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Article

Variation in the determination of preconsolidation stress, compressibility coefficient, and expansion coefficient of organic soil from southern Quito, Ecuador, based on modifications of the load increment ratio (LIR).

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Abstract: The objective of this research is to analyze the influence of the load increment ratio (LIR) on the determination of the preconsolidation stress and compressibility parameters of an organic soil from the south of Quito. Using carved samples of an undisturbed soil block recovered at a depth of 50 cm, which according to the characterization carried out correspond to organic silt with sand (OH). One-dimensional consolidation tests were carried out following method B of ASTM D2435, applying LIR values of 0.5, 0.7, 1.0, 1.2, 1.5. The results show that, as the LIR value used in the consolidation increases, the values of preconsolidation stress determined increase, reaching the highest value with the highest LIR tested. Similarly, it is observed that the compressibility and unloading index show variation as a function of the LIR applied. The findings of the present investigation provide a fundament for optimizing the selection of the LIR considering the behaviour of organic soils under different loading conditions, as well as offering tools to estimate consolidation parameters in soils with similar characteristics as a function of the LIR used in the consolidation.

Keywords: LIR, consolidation, preconsolidation stress, organic soil, compression index, expansion index.

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1. Introduction

This study focuses mainly on the determination of the preconsolidation stress (σ'p) and geotechnical parameters, such as the compression index (Cc) and expansion (Cs) derived from the consolidation test. For this purpose, samples of organic soil from the south of Quito were used to evaluate their behavior and variation in the results obtained from different one-dimensional consolidation tests carried out with different values of applied external loads. For this purpose, samples of organic soil from the south of Quito were used to evaluate their behavior and variation in the results obtained from different one-dimensional consolidation tests carried out with different values of applied external loads.

For the study site, the sector of southern Quito known as 'El Garrochal' was chosen because it is an urban area in which urban development projects have been developed that currently present geotechnical problems corresponding to differential settlements of up to 16 cm, which have led to various studies focused on the characterization of the soil material [1].

The one-dimensional consolidation test is essentially performed in the laboratory on fine soils with the objective of analyzing the settlement under the action of loads over time, providing information on compressibility and consolidation properties, which are fundamental parameters in the design of all types of structures [2], [3].

The load increment ratio (LIR) corresponds to the ratio between the load increment and the previous load used in the consolidation test; usually, the value of LIR =1.0 is used. The variation in the load increment is manifested in the experimental results, therefore at small values lower than 1.0 the tested sample presents smaller deformations, while with larger stress increments a greater compression is presented, being possible to reach an unbalance of the soil structure [4], [5].

In order to identify the influence of the load incremental ratio (LIR) on the results of consolidation parameters corresponding to pre-consolidation stress, compression index (Cc) and recompression (Cs), in specimens moulded from the same block of soil, one-dimensional consolidation tests were developed by varying the experimental LIR to identify and evaluate its effects. It is known that in general in one-dimensional consolidation tests the standard LIR value is set at 1.00, in order to identify the variations influenced by the LIR value, starting from the standard value, lower and higher values were chosen in order to contrast the results obtained with LIR values of 0.5, 0.7, 1.0, 1.2, 1.5.

Organic soils, due to their compressible nature, present a behaviour that depends on their loading history, which is why the present study deals with the determination of the overconsolidation index. For the consolidation process of this type of soil, it is expected to demonstrate the influence of the values used corresponding to the ratio of LIR load increments in both the initial compression stage, which is characterised by occurring in a very short period of time, and the secondary consolidation stage, in which linear or constant deformations with respect to time are reached [6].

In the context described above, it is hoped that the results presented here will provide a basis for predicting the behavior of these soils under different loading conditions, as well as contribute to the correct choice of the LIR in the execution of consolidation tests on soils at this study site and promote the development of research based on the present study.

2. Materials and Methods

2.1. Study area

The city of Quito, Ecuador is located at an altitude of 2850 m.a.s.l., in a narrow mountain valley in the Andes, with a length of over 30 km and up to 5 km wide [7], [8].

