13th Australia New Zealand Conference on Geomechanics – Acosta-Martínez & Lehane (Eds.)
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What you design is what you get – An economical way to the stability design of propped cantilever walls

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ABSTRACT: Determination of cantilever wall toe embedment for stability is critical in geotechnical engineering design and there are currently a number of different ways available to assess this. Depending on the nature of the geotechnical data used and the methods chosen the design 'Factor of Safety' results could be different between them, ranging from overly conservative to overly optimistic and somewhere in-between. It is difficult to determine precisely what these results mean to designers, asset owners and constructors. Most of these methods are also known for their numerical issues that restrict them from application in certain conditions.

Based on limit equilibrium conditions a different way is developed for geotechnical stability design of propped cantilever walls. The formulation overcomes the known numerical problems and is applicable to frictional, cohesive and layered materials. Unlike the existing methods this design maintains a constant margin of overturning capacity for a chosen factor of safety and what you designed is what you get. The Factor of Safety on wall stability is calculated as a function of the restoring moment at critical equilibrium. The approach offers an economical, reliable and consistent design for this type of wall.

1 INTRODUCTION

Propped cantilever walls are popular retaining structures. Design and analysis of the wall elements are often undertaken by using sophisticated computer software nowadays. However, when it comes to determine the wall toe embedment below the excavation level for stability, not even the finite element technique is able to give an objective answer. Against this a number of models have been developed and used in the past. It is recognised that each of this model introduces its own assessment criteria. Furthermore, the 'factors of safety' (FoS) calculated are somewhat different even for the same condition. Hence their results may not be directly comparable. In another words the same FoS calculated by a different model will not give the same margin of stability to the design. To the unsuspected designers this could create concerns on choices of the models to use. Is one more reliable than the others? Does a higher calculated value mean better stability? It is common for projects to specify a minimum FoS for stability design. Will a conforming design be delivering safety and economy? There needs a host of questions to answer before one may decide on a choice. It is not the intention of this paper to analyse the existing methods but we will attempt to understand some of the significant issues faced by designers and then go on to present an alternative method.

It must be noted that the discussion contained in this paper is only limited to geotechnical stability and is not a full design of the retaining wall. For more comprehensive designs readers need also to consider such requirements as strength, deformation, constructability, safety, ease of maintenance and durability of the wall.

2 AN APPRECIATION OF THE PROBLEMS

A best way to illustrate the issues confronting design engineers is by using a couple of simple examples. The first example is a 5m deep excavation with 2.28m toe embedment in a uniform soil with an internal friction angle of 35 degrees. A 10kPa surcharge is also considered at the crest level of the wall. The calculated results using the four common assessment methods are tabulated in Table 1 in Case 1 below. The four methods considered are the Code of Practice method (CP2), the British Steel method (BS), the Burland *et al* method (BP) and the Strength Factor method (SF) respectively.

Table 1. Comparison of existing design methods

Model	Case1:Effective Stress FoS[4]		Case2:Total Stress FoS[4]	
	Calc	Acceptable	Calc	Acceptable
CP2	1.63	1.5-2.0[1]	1.36	2.0
BS	2.66	2.0	2.01	2.0
BP	1.72	1.5-2.0[1]	1.19	2.0
SF[3]	1.26	1.2-1.5[2]	1.15	1.4-2.0[2]

[1] the acceptable factor varies with strength of the materials and nature of the works

[2] these values vary with design standards

[3] the acceptable factor varies with method of analysis

[4] FoS computed using commercial package WALLAP

Whilst the actual margin of stability is the same in the example above, the 'FoSs' calculated by these methods range between 1.26 and 2.66, low number by using the SF method and high by the BS method. Deciding on a method to use for stability design on the basis of the calculated numerical value alone is not as easy as one would think and it could be very tricky.

