A FEW NOTES ON EMBEDMENT DESIGN WITH THE ‘WHAT YOU DESIGN IS WHAT YOU GET’ WYDIWYG METHOD FOR PROPPED CANTILEVER WALLS

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ABSTRACT

The WYDIWYG method for stability design of propped cantilever walls was recently published in the 2019 ANZ Geotechnical Conference. The new method has been shown to be consistent between total and effective stress designs, numerically friendly, stable, and also produces economical designs. The paper focussed the consideration on overturning stability, which is a critical design for this type of structures. In geotechnical engineering designers often treat passive earth pressures as soil resistances and active earth pressures as soil loads. Are active pressures really loads and passive pressures really resistances? It raises an interesting question and the proposition forms an important assumption in the formulation of the new method. Given the interests from the geotechnical design community a more general discussion on the model development will be given together with application of the method to design. Worked examples are also included to demonstrate simplicity of the design process.

1 BACKGROUND

In the 2019 ANZ Geotechnical Conference, the new ‘What You Design Is What You Get’ WYDIWYG method was introduced for embedment design of propped cantilever walls (Yuen, 2019). To establish the new model, the paper stated a few assumptions:

- the disturbing load on the active side of the wall extends below the excavation level but only to the depth at which the wall is at critical equilibrium
- the earth pressure on the passive side remains passive above the critical depth
- the embedded wall beyond the critical depth provides a ‘reserve’ capacity to stability and such capacity is derived from the ‘net’ limiting earth pressures on either side of the wall

The WYDIWYG model is shown below:

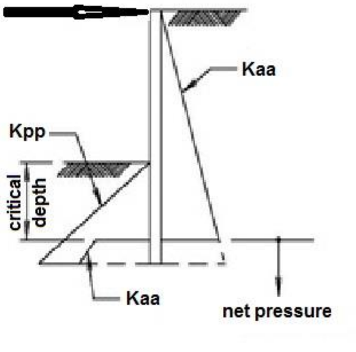


Figure 1: The WYDIWYG model

Where: K_{aa} is the active earth pressure on the retained side of the wall

K_{pp} is the passive earth pressure on the excavated side of the wall

On the basis of the model shown in Figure 1, the Factor of Safety on overturning, $FoS_{overturning}$, may be expressed as follows:

$$FoS_{overturning} = 1 + M_r/M_{pcr} \qquad (1)$$

Where *Mr* is the reserve moment capacity and

Mpcr is the restoring moment capacity at critical equilibrium

The new design method raised a few questions with the design community and this paper attempts to provide clarification to the queries which are needed for establishment of the new design method. A couple of worked examples are also included to demonstrate simplicity of the calculation process.

2 IS THERE A NEED FOR A NEW METHOD

Many methods exist for evaluation of a margin on overturning stability and most designers are used to these methods. For obvious reasons one may argue that the existing methodologies are adequate for design purpose. Yuen (2019) pointed out the key issues with the existing methods. A principal concern is the design community until now have not had a consistent platform for communication of the margin of stability for embedment design of cantilever walls. It is not easy to understand the value calculated by the factor of safety associated with each individual method. Table 1 compares the calculated factor of safety for a given problem using four different methods, and they include the Codes of Practice (CP2), British Steel (BS), Burland et al (BP) and Strength Factor (SF). For demonstration purpose no water was considered in the effective case, which if present will need to be considered in the usual way. One will notice the calculated values vary between 1.26 and 2.66, a wide range for a problem with the same margin of stability. Although a similar ratio of resistance to disturbing load is used in the calculation, it is clear that without attributing the values to a particular method of calculation it is not possible to understand the kind of stability included in a design nor is it possible to compare between design cases to gauge adequacy of a design. It is recognised that some of these factor of safety values may not necessarily convey the intended state of stability but could instead provide a misleading sense of security. This is particularly so for permanent structures which need a higher level of certainty on stability throughout their service life.

Table 1: Comparison of existing design methods

Model	Case 1: Effective Stress		Case 2: Total Stress	
	FoS[4]		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

There seems still a need to clarify between the design communities and stakeholders on what margin of stability is being adopted in designs, both objectively and consistently. This would also help evaluate and ascertain an optimal stability margin for modern day developments.

