A Note on Design of Rock-socketed Embedded Wall

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Abstract

The design of excavation and lateral support works in Hong Kong generally follows the guidelines of GCO Publication No. 1/90. The document provides guidelines for determining the overall factor of safety against kickout failure of embedded walls in soil. There is limited discussion in this document for embedded walls partially socketed in rock. A method is proposed in this paper for determining the required socket length of a rock socketed embedded wall. The method allows the overall factor of safety to be applied consistently to resisting forces in soils and in the rock socket.

Keywords: Retaining wall, Rock socket, Design

1 Introduction

When performing design of excavation and lateral support (ELS) works in Hong Kong, it is a common practice to check the factor of safety of the embedded wall against the so-called kickout failure. The design procedures for checking the kickout stability of an embedded wall fully installed in soils usually follow the guidelines described in GCO Publication No. 1/1990 (GCO, 1990), but there is no guideline in this publication for design checking of embedded wall socketed in rock. Guidelines for design checking the stability of a rock-socketed retaining wall are provided in the second edition of Geoguide 1 (GEO, 1982), hereafter referred simply as Geoguide 1 for brevity. The two guidance documents are not fully compatible with each other. The former is based on a hybrid of the overall factor of safety (FOS) and working stress approach and the latter is a combination of the partial factor approach. This paper presents a method of combining the two guidelines to produce a consistent design procedure for checking of the kickout stability of an embedded wall partially embedded in rock for the design of ELS works based on the overall factor of safety approach.

2 Current Design Practice

The design equations and procedures for checking of cantilever and propped embedded walls are only slightly different. Only the principles for checking a propped embedded wall will be discussed in detail in this paper.

Geotechnical engineers usually follow the guidelines of GCO Publication 1/90 in their design of ELS works in Hong Kong. This publication is based on the overall FOS approach. Figure 1 shows the definition of the overall FOS for kickout failure for a propped retaining wall embedded in soils based on GCO Publication No. 1/1990.

According to the design equation in Figure 1, the overall FOS is applied to the resultant forces due to effective passive pressure and water pressure on the excavation side. The definition of overall FOS in Figure 1 can be re-written as:

$$F = \frac{P_p \times L_p + P_{wp} \times L_{wp}}{(P_a \times L_a + P_{wa} \times L_{wa}) - M_R} \qquad (1)$$

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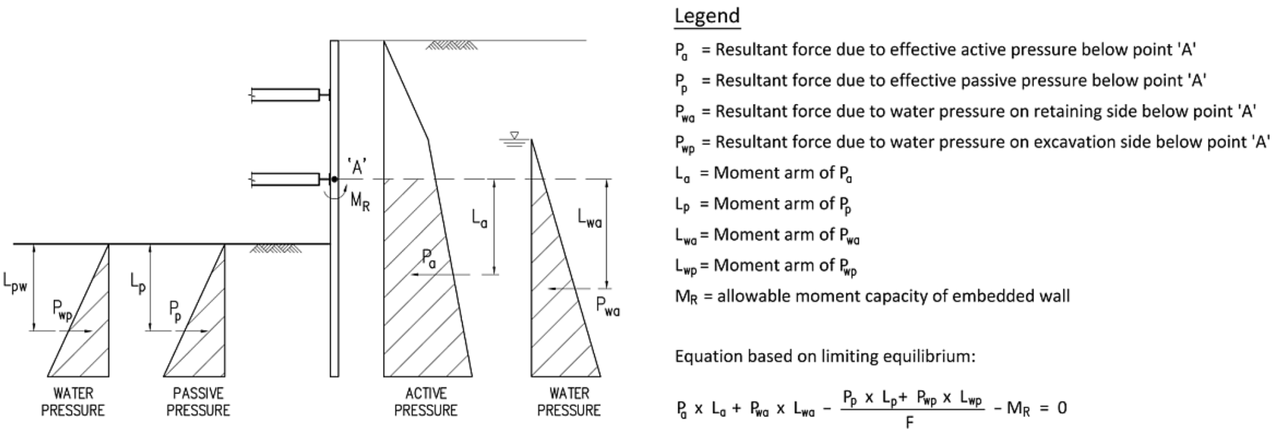


Figure 1: Design equations for checking of overall FOS for kickout failure based on GCO Publication 1/90

As discussed by Li & Lee (1993), the overall FOS approach is a 'variant' measure of geotechnical safety because the calculated value of overall FOS depends on its definition. In Eq.1, M_R is treated as a reduction of disturbing moment and hence it appears in the denominator of the equation. If M_R is treated as another component of the resisting moment, it should appear in the numerator and the calculated value of *F* will then be different.

