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Measurement of the Lateral Earth Pressure Coefficient of Clayey Soils by Modified Oedometer Test

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HIGHLIGHTS

- Direct evaluation of lateral earth pressure at rest.
- Force-sensitive resistor was used.
- K_0 decreases as LOI increases.

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ABSTRACT

The coefficient of lateral earth pressure at rest (K_0) explains the connection between the effective vertical and lateral stresses. Geotechnical engineers have studied K_0 for many years for its being a key element in the designs and analysis of various geotechnical problems such as slope stability, piles, and earth retaining structures. Moreover, K_0 has played a critical phase in any numerical study of the soil-water combined geotechnical boundary value issues requiring parametric stress-strain time formulations During the previous few decades. A modified apparatus consisting of a standard Oedometer equipped with Force Sensitive Resistance (FSR) is used to investigate the value of lateral pressure (σ_h') due to the vertical stress. The Oedometer test is carried out on three samples with different organic contents, with the K_0 values obtained from each sample; empirical equations were also used to estimate K_0 values for comparison purposes. From the analysis of the results, it can be stated that the K_0 value is inversely proportional to the organic matter percent in the soil. It varies from 0.6125 in soil with 25.1% organic percent to 0.76 at a percent of 9.8%. The Force Sensitive Resistance (FSR) technique's performance is practical enough for estimating lateral earth pressure at rest (K_0) of normally consolidated organic soil with many advantages; it is far less time-consuming and has a low operating cost than the traditional K_0 estimate methods. Furthermore, K_0 decreases with the increase of organic content.

1. Introduction

As a factor in many geotechnical design projects, the ground's steady-state stress is an important parameter that must be known. The effective vertical stress, σ_v' is that is present in situ. The overburden pressure and pore water pressure can be determined from the profiles of any depth. In contrast, it is difficult to measure the in-situ horizontal effective stress σ_h' directly and even more, due to the influence of geological history and soil conditions, it isn't easy to accurately estimate its value [1].

Soil mechanics recognizes three types of horizontal stresses: active, resting, and passive earth pressures. Many researchers have explored ways to measure the coefficients of the three pressures exerted by the earth under various circumstances. The coefficient of earth pressure at rest (K_0) may be less than the coefficient of passive earth pressure (K_p) but greater than the coefficient of active earth pressure (K_a), i.e., $K_a<K_0<K_p$. The relationship between the effective vertical stress and the effective horizontal stress under conditions of no lateral displacement usually gives the coefficient (K_0) [2–5];

$$K_o = \frac{\sigma_h'}{\sigma_v'} \tag{1}$$

According to published research, other factors may also affect the K_0 value, including, at a minimum, the soil type, degree of consolidation [6–8], the void ratio [9], state of stress [10], the saltiness of pore water [11] and the shape of particles [12].

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Nevertheless, many studies have published experimental measurements of K_0 employing techniques designed to verify no lateral strain. Therefore, they can be categorized as two separate techniques, laboratory and in situ methods.

1.1 Laboratory Techniques

There are two different categories of laboratory techniques. The first method utilizes a rigid lateral boundary. This allows for "zero lateral strain" condition, similar to the Consolidometer type [13], Null Type Confining Ring [14], [15], COWK (Cambridge-Ohta-Wroth-Kyoto) [16] and Semi-rigid Consolidometer [4], [17–20] .

The second method utilizes a flexible lateral boundary with a feedback control system for boundary position maintenance, such as a Rigid cell [21], Controlled Volume Triaxial, Null Type Triaxial Test [22], [23], and a triaxial cell to automatically simulate K_0 consolidation and swelling [24], A Simple K_0 Triaxial Cell [25], Double cell K_0 triaxial apparatus [26], K_0 consolidation test in triaxial apparatus [27], triaxial strain path testing [28], an automated three-dimensional (3D) cell-consolidation device [29], [30].

1.2 On-Site Procedures

There are three groups of researchers have proposed their tests to evaluate on-site K_0. The direct shear test with very small disturbance like the Self-Boring Pressure meter [31–33] was inserted into the soil. Semi-direct testing must be performed with no regard for surface stability because of the placement of several probes in the ground using a total pressure cell [34], Hydraulic Fracturing [33], [35], [36], Total Pressure Cells [37]–[39], Dilatometers [33], [40], K_0 Stepped Blade [41], and Cone penetration test [42], and the non-destructive approach [43], which is an easy way to measure cohesionless soil shear wave velocity [44–47]. However, in-situ testing of K_0 generated various values of K_0 due to uncertainty over the sensitivity of K_0 to minor disturbances that arise when the probe is inserted into the ground.

