The efficiency of earth berms supporting embedded retaining walls

Tom Tavares

Abstract

Earth berms are often used to provide temporary support for embedded retaining walls as an alternative (or in conjunction with) props/anchors. There are several means by which the stabilizing effect of an earth berm can be accounted for in the design. The most common methods are Equivalent Surcharge Method (ESM), Raised Effective Formation (REF) and Multiple Coulomb Wedge (MCW) method. The use of MCW method (effectively a limit equilibrium analysis) is one of the more popular however it is well known that the passive resistance derived by a linear slip surface using this approach is not always conservative, especially when the soil angle of shearing resistance and/or the wall interface friction is high. The Finite Element Analysis (FEA) is another common method for the evaluation of the support provided by berms, which allows performing the analysis with different parameters for the soil and wall properties. Analysis of a different set of geometry layouts was carried out using the aforementioned MCW and FEA methods. The obtained results were compared with each other and with other methods. The results showed a great discrepancy in terms of stress distribution along the wall between the two methods as well as some unrealistic stress distribution along the wall in MCW method, also it was found that variation of parameters that affect the initial horizontal stresses, soil stiffness and wall stiffness do not affect greatly the stress distribution inside the berm.

1. Introduction

The objective of this project is to examine existing methods for the evaluation of the support provided by earth berms and to develop an improved methodology in terms of accounting for the passive restraint offered by the berm. The main advantage of the MCW method over the other two methods is the possibility to obtain the earth pressure distribution instead of just the resultant impulse, furthermore in the case of the ESM method it is assumed that the contribution of the berm to the overall resistance is the contribution of the surcharge associated with the weight of the berm providing no direct lateral resistance at all. In the REF method the later resistance partially simulated as the raise in the ground level, however, this assumption is only empirical and it is common to obtain over-conservative results when using this method. The MCW method for drained analysis has been assessed. An automatic spreadsheet was developed (with use of the internal solver algorithms for the problem solving). Even though the MCW method seems to deliver more information than the other methods it is still considerably limited due to the fact that it is a limit-equilibrium method so the pressure distribution obtained by this method is associated with the ultimate limit state which is close to failure. It is known that for the full mobilisation of the passive earth pressures greater displacements are needed then for the mobilisation of the active pressures and as one of the main concerns during the wall retained constructions is the control of the displacements due to possible existence of the nearby structures and the quality control, it makes this method less feasible for that intent. The other parameters that are not being accounted by this method are the material properties like soil stiffness, wall stiffness or initial horizontal stresses. Taking this into account the Finite Element Analysis (FEA) was carried out with variations of these parameters in order to evidence the change in the output provided by them. The finite element software PLAXIS was used to perform this evaluation.

2. Available methods for the evaluation of berm effects

Most methods of representing the effect of the earth berms utilize the limit equilibrium approach and are semi-empirical. The most common methods are Equivalent Surcharge Method (ESM), Raised effective formation (REF) and Multiple Coulomb's Wedges (MCW). There is also the graphical method suggested by Culmann Method for Determining Passive Resistance of Earth, NAVFAC 7.02 (1986). Another approach is used in the program Wallap (WALLAP, 2012) which has some similarities with the MCW approach. The effect may also be calculated using finite element analysis (FEA). Another approach that may be of interest is the approach that evaluates the resistance of the retaining walls with the backfill that has a negative inclination, e.g. Lam (1991), Shiau et al. (2008).

It is important to note that for the aforementioned methods (except for FEA) the stability of the berm face, as well as the general stability of the whole soil-wall system, must be assured.

2.1 Equivalent Surcharge Method (ESM)

The ESM method considers the berm as an equivalent surcharge. The weight of the berm is calculated and is applied as the surcharge over a distance defined by the intersection with the excavation level of the line emanating from the toe of the wall at the angle (45° - ϕ'/2) to the horizontal. The lateral resistance offered by the berm is not taken into consideration, thus making this approach very conservative. The analysis carried out in Smethurst & Powrie (2008) for effective stresses and Daly & Powrie (2001) for undrained cases confirm that this method is conservative Simpson & Powrie (2001).