In the sections below we will explore the justifications to the few assumptions forming the basis for the new model.

3 WHAT IS THE CRITICAL DESIGN SOIL LOAD

In the calculation of factor of safety a simple engineering ratio is often used between resistance and load. The conventional design approach generally does not differentiate between active earth pressure and load, and hence earth pressures on the retained side, often referred to as the active side, are treated as loads and those on the excavation side as resistances. The CP2 approach is one typical example where the earth pressure on the retained side is taken to be a load extending to the design toe level of the wall. Questions are asked should the design loads be applied over the full depth of the wall, would they have been over estimated, what if they are not, where should they be?

To elucidate the point, let us take a step back to consider a propped cantilever wall at critical equilibrium. The active load on the retained side is balanced by the passive resistance on the excavation side, and the disturbing moment is balanced by the restoring moment provided by the passive resistance about a support at the top of the wall.

This critical condition is not acceptable for construction and additional wall embedment is needed to provide for safety, and also for functional performance on strength and deformation of the wall. Would the additional embedment affect the design load? As embedment is increased the earth pressures on the retained side change in response to the increased toe fixity. This will have an effect on the earth pressure distribution and hence change the structure loads. In modern day computation of wall bending moments and shear forces lateral earth pressure distributions that take into account of soil structure interaction are used.

For stability design using the WYDIWYG method limiting earth pressure conditions are considered instead. The lateral earth pressures above the critical equilibrium level stay at their limit states and hence the loads remain unchanged. The consideration leading to this ultimate condition on the embedded wall is discussed in the next section. Another situation that could affect the design load is the change of water flow condition below the wall toe due to increase of wall embedment. Where there is no water balance considered at the toe, the design load will remain the same. Where toe water balance is considered, change in the design load could be expected. For the purpose of stability design the change in this load is not expected to be significant if a similar approach is adopted between the calculations. For the above reasons and because there is no change in the excavation geometry or external loading conditions, the total design load for stability design can be taken to be similar to that at critical equilibrium. Byrne et al (1995) suggested wall design bending moments and shear forces to be determined based on the wall at critical equilibrium. Although the author does not necessarily agree with this recommendation it does suggest that the disturbing load at critical equilibrium is appropriate for design.

The schematic WYDIWYG model shown in Figure 1 shows the design load to extend to the critical depth. This load is balanced by the passive resistance, which forms the second assumption above. As the wall embedment is increased to provide the needed stability, we will explore how these earth pressures on the extra length of wall are considered for the proposed WYDIWYG model.

4 IS EARTH PRESSURE A LOAD

As said above for acceptable stability the wall embedment needs to be increased beyond the critical depth and the earth pressures will act instantaneously on either side of this extra embedment. Traditionally designers seldom differentiate between load and active earth pressure. These terms are used interchangeably for L-shape retaining wall or embedded walls at limit equilibrium. The active pressure is taken to be a load. For embedded walls engineers have long been aware of a fix-earth support situation for walls penetrating beyond the critical equilibrium level. There have been practical difficulties to locate the theoretical pivot point on the embedment where the role of earth pressures as load and resistance changes. The differentiation has been made difficult by the fact that neither instrumentation nor numerical calculation is able to identify the earth pressures as loads or resistances, which may be engineering terms to define conditions creating disturbance and restoration for stability consideration respectively. The free earth support became a favourable simpler model to use where all earth pressures on the retained side are treated as loads. However, if the earth pressures on the retained side of this extra embedment are considered as a load then the total load will be larger than that considered for the design excavation, and one could be analysing a different problem. In the CP2 model, the earth pressures on the active side are considered as loads, extending to the toe level of the wall. Higher load requires higher resistance with deeper wall embedment, and the conservatism of the CP2 model was readily recognised (Burland et al, 1981; Yuen, 2019). Variations to this model occurred to improve the stability safety margin. Figure 2 shows a schematic pressure distribution of the common methods.