Despite the various suggestions to the contrary, the standard procedure, as recommended by [48], and reported, for example, by [49], follows this general pattern:

$$K_0 = 1 - \sin\varphi' \tag{2}$$

φ' is for the effective internal friction angle of soil. Fattah et al. [50] concluded that the effect of using a reduced k0 zone on excess pore water pressure and surface settlement (vertical and horizontal) of tunnels was also considered. It was found that the excess pore water pressure increases while the settlement trough becomes deeper and narrower using reduced K0.

Fattah et al. [51] developed the multistage oedometer relaxation test to measure the vertical stress, lateral stress, and pore water pressure with time and estimate the coefficient of lateral earth pressure in the soil. A new factor for relaxation in organic soil is suggested. The test consisted of six stages; each stage is 10 – 30 minutes long, except if pore water pressure is not dissipated. The objective of the present study is to produce a practical method to measure the Ko value through the consolidation test.

2. Methodology and Test Procedure

Most of the existing laboratory processes are intricate and generally time-consuming, making it difficult to consolidate a specimen. The benefit of employing a flexible lateral border is that it reduces side friction. Even so, the drawback is regulating the soil specimen such that the strain is zero and ensuring that the effective stress is homogeneous across the specimen. In this study, a new approach for determining K_0 is examined using the Force-Sensitive Resistant (FSR). This study's approach can be classified as a direct rigid ring type. The advantages are that the soil can be consolidated under perfectly no lateral deformation conditions, lesser time, and low operational cost.

The tests were conducted on three disturbed organic soils with the properties listed in Table 1. The soil samples were brought from the sanitary landfill site near Al-Rustamiya wastewater treatment plant in southeast Baghdad.

The test specimen size was 76 mm in diameter and 19 mm in height. It was selected from American standard test methods for one-dimensional consolidation properties of soils. The sample was prepared by mixing the disturbed sample with the desired moisture content, which was determined previously by establishing a relationship between the water content and undrained shear strength.

The soil was compacted by wet tamping and static compaction inside the one-dimensional consolidation ring after sticking a Force-Sensitive Resistance (FSR) to the mid-height of the ring wall, as shown in Figure 1, to measure the horizontal stress on the spacemen. This FSR, with a 12.7 mm effective diameter and range of sensing (7.74 - 774.4 kPa), is controlled with Arduino Uno for data logging, as shown in Figure 2.

After saturation for 24 hours, the top surface of the test specimen was subjected to static pressure levels of 50, 100, 200, and 400 kPa, in consecutive order, during testing according to ASTM D2435 [52]. The horizontal stress was measured for each applied normal stress until the vertical deformation was less than 0.01 mm in one hour during the creeping stage of the test. Figure 1 illustrates the stages of the consolidation test.

The angle of shearing resistance and the plasticity index have been related to Ko empirically or semi-empirically by many researchers. In this work, the effective friction angle (ϕ') achieved from the consolidated undrained shear box test.

Table 1: Soil properties

Property		**Value**		
		TS-01	***TS-02***	***TS-03***
Loss of Ignition (%)	LOI	9.8	15.2	25.1
Dry unit weight (kN/m^3)	γ_d	13.1	12.9	12.2
Moisture content (%)	Wc	31.1	31.1	31.1
Angle of Internal Friction (degree)	φ'	20.8°	22.72°	24.67°
Specific gravity	Gs	2.59	2.55	2.4
Liquid limit (%)	LL	80	83	87
Plastic limit (%)	PL	25	33	39
Plasticity index (%)	PI	55	50	48
Compression index	C_c	0.112	0.127	0.194
Rebound index	C_r	0.013	0.019	0.025
Coefficient of secondary compression	$C\alpha$	0.003	0.005	0.012

