clay on their physical properties regardless of pore fluid salinity (Burland 1990; Di Maio, Santoli, and Schiavone 2004; Hong, Yin, and Cui 2010) and regarding the pore fluid salinity (Song, Zeng, and Hong 2017; Deng et al. 2018) has been well documented.

Natural clays are fundamentally different from reconstituted clays because of their in-situ structure, including fabric and bonding. The properties of the reconstituted material, referred to as intrinsic properties, provide a key reference for analyzing the behavior of natural clays (Burland 1990). Clay minerals are also classified based on their activity, with active clays (e.g., montmorillonite) having a high specific surface area and inactive clays (e.g., kaolinite) showing lower sensitivity. These mineralogical-difference control their plasticity characteristics and overall engineering behavior (Collins and McGown 1974). The behavior of the carbonate clays is more similar to the inactive clays (Khabazian, Mirghasemi, and Bayesteh 2020; Bayesteh and Hashemi 2025).

For engineering projects, it is more convenient to calculate the compression index from LL. According to available empirical C_c-LL relationships obtained from previous research, several correlations have been proposed to predicting the C_c using different index properties. These relationships, developed for a wide range of soil types, are presented in Table 1. Some of these correlations have been generalized for all clays, while others are location-specific due to the database used. It is generally recommended that local correlations be developed based on the soil mineralogy and water condition of the area. Accordingly, some researchers have been tried to proposed C_c-LL correlation for case area such as: Brazil (Cozzolino 1961), Hong Kong (Lumb and Wroth 1968), Thailand (Balasubramaniam and Brenner 1981), China (Gao et al. 2019). However, no reliable *Cc-LL* correlation has yet been established for marine carbonate clays, particularly along the Persian Gulf coastal line. The present study is an attempt to address this.

126
127 **Table 1.** Empirical Correlation for Predicting the C_c from Index Properties (NAVFAC 2022)
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No.	Empirical equation	Soil type	Reference
1	$C_c = 0.007(LL - 10)$	Remolded clays	Skempton (1944)
2	$C_c = 0.0046(LL - 9)$	Clays from Sao Paulo, Brazil	Cozzolino (1961)
3	$C_c = 0.006(LL - 9)$	Clays for Greece and USA	Azzouz, Krizek, and Corotis (1976)
4	$C_c = 0.009(LL - 10)$	Undisturbed clay of sensitivity less than 4. Reliability 30%	Terzaghi, Peck, and Mesri (1996)
5	$C_c = 0.00797(LL - 8.16)$	Indiana soils	Lo and Lovell (1982)
6	$C_c = 0.0083(LL - 9)$	Remolded clays	Schofield and Wroth (1968)
7	$C_c = 0.003(LL - 10)$	Cohesive soils of the Rhone Alpes and Valley of the Seine River	Gielly, Lareal, and Parrier (1969)
8	$C_c = 0.008(LL - 5)$	Dredging material	Salem and Krizek (1976)
9	$C_c = 0.01(LL - 13)$	All clays	USACE (1990)
10	$C_c = 0.54(0.06w_n - 0.35)$	All clays	Nishida (1956)
11	$C_c = 0.008w_n + 0.2$	Weathered and soft Bangkok clays	Adikari (1977)
12	$C_c = 0.0126w_n - 0.162$	Indiana soils	Lo and Lovell (1982)
13	$C_c = 0.0115w_n$	Organic Silts and Clays in the southeastern coastal US	Cepero and Valeria (2014)
14	$C_c = 0.013(w_n - 3.85)$	Marine clay in South coast of Korea	Yoon, Kim, and Jeon (2004)
15	$C_c = 0.01w_n$	Chicago clay	Osterberg (1972)
16	$C_c = 0.01(w_n - 7.549)$	All clays	Rendon-Herrero (1983)
17	$C_c = 0.01(w_n - 5)$	3/4 from Greece and its environs	Azzouz, Krizek, and Corotis (1976)
18	$C_c = 0.0147w_n - 0.213$	French clays	Vidalie (1977)
19	$C_c = 1.15(e_0 - 0.91)$	All clays (Lower limit)	Nishida (1956)
20	$C_c = 0.30(e_0 - 0.27)$	Inorganic silty clays	Hough (1957)
21	$C_c = 0.256 + 0.43(e_0 - 0.84)$	Brazilian motley clays	Cozzolino (1961)
22	$C_c = 0.75(e_0 - 0.50)$	Soils of very low plasticity	Sowers (1970)
23	$C_c = 0.40(e_0 - 0.25)$	Clays for Greece and USA	Azzouz, Krizek, and Corotis (1976)
24	$C_c = 0.22 + 0.29e_0$	Weathered and soft Bangkok clays	Adikari (1977)
25	$C_c = 0.575e_0 - 0.241$	French clays	Vidalie (1977)
26	$C_c = 0.5621(e_0 - 0.4215)$	Outwash and alluvial deposits	Goldberg, Lovell, and Miles (1979)
27	$C_c = 0.496e_0 - 0.195$	Indiana soils	Lo and Lovell (1982)
28	$C_c = 0.3745e_0$	Soils from nine states in the USA	Rendon-Herrero (1983)

3. Method

The study areas are located along the northern coast of the Persian Gulf and the Oman Sea in southern Iran. Soil samples were obtained from boreholes from two regional area of Persian Gulf named *Jask* and *Bushehr* coast line which are represented as a two different location. The data used to investigate the relationships between the C_c and index parameters were extracted from laboratory tests performed on these samples as shown in the zoomed area in Figure 1.

