Earth Pressures on Retaining Structures

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Abstract- This study assessed John Neville's work on active earth pressure theory and compared it to the accepted design standard for estimating active earth pressure in section 9 of Eurocode 7 using the analytical procedure and other calculation methods. The assessment indicated thatJohn Neville's theory on active earth pressure performed well for the horizontal retained surface with zero external frictional angle when compared. The analytical procedure for estimating earth pressures in Eurocode 7 was compared with other calculation methods including the chart procedure presented in Eurocode 7 for estimating earth pressures. The importance of providing clarity in Eurocode 7 was presented.

Keywords: Eurocode 7, Earth pressure, John Neville, Analytical procedure, clarity in Eurocode 7.

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1. INTRODUCTION

Civil and Geotechnical Engineers need to estimate the earth pressures required when designing retaining structures. Structures with the capability to retain earth banks and other materials including water, are generally referred to as ‘retaining structures’.Retaining structures are designed based on accepted earth pressure theories. Traditionally, Coulomb and Rankine’s earth pressure theories were the generally accepted theories used for estimation of earth pressures.

In the development of each theory, the properties of the retaining wall and the retained material must be taken into consideration in order to efficiently estimate earth pressures acting on a given retaining structure. Some of the early earth pressure theories published including Neville[1] and Rankine[2], assumed that the surface facing the retained material was smooth, indicating that a frictionless interaction occurs between the retaining wall and the retained material.

Earth pressure has been explained in several publications. Venkatramaiah[3] explained the principle behind the Wedge analysis approach for the estimation of earth pressures. The author made use of Coulomb earth pressure theory to explain the wedge analysis. Murthy[4]explained the Limit State Equilibrium which Rankine’s earth pressure theory is based on.

These assumptions and approaches (such as wedge analysis, stress analysis, log-spiral and so on) used in the development of earth pressures theories determine the accuracy with which a given earth pressure theory will estimate the earth pressure on a given restructure. The need to examine the various earth pressure theories that have been published therefore becomes important.

Subsequently, earth pressure theories have been based upon the log spiral approach.

2. Wedge Analysis - John Neville and Coulomb

On May 13, 1845, John Neville delivered a report titled ‘Investigation of some formula for finding the maximum amount of resistance required to sustain banks of earth, or other materials, and the position of the fracture requiring that resistance’[1]. In John Neville investigation, formulas for calculating the active pressure or resistance acting on a retaining wall were provided for the following conditions:

a) Horizontal retained surface

$$R = \frac{h^2 W}{2}\ x\ tan^2(c/2) \qquad \text{Equation 1}$$

b) Inclined retained surface

$$R = \frac{H^2 W}{2}\ x\ \left(\frac{\sec.c - \sqrt{tan.b}\tan c + 1}{\tan c}\right)^2 \qquad \text{Equation 2}$$

John Neville in investigating Tredgold’s work on Masonry as reported in Encyclopaedia Britannica, seventh edition, pointed out that Tredgold equation for calculating resistance was given as

$$R = \frac{h^2 S}{2\tan i}\ x\ \left[\tan i + \tan c + \frac{2}{\tan i} - 2\left(\tan c \tan i + \frac{\tan c + 1}{\tan i}\right)^{\frac{1}{2}}\right] \qquad \text{Equation 3}$$

Where, i is the complement of the angle of repose, h is the vertical height, and $S$is the weight of a cubical foot of the material.Neville [1] stated that Tredgold’s Equation 3 is not correct, that the correct equation is shown in Equation 4.

$$R = \frac{h^2 S}{2\tan i}\left[\tan i + \tan c + \frac{2}{\tan i} - 2\left(\tan c \tan i + \frac{\tan c\ tani + 1}{\tan^2 i}\right)^{\frac{1}{2}}\right] \qquad \text{Equation 4}$$

Coulomb [5]provided the theoretical formula for calculating the coefficient active earth pressure, K_a. Which is given as:

$$K_a = \frac{\sin^2(\alpha + \emptyset)}{\sin^2\alpha \sin(\alpha - \delta)\left[1 + \sqrt{\frac{\sin(\emptyset + \delta)\sin(\emptyset - \beta)}{\sin(\alpha - \delta)\sin(\alpha - \beta)}}\right]^2} \qquad \text{Equation 5}$$

While Coulomb’s proposed earth pressure coefficient,K_p is given as:

$$K_p = \frac{\sin^2(\alpha - \emptyset)}{\sin^2\alpha \sin(\alpha + \delta)\left[1 - \sqrt{\frac{\sin(\emptyset + \delta)\sin(\emptyset + \beta)}{\sin(\alpha + \delta)\sin(\alpha + \beta)}}\right]^2} \qquad \text{Equation 6}$$

Rankine proposed a theory used to estimate the active and passive earth pressure. The wedge analysis approach was not used by Rankine, but a different approach known as “State of Stress” was used to estimate the coefficient of active and passive earth pressures acting on a given retaining wall. In Venkatramaiah[3], Rankine’s active earth pressure formula is given as:

$$K_a = \frac{1 - \sin\emptyset}{1 + \sin\emptyset} = \tan^2(45^o - \frac{\emptyset}{2}) \qquad \text{Equation 7}$$

and for passive earth pressure:

$$K_p = \frac{1 + \sin\emptyset}{1 - \sin\emptyset} = \tan^2(45^o + \frac{\emptyset}{2}) \qquad \text{Equation 8}$$

In order to tackle the disadvantage of assuming a plane failure surface by Coulomb[5] and Rankine[2], Caquot and Kerisel[6] developed a theory for earth pressure which was based on Log spiral theory. Senoon[7] worked on passive earth pressure against retaining walls. In his research paper, he also focused on the surface of failure. He proposed a set of equations that take into account a combined log-spiral curved failure surface and a linear segment failure surface, which can be solved with high degree of accuracy using a computer.

