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THEORETICAL STUDY OF EARTH PRESSURE AT – REST FOR SANDY SOILS

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The solution of many foundations - engineering problems requires knowledge of the lateral pressure which may be exerted by the earth or surcharge loads.
The lateral earth pressure is a significant design parameter in many of the foundation engineering problems subjected to lateral pressures commonly used as parts of many civil engineering projects. Some examples of these structures are, retaining walls, sheet-pile walls, both braced and unbraced excavations, trench excavations, grain pressures on silo walls, cofferdams, caissons, embedded shells and other types of underground structures requiring an estimation of the lateral pressure for design or stability analysis.
The different formulae such as Jaky , Hendron , Brooker and Ireland, Vierzbiczky , Saglamer , Wenkow , Robert Szepeshazi , Matsuoka et al, Bolton , and others were used to determine the factor K_o.
The main aim of this research is to estimate the coefficient of earth pressure at rest equation depending on the theoretical relationship between the active, passive earth pressures and the lateral strain of soil.
The important result from this research is:

$$K_o = (1 - \sin^2\phi)/(1 + \sin^2\phi)$$

The research included other important results.

***KEYWORDS**:* Earth pressure, K_o, coefficient of earth pressure at rest.

INTRODUCTION

The internationally most recognized achievement of soil mechanics research in Hungary has been the formula for the earth pressure at- rest. Jaky[3]

$$K_o = 1 - \sin\phi \qquad (1)$$

The earth pressure at - rest represented by its coefficient K_o, has first been interpreted by Donath [1], while Terzaghi [2] was the first to publish measurement data for K_o. The first theoretical approach to the problem is due to Jaky [3], and subsequent modifications of his theory formulated at that time resulted in Eq. (1).

In up–to–date computerized F.E.M geotechnical design procedures, the K_o factor is usually required as an input, and computations show this value to have a significant effect on the safety factor of slope stability (Lo and Lee [4]), or slurry trench wall behavior (Fourie and Potts [5]).

NOTATION

E	modulus of elasticity of soil	υ	poisson ′ s ratio.
E_h	horizontal modulus of elasticity of the soil.	σ_1	vertical pressure.
E_v	vertical modulus of elasticity of the soil.	σ_3	lateral pressure.
k_a	coefficient of active earth pressure.	σ_h	horizontal earth pressure.
K_o	coefficient of lateral earth pressure at – rest	σ_v	vertical earth pressure.
K_p	coefficient of passive earth pressure.	ϕ	the angle of internal friction of soil.
P_a	active earth pressure.	ϕ_e	the angle of shear strength mobilized at – rest.
P_o	lateral earth pressure at – rest.	ϕ_{mob}	mobilized angle of internal friction of soil.
P_p	passive earth pressure.	ε_3	the lateral strain.

The coefficient of lateral earth pressure under condition of no lateral deformation, K_o has been of interest to soil engineers for over 100 years. K_o is an essential parameter in the design or analysis of many conventional problems. For example, K_o is commonly used to compute lateral thrusts against earth – retaining structures where the lateral movement is too small to mobilize the active state of stress. The coefficient K_o has also been used in the computation of lateral swelling pressures against friction piles in expansive soils.

Donath [1] was the first to introduce the term "coefficient of earth pressure at-rest" K_o, referring to the condition where no yielding occurs. He defined this coefficient as the ratio of the horizontal (σ_h) to the vertical (σ_v) earth pressure resulting in soil due to the application of vertical load with constrained lateral deformation ($K_o = \sigma_h/\sigma_v$).

Terzaghi [2] reported results of a comprehensive study on the evaluation of K_o for a variety of soils, and studied the effect of compaction on the value of K_o .He found that the value of K_o for coarse sand was 0.42, and when the sand was compacted in layers with a hand compactor, K_o increased to a value between 0.6 and 0.7.