A high calculated FoS by one method does not then necessarily mean a higher margin of stability. The converse of it may also be said about another method with a lower FoS. So how does one determine what to do and how to do it? The conventional wisdom is to set a reference for the design. An arbitrary 'FoS' value of 2.0 is commonly used. However, if the embedment is designed to this requirement as in the above example, then there is only the BS method that satisfies this criterion, which would result in a shallower wall embedment. All the other methods will require a deeper wall embedment of varying degrees. This one reference approach then throws the margin of stability for different methods into disarray. The BS method will yield a design with lower margin of stability, whereas the SF method will probably need to increase the wall embedment significantly to satisfy the design requirement, giving an unnecessarily high margin, and of course cost, to the design than would be necessary. It becomes clear that a single reference approach may not be suitable for all methods and a separate reference of 1.5 is often used for the SF method in recognition of its formulation. This begs the question that if one reference FoS value is not suitable for all then how should the stability margin be assessed?

A second example is again 5m deep excavation but with only 1.49m embedment constructed in a uniform clay with an undrained cohesion of 40kPa. The results are presented in the above table as Case 2. Again for the same margin of stability, a very wide range of values is calculated by the methods. If a FoS value of 2.0 is used as a design reference then all except the BS method are unsatisfactory and a deeper embedment would be needed. Even if the designer wishes to increase the embedment, the calculation using these methods does not converge and hence it could not give guidance to design. Clearly there is a numerical issue in their formulation.

3 CONVENTIONAL DESIGN METHODS

To understand the background of the problems it may be worthwhile to revisit some of the conventional design methods. They are well-documented (e.g. Williams & Waite, 1993; CIRIA C580, 2003). An overview summary only is given below. Depending on the ways that the embedment is determined, the methods may be grouped according to the types of stability factors used, as follows:

(a) By using moment ratios. Design using methods CP2, BS and BP above falls into this category.
(b) Factor by increasing the critical embedment depth. Design using FTP method belongs to this category.
(c) Factor by soil shear strength ratios. Design using SF method falls into this category.

(a) Factor by using moment ratios

In general, the methods express the factor of safety as a ratio of the 'restoring' moment from the passive side to the total 'overturning' moment from the active side. For an economic design these ratios usually lie between 1.5 and 2.0.

In the CP2 method, limiting earth pressure is considered over the full section of the wall, and the moment ratio, F_p, is defined as follows:

F_p = (moment of passive earth pressure) / (moment of active earth pressure + moment of net water pressure)

In the BSC method, the moment ratio, F_{np}, is defined as follows:

F_{np} = (moment of net passive earth pressure) / (moment of net active earth pressure + moment of net water pressure)

For the Burland-Potts method, the moment ratio, F_r, is defined as follows:

F_r = (moment of modified passive earth pressure) / (moment of modified active earth pressure + moment of net water pressure)

Depending on the model used, a different moment ratio value for assessment of factor of safety can be calculated for the same situation.

(b) Factor by increasing the critical embedment depth

A multiplying factor is applied to increase the embedment depth required for limiting equilibrium. This is a simplistic approach rarely permitted by contemporary standards and codes of practice. This method is not further discussed in this paper.

(c) Factor by using shear strength ratio

This approach is more commonly known as the strength factor method. The approach determines the depth of toe embedment by ensuring that the wall is still in equilibrium even if the soil shear strength parameters are reduced by a pre-determined amount. Conventional approaches use separate factors for the frictional component and the cohesive component primarily because of their different reliability. It is noticed that some engineers tend to use a single factor for both components and different factors are used for effective and total stress analyses.

The essential features of the above common methods is summarised in Figure 1.

The shaded areas indicate the schematic modification of earth pressures considered in these methods.

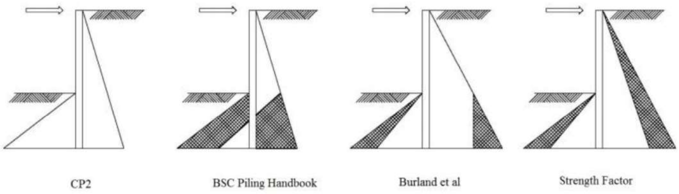
CP2 BSC Piling Handbook Burland et al Strength Factor