In the Annex C of the Eurocode 7, the general equation for calculating the normal coefficient of earth pressures is given as:

$$K_n = \frac{1 + \sin\varphi \sin(2m_w + \varphi)}{1 - \sin\varphi \sin(2m_t + \varphi)} \exp(2v \tan\varphi) \qquad \text{Equation 9}$$

Where, $\text{Cos}(2m_t + \varphi + \beta_o) = -\frac{\sin\beta_o}{\sin\varphi}$ Equation 10

$$Cos(2m_w + \varphi + \delta) = \frac{\sin\delta}{\sin\varphi} \qquad \text{Equation 11}$$

$$v = m_t + \beta - m_w - \emptyset \qquad \text{Equation 12}$$

In assessing Sigurdur[8]work, he provided a single equation represented as Equation 13for both active and passive earth pressure coefficient basedonEurocode 7.

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$$K_{p/a} = \frac{1 \pm \sin\phi' \sin(2m_w \pm \phi')}{1 \mp \sin\phi' \sin(2m_t \pm \phi')} e^{\pm 2(m_t + \beta - m_w - \theta)(\tan\phi')} \quad \text{Equation 13}$$

Where, $$m_t = 0.5\left(\arccos\left(\frac{-\sin\beta}{\pm\sin\phi'}\right) \mp \phi' - \beta\right) \text{Equation 14}$$

$$m_w = 0.5\left(\arccos\left(\frac{\sin\delta}{\pm\sin\phi'}\right) \mp \phi' \mp \beta\right) \text{Equation 15}$$

For the calculation of the passive earth pressure coefficient, the top sign of the double sign will be used and for the calculation of the active earth pressure, the lower bottom sign will be used.

The need to compare the various earth pressure formulas with field measurements cannot be neglected. This comparison is not commonly done due to the difficulties associated with measuring the earth pressures itself. This view was reported in AIJ Recommendations for Loads on Building[9].

3. ASSESSMENTS

In carrying out these assessments, the analysis has been divided into the active and passive earth pressure theories. Each of the earth pressure theories will be tested using two cases based on the retained surface's slope. The first case will be based on the horizontal case and the second case will treat the inclined case.

In order to carry out accurate comparison of the charts, readings taken from the charts in Figure C.1.1 to Figure C.1.4 of the Eurocode 7 for K_a values and for the charts in Figure C.2.1 to Figure C.2.4 of the Eurocode 7 for K_p values will be compared.Additional calculation methods were also included for comparison, such as the tables presented by Senoon[7], Caquot and Kerisel[6].

In the literatures reviewed, it was understood that, one of the challenges associated with the current Eurocode 7, was the absence of clarity in some formulas presented in the Eurocode 7 document.

4.Proposed equations Layout for estimating the coefficient of earth pressures based on the analytical procedure in Eurocode 7.

In this research work, Equation C.3 to Equation C.6 provided in Eurocode 7 were broken into the coefficients of active and passive earth pressure state, ensuring the right sign and terms. The proposed layout for estimating the coefficient of earth pressures based on literature reviewed and the Eurocode 7 itself, gives:

$$K_{a/p} = \frac{1 \mp \sin\varphi \sin(2m_w \mp \varphi)}{1 \pm \sin\varphi \sin(2m_t \mp \varphi)} e^{\mp 2(m_t + \beta - m_w - \theta)(\tan\varphi)} \quad \text{Equation 16}$$

Where, $$m_t = 0.5\left(\arccos\left(\frac{-\sin\beta}{\mp\sin\varphi}\right) \pm \varphi - \beta\right) \text{ Equation 17}$$

$$m_w = 0.5\left(\arccos\left(\frac{\sin\delta}{\sin\varphi}\right) \pm \varphi \pm \delta\right) \quad \text{Equation 18}$$

The upper sign representing the active earth pressure state and the lower sign representing the passive earth pressure state.

5.0 Coefficients of Active Earth Pressure

The various formulas provided for estimating the coefficients of active earth pressures in this research work, will be assessed they include those provided bySigurdur, analytical procedure in Eurocode 7, John Neville and Tredgold.

5.1*Coefficient of Active Earth Pressure based on Sigurdur (2011)*

From Equation 13, Equation 14 and Equation 15, based on Sigurdur[8], the coefficient of active earth pressure were estimated for each case.

In Figure 1, the broken line represents the $K_a$values measured from Figure C.1.1 in Eurocode 7 for horizontal retained surface. Result presented for horizontal retained surface with the normalization of various interface friction, showed that the K_a values obtained for corresponding $\boldsymbol{\varphi}$ based on Sigurdur's equations are very close to those of the chart values obtained in the Eurocode 7.