Kjellman [6] developed a complicated triaxial apparatus, in which the three principal stresses could be reported and values of K_o vary between 0.5 and 1.5 for the tested sand. He concluded that K_o was a function of the stress history of the sand.

Jaky [7] conducted a theoretical study on K_o and introduced the following theoretical expression to calculate the value of K_o as:

$$K_o = \left[1 + \frac{2}{3}\sin\phi\right]\left[\frac{1-\sin\phi}{1+\sin\phi}\right] \quad (2)$$

Where ϕ = the angle of shearing resistance of the soil.

Jaky [8] presented a simplified version of the expression given by:

$$K_o = 1 - \sin\phi \quad (3)$$

These expressions were the first attempts to relate the coefficient of earth pressure at rest with the angle of shearing resistance of the soil. The expression is still widely used due to its practical significance and attractive simplicity.

Bishop [9] stated that K_o is the ratio of the lateral to the vertical effective stresses in a soil consolidated under the condition of no lateral deformation.

Hendron [10] proposed the following expression relating K_o and ϕ

$$K_o = \frac{1}{2}\left[\frac{1+\frac{\sqrt{5}}{8}-3\frac{\sqrt{5}}{8}(\sin\phi)}{1-\frac{\sqrt{5}}{8}+3\frac{\sqrt{5}}{8}(\sin\phi)}\right] \qquad (4)$$

He concluded that the values of K_o for round sand are lower than for an angular one at identical values of the angle of shearing resistance, and suggested that the angle of shearing resistance is not a completely unique parameter for the value of K_o.

Saglamer [11] proposed the following equation to calculate the value of K_o for sands as:

$$K_o = 0.97\,[1 - 0.97\,(\sin\phi)] \qquad (5)$$

Wenkow [12] tested the cohesive and non – cohesive soils and presented for case of sand clayey sands the following theoretical relation:

$$K_o = \sqrt{K_a} \qquad (6)$$

Where:

K_a= the coefficient of active earth pressure.

Tschebotarioff [13] estimated the coefficient of earth pressure at- rest by theory of elasticity. The general equation for the lateral unit strain ϵ_3 within a large elastic body is as follows:

$$\epsilon_3 = \frac{1}{E}\,[\sigma_3 - \nu(\sigma_1+\sigma_3)] \qquad (7)$$

Where $\epsilon_3 = 0$ then this equation leads to

$$K_o = \frac{\sigma_3}{\sigma_1} = \frac{\nu}{1-\nu} \qquad (8)$$

Where ν the Poisson 's ratio of soil.

Robert Szepeshazi [14] determined K_o , omitting details, as:

$$K_o = (1-\sin\phi)\,[1- \frac{\sin\phi}{(1+\sin\phi)(\sin\phi+3+\sqrt{4.5+4\sin\phi}}] \qquad (9)$$

At $40° > \phi > 20°$ this intricated formula may be properly approximated (with a maximum error 1.2$\%$) as:

$$K_o = 0.95\,(1-\sin\phi). \qquad (10)$$

Vierzbiczky [14] applied the Rankine factor, assuming a mobilization of two thirds of the internal friction angle and suggested that the coefficient of earth pressure at-rest to be:

$$K_o = \tan^2\left(45 - \frac{\phi}{3}\right) \qquad (11)$$

Brooker and Ireland [15] suggested the coefficient of earth pressure at-rest to be:

$$K_o = 0.95 - \sin\phi \qquad (12)$$

Matsuoka and Sakakibara [16] suggested the coefficient of earth pressure at-rest as:

$$K_o = \frac{1}{(1 + 2\sin\phi)} \tag{13}$$

Where ϕ is the angle of internal friction of soils.

