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The laterally confined consolidation of initially compacted and wetted swelling clay

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Abstract. This paper describes the laterally confined consolidation of an Israeli clay following compaction and swelling on wetting, including the measurement of lateral stresses. The results of the tests are compared to those obtained during consolidation of the clay from an initially slurried condition. In comparing the compression and expansion indices relative to vertical, lateral and mean stress, it was found that they varied, depending on the initial, preparation conditions; the values approached the slurried values with decreasing initial dry density. During unloading, the expansion indices were found to be independent of initial conditions, and essentially the same as those of the slurried soil. The coefficient of lateral earth pressure at rest during loading, K_0, of the compacted and then wetted specimens was found to be reasonably constant regardless of initial soil conditions, but significantly higher than the value of the slurried soil. However, during unloading, the relationship between the normalized coefficients of lateral earth pressure at rest, K_0'/K_0, and the overconsolidation ratio, OCR, was found to be essentially the same as that obtained for the slurried soil.

1 Introduction

The swelling and subsequent consolidation of expansive clay, compacted in the field adjacent to a rigid boundary, or distant from the boundaries of a large area, may be modelled in the laboratory under laterally confined boundary conditions. This paper describes the laterally confined consolidation of an Israeli clay following compaction and swelling on wetting, including the measurement of lateral stresses. The results of the tests are compared to those obtained during consolidation of the clay from an initially slurried condition.

The formation process of clayey soil deposits in the field can occur in different scenarios. In many cases, sedimentation takes place under flooding conditions, while in other cases, the soil is compacted in an unsaturated condition, and becomes saturated only after. This paper discusses and compares the mechanical behavior of the soil in these two cases.

Two main aspects of the consolidation behavior of the compacted-swelled soil compared to that of initially slurried soil are considered: (1) The compression and expansion indices relative to vertical, lateral and mean stress. (2) The coefficients of lateral earth pressure at rest during loading, K_0, and unloading, K_0'.

2 The soil and testing procedure

The tests were performed on a natural, montmorillonite clay sampled from the Jezreal valley of northern Israel. Geotechnical characteristics of the material are presented in Table 1.

Table 1. Indicative properties of clay tested.

Specific gravity of solids (G_s)	2.72
Liquid Limit (ω_l)	75
Plastic Limit (ω_p)	21
USCS classification	CH
Maximum dry density, Proctor (kN/m^3)	14.4
Optimum water content (%)	25.7

The tests were carried out in a prismatic aluminum cell with specimen plan of 60 mm by 60 mm (Fig. 1), described by Talesnick et al. [1]. The test cell is constructed of four interchangeable, highly polished side walls each 25 mm in thickness. Lateral soil stresses were measured using two Null Soil Pressure Gauges [e.g. 2, 3], mounted and fixed flush with the inner sides of two opposing cell walls. These gauges maintain zero membrane deflection and have been shown to eliminate the issues of soil arching and associated particle rearrangement. The two gauges operated independently, allowing comparison of results obtained from each; excellent agreement was observed, and the average of the two measured stress values was adopted.

The vertical force was applied through a levered, dead weight system. The cell's walls were not connected to the base, and so it acted as a floating cell. The specimen base pedestal was placed upon a load cell

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allowing the force reaching the specimen bottom to be monitored (Fig. 1). The difference between the force applied on the upper surface of the specimen and that registered at its base represents the vertical frictional load developed on the sidewalls of the cell. The base contains 36, 6-mm diameter porous stones, all connected by a network of channels to a water supply tube in the lower surface of the base. These allowed wetting of the compacted specimens and drainage during consolidation of all specimens.

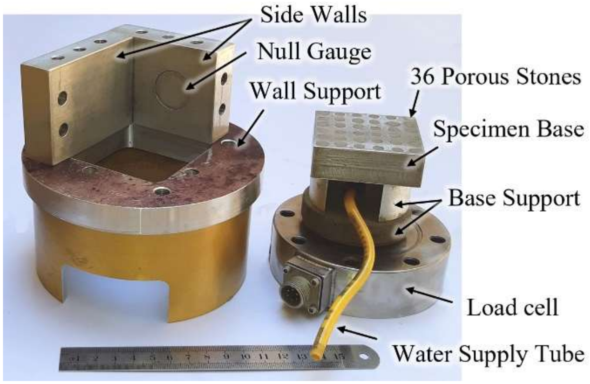

Fig. 1. Cell set up.