Eq.1 is not a reasonable definition of *F* in dealing with water pressures. The forces due to water pressures appear both in the numerator and denominator of Eq. 1. Consider a somewhat extreme condition of an embedded wall immersed in a pool of still water for which the water pressures on both sides of the embedded wall are fully balanced. If the wall is hung at the wall top, M_R is zero and Eq.1 will always be equal to unity. One cannot achieve a factor of safety higher than unity no matter how deep the wall is dipped into the water.

In Hong Kong, the structural moment capacity of the embedded wall M_R is usually based on the allowable capacity under working condition. Eq.1 may therefore regarded as a hybrid of overall FOS and working stress approach.

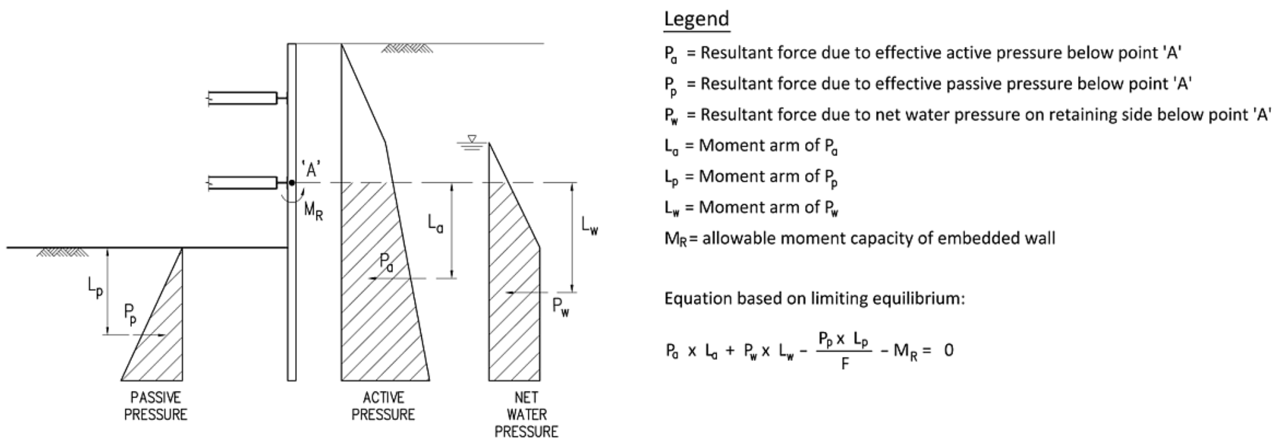
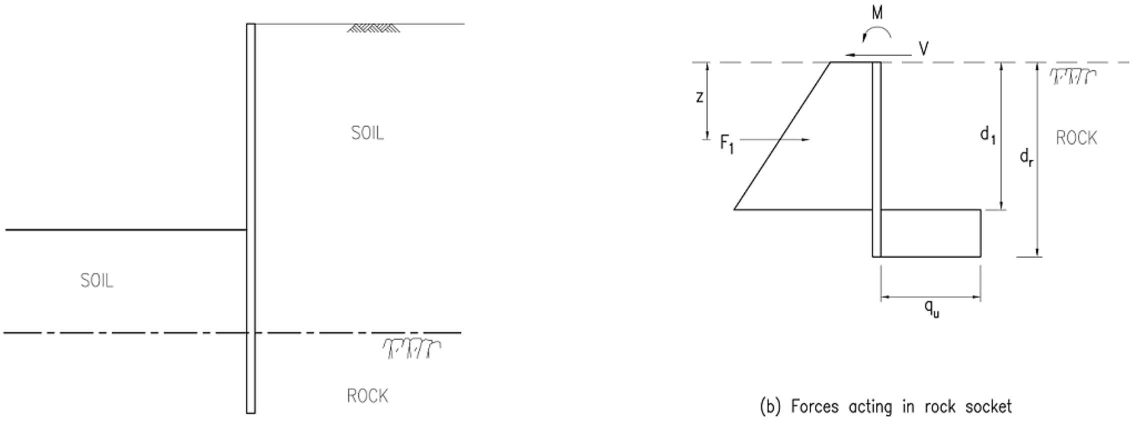