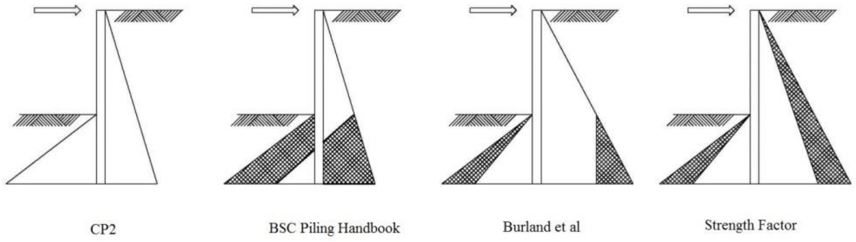


Figure 2: Schematic pressure distribution used by the common methods

Most of these models consider earth pressure modification from below the excavation level and the modified loads still extend to the toe of the wall. From this conjecture, one may interpret that the CP2 design load was considered excessive and the earth pressure modifications by the other methods were introduced to allow a better estimate of the design load. These model developments were based on logic but the questions on magnitude and extent of the active design load have never been adequately addressed. In the following paragraphs we will explore via a different perspective to show the role of the earth pressures on this extra embedment below the critical equilibrium depth.

In L-shape retaining walls, the definition of load in terms of earth pressure on the structure is fairly straight forward. The structure is moving away from the retained soil, and the active earth pressure developed is a load. Equilibrium is achieved by mobilising the frictional resistance on the wall base. Additional sliding and overturning stability are often obtained by extending the wall base. For propped cantilever walls at critical equilibrium the active earth pressure condition is similar to that of the L-shape wall and the active pressure is a load. The passive earth pressure over the critical embedded length is comparable to the frictional resistance from the base of an L-shape wall at critical equilibrium. The earth pressures on the extra embedment though may not be interpreted as straight forward. The earth pressure condition changes as the wall embedment is increased beyond the critical depth to derive stability. Figure 3 shows the earth pressure changes for a wall at critical equilibrium to one of a stable condition following an increase of wall embedment.

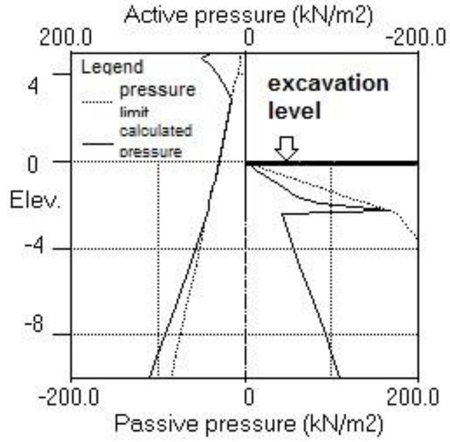


Figure 3: Pressure diagram for a stable wall (by WALLAP)

Earth pressure redistribution occurs once the wall embedment is beyond the critical depth. It is apparent from Figure 3 that the earth pressures are no longer at limiting conditions. The earth pressure on the retained side increases whilst that on the excavation side decreases. The wall is stable and the stability must have been derived from the extra embedment beyond the critical depth. The argument follows that the earth pressure on the retained side of the extra embedment is not a load. It serves as a component to provide extra capacity for stability such that the wall can sustain additional load. As the passive pressure also acts coherently with the active pressure, it is logical to consider that the net of these pressures are responsible for the additional capacity. This is referred to as the reserve capacity in the WYDIWYG method (Yuen, 2019) and in Equation 1 above. The maximum reserve capacity that the ground can provide for stability occurs when these net earth pressures are returned to their respective pressure limits. The consideration is similar to the BSC approach only it commences from below the critical depth. It should be pointed out that the pressure limits adopted here are for the sole purpose of calculating the reserve capacity for stability. This should not be confused with the earth pressures from soil-structure interaction used for wall deformation, bending moment or shear force calculations. The calculation of the wall functional performance is beyond the scope of the current discussion but it suffices to say that such pressure distributions should be considered for more realistic calculation of wall structure loads.