In tests of initially compacted soil, friction reduction measures were applied to the cell walls [e.g. 4]. In the slurried soil tests, due to the large vertical compressions, these measures were found to be unsuitable. The vertical stress adjacent to the location of lateral stress measurement was, therefore, estimated assuming a linear distribution between the load applied to the specimen top and that measured at the specimen bottom. The test specimens were prepared by first crushing the soil to pass a 4# (4.75 mm) sieve. The soil for the slurried specimens was then wet to a water content of 88% - 90% (above the liquid limit), de-aired in a vacuum desiccator, and poured into the cell. The soil for the compacted specimens was wet with a pre-determined mass of water, to obtain a specified nominal gravimetric water content (24% and 15%). The material was then cured for 24 h in a sealed, nylon bag, remixed, placed loosely into the test cell, and statically compacted to the required initial dry unit weight.

3 Results

3.1 Slurried specimens

Three tests were performed in which vertical pressure was applied in stages to the specimen top, up to a predetermined maximum value, and then reduced in stages. In each stage, the specimen was allowed to undergo consolidation until deformation and measured lateral stress stabilized. At this stage it was considered that consolidation was completed, that excess pore pressure was dissipated, and stresses were effective. The compression and swelling curves measured in these tests, showing results relative to vertical, lateral, and mean stress, σ'$_v$, σ'$_h$, and p', are presented in Fig. 2.

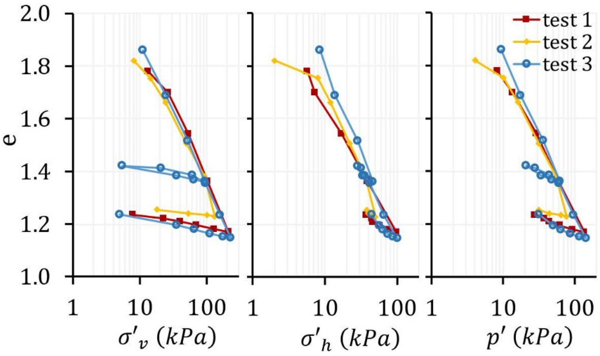

Fig. 2. Compression curves from three replicate slurry consolidation tests.

The best fit lines to the straight sections from all three tests indicate that compression indices relative to vertical, lateral and mean stress are 0.532, 0.530 and 0.539 respectively – essentially equal. This equality is consistent with the assumed equivalence between the compression index, C_c, and the critical state compression parameter, λ, that is common in the critical state soil mechanics literature (for example [5-9]).

A similar equivalence is commonly assumed between the swelling index, C_s, and the critical state swelling parameter, κ. Since unloading in the three tests was initiated from different maximum vertical stresses, a normalized comparative presentation of the swelling relations is presented in Fig. 3 in terms of σ/σ_{max} versus void ratio change, Δe. The slopes of these lines are values of the swelling index. If C_s = κ, these relations would be expected to coincide. Fig. 3 shows clearly that this is not the case; the swelling index values relative to vertical, lateral and mean stress are 0.050, 0.196 and 0.104 respectively.

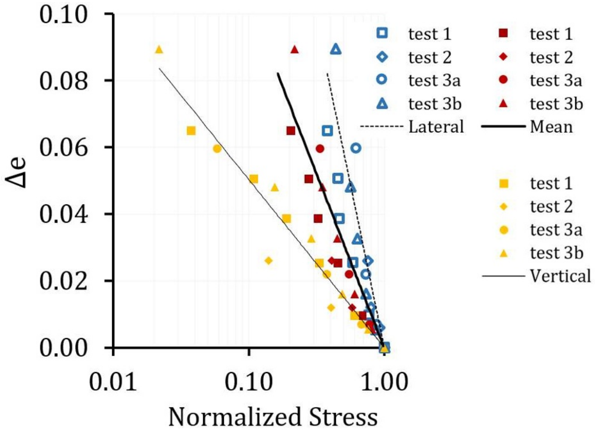

Fig. 3. Swelling relations from replicate consolidation tests on slurried specimens**.**

Fig. 4 shows the relationship between the measured effective lateral stress, σ'$_h$ and the corresponding effective vertical stress, σ'$_v$ (estimated adjacent to the lateral stress measurement) during loading, in the three tests. The figure indicates a constant K_0 value throughout the loading, as is usually observed, equal to 0.44.