A combined sampling strategy was employed to address the mixed nature of carbonate soils in the coastal regions of Jask and Bushehr. This methodology follows established recommendations for geotechnical investigation in heterogeneous carbonate formations, which emphasize the use of different coring and drilling techniques adapted to varying soil conditions (Le Tirant and Nauroy 1994). Wash boring was applied for initial borehole advancement in non-cohesive layers, while continuous coring was adopted as the primary method to ensure representative recovery and accurate identification of stratigraphic variability. In addition, rotary drilling and coring were used in boreholes where stiffer or cemented carbonate layers were encountered. The samples obtained from these boreholes formed the basis for the laboratory tests described in the following section. Samples obtained from these boreholes formed the basis of laboratory tests.

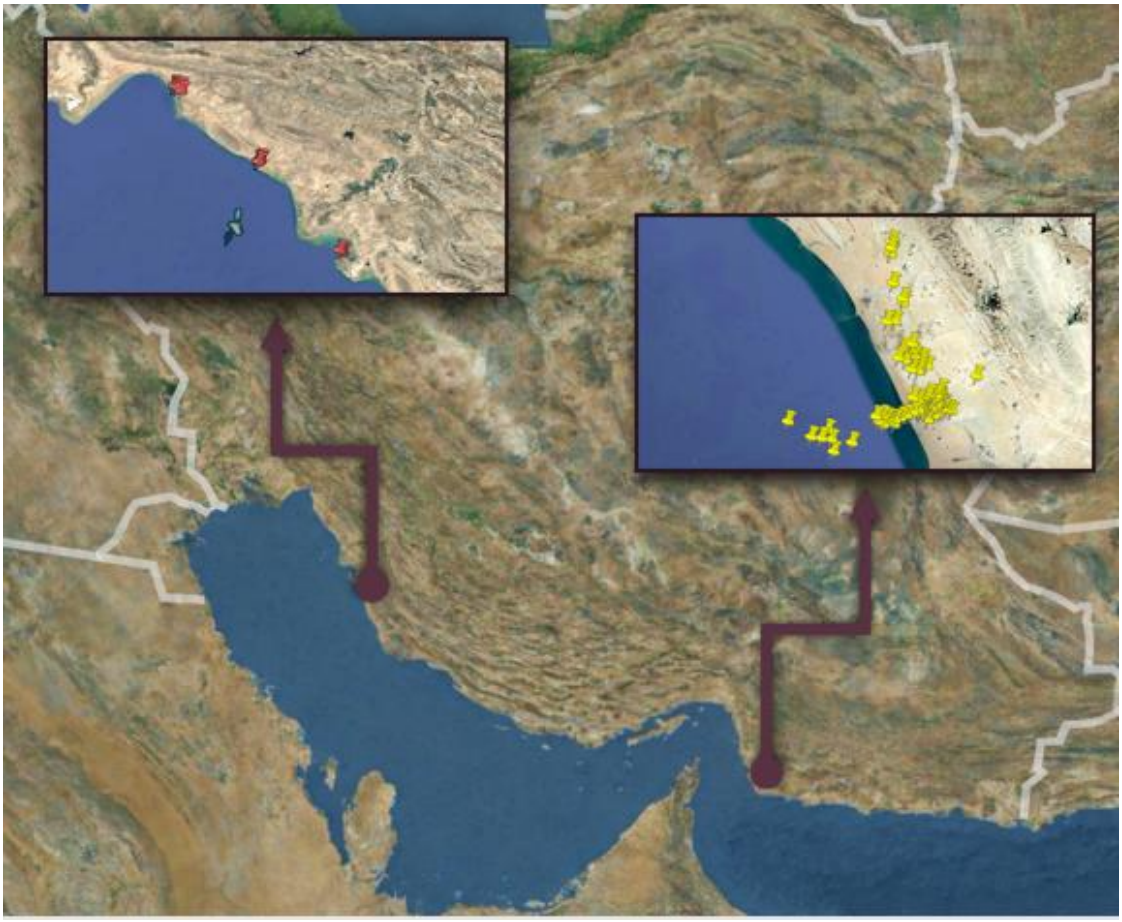


Fig. 1. Study areas and borehole locations in Bushehr and Jask, southern Iran.

Previous studies on soft coastal sediments have successfully combined field surveys and laboratory tests to characterize soil behavior (Bayesteh and Mansouriboroujeni 2020). Laboratory tests were conducted to determine the key geotechnical parameters. On high quality undisturbed specimens, one dimensional consolidation tests were performed (ASTM D2435). The specimens, obtained using thin-walled Shelby tubes, were saturated for 24 hours before testing and subjected to incremental loading to determine the C_c. Liquid limit tests were performed on remolded soil passing the No. 40 sieve (ASTM D4318). The obtained parameters were then analyzed to determine the desired correlations.

The soil samples were extracted from the boreholes in a tidal flat in the Persian Gulf as depicted in Figure 1. The clayey generally were low plasticity, brown in color and was classified by the Unified Soil Classification System (USCS) as CL. In order to identify the dominant clay minerals and understand the microstructural composition of the soils, X-ray diffraction (XRD) analysis was

performed on selected samples from the Jask and Bushehr regions. The samples were prepared and analyzed according to standard XRD methods (ASTM D3906).

Figure 2 shows the XRD patterns a of the marine carbonate clays for the both of Jask and Bushehr locations. It can be seen that the marine clay sample in Bushehr contained 50% calcium carbonate ($CaCO_3$), 22% dolomite ($CaMg(Co_3)_2$) and 28% quartz (SiO_2). However, in Jask carbonate clays, the values of carbonate are approximately 25% less than Bushehr and its kaolinite contents is more than Bushehr clay.