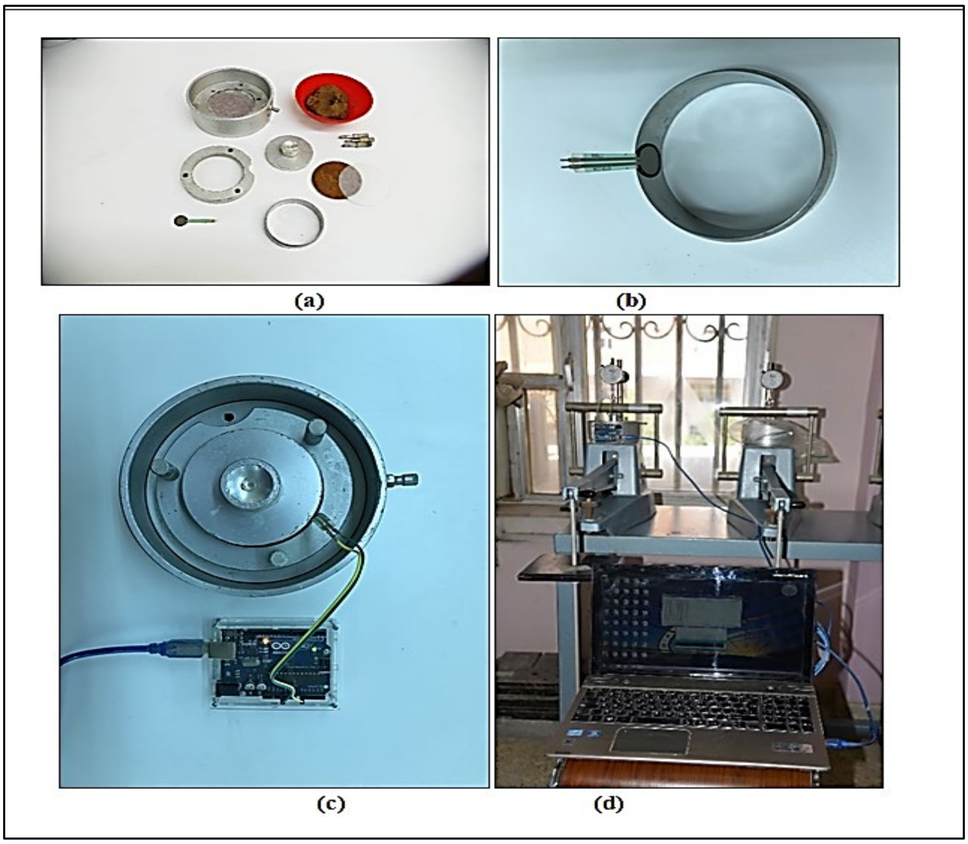
(a) (b) (c) (d)

Figure 1: Test procedure (a) tools and soil sample (b) soil spacemen and fixed FSR inside oedometer ring (c)oedometer apparatus cell and Arduino Uno (d) logging the results during the test

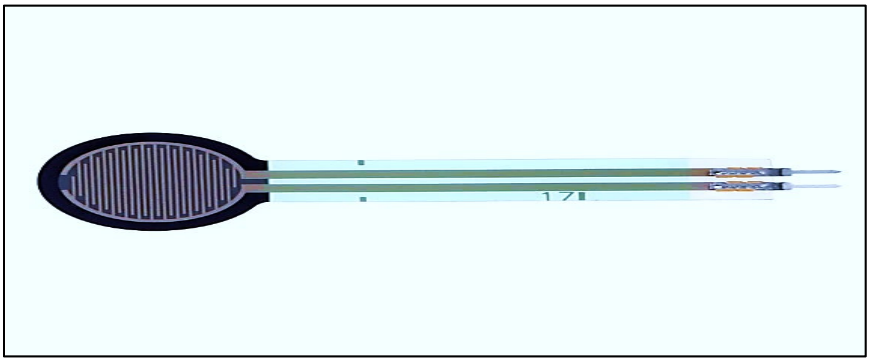

Figure 2: Force sensitive resistance

3. Results and Discussion

3.1 Results of Direct Shear Test

The direct shear test results are illustrated in Figures 3 to 5. The results reveal that the angle of internal friction is 20.8°, 22.72°, and 24.67° for soils TS-01, TS-02, and TS-03, respectively.