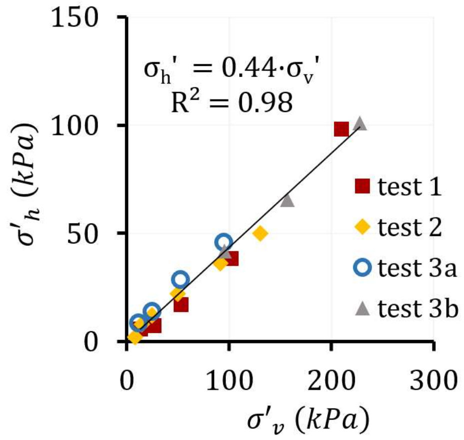

Fig. 4. Relationship between σ'_h and σ'_v during loading.

During unloading, the coefficient K_0' depends on the over-consolidation ratio (OCR). As seen in Fig. 5, the test results agreed with the empirical relation $K_0' = K_0 \cdot OCR^{\alpha}$ as suggested in [10]. The value of α according the best fit line from all three tests is 0.76.

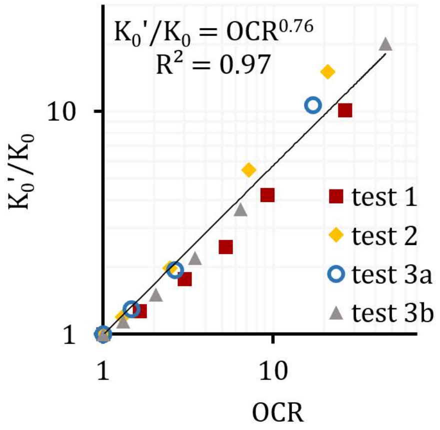

Fig. 5. K_0'/K_0 as a function of OCR for slurried specimens.

3.2 Compacted-swelled specimens

Several test series were performed. In each series, test specimens at the same moisture content were statically compacted in the cell, to the same initial dry unit weight. The initial moisture contents and dry unit weights varied between series as shown in Table 2. The specimens were then wetted from the base under different axial loads.

Table 2. Test series.

Moisture contents, ω	Dry unit weight, γ_d, kN/m^3	Axial load, σ'_v, at swelling, kPa
24 %	12.3	16 , 41, 71
	12.7	17
	13.3	18
	14.5	15 , 48 , 190
15 %	12.3	16 , 40 , 69
	12.9	13

3.2.1 Specimens prepared at ω=24% and wetted under σ'_v of 16 - 18 kPa

Following conclusion of swelling, the specimens underwent consolidation loading and unloading. Figs. 6 and 7 show the compression curves in these tests relative to vertical and mean stress respectively.

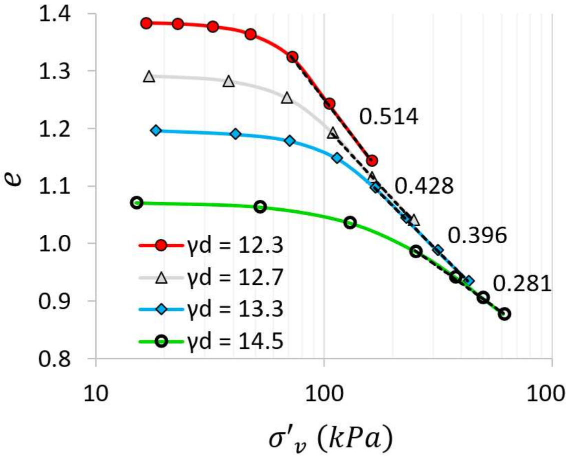

Fig. 6. Compression curves relative to vertical stress for specimens prepared at ω=24% and wetted under σ'_v 13-18 kPa.