2.2 Raised Effective Formation Method (REF)

Another limit equilibrium method which is highly empirical is the Raised Effective Formation method (REF). Described in Smethurst & Powrie (2008), the raised effective formation approach defines a design berm geometry that has the same base width b as the actual berm but has a slope of 1:3, the maximum height of the design berm then becomes b/3. The design berm is modeled in the analysis by raising the formation level by half the design berm height, i.e. b/6. Any of the actual berm extending above the design berm geometry (the area shown shaded in **Figure 1** can then be applied as a surcharge to the new dredge level using the equivalent surcharge approach.

The passive pressure restraint exerted by the berm is partly modeled by this approach. One of the main differences between this method and the ESM is that the lateral resistance of the berm is partially modelled so the effect of the berm is not only due to its weight but also in the alteration of the point of the application of the resulting earth impulse, which in this method applied at the point higher hence increasing the leverage in relation to the rotating point resulting in the greater stabilizing moment.

The results of this methods tend to be un-conservative for both drained and undrained analysis, as shown in the intersection with the excavation level of the line emanating from the toe of the wall at the angle (45° - ϕ'/2) to the horizontal. The lateral resistance offered by the berm is not taken into consideration, thus making this approach very conservative.

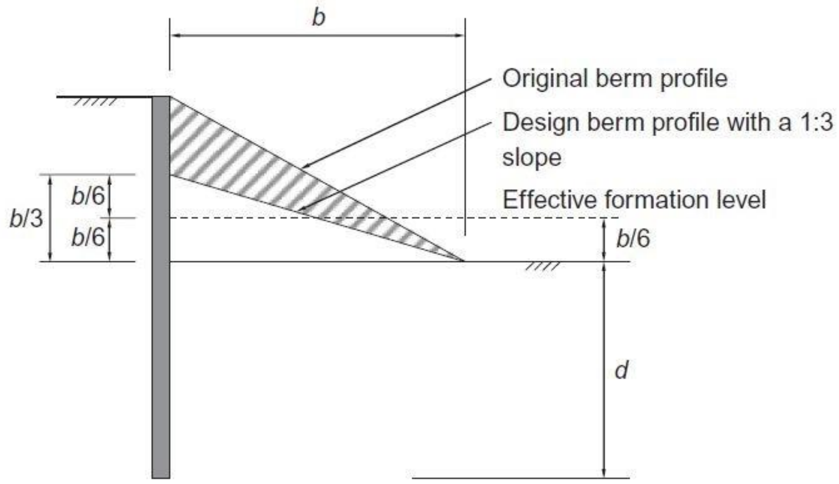

Figure 1 – Schematic representation of the REF method, Smethurst & Powrie (2008)

2.3 Multiple Coulomb Wedge Approach (MCW)

The multiple Coulomb wedge approach uses a series of Coulomb wedges spaced at regular intervals along the wall to calculate the lateral pressure distribution from the berm. Daly & Powrie (2001) present a limit equilibrium stress analysis for berm-stabilized walls that, as well as providing an estimate of the lateral pressure exerted by the berm, enables the factor of safety on soil strength to be calculated for any given combination of berm and wall geometry and undrained soil strength properties. This analysis may be modified to use effective stress soil parameters, Smethurst & Powrie (2008) and **Figure 2**.