Case 1: *Horizontal retained surface for the coefficients of active earth pressure based on Sigurdur.*

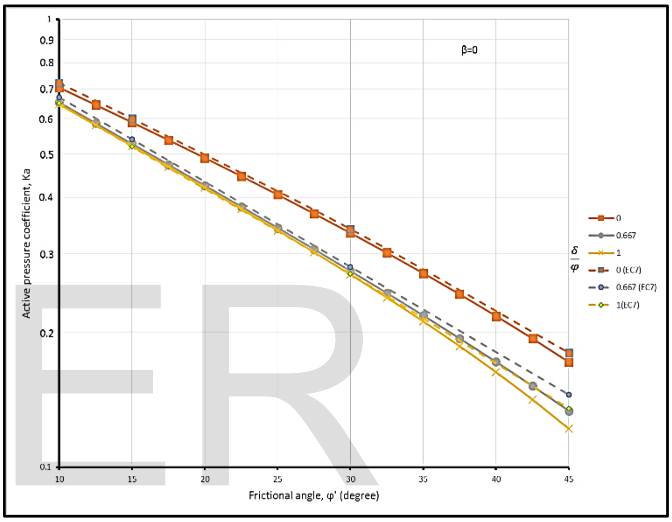

Figure 1: Coefficient of active earth pressure, K_a for horizontal backfill based on Sigurdur.

The formula presented by Sigurdur (2011) was further tested for inclined retained surface, the results indicated that, the values of K_a obtained from Sigurdur's equations deviate from the values obtained from the Chart in Figure C.1.4 of the Eurocode 7.

Case 2: *Inclined retained surface for the coefficients of active earth pressure based on Sigurdur.*

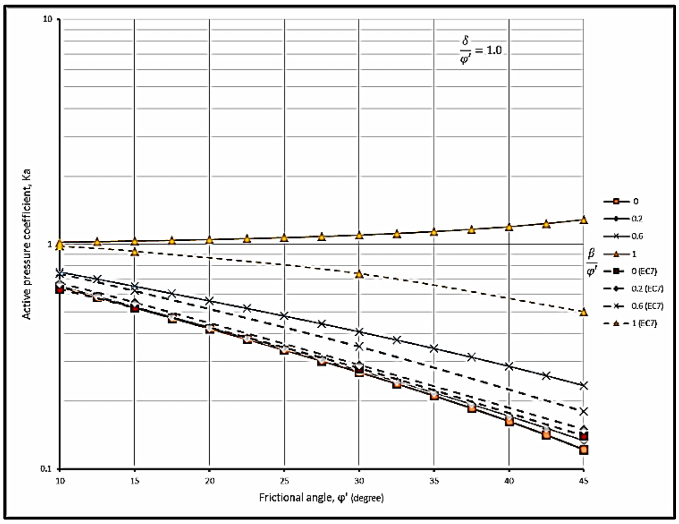

Figure 2: Coefficients of active earth pressure (K_a), for inclined retained surface based on Sigurdur (2011).

In Figure 2, the deviation increases as the internal friction φ increases for various β values. The greatest deviation from the actual chart presented in Eurocode 7 can be seen when $\frac{\delta}{\varphi} = 1$ and $\frac{\beta}{\varphi} = 1$. At these conditions, with increase in φ, the K_a begins to produce results similar to that expected from K_p. That is, the K_a values begin to increase rather than decrease for a corresponding increase φ, when $\frac{\delta}{\varphi} = 1$ and $\frac{\beta}{\varphi} = 1$.

5.2 *Coefficients of active earth pressure based on analytical procedure provided in Eurocode 7.*

The active earth pressure state from Equation 16 to Equation 18were used to produce charts for the horizontal and inclined retained surface.

Case 1: Horizontal retained surface based on analytical procedure of Eurocode 7.

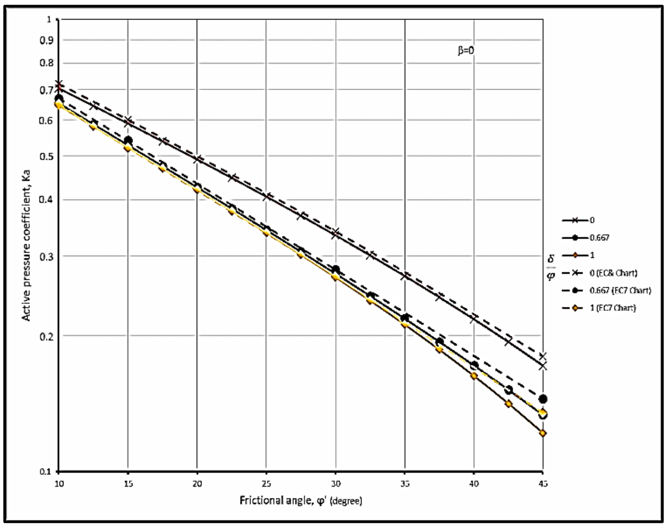

Figure 3: Coefficients of active earth pressure (K_a), for horizontal retained surface based on analytical procedure from Eurocode 7.

The analytical procedure and chart presented in Figure C.1.1 of Eurocode 7shows that, the results are good and coherent for $\varphi < 25^o$. For $\varphi > 25^o$, the K_a values from the analytical procedure are lower than the K_a values provided in Figure C.1.1 of Eurocode 7.

Case 2: inclined retained surface for the coefficients of active earth pressure based on analytical procedure in Eurocode 7.

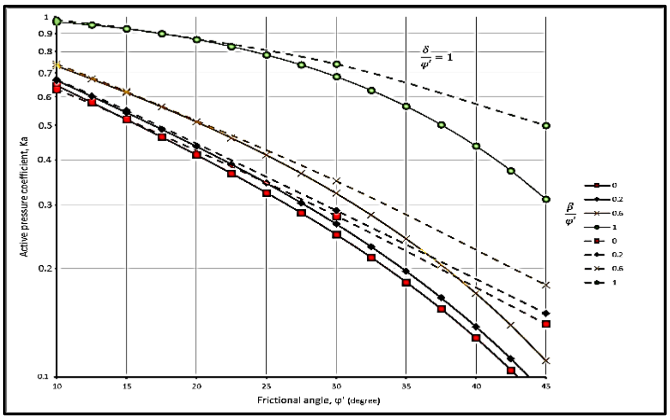

Figure 4: Coefficient of active earth pressure (K_a), for inclined retained surface based on analytical procedure from Eurocode 7.