The present study was focused in the “El Garrochal” sector at Southern Quito, where a prehistoric lagoon was located which was drained leaving fluvio-lacustrine material and a superficial water table that nowadays causes the presence of swampy soils [9]. The coordinates of the specific “Pucará” neighborhood are 0°20'22.7” S 78°33'52.6” W, as shown in Figure 1.

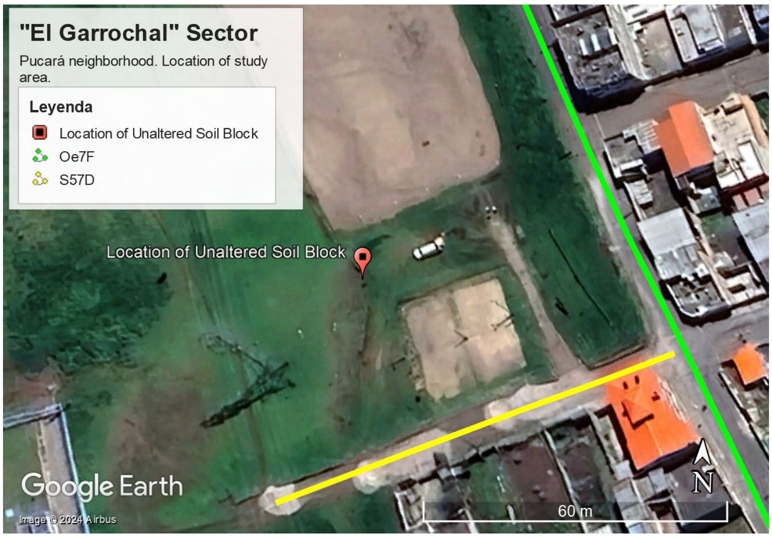


Figure 1. Location of study area. Obtained from: Google Earth, 2024.

2.2. *Sample extraction*

Based on Method A of ASTM D7015/D7015-18 [10], an intact soil block of approximately 0.40 x 0.40 m was extracted from a depth of 0.50 m, as shown in Figure 2.

The soil block extraction process consisted of removing the superficial organic matter, followed by an L-shaped trenched 0.50 m deep layer (Figure 2a). Next, the top of the block was marked and the sample was covered with plastic, cheesecloth, and wax (Figure 2b, c). Finally, the block was placed inside a wooden box with sawdust to preserve the in situ conditions of the sample during transportation (Figure 2d).

(a) **(b)**

(c) **(d)**

Figure 2. Soil block extraction. (**a**) Soil block sampling, **(b)** conservation of extracted blocks, **(c)** block preparation, and **(d)** sample before transport.

2.3. *Material characterization*

To obtain the physical properties of the samples, a summary of the laboratory tests is presented in Table 1.

Table 1. Summary of laboratory tests.

Laboratory Test	Parameters	Unit	Results	Ref.
USCS Clasification	Soil Clasification	-	OH (Organic silt with sand)	[11]
Moisture content	w	[%]	42.79	[12]
Atterberg Limits	LL, PL, IP		62 (LL), 40 (PL), 22 (PI)	[13]
Particle – Size distribution	Sand, Fine	[%]	17 (Sand), 83 (Fine)	[14]
Specific Gravity	Gs	-	2.48	[15]
Ash content	Ash average	[%]	92.42	[16]
Organic Content	Organic content	[%]	7.58	[16]

2.4. *Instrumentation*

Consolidation tests were performed with a consolidation frame EL25-0402 (Figure 3), which had a loading beam fitted with a counterbalance weight to apply a vertical load to the specimen. The consolidation frame can load the specimen with three beam ratios that are 9:1, 10:1 and 11:1; and its high capacity is 8800 kPa using a 50 mm diameter of consolidation cell with a beam ratio of 11:1 [17].

To develop the study, a consolidation frame was used with a beam ratio of 10:1 and a consolidation cell of approximately 63 mm in diameter and 20 mm in height.