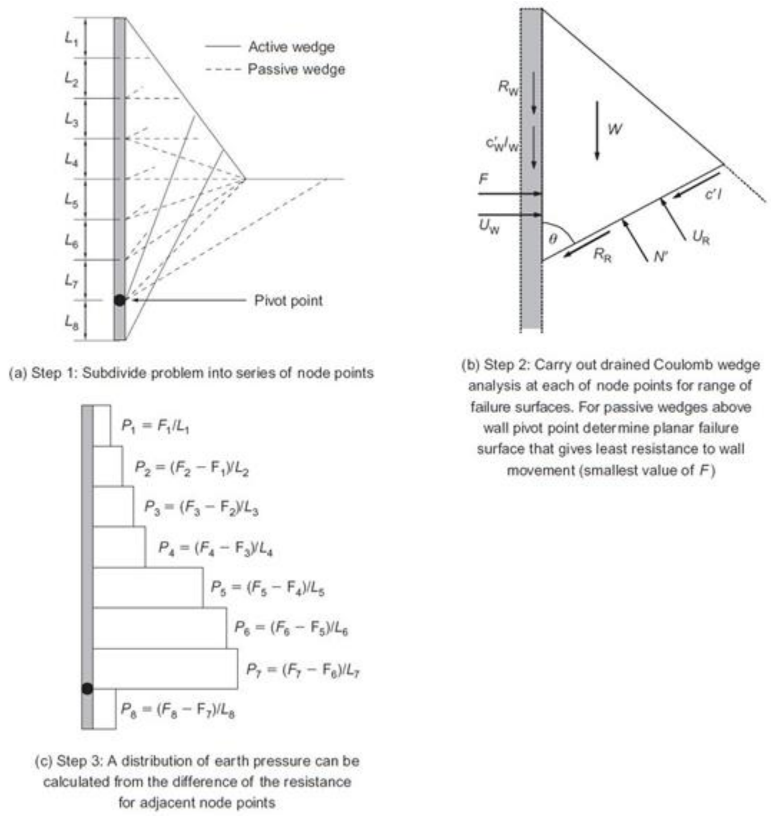

Figure 2 – MCW application steps, Smethurst & Powrie (2008).

2.4 WALLAP

The program Wallap uses an approach that has some similarities with the MCW method. The limiting passive resistance is evaluated at each node based on a number of different planar failure mechanisms. The distribution of forces is then checked to ensure that the available force at higher elevations is never greater than that at lower elevations, WALLAP (2012).

2.5 Finite Element Analysis (FEA)

The other tool at hand is the Finite Element Analysis that can be carried out by using such software as Plaxis, CRISP, and FLAC. The FEA that's presented in the next section was performed using Plaxis. There are numerous advantages of using FEA. One of the advantages that were already mentioned before was the possibility to effectuate three-dimensional analysis using the appropriate software, allowing the possibility to simulate partial excavations of the berm, this is especially important for construction sites that require support over an extended length such as road embankments. However, there are many other advantages such as the possibility to evaluate the displacements which are important for the SLS. Also, the effect of the parameters that represent the material properties cannot be conveniently introduced in the limit equilibrium methods, but their effect can be easily simulated by using the FEA. Another possibility is the simulation of the stage construction even in two-dimensional analysis.

2.6 Earth pressures with sloping ground

Another possible way to address the passive resistance provided by the berm is to utilize the approaches like charts that give the horizontal pressure coefficient for the retaining walls with negatively inclined backfill. Lam (1991) Carried out a series of calculation using the MJSM program which is based on the method the Simplified Method of Slices in order to estimate the passive resistance coefficient for different shear angles, wall frictions, and ground inclinations. Those results were compared with the results of Caquot & Kerisel (with log spiral surfaces) and simple Coulomb equilibrium method. The comparison of the results indicates that they are considerably close for the negatively inclined backfills (that can be compared to berm geometry) even with an increasing value of the wall friction which indicates that in those cases a planar slip surface is an adequate assumption.

For the horizontal or positively inclined backfills, the Coulomb method tends to overestimate the passive resistance. The discrepancy also tends to increase with the angle of shearing resistance, which also may be due to the fact that the wall friction is not given an absolute value but is calculated as the direct proportion to the value of the angle of the shearing resistance of the soil. The resulting values of the coefficients of the horizontal soil pressure will be compared with the values obtained by the MCW approach for similar configurations.

3. Application of MCW & FE methods

3.1 Multiple Coulomb Wedge Analysis

Using an automated spreadsheet calculation, the MCW method was applied to two different berm geometries 2H:1V (horizontal to vertical) and 3H:1V with characteristics presented in **Table 1.** The geometry of the berms considered in this study is presented in **Figure 3.**

Table 1 – Parameters for the analysis.