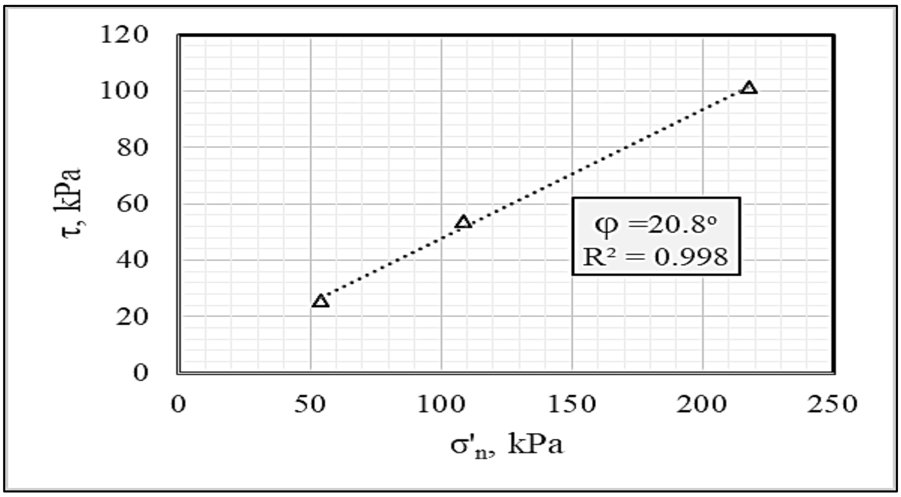

Figure 3: Consolidated undrained direct shear results of soil TS-01

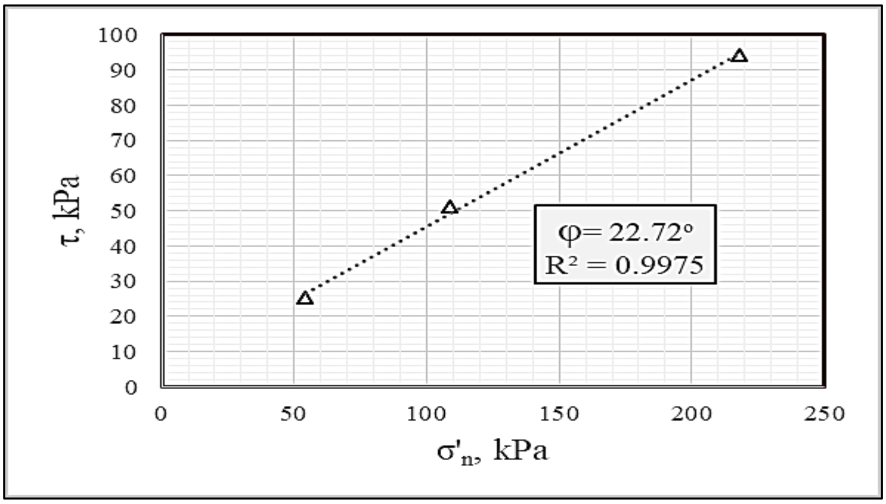

Figure 4: Consolidated undrained direct shear results of soil TS-02

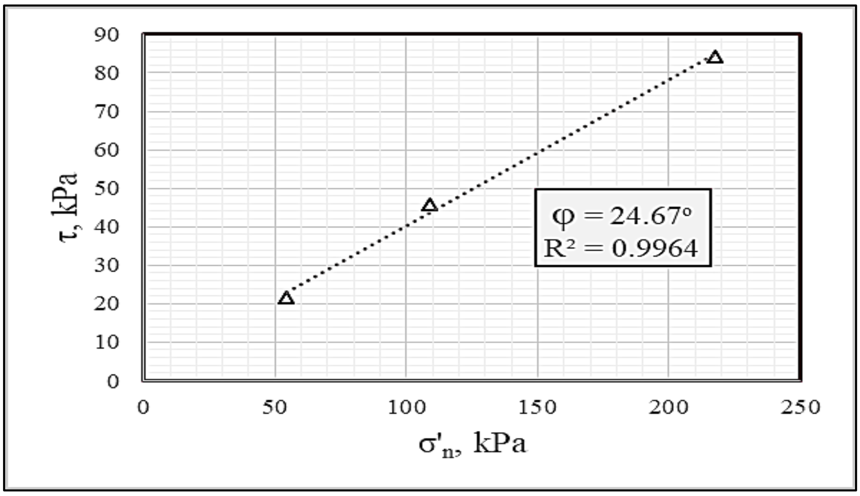

Figure 5: Consolidated undrained direct shear results of soil TS-03

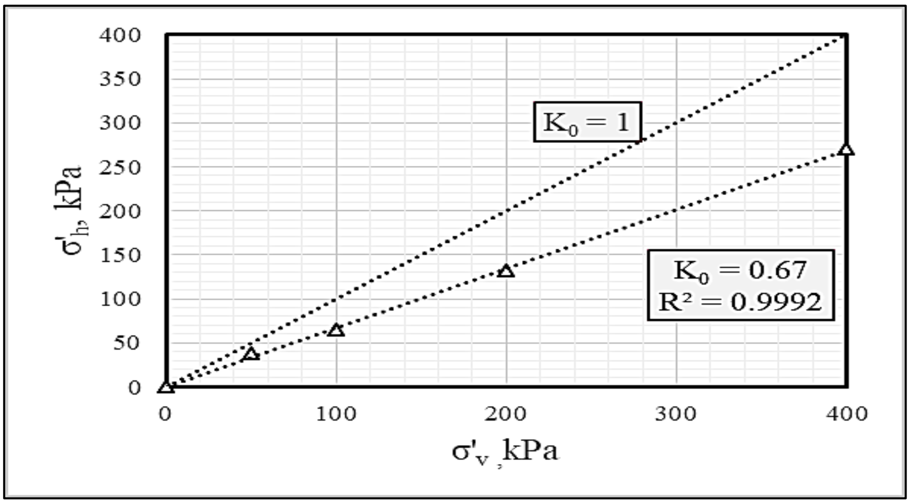

Figure 6: Vertical and horizontal stresses during the consolidation of soil TS-01

3.2 K_0 From Modified Oedometer Test

The effective normal stress was applied on the top surface of the spacemen, and the change in lateral stresses of the organic soils at the wall of the rigid ring was monitored during the one-dimensional consolidation test. Figures 6 to 8 illustrate the variation of total and horizontal stresses during the test. Table 2 shows a typical vertical-horizontal effective pressure relationship. In every plot, it is evident that the effective horizontal pressure increases linearly with the increase in the effective vertical pressure along a fitting straight line through the coordinate of origin.