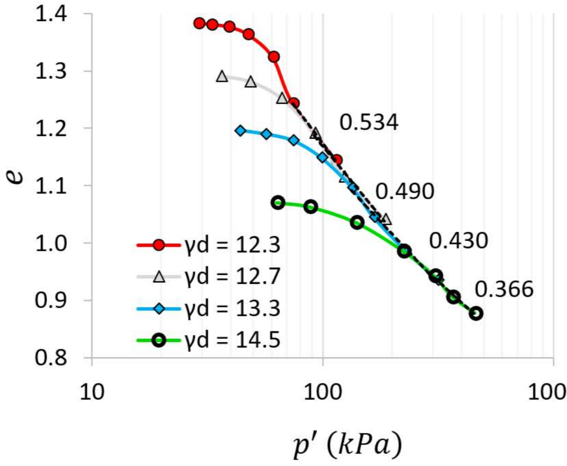

Fig. 7. Compression curves relative to mean stress for specimens prepared at ω=24% and wetted under σ'_v 16-18 kPa.

According to Figs. 6 and 7, the compression indices relative to vertical and mean stress varied, depending on the initial dry unit weight, approaching the slurried value with decreasing initial dry density.

During unloading, the expansion indices were found to be less dependent on the initial conditions, and essentially the same as those of the slurried soil, as shown in Fig. 8.

The vertical confining stress during wetting, σ'_v, was found to have insignificant effect on the compression and expansion slopes, as shown in Figs. 9 and 10.

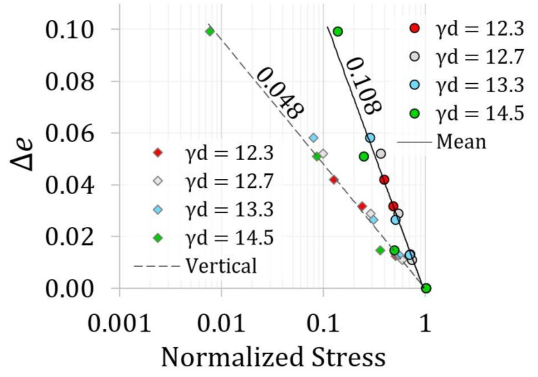

Fig. 8. Expansion curves for the specimens prepared at ω=24% and wetted under σ'$_v$ 13-18 kPa.

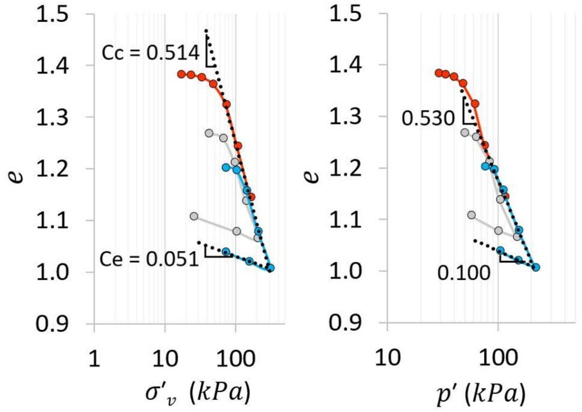

Fig. 9. Compression curves for specimens prepared at ω=24% and γ_d=12.3 kN/m^3, various σ'$_v$ during wetting.

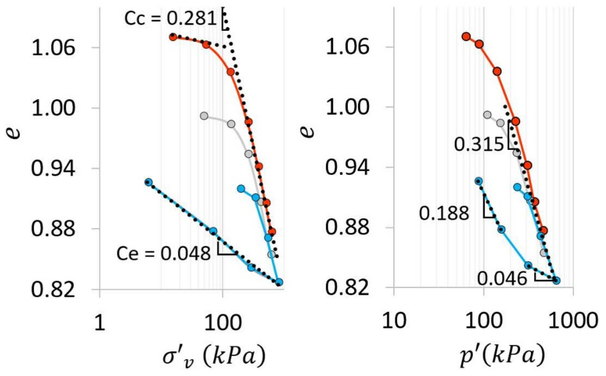

Fig. 10. Compression curves for specimens prepared at ω=24% and γ_d=14.5 kN/m^3, various σ'$_v$ during wetting.

3.2.2 Specimens prepared at ω=15%

Fig. 11 shows the compression and swelling curves measured in the series of three tests prepared at dry unit weight 12.3 kN/m^3.

It can be seen that the compression indices were, again, relatively independent of the axial load, σ'$_v$, during swelling, as was the case for in the series prepared at a moisture content of 24%.

Fig. 12 shows the compression and swelling curves for the test prepared at a dry unit weight of 12.9 kN/m^3.