In the chart presented in Figure 4, the broken line represents the reading from Figure C.1.4 in Eurocode7 for inclined retained surface. The deviation between the analytical procedure and chart increases significantly from $\varphi > 25^o$.

5.3 Coefficient of active earth pressure based on John Neville, Tredgold and analytical procedure in Eurocode 7.

The coefficient of active earth pressure derived from Equation 3 and Equation 4 for John Neville were compared with the analytical procedure in Eurocode 7 including Tredgold's calculation method.

Case 1: Horizontal retained surface for the coefficients of active earth pressure, based on John Neville, Tredgold and analytical procedure in Eurocode 7.

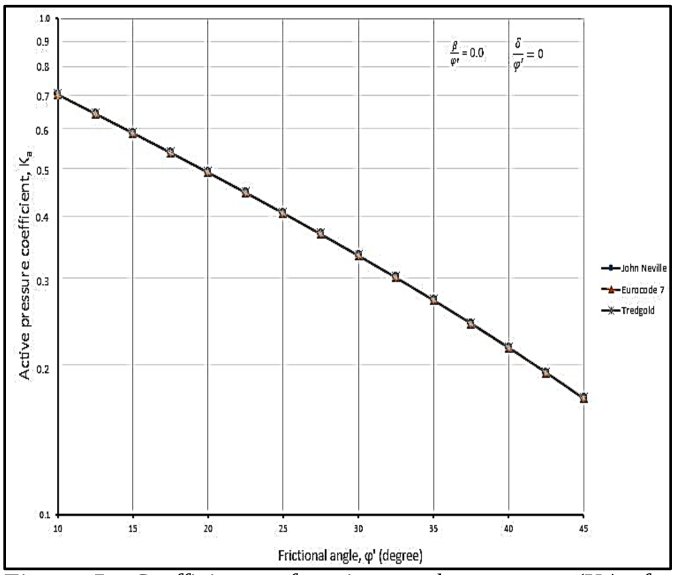

Figure 5: Coefficients of active earth pressure (K_a), for horizontal retained surface based on John Neville, Tredgolds and the analytical procedure in Eurocode 7.

In Figure5, it can be seen that John Neville, Tredgoldand the analytical procedure produced the same result. This is expected as they both have the same equation for the estimation of horizontal retaining surface.

Case 2: Inclined retained surface for the coefficients of active earth pressure, based on John Neville, Tredgold and the analytical procedure in Eurocode 7.

The behaviour of these theories (John Neville, Tredgolds and Eurocode 7) when an inclined retained surface is involved can be seen in Figure 6.

In Figure 6, for $\frac{\beta}{\varphi} = 0.2$ retained surface condition, Tredgold's equation becomes very unsafe when compared with Neville and the analytical result from the Eurocode 7. Unlike Tredgold's equation, John Neville's equation still presented good estimation of the active earth pressure when compared with the analytical procedure in Eurocode 7.

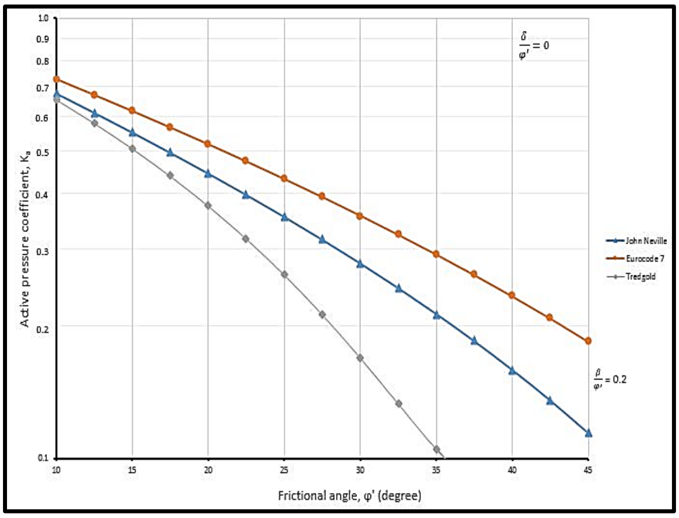

Figure 6: Coefficient of active earth pressure, K_a for Inclined retaining Surface based on John Neville, Tredgolds and the analytical procedure in Eurocode 7.

It must be noted that, the estimated K_a values are lower than the analytical procedure. Furthermore, the behaviour as the value of $\frac{\beta}{\varphi}$ becomes unity is shown in Figure 7.

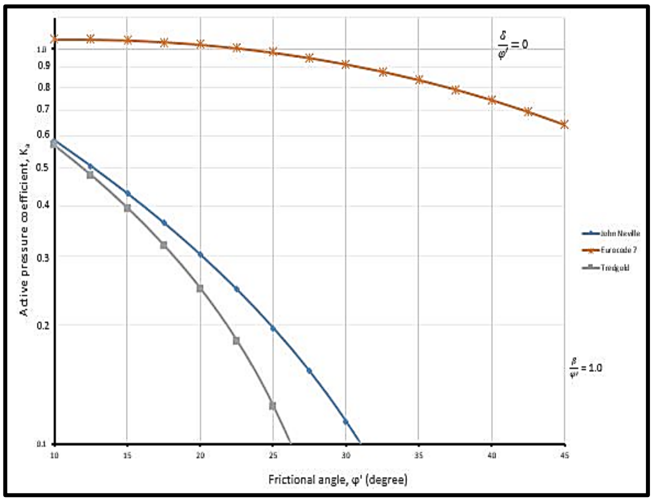

Figure 7: Coefficient of active earth pressure, K_a for inclined retaining surface based on John Neville, Tredgolds and the analytical procedure in Eurocode 7.