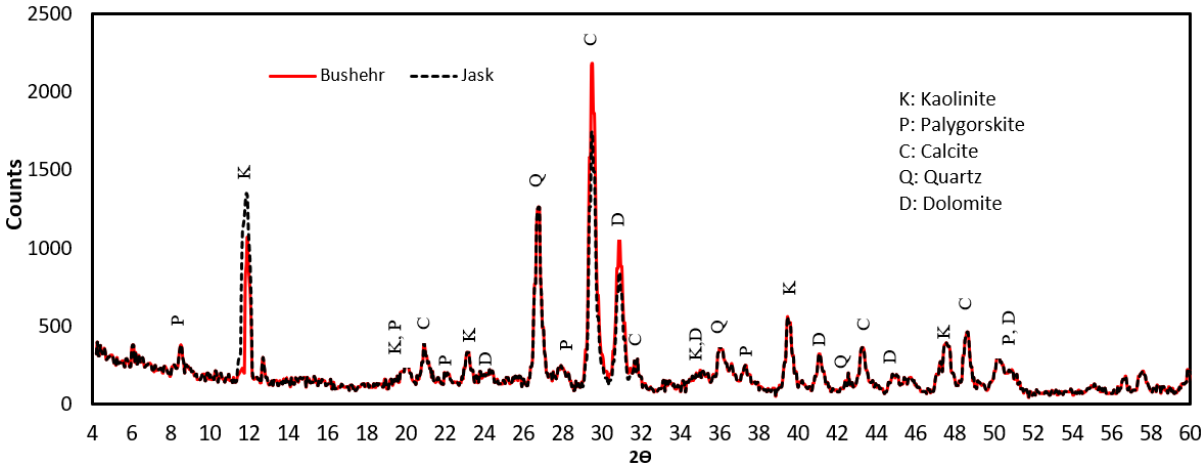


Fig. 2. X-ray diffraction (XRD) pattern of the clay fraction from a representative Bushehr and Jask soil sample

The study is based on a database of 237 one dimensional oedometer test on undisturbed carbonate clay samples from Jask and Bushehr regions. For each test, the C_c, w_n, LL, and e_0 were determined. To analyzed the data, simple linear regression was first used to examine the individual relationships between C_c and each index parameters (LL, w_n, e_0). Empirical correlations provided by several key researchers (e.g., Skempton 1944; Azzouz, Krizek, and Corotis 1976) were also plotted alongside the measured data for comparison. Then the suitable correlation for Cc-LL and Cc-e_0 relation will be selected regarding the tests results and analysis.

4. Results and Discussion

XRD analysis indicates that the marine clay of Bushehr is mainly composed of calcite, quartz, and kaolinite, with minor amounts of palygorskite and dolomite (Fig. 2). The dominance of carbonate minerals, particularly calcite, reflects the marine sedimentary environment of the study area. The

identified clay minerals exhibit moderate plasticity, which directly governs the compressibility behavior observed in consolidation tests. The one-dimensional consolidation curves for the marine carbonate clay samples from Bushehr and Jask exhibit the typical $e - \log\sigma'_v$ relationship common to cohesive soils. During loading, the void ratio decreases with increasing effective stress, while a partial recovery is observed upon unloading, demonstrating the irreversible and inelastic nature of soil compression (Fig. 3).

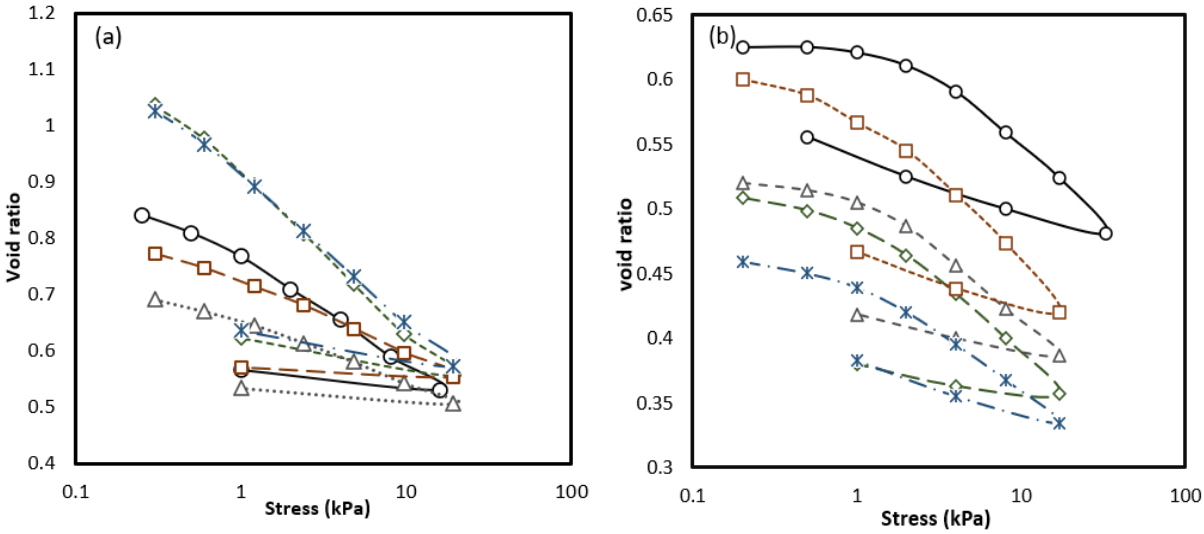


Fig. 3. One dimensional consolidation curves for undisturbed carbonate clay samlpes: **(a)** Bushehr and **(b)** Jask