Figure 1. Earth pressure distributions of the common methods

CP2 does not have earth pressure modification and both the active and passive pressures are assumed to extend to the base of the wall (CP2, 1951; BS8002, 2001). BS uses a net pressure approach (BSC, 1988) whereby the active pressure below the excavation level is reduced by the passive pressure and only the net passive pressure is considered contributing to restoring capacity. BP considers modification to both the active and passive pressures from below the excavation level (Burland *et al*, 1981). SF reduces strength of the materials (BS8002, 2001; CIRIA C580, 2003). This has the effect of increasing the active pressure and at the same time decreasing the passive pressure for restoration purpose. Whilst the pressure diagrams are means to provide measures for stability, the resultant earth pressures do not necessarily reflect the ground responses. The design loads and restoring capacities are thus different between them.

4 THE WHAT YOU DESIGN IS WHAT YOU GET (WYDIWYG) METHOD

Recognising the issues with the existing methods, it was observed that the behaviour of the earth pressures, particularly at the stable equilibrium state, may not necessarily be following the above model assumptions. It was observed that the earth pressure above the critical equilibrium state remained substantially active and the same may also be said of the passive pressure. This begs a question on why the design loads need to continue beyond this depth. Three key assumptions are subsequently made. The first one is that the disturbing load extends below the excavation level, but only to the depth at which the wall is at critical equilibrium. From a design point of view, this is the intended load to be catered for and there is no reason for this load to continue further than the critical depth. Obviously this simple assumption is for stability consideration only. When the wall flexibility reduces with increased fixity from wall penetration, a higher earth load could be experienced by the structure and this load reaction must be considered through the soil structure interaction process. The second assumption is that the earth pressure remains passive above the critical depth, similar to the critical case. Calculations suggest that this passive earth pressure is mostly mobilised and pressure modification is hence not proposed.

The third assumption is made from a number of observations. It is noted that the existing formulation includes load beyond the critical depth in the denominator. It is well known that a large denominator requires a larger numerator to give a bigger number for the fraction. In this case a higher resistance is needed to increase the FoS value. In effective stress cases convergence is seldom a problem as the increase in restoring moment rises rapidly but it is a problem in total stress analysis as shown in Case 2 of the example above. The deeper the embedment the higher the active load and a higher restoring capacity is needed. This is a primary reason for the CP2 method to always require a deeper wall than the others. As the design loads are already considered above the critical depth one should question if the earth pressures beyond that depth on the active side should be considered as active loads. Engineering intuition suggests that any wall penetration beyond the critical depth increases stability, i.e. the wall could only become more stable. This stability is provided by the earth pressures acting concurrently on either side of the wall beyond the critical depth and they are no longer at limit states. It could be argued that it is the net pressure below the critical depth that is providing the stability and the margin may be understood as a ‘reserve’. In order for designers to calculate the maximum ‘reserved’ restoring moment capacity one may imagine these pressures to be brought up to their limits, which is the maximum the ground could sustain. In another words the earth pressures on the active side of the wall below the critical depth are not considered as loads but are part of the restoring system. The WYDIWYG model is shown in Figure 2 together with the other models for demonstration purpose. It should be pointed out that the model is suitable for overturning stability and considerations for calculation of the other design action effects on the wall will be discussed separately.

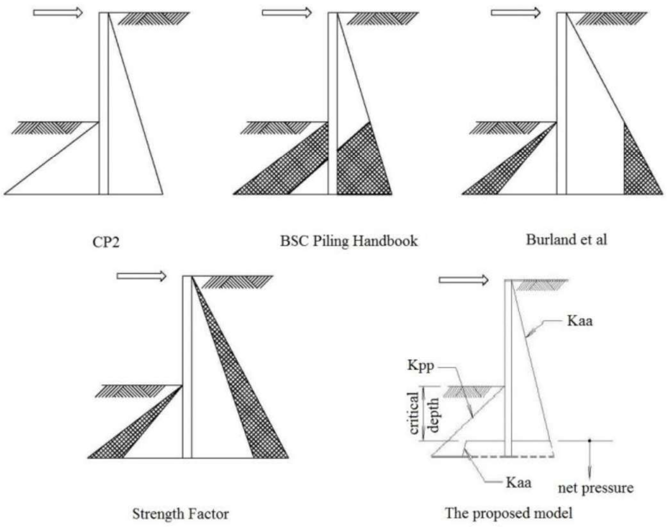

Figure 2. The WYDIWYG method with the existing methods

On the basis of the above discussion, the stability calculations for the WYDIWYG method can be formulated and the dry case is shown below to demonstrate this.