In Figure 7, the extreme inclined retained surface situation is shown for $\frac{\beta}{\varphi} = 1$. The results indicated that the estimated K_a is very unsafe when using John Neville or Tredgold's equation. In the chart, when $\varphi = 30^o$, John Neville's underestimates the K_a value by more than 80% when compared with the K_a value predicted by the analytical procedure in the Eurocode 7.Table 1 shows the summary of results for three design situation using three different active earth pressure theories.

Table 1: Design Example active earth pressure coefficient.

Active Earth Pressure Theory	**K_a**		
	β = 0	**β = 0.4 ϕ**	
	δ = 0		**δ = 0.667 ϕ**
	$\varphi = 15^o$	**$\varphi = 30^o$**	**$\varphi = 30^o$**
Neville (1845)	0.5888	0.2580	NA
Analytical Procedure (EC7)	0.5888	0.3874	0.3175
Tredgold	0.5888	0.1636	NA
Sigurdur (2011)	0.5888	0.4670	0.3385

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The results presented in Table 1 for β = 0, φ = 15^o and δ = 0, shows that all the theories analysed estimated the same K_a. While for β = 0, φ = 30^o and δ = 0, a graphical representation of the results obtained is shown in Figure 8.

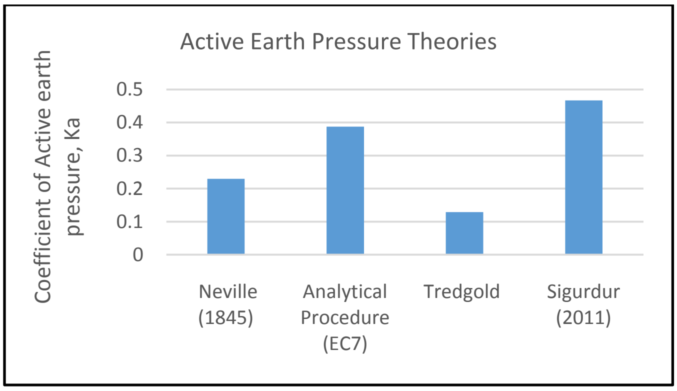

Figure 8: Results for Example 1b.

The results presented in Figure 8 for β = 0.4 , φ = 30^o and δ = 0, shows the K_a value for Sigurdur[8] is the highest, followed by analytical procedure (EC7), Neville [1]and Tredgold.

6.0 Coefficients of Passive Earth Pressure.

The various calculation methods provided for the estimation the coefficients of passive earth pressure in this research work, will be assessed.

6.1 Coefficient of passive earth pressure based on Sigurdur.

Equation 13 to Equation 15, were used to determine and estimate the K_p for different internal angle of frictions$\boldsymbol{\varphi}$. The horizontal and inclined was assessed also.

Case 7: Horizontal retained surface for coefficients of passive earth pressure based on Sigurdur.

Sigurdur**[8]** formula for K_p, which was based on the analytical procedure in Eurocode 7, was used to produce K_p values for various normalized external friction δ condition while keeping the slope at zero. This same style was adopted in the Chart in Eurocode 7. The results obtained are shown in Figure 9.

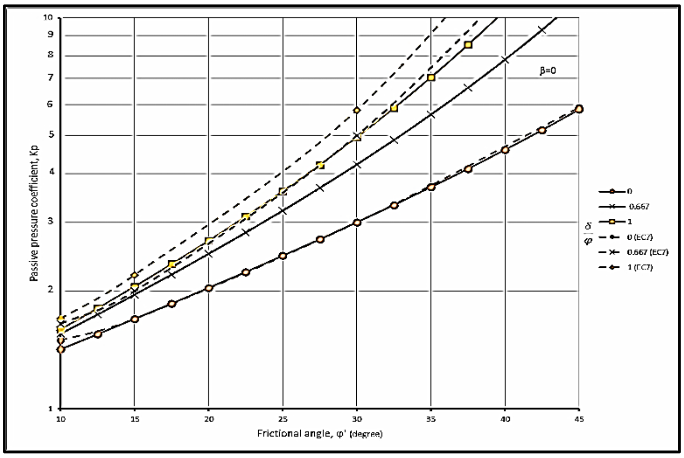

Figure 9: Coefficient of passive earth pressure, K_p for horizontal retained surface based on Sigurdur.

In the chart presented in Figure 9 for a zero degree slope, themeasured K_p values from Figure C.2.1 in Eurocode 7 for $\frac{\boldsymbol{\delta}}{\boldsymbol{\varphi}} = \mathbf{0}$ are same with Sigurdur's estimate. However, themeasuredK_p values begin to drop as$\frac{\boldsymbol{\delta}}{\boldsymbol{\varphi}} > 0$. Additionally, it can be observed that for $\frac{\boldsymbol{\delta}}{\boldsymbol{\varphi}} = \mathbf{0.667}$the measured K_p values from Figure C.2.1 in Eurocode 7 is approximately equal to the K_p values for $\frac{\boldsymbol{\delta}}{\boldsymbol{\varphi}} = \mathbf{1}$ estimated by Sigurdur's equation for the horizontal retained surface case.