The loading segment of each curve defines a distinct virgin compression line, which is linear in $e - \log\sigma'_v$ space. The slope of this line represents the C_c, which governs primary consolidation settlement under increasing stress (Spangler and Handy 1973). The consolidation curves show clear variations in vertical position and slope among samples from different depths at each site. These variations reflect differences in initial void ratio and intrinsic compressibility, underscoring the inherent heterogeneity of natural marine carbonate clay deposits (Burland 1990). Consolidation curves from Bushehr and Jask are similar in shape, but their position and slope differ, likely due to variation in mineralogy, depositional history, or in-situ stress conditions. These local differences are consistent with earlier studies of coastal and marine carbonate clays (Le Tirant and Nauroy 1994).

Figure 4 shows the relationship between C_c and LL for the studied marine carbonate clay samples. It is possible to observe that the trend shows the higher liquid limit, the higher the compression index. Most data are in range $C_c = 0.05 - 0.3$ and $LL = 15 - 50\%$. Higher C_c values (> 0.3 at $LL > 50$ %)

belong to high activity clay, while lower C_c values (< 0.050 at $LL < 15\%$) are more characteristic of low-plasticity soils. Samples from Bushehr at relatively lower C_c and lower LL are placed close to the lower-bound trends; in contrast, Jask samples with more C_c value and higher LL are plotted higher and show more scatter. This consistent offset is observed in XRD patterns clearly (Fig. 2). Samples from Bushehr exhibit sharp calcite and dolomite peaks, indicating high carbonate content (approximately 50%); by comparison, samples from Jask include weaker carbonate signals and more noticeable kaolinite and palygorskite peaks with lower carbonate contents. The higher carbonate in Bushehr stiffens the soil fabric and limiting volume change, therefore reducing both LL and C_c (Gerivani and Gerivani 2017). Gouy-Chapman diffuse double layer (DDL) theory indicates that the microfabric and macroscopic behavior of clays are strongly influenced by DDL thickness (Sridharan and Jayadeva 1982; van Olphen 1991; Komine 2008; Bayesteh and Mirghasemi 2013). Sridharan and Rao (1975) demonstrated that the LL of active clays such as montmorillonite is primarily governed by DDL expansion. In contrast, Horpibulsuk et al. (2011) observed that for non-active clays, an increase in cation concentration promotes flocculation and an edge-to-face particle arrangement, thereby enhancing water retention capacity and increasing the LL. When compared with existing empirical equations, the data from Bushehr tend to follow the relationship proposed by Azzouz, Krizek, and Corotis (1976) for Greece and USA clays in Eq. (1):

$$C_c = 0.006(LL - 9) \quad (1)$$

which is consistent with its low-activity nature; the samples from Jask, by contrast, plot closer to the relationship proposed by Salem and Krizek (1976) for dredging materials in Eq. (2):

$$C_c = 0.008(LL - 5) \quad (2)$$

which is showing its higher clay activity. Regression analyses performed on the present dataset yield the linear Eq. (3) and Eq. (4) for Bushehr and Jask, respectively.

$$C_c = 0.005(LL - 3) \quad (3)$$

$$C_c = 0.0004(514 - LL) \quad (4)$$

Based on the observed scatter and the global trends, approximate upper and lower bounds can be expressed for each area. For Bushehr the upper bound and lower bound are compatible with Eq. (5)

and Eq (6), respectively. For Jask the upper bound and lower bound are compatible with Eq. (7) and Eq (8), respectively.

$$C_c = 0.006(LL - 5) \quad (5)$$

$$C_c = 0.004(LL - 10) \quad (6)$$

$$C_c = 0.012(LL - 7) \quad (7)$$

$$C_c = 0.007(LL - 10) \quad (8)$$

The number of samples is still limited, and additional consolidation tests are needed to strengthen the correlations. Improving the database will enable more reliable predictions of C_c along the southern coastline.