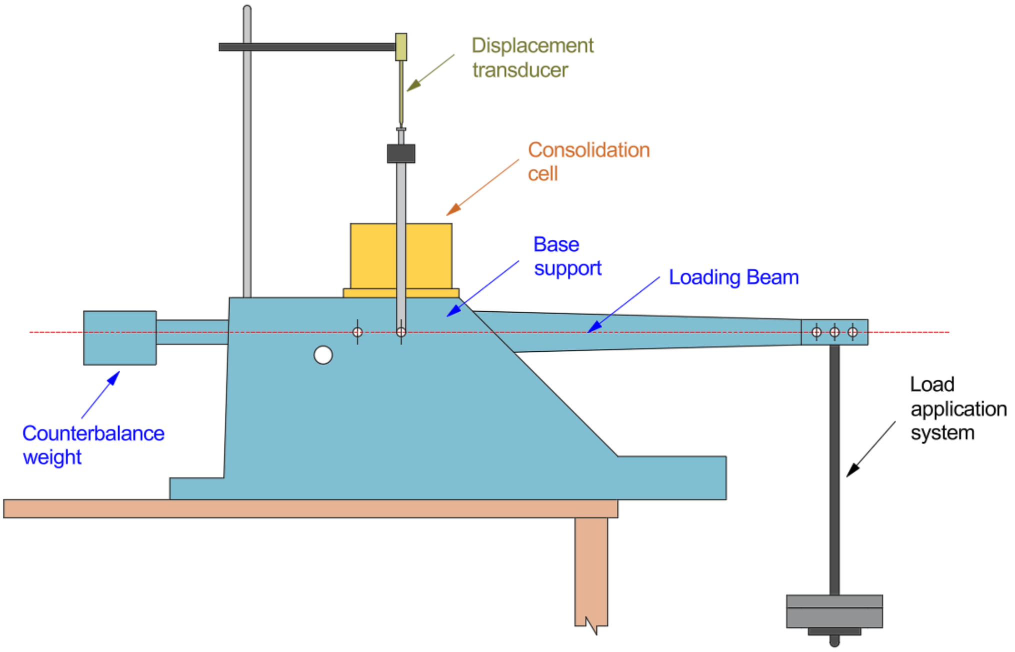


Figure 3. Schema of consolidation equipment. Adapted from: [17].

2.5. *Specimen preparation*

For the consolidation tests, five cylindrical specimens were obtained from the undisturbed block, with approximate dimensions of 63.5 mm diameter and 25.4 mm height, as shown in Table 2.

Table 2. Summary of specimen dimensions used in the consolidation test.

Sample	Diameter [mm]	Height [mm]	Relation D/H
M1	63.41	20.24	3.13
M2	63.22	20.11	3.14
M3	63.09	18.28	3.45
M4	63.22	20.03	3.16
M5	63.48	20.05	3.17

2.6. Stress application criteria

To define the standard load increment ratio (LIR) equal to 1, the Method B from ASTM D2435/D2435M-11 [18] was applied, where every axial stress was applied for a period of approximately of 24 hours to 60 hours, considering that the change of load must be made when primary consolidation ends and that each load increment corresponds to double the previous one.

However, the test methodology changed the LIR value as shown in Table 3.

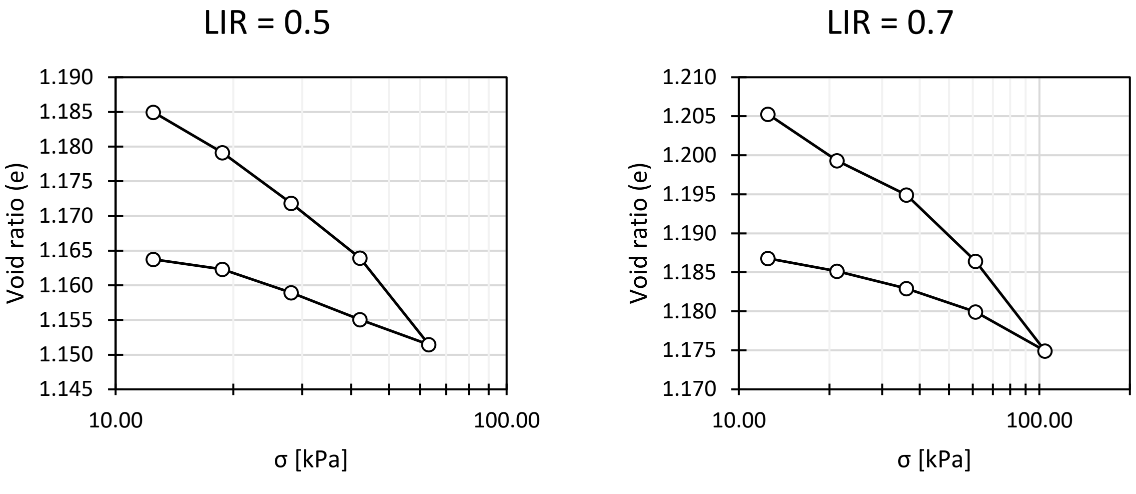
Table 3. Summary of the applied stress.