In Figure 10, the deviation of the value of K_p increases as the internal friction $\boldsymbol{\varphi}$ increases for β values greater than zero. The greatest deviation from the actual chart presented in Eurocode 7 can be seen when $\frac{\boldsymbol{\delta}}{\boldsymbol{\varphi}} = \mathbf{1}$ and$\frac{\boldsymbol{\beta}}{\boldsymbol{\varphi}} = \mathbf{1}$.

Case 2: Inclined retained surface for coefficient of passive earth pressure based on Sigurdur.

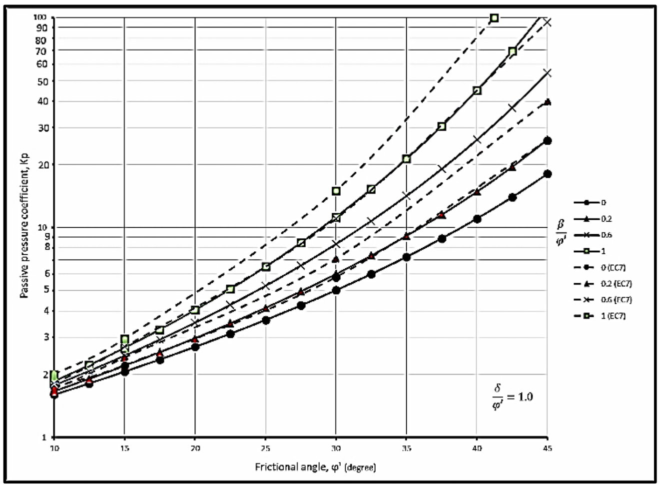

Figure 10: Coefficient of passive earth pressure, K_p for Inclined retained surface based on Sigurdur.

6.2 Coefficient of passive earth pressure based on analytical procedure provided in Eurocode 7.

The passive earth pressure coefficient for the analytical procedure in Eurocode 7were used to evaluate the horizontal and inclined retained surface each.

Case 1: Horizontal retained surface for coefficient of passive earth pressure based onanalytical procedure provided in Eurocode 7.

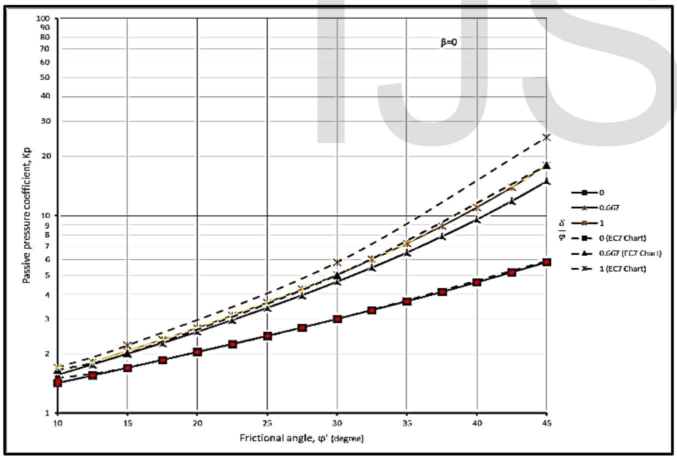

Figure 11: Coefficient of passive earth pressure (K_p), for horizontal retained surface based on analytical procedure from Eurocode 7.

In Figure 11, the $K_p$values from the analytical procedure and the values from Figure C.2.1 in the Eurocode 7 shows that both produced same result when the external frictional angle is at zero$\frac{\delta}{\varphi} = 0$.

Case 2: Inclined retained surface for coefficient of passive earth pressure based onanalytical procedure provided in Eurocode 7.

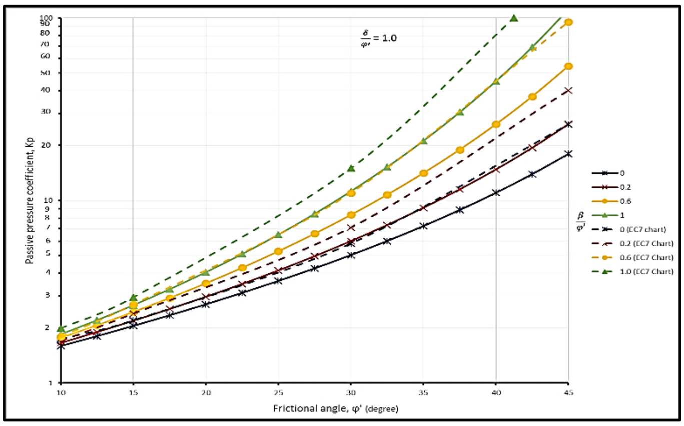

Figure 11: Coefficient of passive earth pressure (K_p), for inclined retained surface based on analytical procedure from Eurocode 7.

The chart in Figure 11, shows that the analytical procedure from Eurocode 7 begins to overestimate the K_p when the retained surface is inclined.

7.0 Published coefficient of passive earth pressure tables vs analytical procedure in Eurocode 7.

The table of values provided by Senoon[7]for passive earth pressure coefficients were compared with the analytical procedure from Eurocode 7 for both the horizontal and inclined situation. The result is presented in Figure 12.

Case1: Horizontal retained surface for coefficient of passive earth pressure based on Senoon.