Bolton [17] proposed an equation based on the study of sands in the form:

$$K_o = \frac{1 - \sin\phi_{mob}}{1 + \sin\phi_{mob}} \tag{14}$$

Where $\phi_{mob} = \phi - 11.5°$ (15)

Rowe [18] derived the following expression:

$$K_o = \tan^2\left(45 - \frac{\phi_e}{2}\right). \tag{16}$$

In which ϕ_e = the angle of shear strength mobilized at – rest

$$\phi_e = 1.15\,(\phi - 9) \tag{17}$$

Andrawes and El- Sohby [19] concluded that the K_o value depends not only on the angle of internal friction ϕ but also on the surface roughness and angularity, they concluded that K_o decreases with increasing the angularity and the grain size.

Andrawes and El-Sohby [20] concluded that the increase in the value of porosity, crushing, and modulus of elasticity of the mineral particles causes the value of K_o to increase. Also, they concluded that K_o is not solely a function of the angle of shearing resistance (ϕ), as suggested by Jaky (1944, 1948).

Hanna and Ghaly [21] concluded that the coefficient of earth pressure at rest K_o is affected by the effective angle of shearing resistance, shape and interlocking of soil particles, amount of fines in the soil, porosity, crushing, Modulus of elasticity of the mineral particles, compacting method, stress history, and applied stress level.

Moroto and Muramatsu [22] derived a theoretical equation to determine K_o based on the anisotropy of an over consolidated clay soil. Their equation is based on the ratio of the horizontal modulus of elasticity (E_h) of the soil to it's vertically elasticity (E_v) as:

$$K_o = \sqrt{\frac{E_h}{E_V}}. \tag{18}$$

$$K_o = \frac{1 - \sin^2\phi}{1 + \sin^2\phi} \tag{19}$$

ANALYSIS OF THE PRESENT EQUATION

Referring to Fig. (1), it is noted in the relationship between lateral strain and lateral pressure coefficient that the active earth pressure appeared when the construction moves away from backfill in this case lateral expansion of the soil occurs. The passive earth pressure appeared when the construction moves towards the backfill, this is analogous to pushing a wall laterally against the soil

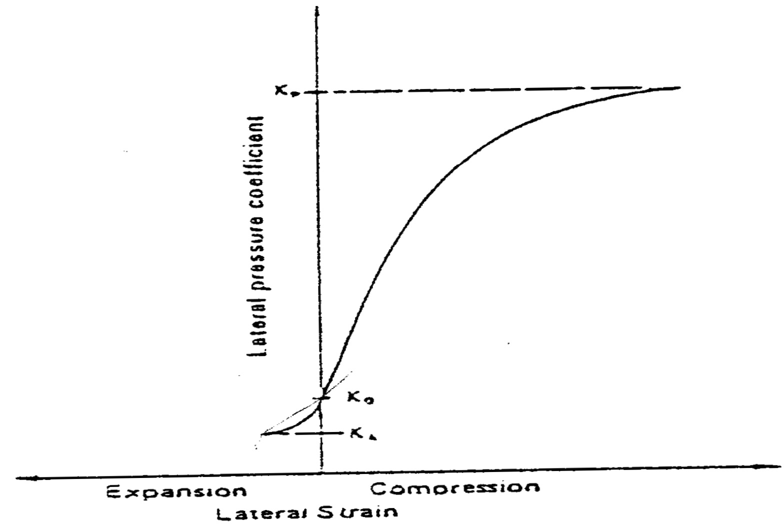

Fig. (1) Relation between lateral strain and lateral pressure coefficient [23]

If the lateral strain in the soil is zero or very small in the structure or if earth pressure acting on motionless retaining wall, the corresponding lateral earth pressure is called the pressure at-rest