Definition	Symbol	Unit	2H:1V	3H:1V
Top bench width	b	m	2.0	2.0
Slope inclination	α	°	26.57	18.43
Height	h_{berm}	m	7.0	7.0
Wall geometry:				
Wall length above the ground level	f	m	7	7
Wall length below the ground level	d	m	5	9
Depth of the pivot point	Z_p	m	11.5	15.5
Node spacing	h*	m	0.25	0.25
Material characteristics				
Angle of shearing Resistance	ϕ'	°	28	20
Apparent cohesion	c'	kPa	0.00	0.00
Wall adhesion	c_w	kPa	0.00	0.00
Passive wall friction	δ_p/ϕ'	-	0.667	0.667
Active wall friction	δ_a/ϕ'	-	0.667	0.667
Unit weight of soil	γ	kN/m^3	20.00	20.00
Pore water pressure				
Unit weight of water	γ_w	kN/m^3	9.81	9.81
PWP at the bottom of the wall	u_f	kPa	69.25	113.01
PWP gradient in front of the wall	$u_{gr,f}$	kPa/m	13.85	12.56
PWP gradient behind the wall	$u_{gr,b}$	kPa/m	5.77	7.06

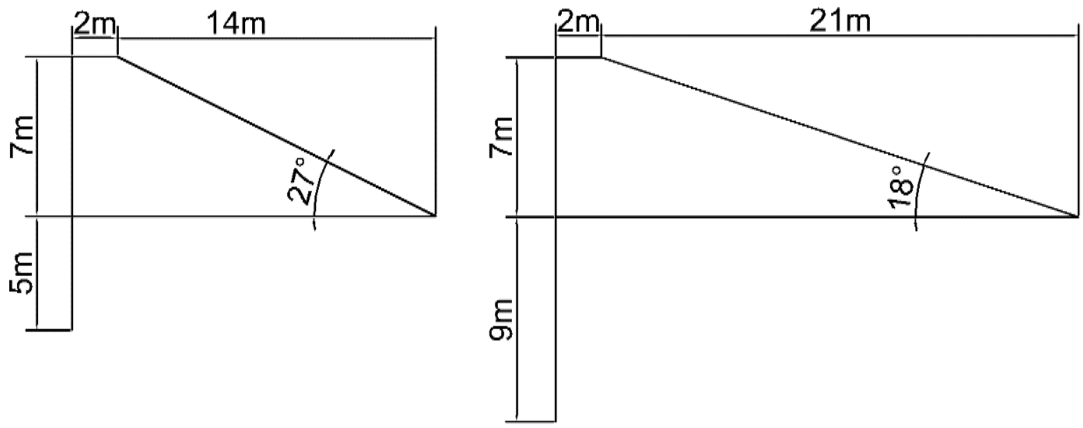

Figure 3 – Berm configurations

3.2 Finite Element Analysis

Finite element analysis (FEA) was carried out based on the parameters presented in **Tables 1 & 2.** The geometry and common parameters were the same that used in the application of the MCW method described above. As with the MCW method above, steady state seepage was assumed.

Table 2 – Summary of soil parameters.

Parameter	Symbol	Units	Base value	Variations
Unsaturated unit weight	γ_{unsat}	kN/m³	20	
Saturated unit weight	γ_{sat}	kN/m³	20	
At-rest earth pressure coefficient	K_0	-	0.5	1, 1.5, 2
Horizontal permeability	k_x	m/day	0.1	
Vertical permeability	k_y	m/day	0.1	
Base soil stiffness	E_{ref}	MN/m²	50	100, 150
Poisson Ratio	ν		0.2	
Cohesion	c'	kN/m²	0.1	
Angle of shearing resistance	φ'	°	2H:1V: 28 3H:1V: 20	
Angle of dilatancy	ψ	°	0.0	
Increase in soil stiffness with the depth	E_{inc}	kN/m²/m	5000	
Cohesion increment	$c_{increment}$	kN/m²/m	0.00	
Soil-wall friction coefficient	$R_{inter.}$	-	0.667	

The geometry of the berms considered in the FEA was the same as those shown in **Figure 3** and the overall mesh geometry was as indicated in **Figure 4** where H = 7 m. The side boundaries were fixed against horizontal movement and the bottom boundary was fixed vertically and horizontally. In the base model, initial horizontal effective stresses in the soil were defined based on an at-rest earth pressure coefficient, K_0 of 0.5 and this parameter was varied as indicated in Table 2, above.