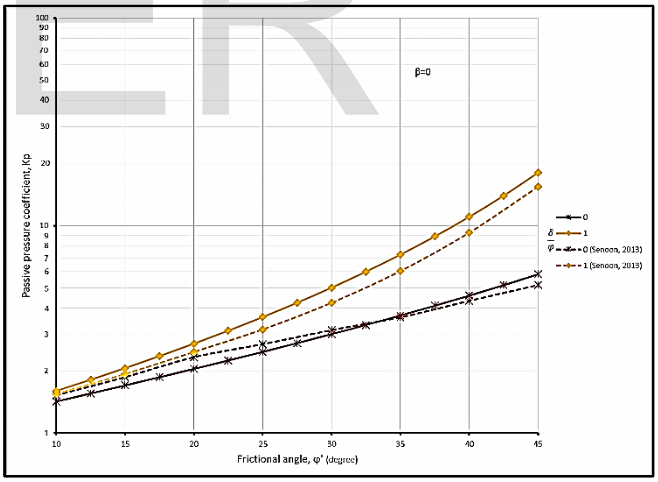

Figure 12: Coefficient of passive earth pressure (K_p), for horizontal retained surface based on Senoon.

The horizontal case showed an interesting response when the analytical procedure was compared with the values provided by Senoon[7]. For zero frictional case and $\varphi < 32.5^o$, Senoon's estimation for the passive earth pressure was slightly overestimating the K_p values when compared with the K_p values from the analytical procedure from Eurocode 7. However, Senoon's equation begins to underestimate the K_p values for $\varphi > 32.5^o$.

Case 2 : Inclined retained surface for coefficient of passive earth pressure based on Senoon..

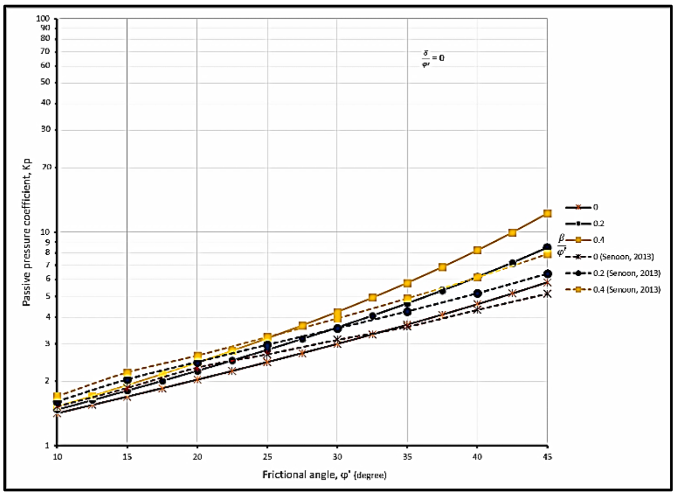

Figure 13: Coefficient of passive earth pressure (K_p), for inclined retained surface (δ =0) based on Senoon.

In Figure 13, the chart shows that, for initial values of φ the K_p values slightly overestimated, but as the values φ increases significantly, Senoon's proposed formula begins to underestimate the K_p values when compared with the analytical procedure. In order to analyse the performance of Senoon's passive earth pressure theory in fully mobilized frictional surface for inclined state, the $\frac{\delta}{\varphi} = 1$ case was used to plot and compare with the analytical procedure. Figure 14 present the results obtained in the form of a chart.

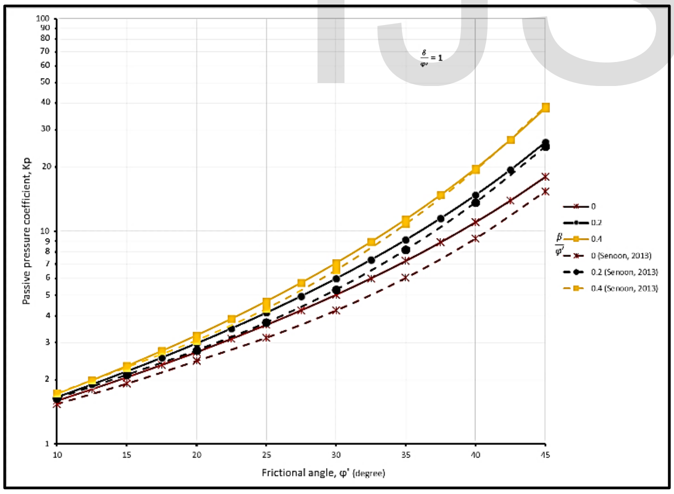

Figure 14: Coefficient of passive earth pressure, K_p for inclined retained surface (δ =φ) based on Senoon.

In Figure 14there are no excessive deviations from the analytical procedure when compared with Senoon's equation.

The result published by Caquot and Kerisel[6] for the coefficient of passive earth pressure were also compared with the analytical procedure in Eurocode 7 and Senoon's results.

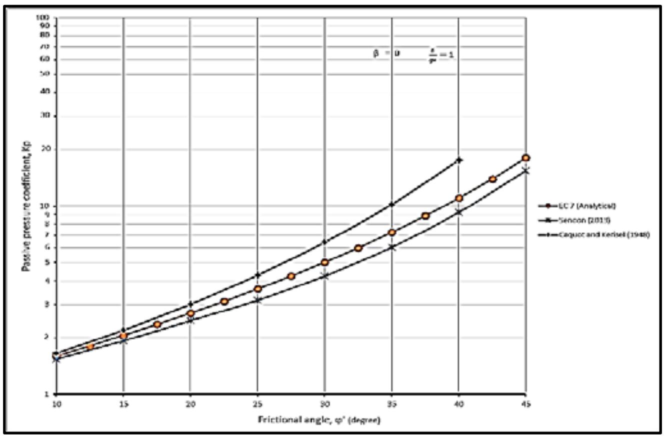

Figure 15: Horizontal retained surface (δ = φ) based on Caquot and Kerisel, analytical procedure in Eurocode 7 and Senoon.