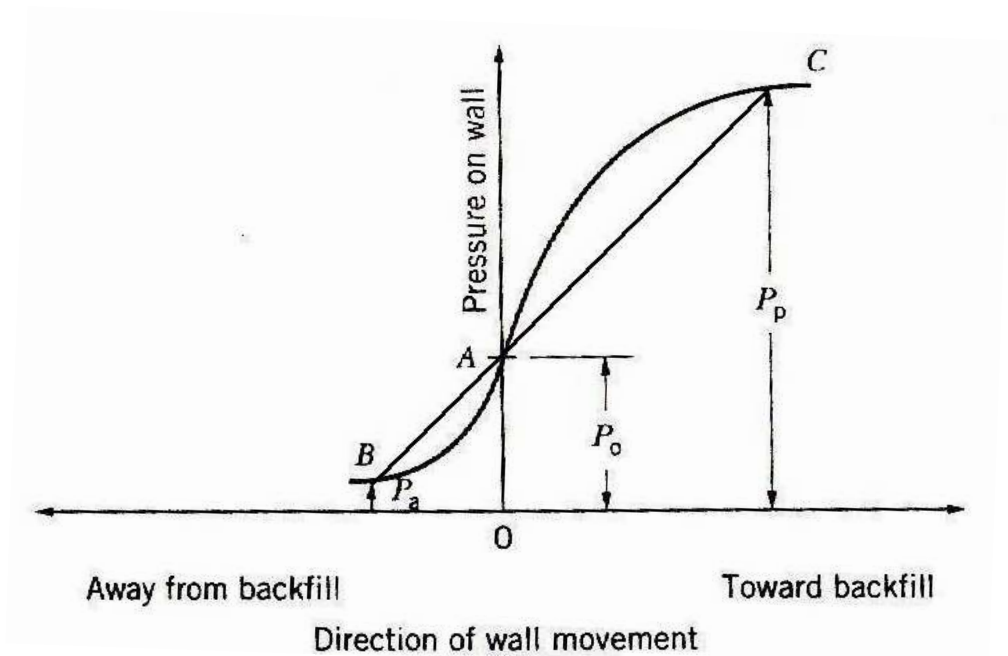

Fig. (2) Relationship between lateral strain and lateral pressure coefficient.

By considering the soil as elastic, isotropic, homogenous, and considering the idealized relationship between lateral strain and lateral pressure (line BC).
The geometric shape in Fig. (2) Leads to

$$\frac{P_o - P_a}{P_p - P_a} = \frac{\epsilon_a}{\epsilon_a + \epsilon_p} \tag{20}$$

$$\frac{P_o - P_a}{P_p - P_a} = \frac{\frac{P_a}{E}}{\frac{P_a}{E} + \frac{P_p}{E}} \tag{21}$$

$$\frac{P_o - P_a}{P_p - P_a} = \frac{P_a}{P_a + P_p} \tag{22}$$

$$(P_o - P_a)(P_a + P_p) = P_a (P_p - P_a). \tag{23}$$

$$K_o K_a + K_o K_p - K_a^2 - K_a K_p = K_a K_p - K_a^2 \tag{24}$$

$$K_o K_a + K_o K_p = 2 K_a K_p \tag{25}$$

$$K_o = \frac{2K_a K_p}{K_a + K_p} \tag{26}$$

$$K_a = \frac{1}{K_p} = \frac{1 - \sin\phi}{1 + \sin\phi} \tag{27}$$

Substituting in Eq.(27) into Eq.(26), we obtain

$$K_o = \frac{1 - \sin^2\phi}{1 + \sin^2\phi} \tag{28}$$

RESULTS AND DISCUSSION

Jaky's equation is often referred to as the base of comparison in appreciating most of new theoretical or measurement results [14]. It's better to compare all different types of equation which used to determine the coefficient of earth pressure at rest including of course the current equation to Jaky's equation. The relationship between the angle of internal friction, ϕ and the coefficient of earth pressure at rest, K_o for sandy soils are plotted in Fig. (3).