Figure 2: Revised definition for the overall FOS for kickout failure based on TGN41

The definition of the overall FOS has recently been modified by GEO (2014) in TGN41. Net water pressure is now used in the definition of F as described in Figure 2. This gives a more reasonable definition and, as discussed by Li (2010), a less conservative design. The revised definition for overall FOS can be expressed as:

$$F = \frac{P_p \times L_p}{(P_a \times L_a + P_w \times L_w) - M_R} \qquad (2)$$

If the embedded wall is socketed in rock, guidelines for determining the required rock socket length can be obtained from Geoguide 1 as depicted in Figure 3 for a cantilever wall.



(a) Embedded wall socketed in rock

(b) Forces acting in rock socket

$$d_1 = \frac{M + F_1 z}{F_1 - V} - \frac{F_1 - V}{2q_u}$$

$$d_r = d_1 + \frac{F_1 - V}{q_u}$$

(c) Design equations

Legend

M = Moment at top of rock socket

V = Shear force at top of rock socket

F_1 = Reaction at rock wedge in rock socket

z = Moment arm of F_1

q_u = Allowable horizontal bearing stress of rock

d_1 = Depth of rock wedge below top of rock socket

d_r = Total socket length

Figure 3: Design equations for determination of rock socket length based on Geoguide 1 (2nd Edition)

If the limit state approach based on partial factors is used for design of ELS works as described in Practice Note PNAP APP-57 (BD, 2012) for analysis, the calculated values of moment *M,* shear force *V* and passive resistance of rock in the rock socket F_1 will all be consistently obtained based on factored parameters. It will then be appropriate to use the "allowable" horizontal bearing stress capacity of rock as input value for q_u. In Hong Kong, the allowable value q_u is usually taken as 1/3 of allowable vertical bearing capacity of rock recommended in the Code of Practice for Foundations, although it is unclear about the origin of the factor.

Geoguide 1 gives no guideline on what appropriate distribution of water pressure should be used when applying the formulas in Figure 3, but designers commonly adopt the submerged unit weight of rock in the determination of rock socket length. This assumption may be inaccurate, but is considered a practical simplification given that the approach in Geoguide 1 for estimation of rock socket is itself conservative.

Based on the sign conventions shown in Figure 3(b), the bending moment *M* is expected to be a positive value when the embedded wall is acting as a cantilever wall before installation of first layer of struts. After struts are installed as shown in Figure 4(a), the situation will be different. If the portion of wall embedded in soil kicks out about point 'A' at the strut level, it will rotate in a clockwise direction at limiting equilibrium. To restrain the clockwise rotation of the embedded wall in soil, the resisting force *V* and moment *M* should be acting in the directions shown in Figure 4(b).