Sample	LIR	Applied stress [kPa]				
		Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
M1	0.5	12.50	18.75	28.13	42.19	63.28
M2	0.7	12.50	21.25	36.13	61.41	104.40
M3	1.0	12.50	25.00	50.00	100.00	200.00
M4	1.2	12.50	27.50	60.50	133.10	292.82
M5	1.5	12.50	31.25	78.13	195.31	488.28

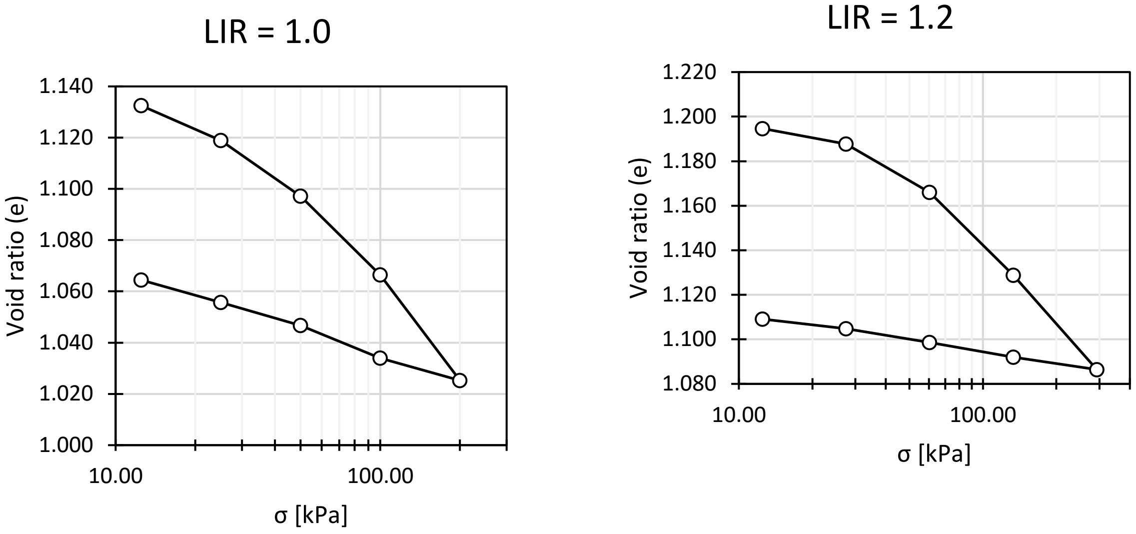
3. Results

3.1. Compresibility curve

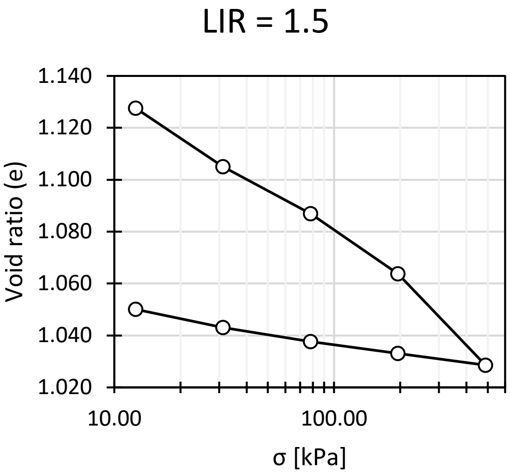
The compressibility curve is typically used to evaluate soil behavior under different stress levels [19]. As shown in Figure 4, the variation in the LIR in the loading stage affects the determination of consolidation parameters, such as the compressibility index (Cc), expansion index (Cs), and pre-consolidation stress (σ'$_P$), because every curve had its trajectory, directly influencing the determination of these parameters.