Summarizing the compressibility observations, it has been found that while the compression indices varied between the different test series, the expansion indices are seen to be essentially the same for all the compacted and slurry specimens.

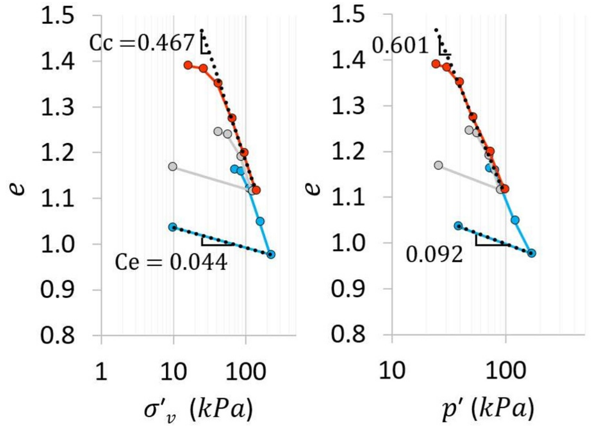

Fig. 11. Compression curves for specimens prepared at ω=15% and γ_d=12.3 kN/m^3.

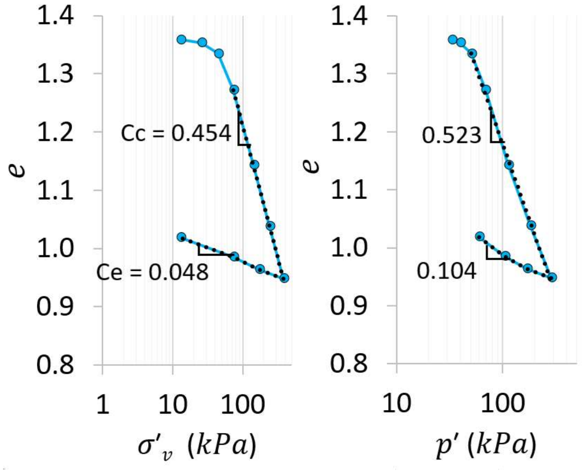

Fig. 12. Compression curves for the specimen prepared at ω=15% and γ_d=12.3 kN/m^3.

3.2.3 Coefficients of lateral earth pressure at rest

Fig. 13 shows the relationship between the measured effective lateral stress, σ'$_h$ and the corresponding effective vertical stress, σ'$_v$ (adjacent to the lateral stress measurement) during virgin loading. The figure shows only points corresponding to the straight portion of the compression curve (Fig. 6). Different sized symbols of the same type represent tests prepared following wetting under different confining stresses. The figure indicates a constant K_0 value throughout the loading, as is usually observed, equal to 0.65. K_0 was found to be reasonably constant regardless of preparation conditions of moisture content, ω, and dry unit weight, γ_d, but significantly higher than the value for slurried soil.

During unloading, the relationship between K_0'/K_0 and the overconsolidation ratio, OCR, was found to be essentially similar to that obtained for the slurried soil and independent of the preparation conditions of moisture content and dry unit weight, as presented in Fig. 14.

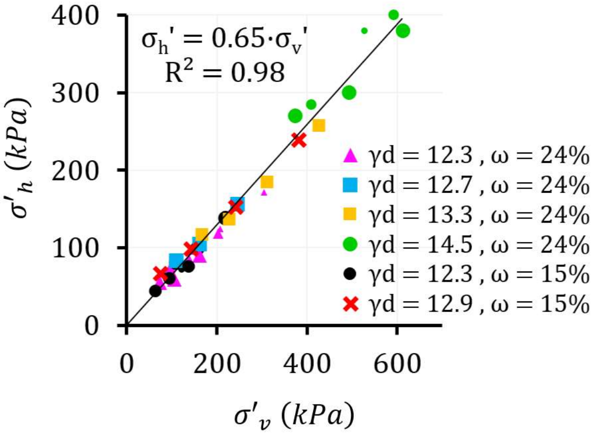

Fig. 13. Relationship between σ'_h and σ'_v during loading; compacted-wetted specimens.