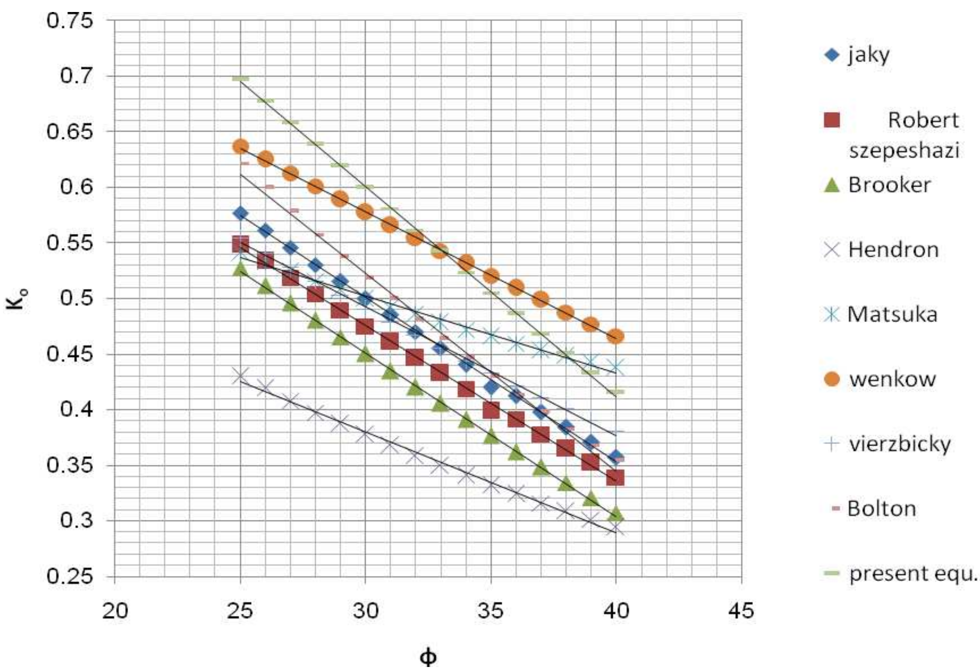

Fig. (3) Relations between φ and different aspects of the formula for the coefficient of earth pressure at rest for cohesionless soils.

The relationships can be represented by straight lines as follows:

$K_o = 0.96429 - 0.01548\ \phi$ .... for Jaky

$K_o = 1.0544 - 0.017946\ \phi$ .... for Bolton

$K_o = 0.895 - 0.014\ \phi$ .... for Robert Szepeshazi

$K_o = 0.8905 - 0.0147\ \phi$ .... for Brooker

$K_o = 0.91887 - 0.011396\ \phi$ .... for Wenkow

$K_o = 0.64925 - 0.009\ \phi$ .... for Hendron

$K_o = 0.8379 - 0.0116\ \phi$ .... for Vierzbicky

$K_o = 0.70925 - 0.00698\ \phi$ .... for Matsuka

$K_o = 1.16414 - 0.01884\ \phi$ .... for Present equ.

Where ϕ is in degrees.

From Fig. (3) it can be noticed that for the present equation, the coefficient of earth pressure at rest, K_o decreases with the increase of the angle of internal friction , ϕ

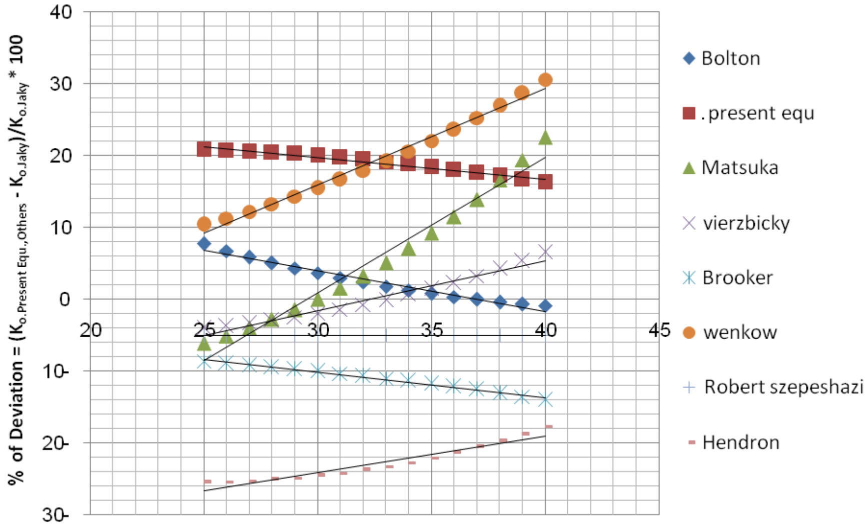

Fig. (4) Relations between the angle of internal friction , ϕ and % Deviation between Jaky and Present Equ. ,Others