In Figure 15, it can be observed that Senoon[7] has the least values of K_p when compared with Caquot and Kerisel[6]and the analytical procedure. Senoon[7]theory performed well for the inclined state when compared with the analytical procedure in Eurocode 7.

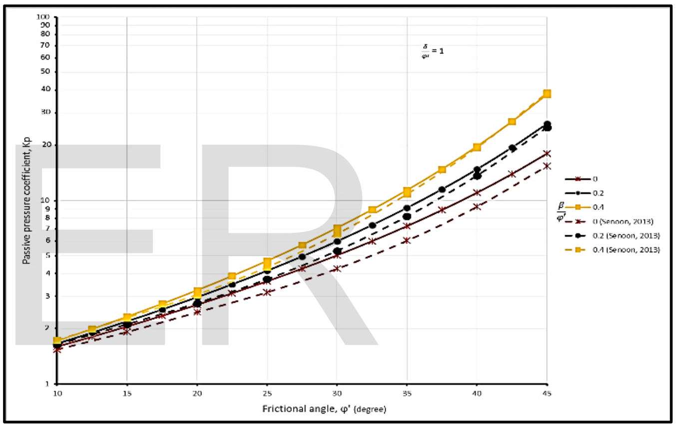

Figure 16: Coefficient of passive earth pressure, K_p for inclined retained surface (δ =φ) based on Senoon.

The result presented in Figure 16 shows that there are no excessive deviation from the analytical procedure when compared with Senoon's equation. Table 2 shows the summary of resultsfor three design situations using various passive earth pressure theories.

Table 2: Design Example passive earth pressure coefficient.

Passive Earth Pressure Theory	K_p		
	β = 0	β = 0.4 ϕ	
	δ=0		δ=0.667 ϕ
	φ = 15°	φ= 30°	φ = 30°
Analytical Procedure (EC7)	2.0569	4.2352	6.5402
Sigurdur (2011)	1.6984	4.7448	6.3285
Caquot and Kerisel (1948)	1.7000	-	-
Senoon (2013)	1.8620	3.9450	-

The results presented in Table 2for $\beta = 0$, $\varphi = 15^o$ and $\delta = 0$, show different estimation of K_p values. A graphical representation of the results obtained is shown in Figure 17.

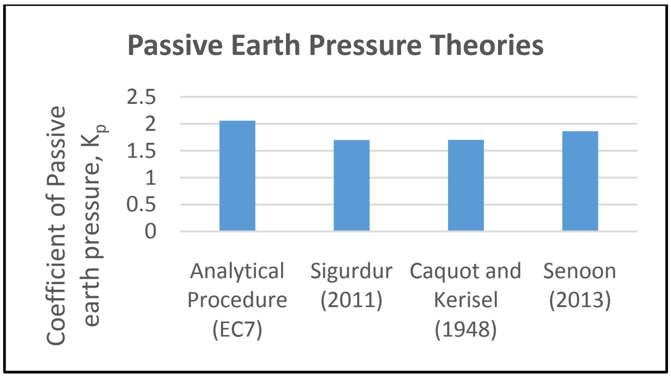

Figure 17: Results for Example 2a.

8. CONCLUSION

John Neville's proposed earth pressure theory performed well for the estimation of active earth pressures when the retaining wall is considered to have a smooth surface and the retained material has a horizontal surface. Also for this condition, the results obtained, show that the K_a value were slightly overestimated when compared with the analytical procedure's K_a values for the same condition. This validation is also true for Tredgolds theory. John Neville's proposed formula for estimating active earth pressure when the retained material is inclined must be used with caution. Specifically, for inclinations greater that $\frac{\beta}{\varphi} > 0.2$, his estimation of active earth pressure becomes unsafe. It was discovered that as $\frac{\beta}{\varphi}$ increases with corresponding increase in φ, the estimated K_a values decrease and eventually becomes unsafe for usage. This a fundamental error that was discovered with John Neville and Tredgold's results.

It has been proven, that the possibility of easily misinterpreting the equations provided in Eurocode 7 for determining the coefficients of earth pressures via the analytical procedure exists. The following equation and format which is based on the analytical procedure in Eurocode 7 is proposed:

$$K_{A/P} = \frac{1 \mp \sin\varphi \sin(2m_w \mp \varphi)}{1 \pm \sin\varphi \sin(2m_t \mp \varphi)} e^{\mp 2(m_t + \beta - m_w - \theta)(\tan\varphi)}$$

where $m_t = 0.5\left(arccos\left(\frac{-\sin\beta}{\mp\sin\varphi}\right) \pm \varphi - \beta\right)$

$$m_w = 0.5\left(arccos\left(\frac{\sin\delta}{\sin\varphi}\right) \pm \varphi \pm \delta\right).$$

The upper sign representing the active earth pressure coefficients and the lower sign representing the passive earth pressure coefficients. It is recommendedthat, this format is adopted in the next revised version of Eurocode 7. In estimating earth pressure coefficients. it is economical and safe to use the analytical procedure. Currently, it is easier to use the charts provided in the Eurocode 7 for estimating earth pressures and the possibilities of the earth pressures being misinterpreted is low.

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