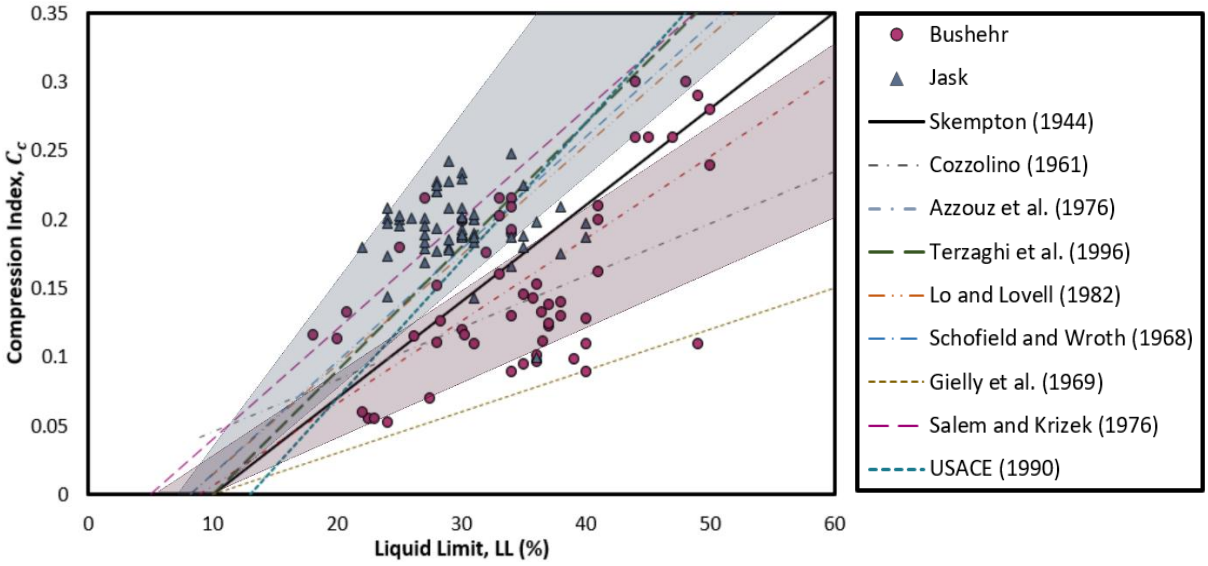


Fig. 4: General overview on the relationship of compression index with LL and Jask and Bushehr Data

Figure 5 illustrates relationship between C_c and w_n for both the Bushehr and Jask samples. The data are plotted alongside some empirical correlations by Lo and Lovell (1982), Yoon, Kim, and Jeon (2004), Cepero and Valeria (2014) and others. A clear positive trend is observable, where C_c increases with w_n; this is consistent with mentioned equations. The data show relatively few scatters because of a reasonably acceptable correlation. Most points placed within $C_c = 0.1 - 0.25$ and $w_n = 17 - 30\%$. Samples from Bushehr cluster at lower C_c $(0.1 - 0.15)$ and w_n (around $17 - 25\%$), with limited scatter. This is attributed to their higher carbonate content, which tends to cement particles, thereby reducing compressibility. In contrast, Jask samples plot higher C_c $(0.15 - 0.25)$ and w_n (around $22 -$

30%), and show slightly more variability; this displays their lower carbonate content and greater ratio of clay minerals (kaolinite and palygorskite) that increase activity and compressibility (Mitchell, Soga, O'sullivan 2025). When carbonate content exceeds about 30%, the C_c tends to decrease noticeably for a given w_n; this is mainly because soil behaves like a granular material, with stronger inter-particle bonding or cementation that limits void collapse and overall compressibility (Sterianos 1988). When compared with existing equations, the data from Bushehr are closer to the relationship proposed by Rendon-Herrero (1983) for soils from nine states in the USA in Eq. (9):

$$C_c = 0.01w_n - 0.07549 \quad (9)$$

The data from Jask are near to the relationship proposed by Azzouz, Krizek, and Corotis (1976) for Greece and USA clays in Eq. (10):

$$C_c = 0.01(w_n - 5) \quad (10)$$

The regression lines obtained from the data are in Eq. (11) and Eq. (12) for "Bushehr" and "Jask", respectively.

$$C_c = 0.007(w_n - 6.77) \quad (11)$$

$$C_c = 0.004(w_n + 17.95) \quad (12)$$

Based on the scatter and global trends approximate upper and lower bound observed that it can be delineated that for Bushehr the upper bound and lower bond are compatible with Eq. (13) and Eq (14), respectively. For Jask the upper bound and lower bond are compatible with Eq. (15) and Eq (16),

$$C_c = 0.009(w_n - 5) \quad (13)$$

$$C_c = 0.006(w_n - 10) \quad (14)$$

$$C_c = 0.008(w_n + 5) \quad (15)$$

$$C_c = 0.008(w_n - 7) \quad (16)$$

The collected data clearly distinguish between the less compressible Bushehr clays, governed by carbonate cementation, and the more active Jask clays with higher clay mineral content. These equations are valuable for predicting the settlement in coastal engineering projects.

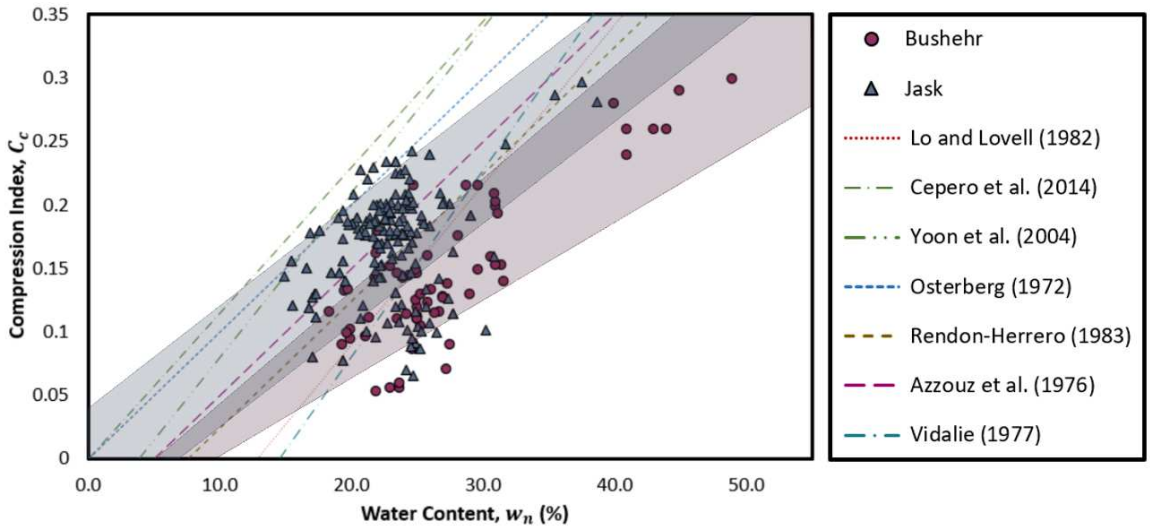


Fig. 5: General overview on the relationship of compression index with w_n and Jask and Bushehr Data