Figure (4) Shows the Relations between the angle of internal friction ϕ, and % of Deviation between Jaky , present equation, and others . It can be noticed that, for the present equ.and Jakys′equ. The deviation is about 20 % at ϕ = 25:30, about 19 % at ϕ = 31:33, about 18 % at ϕ =34:36 and about 16.5% at ϕ = 37:40°

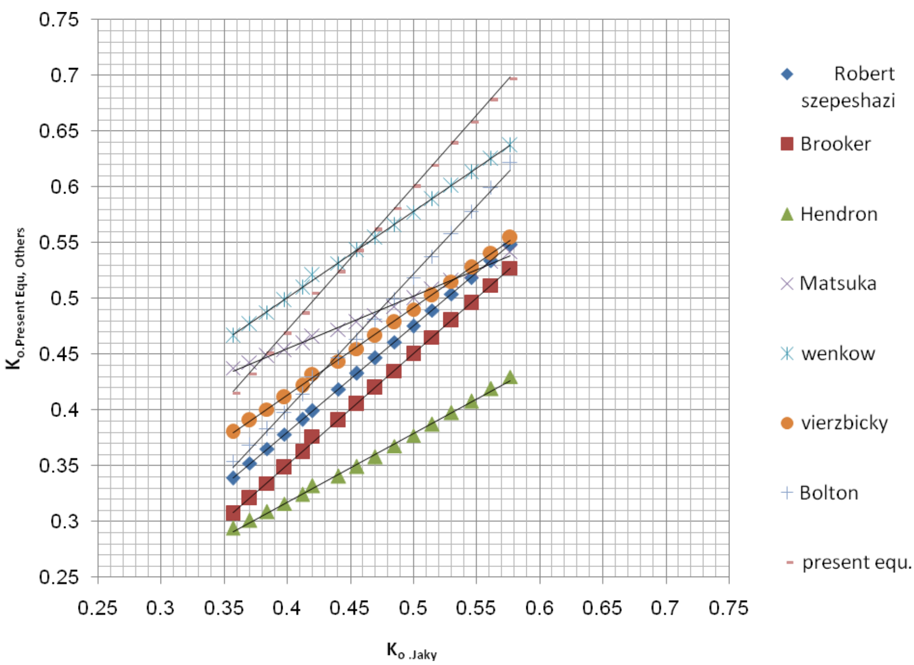

Fig. (5) Relations between $K_{o\ .Jaky}$ and results of K_o.Present equ., Others

The relationships between K_o from Jaky and K_o from present equ. and others for sand soil are plotted in Fig. (5) K_o from present equ. and others relatively with K_o from Jaky.

The relationships can be represented as straight line as follows:

$K_{oRobert} = 0.95\ K_{oJaky}$

$K_{oBrooker} = 0.98707\ K_{oJaky} - 0.04353$

$K_{oHendron} = 0.63736\ K_{oJaky} + 0.05881$

$K_{o\ Matsuka} = 0.46975\ K_{oJaky} + 0.266$

$K_{oWenkow} = 0.7756\ K_{oJaky} + 0.18984$

$K_{o\ vierzbicky} = 0.78852\ K_{oJaky} + 0.09639$

$K_{oBolton} = 1.2165\ K_{oJaky} - 0.08905$

$K_{opresent} = 1.2795\ K_{oJaky} - 0.04044$

From Fig. (5) at $\phi = 25: 40°$ it can be noticed that $K_{o\ present}$ increases with increase $K_{o.Jaky}$