Equation 1 can be used to express the fitting straight line. The slope of the best-fitting straight line equals the value of the coefficient K_0. The findings of the three types of soils with average LOI = 9.8, 15.2, and 25.1%, respectively, are seen in the figures.

The K_0 value for the test materials ranges from 0.6125 in TS-03 to 0.76 in TS-01. Data and information from the publications such as Lee et al. [53] suggest that a vertical stress application has an insignificant effect on the K_0 value. Thus, the K_0 measurement value (the straight-line slope between the vertical and horizontal effective stresses) is computed in this study.

From the data in the K_0 coefficient, it is evident that the K_0 value may be affected by the level of organic matter present in the soil and inversely proportionate to the amount of organic matter.

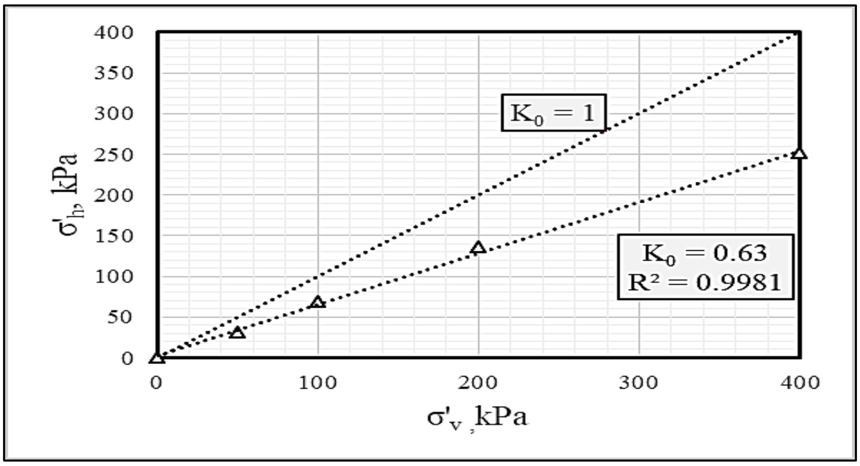

Figure 7: Vertical and horizontal stresses during the consolidation of soil TS-02

Table 2: Results of consolidation test

σ'v (kPa)	σ'h (kPa)			K0		
	TS-01	*TS-02*	*TS-03*	*TS-01*	*TS-02*	*TS-03*
50	38	31	31	0.76	0.62	0.62
100	65	68	61.5	0.65	0.68	0.615
200	131	135	135	0.655	0.675	0.675
400	270	251	245	0.675	0.6275	0.6125