Initial pore water pressures were based on a water level at the upper surface of the model (+50 m elevation). During the excavation of the berm, in order to match the hydraulic boundary conditions assumed in the MCW calculations and to ensure that pore water pressures remained zero in the berm, the drain element available in Plaxis was employed as indicated in **Figure 5**. At each excavation stage, a new total head was defined along the base of the excavation, and a horizontal section of the drain was defined across the berm at the same level.

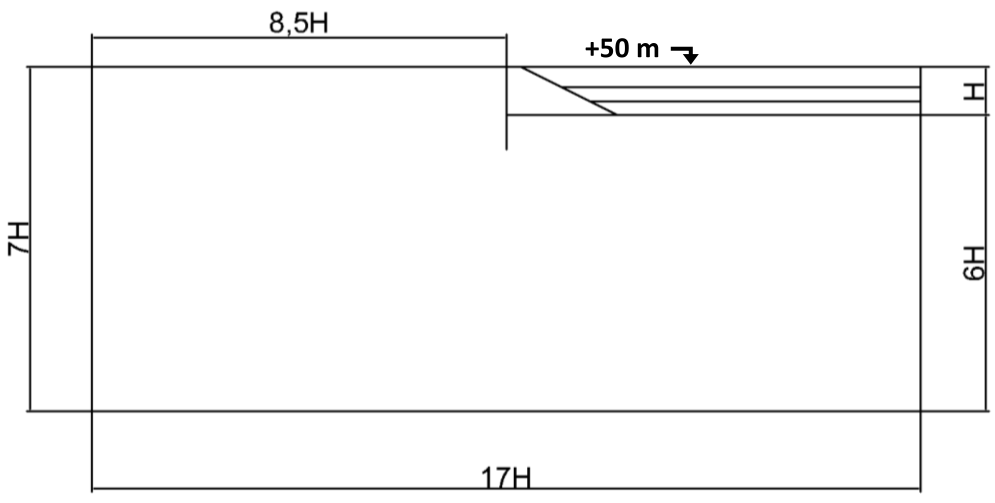

Figure 4 – Overall geometry used for developing finite element mesh.

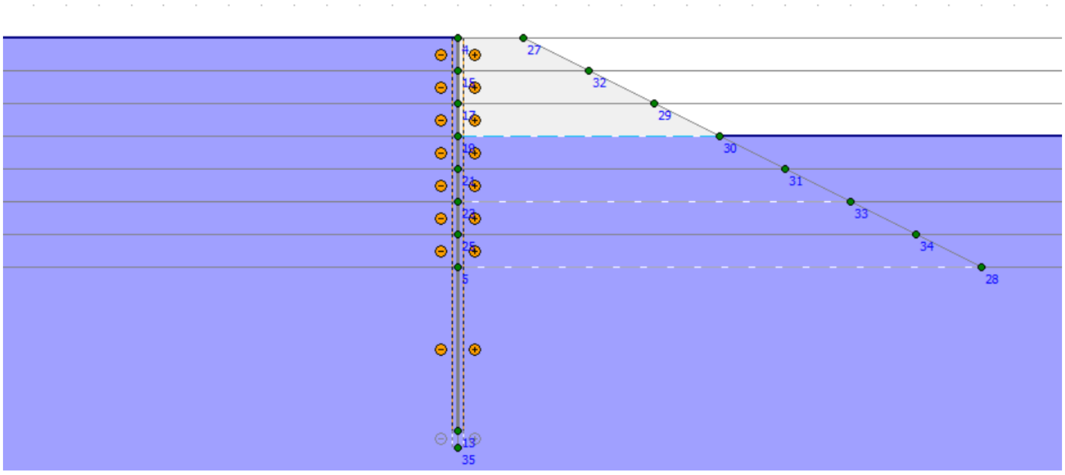

Figure 5 – Stage 1 of FEA - insertion of drains to maintain dry berm assumption (blue dash line - active; white dash - inactive).

4. Comparison of MCW and FE Methods

The results obtained in the previous sections regarding the MCW analysis and FEA are presented in the following **Figure 6** for the 2H_1V geometry and in **Figure 7** for the 3H_1V geometry respectively. In those charts are also plotted the results obtained by utilizing the passive earth pressure coefficient indicated in the chart of (NAVFAC, 1986) for the wall retained soils with inclined backfill. For the 2H_1V case was also plotted the result obtained by utilizing the earth pressure coefficient that is indicated in the aforementioned (Lam, 1991), that was obtained by utilizing the simplified method of slices (SMS) it was possible because of the similarity in the values of to the soil proprieties and the berm geometry.