(**a**) (**b**)



(c) **(d)**



(e)

Figure 4. Compressibility curves. (a) LIR = 0.5, (b) LIR = 0.7, (c) LIR = 1, (d) LIR = 1.2, (e) LIR = 1.5.

In addition, Figure 5 shows a compilation of all the compressibility curves, where the different trajectories of each LIR are visible.

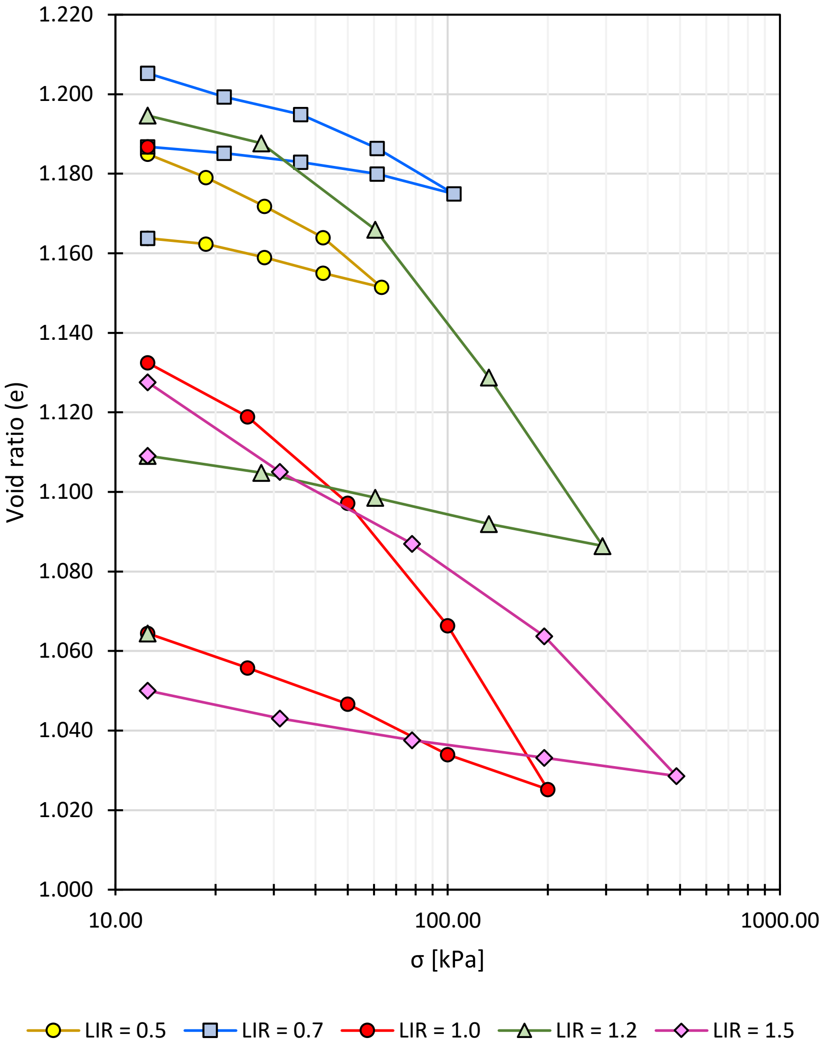


Figure 5. Summary of compressibility curves.

3.2. Preconsolidation stress (σ′ₚ)

The preconsolidation stress is an essential parameter that is used to predict soil behavior under load, that is calculated by Casagrande Method using oedometer tests data by a graphic interpretation of the compressibility curves [20], [21].

A summary of the estimated preconsolidation stresses is presented in Table 4.

Table 4. Summary of pre-consolidation stress.

Sample	LIR	σ'_P [kPa]
M1	0.5	43.32
M2	0.7	46.09
M3	1.0	52.05
M4	1.2	56.10
M5	1.5	62.61

3.3. Overconsolidation ratio (OCR)

The overconsolidation ratio (OCR) is a soil parameter that can change with depth and is used to understand soil behavior under different loading conditions, as well as stress-strain behavior and compressibility [22], [23].