5 SUMMARY OF CHARACTERSITICS OF THE NEW MODEL

The above discussion provides justification for the three assumptions made for the model and that they enable the factor of safety to be expressed neatly in terms of the moment of restoring capacity at critical equilibrium and what you designed is what you get. For example if the design factor of safety is 2 then the design stability is 2 times what is available at critical equilibrium. The unique formulation is able to provide a measure of stability that is tangible and comprehensible. The favourable characteristic could allow consistent margins of stability to be calculated and meaningful comparison made between design cases. The method is consistently applicable to all soil conditions, i.e. total and effective stresses. This is in contrast to some of the existing methods that exhibit numerical problems when performing total stress analysis under some soil conditions. The brief analysis in the paper (Yuen, 2019) also indicates an economic margin when compared with the other methods.

Below are worked examples to demonstrate the calculation process to determine the embedment depths for two different soil conditions.

6 WORKED EXAMPLES

To illustrate application of the WYDIWYG method to embedment design, the two simple examples in the ANZ paper (Yuen, 2019) are used. Instead of calculating the factor of safety (FoS) from a given wall embedment, the FoS is chosen to suit a given design requirement. The first example is a 5 m deep supported excavation in a uniform soil with an internal friction angle of 35 degrees propped at the top of the wall. A 10 kPa surcharge is considered at the crest level of the wall and no groundwater is considered. The target FoS is 1.84. The second example is similar to the first one with 5 m deep excavation, but in uniform clay with an undrained cohesion of 40 kPa. Given the temporary condition for this case the target FoS is 1.55.

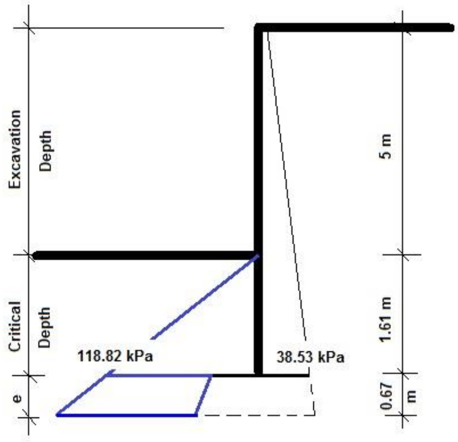
The embedment design using the WYDIWYG method is a two-step process, firstly to calculate the critical wall depth and then from there to determine the critical effective restoring moment. The second step is to proportion the wall embedment to provide the required reserve restoring moment to satisfy the design FoS requirement.

The critical wall depth may be calculated by hand for simple problems and for more complex problems it may be worthwhile to consider technical software instead. In the above examples the critical wall depths for both cases are calculated by using a commercial software called WALLAP. For the total stress case, a minimum fluid pressure of 5 kPa has been considered in the calculation.

6.1 EXAMPLE 1 – EFFECTIVE STRESS CASE

Step 1

The first step in the process is to determine the wall embedment at critical stability, i.e. FoS = 1. The critical embedment depth below the excavation level is calculated at 1.61 m. The earth pressure distribution is shown in Figure 4 for ease of reference.



(Not to scale)

Figure 4: Earth pressure distribution for effective stress case

Depth to toe of wall, H, retained side

$$H = 5 + 1.61$$
$$= 6.61\ m$$

The earth pressures at the critical depth are calculated using the following equations:

Earth pressure at critical wall toe, retained side, K_{aacr}

$$K_{aacr} = (\gamma * H + \sigma_s) * k_a \tag{2}$$
$$= (20*6.61+10)*0.27$$
$$= 38.53\ kPa$$

Where γ is the unit weight of soil, kN/m^3

H is the overall length of the wall, m

σ_s is the traffic surcharge, kPa

k_a is the coefficient of active earth pressure

Earth pressure at critical wall toe, excavation side, K_{ppcr}

$$K_{ppcr} = \gamma * h * k_p \tag{3}$$
$$= 20*1.61*3.69$$
$$= 118.82\ kPa$$

Where h is the wall embedment length below the excavation level, m

k_p is the coefficient of passive earth pressure

The restoring moment capacity at critical equilibrium, M_{pcr}

$$M_{pcr} = K_{ppcr}/2 * h * (5 + 2/3 * h)$$
$$= 118.82/2*1.61*(5+2/3*1.61)$$
$$= 580.91\ kNm$$