By observing the aforementioned chart it can be noted that the pressure slope obtained by using the pressure coefficient of the NAVFAC chart is a close approximation of the slope at the top of the berm obtained by the MCW method. However, the overall pressure distribution obtained by this method are greatly superior when compared to the MCW method. The slope obtained by the SMS method utilized in the (Lam, 1991) does not represent well the pressure values at the top of the berm but on the other hand can serve as an adequate approximation of overall pressure diagram in the berm, having the overall area of the pressure close to the one obtained in the MCW method.

Another observation is regarding the comparison of the results obtained by the FEA and the MCW method which indicates the drastic difference in the pressure distribution. Even for the case where the coefficient of the initial horizontal stresses $K_o = 2$, which mostly affects the values of the pressure below the excavated level but not inside the berm. The pressures in the berm are much greater for the MCW method. Those differences may be addressed to the fact that the MCW method gives the critical values of the pressure for each node by calculating the respective critical slip surface at each node, those values may not be achieved along the whole wall as that would suggest the simulations mobilisation of all of the available passive resistance along the whole wall. The FEA was carried out for the conditions close to failure so more passive resistance could be mobilized. Of all the parameters the initial horizontal pressures are the ones that have the greater effect on the pressure distribution. The difference in the soil stiffness and wall stiffness has a very slight effect on the pressure distribution along the wall. However as was already observed in the previous chapters the Force distribution inside the wall can be considerably affected by those parameters as well as wall displacements, which are crucial for the wall design and the SLS verification respectively.

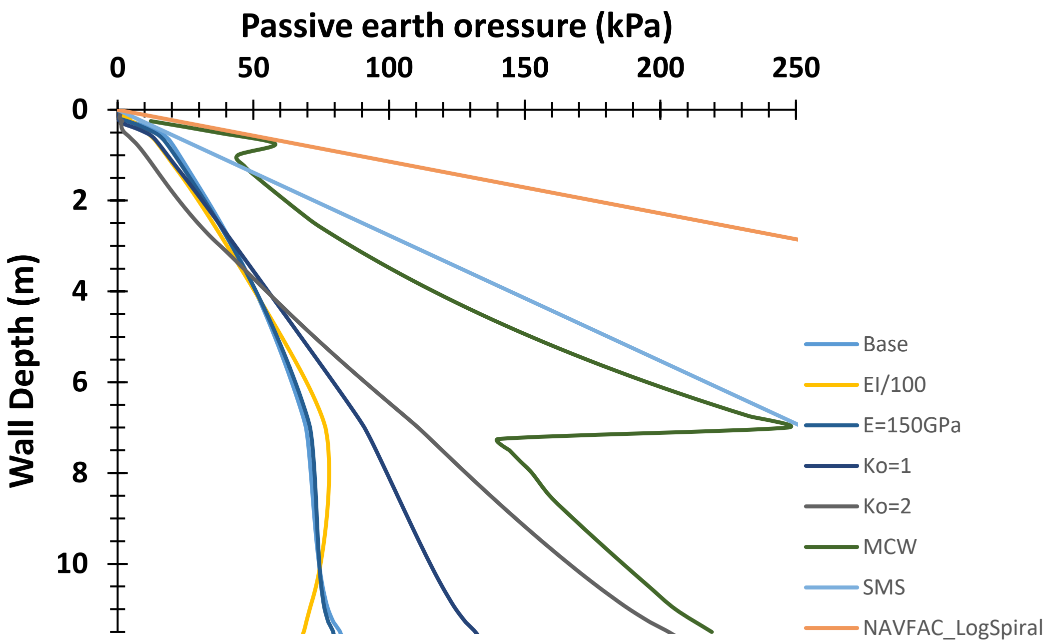

Figure 6 – Effective passive pressures of the 2H:1V geometry obtained by the different

In the diagram regarding the 3H:1V geometry the difference between the results obtained by the FEA analysis and the MCW method is less noticeable, this difference may be explained by the fact that this configuration is closer to failure in the FEA analysis than the 2H:1V configuration. That was addressed in the previous chapter by demonstrating the shear forces diagram, wherein the 3H:1V much greater area had achieved the full mobilization. The same coincidence in the slope at the top of the berm is present when the MCW and NAVFAC results are compared.