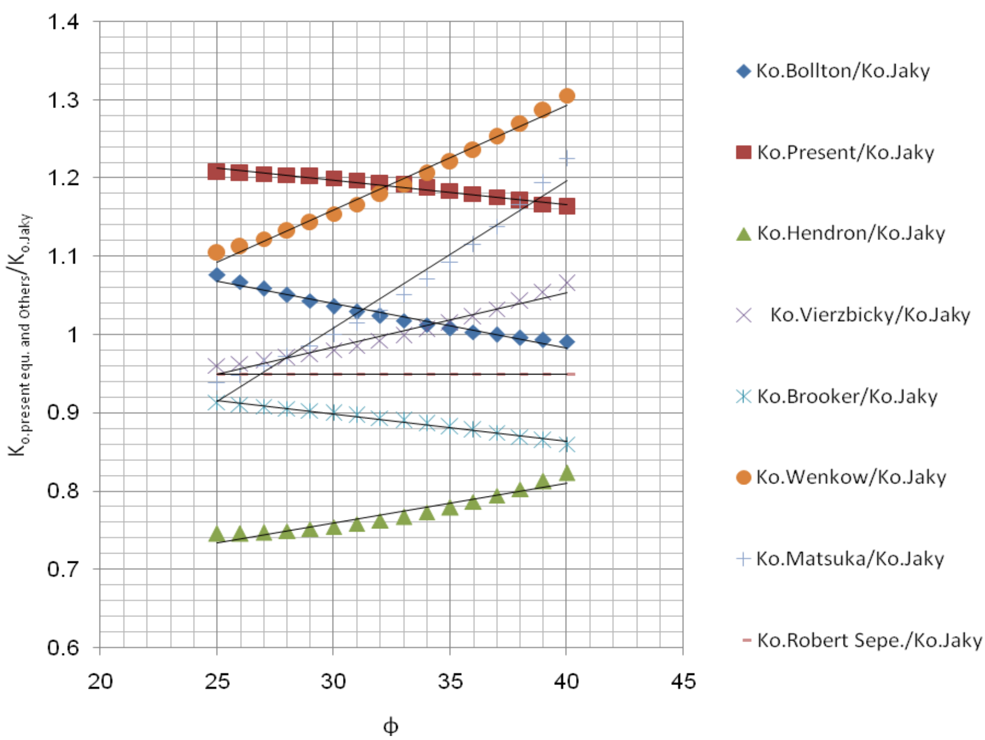

Fig. (6) Relations between $K_{o.present\ equ.and\ Others}/\ K_{o.Jaky}$ and the angle of internal friction, ϕ

The relationship between the angle of internal friction, ϕ and the coefficient of earth pressure at rest, $K_o/k_{o.Jaky}$ for sand soil are plotted in Fig. (6)

The relationships can be represented by straight lines as follows:

$K_{oRobert} / k_{o\ Jaky} = 0.95$.

$K_{oBolton}/K_{o\ Jaky} = 1.1998 - 0.0055\ \phi$

$K_{oPresent}/K_{o\ Jaky} = 1.3011 - 0.0033\ \phi$

$K_{o\ Hendron}/K_{o\ Jaky} = 0.606 + 0.005\ \phi$

$K_{o\ Vierzbicky}/K_{o\ Jaky} = 0.0072\ \phi + 0.76305$

$K_{o\ Brooker}/K_{o\ Jaky} = 1.00719 - 0.00356\ \phi$

$K_{oWenkow}/K_{o\ Jaky} = 0.013\ \phi + 0.758$

$K_{oMatsuka}/K_{o\ Jaky} = 0.01913\ \phi + 0.43042$

Where ϕ in degree

From Fig.(6) for $\phi = 25 : 40^\circ$ the relation between the $K_{o\ present}/K_{o\ Jaky}$ and ϕ presented as nearly horizontal straight line up to 33° and equals 1.2 and deceases to reach 1.16 at 40° .