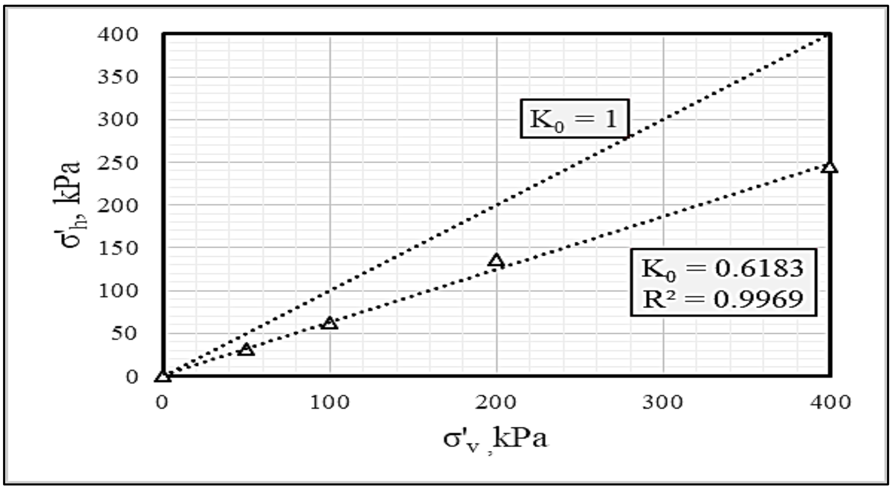

Figure 8: Vertical and horizontal stresses during the consolidation of soil TS-03

Table 3: Results of consolidation test

σ'v (kPa)	σ'h (kPa)			K_0		
	TS-01	*TS-02*	*TS-03*	*TS-01*	*TS-02*	*TS-03*
50	38	31	31	0.76	0.62	0.62
100	65	68	61.5	0.65	0.68	0.615
200	131	135	135	0.655	0.675	0.675
400	270	251	245	0.675	0.6275	0.6125

3.3 K_0 From Empirical Equations

The angle of shearing resistance and the plasticity index have been related to Ko empirically or semi-empirically by many researchers, as shown in Table 3.

Table 4: Emperical detemination of K_0

Reference	Equation	K_0		
		TS-01	*TS-02*	*TS-03*
Jaky [48]	$K_0 = 1 - \sin\phi'$	0.645	0.614	0.582
Lee et al. [53], [54]	$K_0 = 0.9(1 - \sin\phi')$	0.58	0.55	0.524
Lee et al. [53]	$K_0 = \frac{\left(1 + \frac{2}{3}\sin\phi'\right)(1 - \sin\phi')}{1 + \sin\phi'}$	0.589	0.557	0.525
Abdelhamid and Krizek [17], [55]	$K_0 = \tan^2\left(45° - \frac{1.15(\phi' - 9°)}{2}\right)$	0.62	0.572	0.527
Brooker and Ireland [14]	$K_0 = 0.95 - \sin\phi'$	0.594	0.563	0.532
Mssarsch [56]	$K_0 = 0.44 + 0.42\frac{PI}{100}$	0.7	0.65	0.64

By comparison, the laboratory K_0 values are higher than those obtained from the correlation equations for normally consolidated organic soils.

It is possible to observe that when using empirical equations to estimate K_0 value, the estimate is still not exact enough in work that necessitates using K_0 as an input parameter, like the initial conditions for soil/water coupled finite element analysis.

Consequently, from the analysis of the result, it can be stated that the performance of the FSR technique is practical enough for the estimation of K_0 of normally consolidated soil with many advantages. It is far less time-consuming and has a low operating cost than the traditional K_0 estimate methods. Furthermore, the determination of initial conditions of any clayey soil, especially organic clays, is very important in specifying the states of stresses, as argued by Hameedi et al. [57].

4. Conclusions

The following conclusions can be formed based on the study and experiments described in this research:

1) The Ko value is inversely proportional to the percentage of organic matter in the soil, and Ko decreases with the increase of organic content.

2) The experimental technique proposes the estimation method of Ko values using the FSR (Force-sensitive resistance) sensor.
3) K_0 values from the proposed method fall in the range of 0.6125–0.76 for normally consolidated organic soils, sufficiently well agreeing with Ko from empirical approaches.

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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