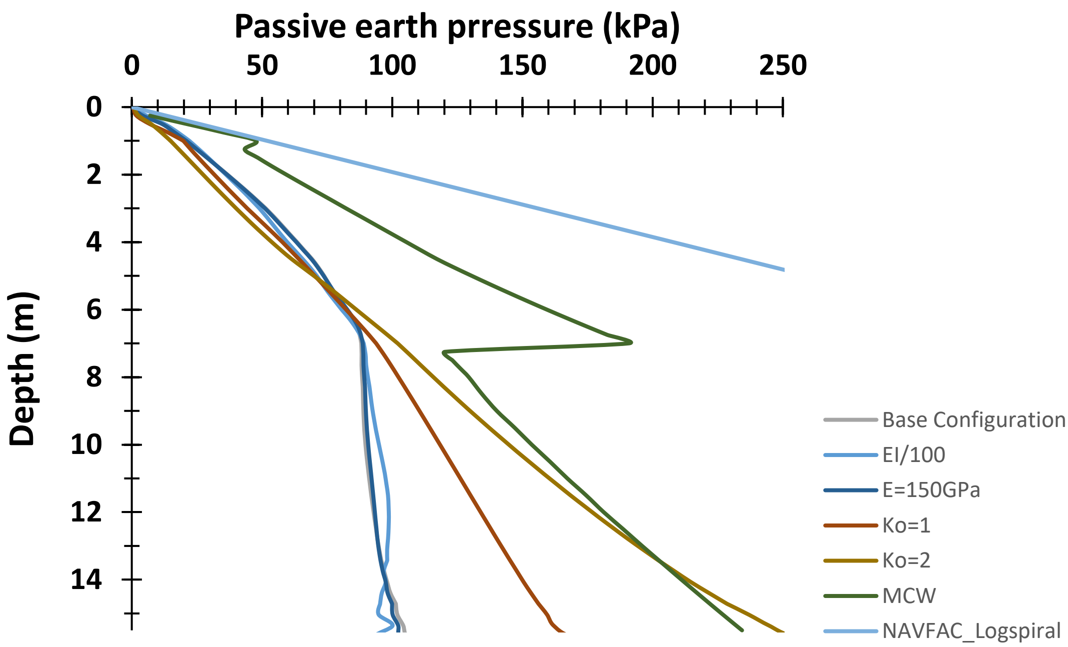

Figure 7 – Effective passive pressures of the 3H:1V geometry obtained by the different methods and configurations (FEA).

Overall independently of the setup variation, the stress distribution in the berm is always significantly lower in the FEA. At the top of the berm, a slight peak might be observed which has the inclination of the Kp obtained by the NAVFAC charts as was mentioned in both cases. Also in the MCW method, the pressures in the berm are getting unrealistically high towards the base of the berm, probably partly because of the geometry being restricted, with the assumption of planar slip surface, not allowing the slip surface to pass below the toe of the berm. This problem is addressed in the Wallap software which for this cases also considers the slip surface below the ground level with two block mechanism. In the case of the node at the excavation level, the slip surface is horizontal. This point is located at the excavated level when transitioning from the berm to the ground and where the water table is set. This offset or drop is more pronounced when the soil-wall friction is increased and is very slight when no friction of the wall is assumed.

5. Conclusions & Recommendations

5.1 Conclusions

It is a common practice to use soil berms as a support of the embedded walls offering the additional resistance and the displacements control. However there not so many methods nor the agreement on to which method should be used. Two main approaches were carried out the FEA and the limit equilibrium MCW method. Finite element analysis performed by the PLAXIS software for two different geometries 2H:1V and 3H:1V and the variations with the different values of the soil and wall stiffness as well as initial horizontal stresses. The MCW was carried out for the same two geometries in order to allow the comparison of the results. Both geometries were set to close to the failure conditions for the greater mobilization of the passive resistance and consequently closer results of the MCW and FEA, as the limit equilibrium methods are close to upper bound solutions which occur at near failure situations.