CONCLUSIONS

Due to the great importance of the coefficient of earth pressure at rest K_o and through the wide investigation performed on the available formulae, it was able to introduce a new equation to compute K_o for sandy soils.

Such equation depends on: the active, passive earth pressure and the lateral strain of soil. This formula is found to be in good agreement with the most famous equations usually used to determine such coefficient.

The findings are summarized as follows:-

1. The present equation is:
   $K_o = (1 - \sin^2 \phi) / (1 + \sin^2 \phi)$
2. The coefficient of earth pressure at rest, $K_{o.\ present\ equ.}$ decreases with increase of the angle of internal friction , ϕ and the relationship can be represented as straight line as
   $K_{o\ present\ equ.} = 1.16414 - 0.01884\ \phi$.
3. The Deviation from present equ.and Jaky equ about 20 % at $\phi = 25{:}30$, about 19 % at $\phi = 31{:}33$, about 18 % at $\phi = 34{:}36$ and about 16.5% at $\phi = 37{:}40^\circ$.
   The deviation decreases with increase of the angle of internal friction, ϕ
4. The relationship between $K_{o.\ present}$ and $K_{o\ .\ Jaky}$ for sandy soils is:
   $K_{opresent} = 1.2795 K_{oJaky} - 0.04044$
   For $\phi = 25{:}\ 40^\circ$ it is noticed that $K_{o\ present}$ increases with the increase of $K_{o\ Jaky}$ and the relationship between them is a straight line.
5. The relationship between the angle of internal friction, ϕ and the relation of $K_{o\ present} / K_{o\ Jaky}$ for sandy soils can be written as:
   $K_{o\ present}/K_{o\ Jaky} = 1.3011 - 0.0033\ \phi$.

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دراسة الضغوط الجانبية للتربة الرملية عند السكون

يعتبر ضغط التربة من اهم الموضوعات فى مجال الهندسة المدنية لان كثير من المنشات الهندسية تتعرض لهذا الضغط مثل الحوائط الساندة – والالواح الخازوقية – السدود – القيسونات (كاساسات او بيارات) – الخزانات الارضية – خنادق التنقيب – الضغط الناتج من الحبوب على حوائط صوامع التخزين – الضغط الجانبى للصخر على الانفاق – والمنشات الارضية وخلافة.

كما يعتبر معامل الضغط الجانبي للتربة عند السكون متغير هام جدا فى تصميم وتحليل العديد من المشاكل الهندسية الخا صة بالمنشات الارضية ويتمثل فى حساب القوى الجانبية الناتجة من التربة على المنشات الساندة حيث انة فى هذة الحالة تكون الحركة الجانبية صغيرة جدا كما يستخدم فى تحليل ودراسة اتزان الميول وخاصة المنحدرات الطينية كما يستخدم ايضا فى حساب ضغط الانتفاخ الناتج من التربة الانتفاخية على جسم الخوازيق او المنشات التحتية.

ولهذه الاهمية قام كثير من الباحثين والعلماء مثل (جاكى – بروكرو ايرلند – ماتسوكا – بولتن – فيرسبيسكى – روبيرت شيبيشاذى – هندرون – وينكو – سيجليمر) وغيرهم بعمل العديد من الدراسات لكيفية حساب هذا المعامل .

وفى هذا البحث اجريت دراسة نظرية باستخدام العلاقة بين الضغط الجانبى (ضغط التربة الفعال – ضغط التربة المقاوم) والانفعال الجانبي ومن خلالها تم التوصل الى معادلة لحساب معامل الضغط الجانبى للتربة الرملية عند السكون .وتم مقارنة هذه المعادلة بمعادلات كل من (جاكى – بروكر وايرلند – ماتسوكا – بولتن – فيرسبيسكى – روبيرت شيبيشاذى – هندرون – وينكو – سيجليمر) حيث وجد نتائج المقارنة النظرية مرضية.

كما يحتوى البحث على بعض النتائج الهامة الاخرى.