Considering the condition for wall installed to the design level, and taking moments about the support, the reserve moment capacity, M_r, is:

$$M_r = M_p - M_a \tag{1}$$

where: M_p is the total moment on the excavation side and M_a is the total moment on the retained side

Expanding Eqn (1) as follows and re-group:

$$\begin{aligned} M_r &= (M_{pcr} + M_{pp}) - (M_{acr} + M_{aa}) \\ &= (M_{pcr} - M_{acr}) + (M_{pp} - M_{aa}) \end{aligned}$$

where: M_{pcr} is the moment above the critical depth on the excavated side; M_{pp} is the moment below the critical depth on the excavated side; M_{acr} is the moment above the critical depth on the retained side; M_{aa} is the moment below the critical depth on the retained side

At critical depth the wall is in equilibrium with $M_{pcr} = M_{acr}$, therefore Eqn (1) may also be written as follows:

$$M_r = M_{pp} - M_{aa} \tag{2}$$

Using the conventional overturning factor of safety definition,

$$FoS_{overturning} = M_{restoring} / M_{disturbing}$$

Since $M_{restoring} = M_{pcr} + M_r$, and $M_{disturbing} = M_{acr} = M_{pcr}$

The factor of safety can be re-written as:

$$\begin{aligned} FoS_{overturning} &= (M_{pcr} + M_r)/M_{acr} \\ &= (M_{pcr} + M_r)/M_{pcr} \\ &= 1 + M_r/M_{pcr} \end{aligned} \tag{3}$$

For a general case in layered materials it may be shown that

$$FoS_{overturning} = 1 + \Sigma M_{rj}/\Sigma M'_{pcri} \tag{4}$$

where the summation is of all layers of materials; i layers to the critical depth and j layers to the toe of the wall; the apostrophe indicates the effective moment capacity.

Following the formulation, it may be apparent that the fractional part of the FoS is equal to the percentage of reserved capacity available from the ground. For example if the FoS required is 1.5 then the reserved capacity provided by using the WYDIWYG is 50% of the overturning load, or restoring capacity of the ground at the critical equilibrium condition. If it is 1.8 then 80% and so on. A direct and simple relationship thus exists between the FoS and the reserved restoring capacity from the ground.

5 COMPARING THE WYDIWYG METHOD WITH THE OTHER METHODS

Applying the derivation in the two examples above, the calculated results are tabulated together with those of the others in Table 2.

Table 2. The WYDIWYG results

Model	Case1:Effective Stress FoS		Case2:Total Stress FoS	
	Calc	Acceptable	Calc	Acceptable
CP2	1.63	1.5-2.0	1.36	2.0
BS	2.66	2.0	2.01	2.0
BP	1.72	1.5-2.0	1.19	2.0
SF	1.26	1.2-1.5	1.15	1.4-2.0
WYDIWYG	1.84	-	1.55	-

A reserved capacity of 84% is chosen for Case 1 and 55% for Case 2. If FoSs of 1.84 and 1.55 are used as the new respective references then both CP2 and BP will still require a deeper wall and will thus conservatively estimating the margin of stability, whereas BS would under estimate it by providing a shorter wall in Case 1. The reference chosen is obviously not suitable for the SF method. For Case 2 a lower FoS of 1.55 is chosen in regard to a possible short term nature of the condition. As in Case 1 all except the BS method would require a deeper wall but their model formulation would not be able to provide reliable guidance on these depths.