The main conclusions are:

a) The MCW method tends to give the values of the effective stresses much greater than FEA analysis, especially inside the berm.

b) The MCW give a great singularity point at the excavated level, which tends to increase for the greater values of the soil-wall friction.

c) The pressures obtained by the MCW method are close to once obtained by using the chart presented in Lam (1991) for the wall retained soils with inclined backfills, however similar chart in NAVFAC 7.02 (1986) give greater values.

d) There is a presence of the unrealistic spike when using the MCW method with suctions.

e) Variation of the initial horizontal stresses by altering the K_o coefficient affect very slightly the pressure distribution inside the berm. But greatly affects the earth pressures below the excavated level.

f) The wall and soil stiffnesses have a very small effect on the earth pressure distribution but have a greater effect on the force distribution along the wall and great effect on the wall displacements.

g) The close to failure conditions assumed in the MCW approach may not be feasible as the displacements needed to achieve that conditions are considerably high.

h) The REF method even though it gives conservative values of stress when compared to the other limit equilibrium methods, when compared to the FEA analysis it is not conservative.

5.2 Recommendations for future work

The work completed in this thesis has provided a comparison of existing procedures for the evaluation of the restraint provided by earth berms supporting embedded retaining walls, a number of interesting features have been identified and of particular concern is the apparently unsafe estimation of passive restraint from simpler methods in comparison to finite element analysis.

In order to address these concerns, the following future studies are suggested:

a) The use of alternative analytical methods and slip surface mechanisms (e.g. log-spiral) to understand how the predicted passive restraint provided by the berm varies, i.e. identify the critical slip surface configuration more precisely, especially below the berm.

b) Evaluation of the same berm effects for different methods but based on undrained soil response in the berm materials, and a deeper examination of the impact of short-term construction induced suctions and long-term effects when the berm is above the groundwater table.

c) Comparison and modification of the methods discussed in this thesis on the basis of experimental data.

References

Daly M P, Powrie, W (2001). Undrained analysis of earth berms as temporary supports for embedded retaining walls, Proc. of the Institution of Civil Engineers - Geotechnical Engineering 149(4): 237-248

Easton M R, Darley P (1999). Case history studies of soil berms used as temporary support to embedded retaining walls (TRL Report 380), Transport Research Laboratory, Crowthorn, Berks, UK.

Fleming K, Weltman A, Randolph M, Elson K (2009). Piling Engineering, 3rd Ed., Taylor & Francis, Abingdon, Oxon, UK.

Gaba A R, Simpson B, Powrie W, Beadman D R (2003). Embedded retaining walls - guidance for economic design (CIRIA C580), Construction Industry Research and Information Association, London, UK.

Gourvenec S M, Powrie W (2000). Three-dimensional finite element analyses of embedded retaining walls supported by discontinuous earth berms, Canadian Geotechnical Journal 37(5): 1062-1077.

Lam T (1991). Computation of passive earth pressure by a simplified method of slices, Geotechnical Engineering J., 22(1): 43-57

NAVFAC 7.02 (1986). Foundations and Earth Structures, Naval Facilities Engineering Command, Washington, USA.

Padfield C J, Mair R J (1984). Design of retaining walls embedded in stiff clay (CIRIA Report 104), Construction Industry Research and Information Association, London, UK.

Shiau J S, Augarde C E, Lyamin A V, Sloan S W (2008). Finite element analysis of passive earth resistance in cohesionless soils, Soils & Foundations, 48(6): 843-850

Simpson B, Powrie W (2001). Embedded retaining walls: theory, practice and understanding, In Proceedings of the 15th Intl. Conf. on Soil Mechanics and Geotechnical Engineering, 2505-2524.

Smethurst J A, Powrie W (2008). Effective-stress analysis of berm-supported retaining walls, Proc. of the Institution of Civil Engineers - Geotechnical Engineering 161(1): 39-48

WALLAP (2012). WALLAP V6.0 User Manual, Geosolve Ltd, http://www.geosolve.co.uk/wallap1.htm