Figure 6 shows that how C_c changes with e_0 for the samples from Jask and Bushehr. The data are plotted next to some correlations from the literature, including Hough (1957), Sowers (1970), Rendon-Herrero (1983). The observed positive trend is consistent with empirical correlations for fine-grained soils. Most data points lie within $C_c = 0.05 - 0.3$ and $e_0 = 0.4 - 1.2$; the observed scatter is attributed to difference in soil fabric and cementation. Bushehr samples exhibit lower C_c $(0.10 - 0.25)$ and e_0 $(0.6 - 1.0)$ with limited scatter, while Jask samples plotted slightly higher with C_c $(0.04 - 0.25)$ and e_0 $(0.4 - 0.8)$. Similar findings have been reported by other researchers working on different soil types. Du et al. (2015b) examined kaolin-bentonite mixtures exposed to lead nitrate solutions and suggested that the e_0 at 1 kPa (e_1) could be used to estimate C_c. They showed the e_1 depends on the e_0 and the void ratio at liquid limit (e_L), following the approach of Zeng, Hong, and Cui (2015). These results show that how factors such as pore fluid chemistry and initial state can influence compression behavior that is analogous to the carbonate cementation effects. Gunduz and Arman (2007) investigated how e_0 and over-consolidation ratio (OCR) effect C_c and reloading index (C_r) in clays; identifying clear trends between OCR and C_c and between e_0 and C_c, which support the idea than multiple parameters should be considered for estimating compressibility.

By comparing the results with the existing equations in the technical literature, the data from Bushehr are close to the relationship proposed by Hough (1957) for inorganic silty clays that presented in Eq. (17):

$$C_c = 0.30(e_0 - 0.27) \quad (17)$$

The data from Jask plotted close to the relationship proposed by Cozzolino (1961) for Brazilian motely clays in Eq. (18):

$$C_c = 0.256 + 0.43(e_0 - 0.84) \quad (18)$$

that it shows its higher clay activity.

The equations obtained from the data are as Eq. (19) and Eq. (20) for Bushehr and Jask, respectively.

$$C_c = 0.26(e_0 - 0.15) \quad (19)$$

$$C_c = 0.23(e_0 + 0.094) \quad (20)$$

Based on the scatter and global trends approximate upper and lower bound observed that it can be delineated that for Bushehr the upper bound and lower bond are compatible with Eq. (21) and Eq (22), respectively. For Jask the upper bound and lower bond are compatible with Eq. (23) and Eq (24),

$$C_c = 0.35(e_0 - 0.2) \quad (21)$$

$$C_c = 0.25(e_0 - 0.3) \quad (22)$$

$$C_c = 0.30(e_0 + 0.1) \quad (23)$$

$$C_c = 0.32(e_0 - 0.24) \quad (24)$$

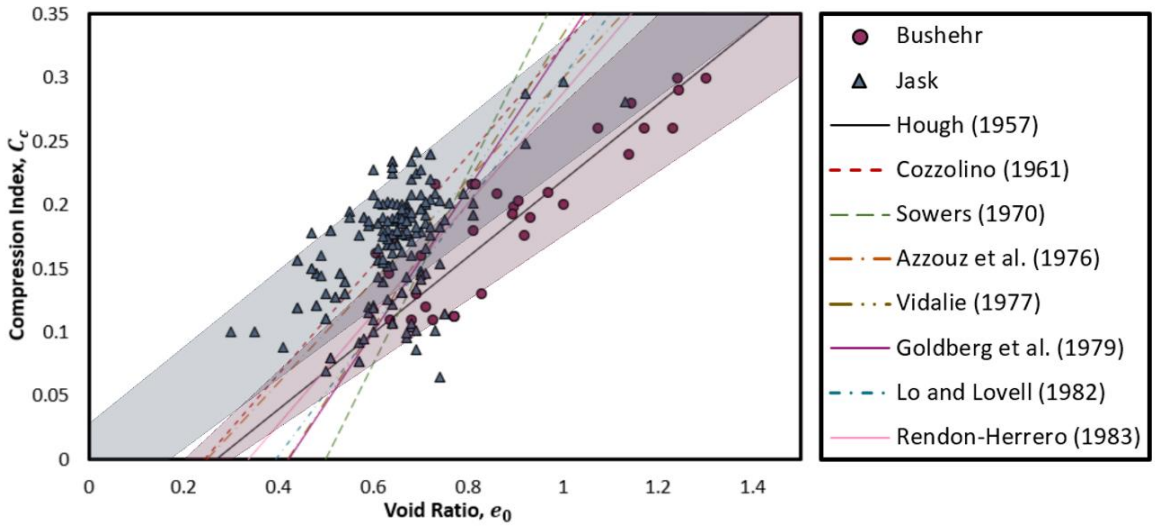


Fig. 6: General overview on the relationship of compression index with e_0 and Jask and Bushehr Data

Figure 7 presents SEM micrographs of the marine carbonate clays from Bushehr (a, b) and Jask (c, d) at two magnifications (500 nm and 1 μm). The Bushehr samples exhibit a denser structure with limited voids, where carbonate particles appear as distinct massive inclusions within a clay matrix. In

contrast, the Jask samples show a significantly more open fabric with larger and more frequent voids. This difference is attributed to the lower carbonate content and higher proportion of clay minerals (kaolinite and palygorskite) in the Jask samples. Repulsive forces between clay particles– particularly in non-active clays– promote flocculation and edge-to-face contact, thereby increasing inter-particle porosity (Collins and McGown 1974; Bayesteh and Hoseini 2021). Compared to the more carbonate-cemented Bushehr samples, the higher e_0 in Jask directly enhances its compressibility, causing steeper consolidation curves and larger C_c values where particle movement is restricted (Khoshsirat, Bayesteh, Sharifi 2019; Bayesteh and Bayat 2021; Farshbaf Aghajani and Salehzadeh 2015). Previous field studies on similar tidal flat deposits have successfully combined microstructural and macro-mechanical observations to characterize soft soil behavior (Collins and McGown 1974; Bayesteh and Hashemi 2025).