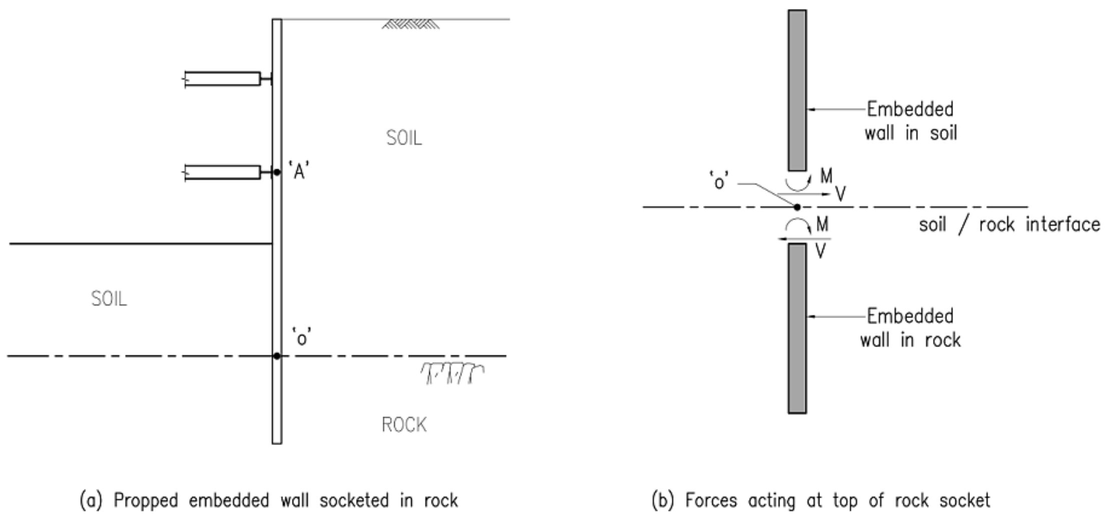


Figure 4: Analysis of a propped embedded wall partially embedded in rock

The directions of moment *M* and shear force *V* with respect the rock socketed portion of the embedded wall will be as shown in Figure 4(b). The direction of moment *M* in Figure 4(b) for a propped embedded wall is different from that shown in Figure 3(b) for a cantilever wall. If the sign convention in Geoguide 1 as described in Figure 3 is to be kept consistently for all analyses, negative values should be used for the input value of bending moment *M* when using the design equations in Figure 3 for calculation of the required rock socket length of a propped embedded wall.

When checking the stability of an embedded wall partially socketed in rock, the following procedures of analysis are commonly adopted by geotechnical engineers in Hong Kong:

a. A geotechnical program such as Plaxis is used to analyze the ELS works and obtain the shear force *V* and bending moment *M* of the embedded wall at the rockhead level. Unfactored parameters are usually used for the analysis.
b. Once the values of *M* and *V* at the top of the rock socket have been obtained, the required rock socket length is estimated using the design equations of Geoguide 1 shown in Figure 3. When performing this design checking, an overall FOS will be applied to the passive resistance of rock F_1 while the horizontal bearing capacity q_u will be based on the allowable value.

Although the above procedures based on the overall FOS approach for checking of embedded walls partially socketed in rock is popular in Hong Kong, it is subject to a strong criticism that unfactored parameters are used for obtaining the values of *M* and *V* in Step (a). This is equivalent to not applying a factor of safety to the passive resistance of the soils above the rock socket. It is not conservative and will lead to underestimation of the required rock socket length.

3 A Suggested Method

To overcome the limitation of the analysis procedures described in the preceding section, a method for design checking of an embedded wall partially rocketed in rock based on the overall FOS approach is suggested as depicted in Figure 5. The meanings of the symbols in Figure 5 are same as those in Figure 2 and Figure 3.