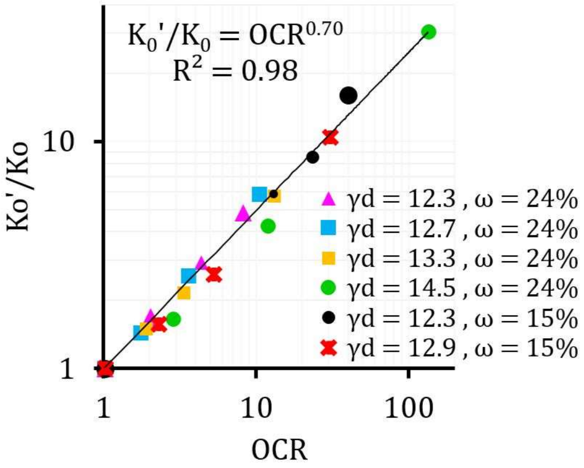

Fig. 14. K_0'/K_0 as a function of OCR.

4 Discussion and Conclusions

The tests results presented above indicate that:

(1) Compression curves (both in terms of vertical stress and mean stress) of compacted-wetted specimens are flatter than those of slurry specimens but appear to converge to the slurry curve with increasing stress. The compression indices of the compacted-wetted specimens are strongly dependent on the preparation dry unit weight, approaching that of the slurry with decreasing initial dry unit weight. The compression indices appear to be less sensitive to initial moisture content, and unaffected by the vertical confining stress during wetting. On the other hand, the expansion indices are similar to the slurry value, regardless of preparation and wetting conditions.

(2) The coefficient K_0 was found to be uniform for all compacted-wetted conditions, but larger than that of the slurry specimens. However, the relationship between the unloading coefficient, K_0', and K_0 was found to be the same for the compacted-wetted and the slurry conditions.

The above observations are generally consistent with results of confined compression tests presented by Tarantino and his colleagues [11-13], Monroy [14] and others. Compression curves on compacted-wetted sample of kaolin, prepared at relatively high void ratios, were observed to merge with the curves of slurry samples, after initially (at early stages of loading) indicating flatter slopes. Alonso et al. [15] showed that soil compression occurs at the expense of the inter-aggregate macro-pores, as the intra-aggregate micro-pores, and the aggregate structure, remain essentially unaffected by the overall change in void ratio. It is suggested that when the soil swells from a lower void ratio, the same aggregates swell into a smaller macro-pore space, and as a result a stiffer structure is obtained, possibly explaining the presently observed dependance of the compression indices on the preparation dry unit weight.

Pedrotti and Tarantino [13] also showed pore size distribution (PSD) curves for compacted and then saturated samples, and compared them with PSDs of samples reconstituted in a saturated condition. They found that the PSDs were very similar, regardless of the different formation conditions. Furthermore, Tarantino and Tombolato [16] found, from direct shear tests on compacted-wetted and reconstituted kaolin samples that ultimate shear strength data appeared to lie on the same strength envelope.

The above observations, from the present and previous studies, suggest that clay compacted to a low initial dry unit weight (high void ratio) and then saturated, has a similar pore structure to reconstituted, saturated clay, and consequently may be expected to demonstrate similar mechanical behavior. This appears to be true with regards the compression curves, but not with regards K_0. The present observation that the compression indices vary with dry unit weight, trending towards the slurry value with increasing void ratio, whereas K_0 of the compacted-wetted soil is reasonably constant regardless of preparation conditions, and significantly higher than the slurry value, requires further investigation. However, the fact that the compacted-wetted specimens behave identically to the slurry specimens during unloading, both with regards expansion indices and with regards the relationship between K_0' and K_0, suggests that on completion of loading, at the onset of unloading, the internal structure of the clay, for all initial, preparation conditions, has become similar.

It is noted that the values of K_0 obtained for both the compacted-wetted, and the slurry samples, are significantly different from the value corresponding to the commonly accepted empirical relation $K_0 = 1\text{-}\sin\varphi'$ (φ' of Israeli highly plastic clay is of the order of 28^o [17]). Furthermore, the form of the relationship between K_0' and K_0 is consistent with the commonly accepted relationship $K_0' = K_0 \cdot OCR^{\alpha}$ [10] but the value $\alpha = 0.7$, observed for both slurry and compacted-wetted soil, is significantly different from commonly accepted values. It is believed that previous evaluations of K_0 and K_0' were based on erroneous measurement techniques, as suggested by [18].

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