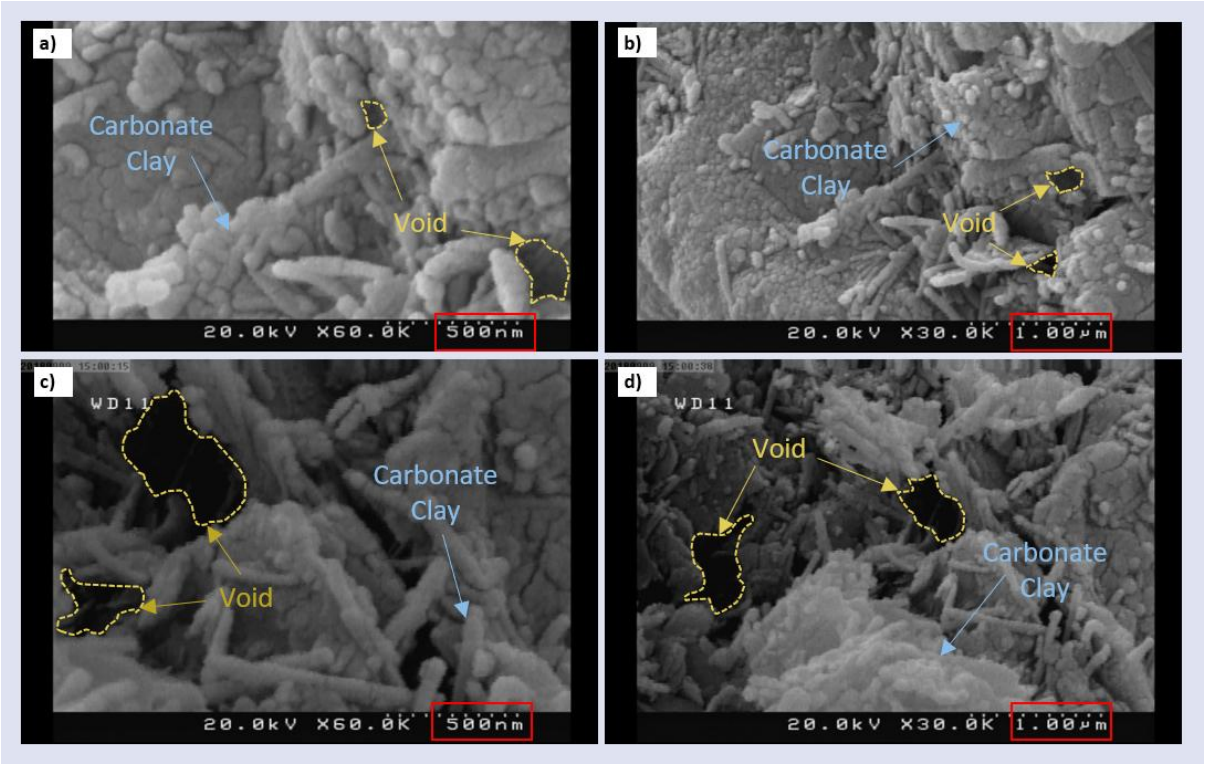


Fig. 7. SEM micrographs of Bushehr and Jask carbonate clays

Figure 8 presents the relationship between the gradient, (a) and intercept, (b) derived from the linear regression of C_c against LL, following the general form proposed by Al-Khafaji et al. (2015):

$$C_c = a(LL - b) \tag{24}$$

401 This form is consistent which the linear model:

402 $$C_c = \beta_L LL + \alpha_L \quad (25)$$

403 where $\beta_L = a(>0)$ and $\alpha_L = -c = -ab(b > 0 \text{ or } b < 0)$ (Shimobe and Spagnoli 2021). In the
404 present study, the coefficient a and b were determined through linear regression analysis of the
405 combined dataset from Bushehr and Jask; therefore, a combined analysis of them was adopted to
406 obtain for the Iran's marine soft carbonate clays. The best fit-line for the combined datasets yielded
407 $a = 0.0035$ and $b = 15.96$.

408 The combined data point locates to the left side of the Compression Liquid Limit (CLL) line ($b =$
409 $44.57 - (0.254)/a$) defined by Al-Khafaji et al. (2015). According to Shimobe and Spagnoli (2021),
410 data separating from the CLL line are mainly marine, alluvial, and organic soils, which typically
411 scatter to the right side of the line. However, the marine soft carbonate clays plot on the left side and
412 this deviation can be directly ascribed to their carbonate content. This left side positioning
413 demonstrates the governing influence of the samples from Bushehr within the merged datasets; which
414 have higher carbonate contents lowers the compressibility gradient (a) and increasing the intercept
415 (b), moving the behaviour leftward. The samples from Jask, with lower carbonate content and higher
416 clay mineral properties independently plot to the right of the CLL line. The datasets make an
417 intermediate point that captures the competing effects of clay mineral activity; therefore, a
418 characteristic behavioural zone delineated referred to as Iran's marine soft carbonate clay zone. This
419 zone is located on the left side of the CLL line and includes the soils with moderated compressibility
420 by carbonate cementation.