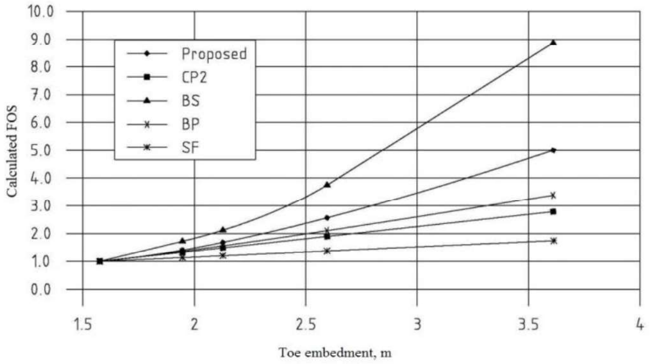

Figure 3. Parametric studies - effective stress case

Figure 3 shows the response of FoS to toe embedment. The responses are consistent with the observations discussed in Case 1 above. At a given toe embedment, representing a constant margin of stability, all the existing methods calculate a lower FoS than WYDIWYG. The exception is the BS method that calculates a higher FoS. Conversely, for a given FoS in design, WYDIWYG gives the shortest penetration amongst the conservative mothods. It should also be pointed out that CP2, BP and SF tend to have a near linear response. When the wall embedment is increased the improvements in their calculated FoS appear to be gentle. The WYDIWYG on the other hand tends to provide a more distinct improvement when the wall embedment is increased.

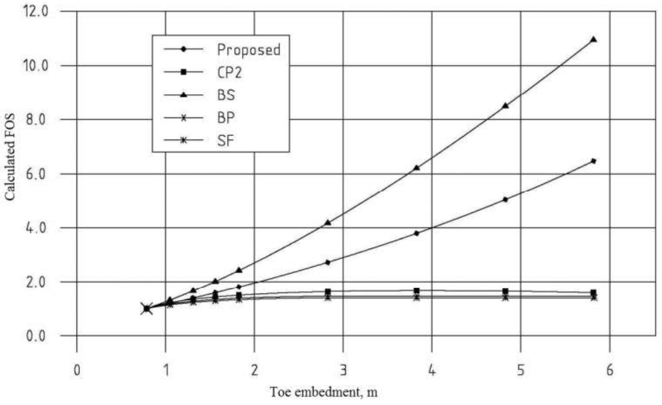

Figure 4. Parametric studies – total stress case

The total stress case is shown in Figure 4. It is evident that CP2, BP and SF models are intuitively incorrect and they may not be relied upon in some total stress conditions. The BS method is able to calculate FoSs for a full range of wall embedment. But once again the improvement in these numerical values may not represent a linear improvement on the margin of stability and they appear to be over represented.

6 SUMMARY AND DISCUSSION

Stability design of cantilever walls is an important step in retaining wall design. Several methods have been used in the past for assessment and a few intriguing problems have been raised, including questions on meaning of the calculated 'factor of safety', fair assessment of margin of stability and applicability of methods to design conditions.

Different from all the existing models the WYDIWYG method maintains a consistent and constant margin of stability at a given FoS value and has been shown to be applicable for all ground conditions. In cohesion friction materials the deeper the wall is installed the higher is the mobilised restoring capacity. The model is shown to posess this favourable characteristic to provide a curvilinear improvement in stability per unit increase in wall toe embedment. This could be an attractive characteristic particularly in stratified ground condition with stepwise increase in material properties. When a higher margin of stability is required there is no need to install the wall to unnecessary depth. Amongst the existing conservative models, WYDIWYG requires the shallowest embedment and thus offers a most economical solution to stability design.

In summary it has been shown that the WYDIWYG mothod is able to relate the calculated FoS directly to a given margin of stability. It provides a new platform for fair and reliable assessment of the margin of stability to designs. For example if a design requires a FoS of 1.8 then it ensures the reserved restoring moment capacity to be at 80% of that at critical equilibrium and what you design is what you get. It is expected that through collective experience on use of this formulation a sustainable stability margin, or FoS, could be developed with higher confidence.

7 ACKNOWLEDGEMENT

The author would like to thank Roads and Maritime Services for the permission to publish this paper and to colleagues in the Geotechnical Engineering Unit for undertaking verification of some of the calculations. The opinions expressed in this paper are those

of the author and do not necessarily represent those of Roads and Maritime Services.

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