A summary of the estimated pre-consolidation stresses is presented in Table 5.

Table 5. Summary of OCR values.

Sample	LIR	σ′p [kPa]	σ′o [kPa]	OCR
M1	0.5	43.32	80.13	0.54
M2	0.7	46.09	79.40	0.58
M3	1.0	52.05	81.66	0.64
M4	1.2	56.10	80.39	0.70
M5	1.5	62.61	81.43	0.77

3.4. Compression index (Cc) and Expansion index (Cs)

These parameters are important because both are used to estimate settlements and evaluate the soil potential to expand. Cc is obtained from the compressibility curve under loading conditions, that influences on settlement and compressibility, while the Cs is obtained under unloading conditions influencing swelling and expansion [24], [25].

A summary of the estimated pre-consolidation stresses is presented in Table 6.

Table 6. Summary of OCR values.

Sample	LIR	Cc	Cs
M1	0.5	0.074	0.026
M2	0.7	0.052	0.011
M3	1.0	0.136	0.033
M4	1.2	0.123	0.019
M5	1.5	0.088	0.018

4. Discussion

4.1. Compressibility curve

As shown in Figure 5, each compressibility curve was influenced by the LIR, resulting in different trajectories of each curve, which were represented as the void ratio and stress range. For example, in Figure 4a and 4b, the difference in the void ratio between the start and end of the test is 0.021 and 0.018, respectively, while in Figure 4d, this difference is the highest at 0.086. However, for the standard LIR of 1 (Figure 4c), the difference was equal to 0.068, which is closer to the LIR of 1.5 (Figure 4e), with a difference value of 0.077.

4.2. Pre-consolidation stress (σ'_p)

As shown in Table 4, as the LIR value increased, the pre-consolidation stress increased. However, as shown in Figure 6, for the lowest values of LIR, the pre-consolidation stress decreased between 16.77% for LIR = 0.5, and 11.45% for LIR =0.7. In addition, for the highest values of LIR, the pre-consolidation stress increased by 7.78% for LIR = 1.2, and 20.29% for LIR = 1.5.

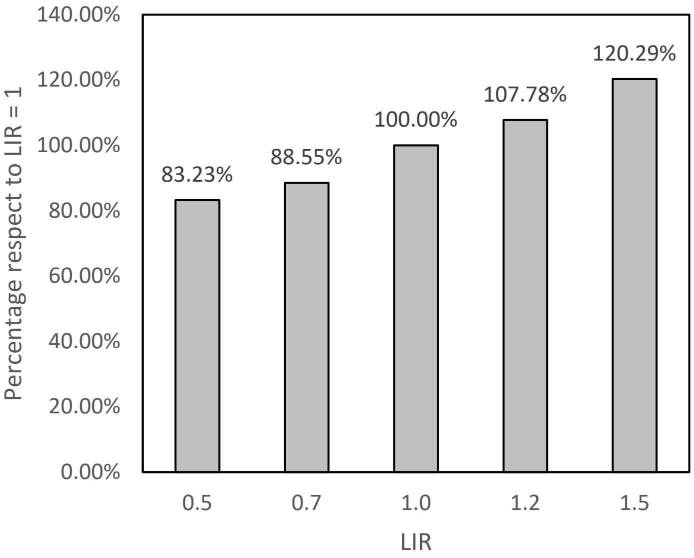


Figure 6. The percentage of preconsolidation stress with respect to LIR = 1.0 value.

Furthermore, it is important to mention that the LIR influence is critical in the determination of this parameter because, as shown in Figure 4, the trajectory of the loading part of the compressibility curve changes. For an LIR value lower than 1.0, the recompression part becomes short, whereas for an LIR value of 1.2, the recompression part is similar to LIR = 1.0, and for an LIR = 1.5, this part of the curve is larger than LIR = 1.0.

4.3. Overconsolidation ratio (OCR)

Based on the results presented in Table 5, for all the samples, the OCR values were lower than 1, corresponding to the Normally Consolidated condition.