Step 2

The next step is to determine the additional wall embedment to satisfy the required stability. For a given FoS the required reserve moment capacity can be calculated using Eqn 1:

$$M_r = (FoS_{overturning} - 1) * M_{pcr}$$

Since the required FoS is 1.84 the above equation becomes

$$M_r = (1.84 - 1)*580.91$$

$$= 0.84*580.91$$

$$= 487.97\ kNm$$

The extra wall embedment is then proportioned to obtain the reserve moment capacity. Take the extra embedment beyond the critical depth to be e, the earth pressures at the new toe level are expressed as follows:

Using equation (2)

$$K_{aa} = [20*(6.61 + e) + 10]*0.27$$

$$= 38.53 + 5.42e$$

Using equation (3)

$$K_{pp} = 20*(1.61 + e)*3.69$$

$$= 118.82 + 73.8e$$

The reserve moment, M_r, may be expressed as follows:

$$M_r = (K_{ppcr} - K_{aacr})*e*(H + e/2) + [(K_{pp} - K_{aa})/2]*e*(H + 2*e/3)$$

$$= (118.82 - 38.53)e(6.61 + e/2) + [(73.8e - 5.42e)/2]e(6.61 + 2e/3)$$

$$= 22.80e^3 + 266.15e^2 + 530.72e$$

From above $= 487.97\ kNm$

Solving the cubic equation, e $= 0.67\ m$

The design wall embedment, D, is hence

$$= 1.61 + 0.67$$

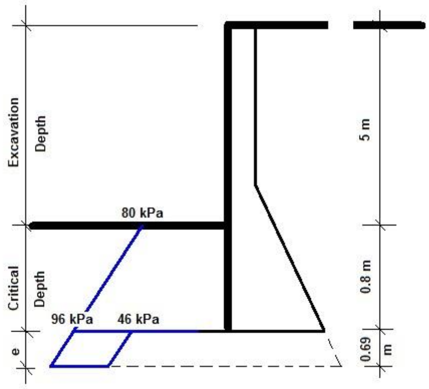
$$= 2.28\ m$$

And the design wall length is 5 + 2.28 = 7.28 m.

6.2 EXAMPLE 2 – TOTAL STRESS CASE

Step 1

The calculation for the total stress case is similar to that of the effective one, and the critical embedment depth is calculated using WALLAP to be 0.8 m. The schematic pressure distribution is shown in Figure 5 for ease of reference.



(not to scale)

Figure 5: Pressure distribution for total stress case

Depth to toe of wall, H, retained side

$$H = 5 + 0.8$$
$$= 5.8\ m$$

Earth pressure at excavation level, retained side, K_{aa}

$$K_{aa} = (5*\gamma + \sigma_s)*k_a - k_{ac}*C_u$$
$$= (5*20 + 10)*1 - 2*40$$
$$= 30\ kPa$$

Earth pressure at critical depth, retained side, K_{aacr}

$$K_{aacr} = (\gamma*H + \sigma_s)*k_a - k_{ac}*C_u$$
$$= (20*5.8 + 10)*1 - 2*40$$
$$= 46\ kPa$$

Where k_{ac} is equal to 2

C_u is the undrained cohesion, kPa

Earth pressure at excavation level, excavation side, K_{pp}

$$K_{pp} = k_{pc}*C_u$$
$$= 2*40$$
$$= 80\ kPa$$

where, k_{pc} is equal to 2

Earth pressure at critical wall toe, excavation side, K_{ppcr}

$$K_{ppcr} = \gamma*h*k_p + k_{pc}*C_u$$
$$= 20*0.8*1 + 2*40$$
$$= 96\ kPa$$

The restoring moment capacity at critical equilibrium, M_{pcr}:

$$M_{pcr} = K_{pp}*h*(5 + h/2) + [(\gamma*h*k_p + k_{pc}*C_u) - (k_{pc}*C_u]/2*h*(5 + 2h/3)$$
$$= 80*0.8*(5 + 0.8/2) + (96 - 80)/2*0.8*(5 + 2*0.8/3)$$
$$= 345.6 + 35.4$$
$$= 381\ kNm$$