421 The other points in figure 8 have been presented by Yamagutshi (1959), Cozzolino (1961), Shouka
422 (1964), Azzouz, Krizek, and Corotis (1976), JSSMFE (1977), Ogawa and Matsumoto (1978), Bowels
423 (1979), Mayne and Mahmoud (1990), Tsuchida (1991), Lav and Ansal (2001), Yoon, Kim, and Jeon
424 (2004), Solanki and Desai (2008), Park and Lee (2011), Laskar and Pal (2012), Abbasi (2013),
425 McCabe et al. (2014), Al-Khafaji et al. (2015), Kumar, Jain, and Dwivedi (2016), Kootahi and Moradi
426 (2017). This observation highlights the importance of considering the location specific mineralogy of

applying global correlations; therefore, the combined analysis provides a baseline correlation for regional engineering assessments.

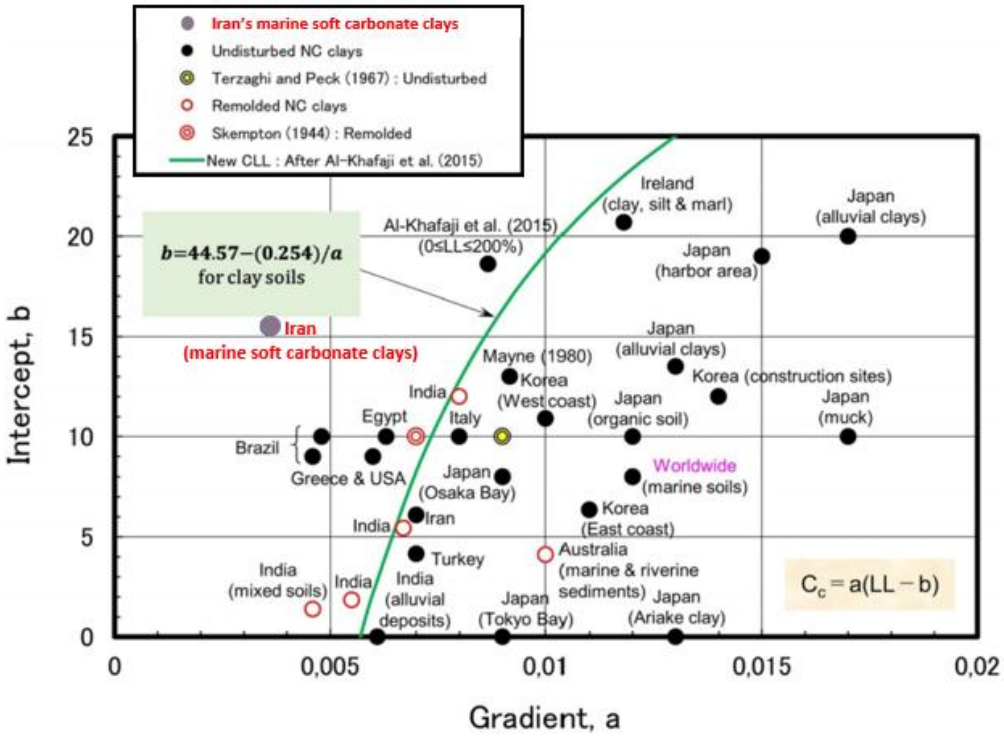


Fig. 8. Relationship between constants a and b for the empirical $C_c - LL$ relationship

5. Conclusion

This study investigated the compression behavior of marine carbonate clays from the northern Persian Gulf and Oman Sea, especially along the *Bushehr* and *Jask* coastlines. A comprehensive database consisting of 237 oedometer tests on undisturbed samples was analyzed to evaluate the relationships between the C_c and index properties including LL, w_n, and e_0.

The consolidation behavior of carbonate-rich marine clays departs significantly from that of typical silicate clays. Even when index properties appear similar, the presence of carbonate minerals alters the compression response through cementation and particle interlocking, which restrict void collapse under loading. Carbonate content has a governing role in determining the C_c. Higher carbonate content, as observed in Bushehr samples (approximately 50%), results in a denser microfabric with limited voids, leading to lower C_c values and reduced settlement potential. In contrast, lower carbonate content in Jask samples (approximately 25% less than Bushehr) allows for a more open

fabric with larger inter-particle voids, which enhances compressibility and produces steeper consolidation curves. Conventional empirical correlations that relate C_c to LL, w_n, or e_0– most were developed for non-carbonate soils– are not directly applicable to Persian Gulf carbonate clays. This limitation arises from the unique fabric, crushability, and cementation characteristics of carbonates sediments, which have been shown to alter compression behavior compared to siliceous clays. For Bushehr samples with higher carbonate content, Eq. (3) provides a reliable estimate of compressibility, consistent with the low-activity behavior of carbonate-cemented clays. For Jask samples, which have lower carbonate content and higher clay mineral proportion, Eq. (4) is more suitable as it reflects their higher activity and greater compressibility.

The combined dataset from both areas is placed on the left of the CLL line defined by Al-Khafaji et al. (2015), a deviation that is directly attributed to the moderating effect of carbonate cementation on compressibility. This area, referred to as the "Iran marine soft carbonate clay zone", highlights the need for regional calibration of empirical correlations when applied to carbonate-rich marine deposits.

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