From the analysis carried out considering that the samples come from the same depth, it can be assured that the higher the LIR of the consolidation test, the higher the OCR value will be congruently higher. It can also be affirmed that based on the calculation expression used for the deeper zones, the actual effective vertical pressure will increase considerably, with higher OCR values tending to be obtained at deeper depths.

4.4. Compression index (Cc) and Expansion index (Cs)

As shown in Figure 7, Cc and Cs vary as the LIR varies. When the Cc values ranged between 0.052 and 0.136, it was evident that the Cs values represented, on average, 23.29% of the Cc values.

In addition, with respect to the standard LIR equal to 1, the lowest values of Cc and Cs correspond to LIR = 0.7.

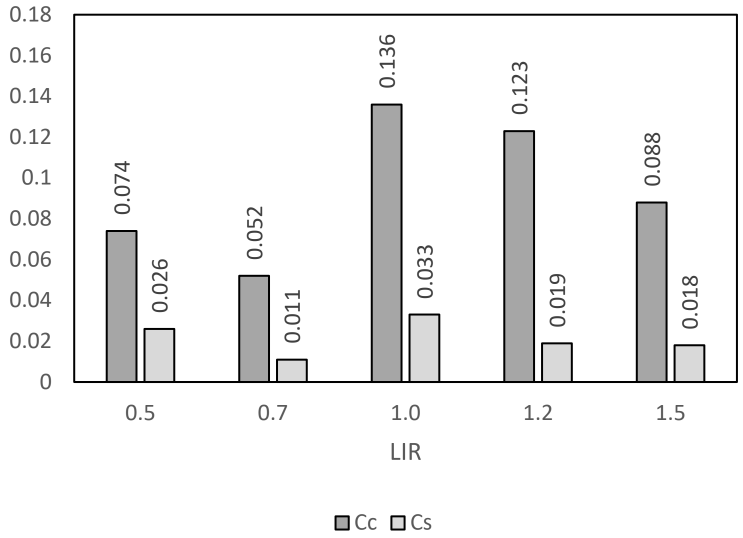


Figure 7. The percentage of pre-consolidation stress with respect to LIR = 1.0 value.

5. Conclusions

The results show that as the load increment ratio (LIR) increases in consolidation tests, the preconsolidation stress values also increase. The lowest preconsolidation stress (σ′p = 43.32 kPa) was obtained with the lowest load increment variation (LIR = 0.5), while the highest preconsolidation stress (σ′p = 62.61 kPa) was achieved with the maximum experimental LIR of 1.5. This trend confirms the importance of proper LIR selection in geotechnical studies to enable accurate interpretation of the soil's stress history.

The determination of the overconsolidation ratio (OCR) for each sample yielded values below 1.0 in all cases, indicating a Normally Consolidated soil. However, it was observed that as the experimental LIR increased, the OCR values approached 1.0 more closely.

Data processing and results indicate that both the compression index (Cc) and the expansion index (Cs) exhibit considerable variations depending on the LIR applied. This demonstrates that the load increment ratio (LIR) influences not only the initial elastic behavior of the soil but also its plastic behavior under prolonged loading conditions.

This study highlights the importance of selecting an appropriate load increment ratio (LIR) tailored to the specific soil type and the loading conditions to which it will be subjected. A well-chosen LIR can enhance the accuracy of estimated geotechnical design parameters, such as load-bearing capacity and deformation.

From the data processing recorded from the experimentation carried out with the different values of the LIR load increase ratio, it is evident that the compressibility curves present changes in their trajectory in each experiment, which is reflected in the variation of the results determined.

The value of the load increase ratio (LIR) used in the experimentation directly affects the determination of the preconsolidation stress, especially when it is obtained by the compressibility curve where it becomes critically important. An increase in LIR tends to expand the recompression phase directly influencing the results.

Based on the results obtained using a reference LIR of 1.0, it can be concluded that as the applied LIR deviates from this reference value, the results differ more significantly. When the LIR is increased beyond 1.0, the values derived from data processing also increase; conversely, when the LIR is reduced below 1.0, the results decrease accordingly, with this trend becoming more pronounced as the LIR value diverges further from the reference.

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