Step 2

Again using Eqn 1

$$M_r = (FoS_{overturning} - 1) *M_{pcr}$$

The required $FoS_{overturning}$ for this case is 1.55

Therefore $M_r = (1.55 - 1)*381$

$$= 209.55\ kNm$$

For total stress cases, the calculation of the extra embedment is slightly simpler since the rate of lateral earth pressure increase on either side of the wall is constant, the net pressure on this part of the wall is uniformly distributed. Hence taking e as the extra embedment,

$$M_r = (Kpp - Kaa)*e*(5.8 + e/2)$$
$$= (80 - 30)*e*(5.8 + e/2)$$
$$= 25e^2 + 290e$$
$$= 209.55\ kNm$$

Solving the quadratic equation:

$$e = 0.69\ m$$

The design wall embedment, D, is hence

$$D = 0.8 + 0.69$$
$$= 1.49\ m$$

And the design wall length is 5 + 1.49 = 6.49 m.

7 DISCUSSION AND SUMMARY

Stability design for embedded walls is a critical consideration in geotechnical engineering design and the stability is commonly measured by a factor of safety. The concept of factor of safety as a ratio of resistance and disturbing load is sound only the definition of the resistance and disturbing load are not so well defined. The simplistic CP2 approach taking the disturbing load to the toe of the wall was considered conservative and variations emerged over the years to provide improved estimation of the ratio. The different approaches to approximate the load and resistance have resulted in a wide range of factor of safety stability values for the same problem. Because of the different formulation it is not possible to objectively comprehend the stability margin offered in a design, and some methods are more conservative than the others. To the owners and asset operators the uncertainty in such designs should be a concern, and there is a need for improved level of certainty to balance between economics of construction and margin of stability in design.

The WYDIWYG method introduces a new set of assumptions to assist the development of the model. The discussion on active earth pressures refreshes the view on disturbing load, how far it should extend. It follows that load on the structure should have been adequately considered by extending it to the critical depth below the excavation level, at which the wall remains at critical equilibrium. This view is also shared by some engineers (Byrne et al, 1995) where they recommended wall loads to be determined from walls at critical equilibrium.

The role of the extra wall embedment beyond the critical depth has not been previously analysed the same way. The fact that it is solely responsible for stability suggests that the earth pressures over this part of the wall are neither a load nor a resistance. This is crucial in the development of the model. The change in the pressures from their limiting states indicates that the increased embedment brings about a reserve in restoring stability. The wall reaches the restoring capacity when these pressures are idealised at their limiting states. Since the limiting pressures are acting coherently it is reasonable to consider that their net pressure on this part of the wall is responsible for the reserve restoring capacity. It is worthwhile to clarify that the aforementioned pressure distribution is only used for stability calculation. For wall load calculations, e.g. bending moments and shear forces, the conventional soil structure interaction earth pressure distribution should be used for more realistic results. For the WYDIWYG method, this process is undertaken after the final wall embedment is determined.

In summary, the critical parts for development of the WYDIWYG model are being analysed and rationalised. The process enables a new definition on load and resistance, and hence a new formulation of the factor of safety. It has been shown that the formulation can be consistently applicable to all soil conditions. As the FoS is made a function of the restoring capacity at limit equilibrium, its design value takes on a tangible meaning, which is unambiguous and straight forward. For example using the WYDIWYG method for design, a FoS of 2 ensures the restoring capacity is 2 times its capacity at limiting equilibrium. This could be a favourable characteristic for assessing stability of this type of walls. It may also allow meaningful comparison of stability performance between design cases and amongst the design community.

Two step-by-step examples are included to demonstrate simplicity of the calculation process. For more complex situations, the calculation may be accomplished by using a spreadsheet, or ideally using a codified program incorporating soil structure interaction for comprehensive and simultaneous consideration of stability and functional performance of the structure.

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