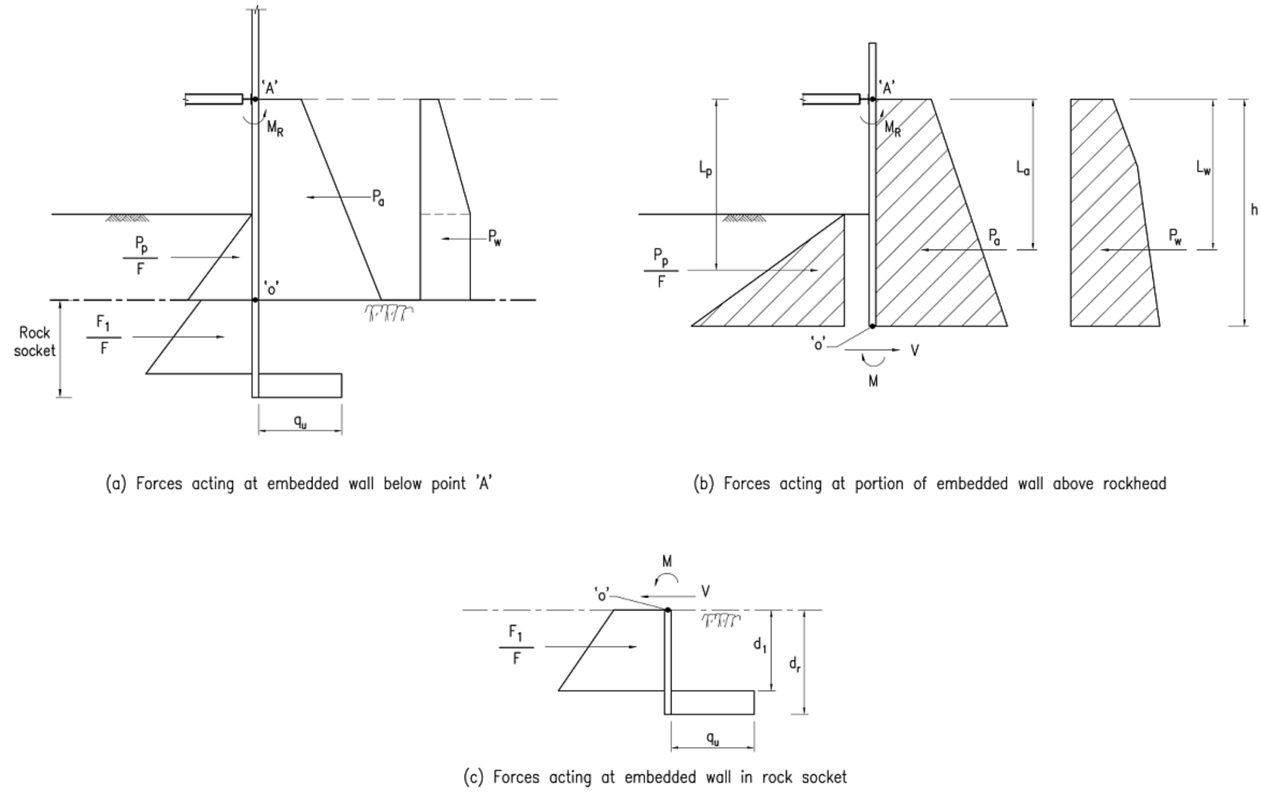


Figure 5: A suggested method for checking kickout failure of rock socketed embedded wall

Figure 5(a) shows the forces acting on the embedded wall. In line with the design guidelines of GCO Publication No. 1/90, an overall FOS (F) is applied to passive resistance of soils P_p above the rock socket. To be consistent, the same overall FOS is also applied to the passive resistance of the rock wedge F_1 within the rock socket. The sign conventions of Geoguide 1 for M and V in Figure 3 are consistently used throughout the analyses.

Figure 5(b) shows the forces and moments acting at the portion of embedded wall in soils between point 'A' at the strut level and point 'O" at the rock socket. The following equation relating M and V can be established by taking moment of the forces under the state of limiting equilibrium about point 'A' at the strut level.

$$V = \frac{M + P_a L_a + P_w L_w - (\frac{P_p L_p}{F} + M_R)}{h} \tag{3}$$

Figure 5(c) shows the free-body diagram for the rock socketed portion of the embedded wall. For a selected value of V, the magnitude of M required to achieve limiting equilibrium is obtained by Eq.3. For this combination of M and V, the required rock socket length d_r can be obtained using the formulas in Geoguide 1 as described in Figure 3. The procedures can be repeated for other combinations of M

and *V* and the longest calculated rock socket length based on the most critical combination of *M* and *V* will be adopted as the design rock socket for the propped embedded wall.

4 A Worked Example

A worked example is presented in this section to illustrate the analysis procedures of the suggested method. The input parameters for the worked example are shown in Figure 6. For simplicity of analysis, the following assumptions are made and parameters are used in this example:

- Wall friction angle is taken to be zero;
- Dry condition in soils;
- Submerged condition is assumed for rock, taking unit weight of water = 10 kN/m^3
- The coefficients of earth pressure are calculated based on the Rankine's theory of earth pressure
- The structural bending moment capacity M_R of the embedded wall is ignored, i.e. $M_R = 0$
- Design overall factor of safety is 2.0.
- Allowable horizontal bearing capacity of rock q_u = 1500 kPa

For this worked example, a closed-form solution can be derived for calculating the rock socket length, although it is beyond the scope of this paper. The analyses for two stages of excavation are considered. Stage 1 involves excavation to a depth of 1.5m before installing the strut at a depth of 1m. Stage 2 relates to excavation to a depth of 6m after installation of strut. The rockhead is assumed to be at the depth of 8.5m. The embedded wall acts a cantilever wall in Stage 1 and a propped embedded wall in Stage 2.

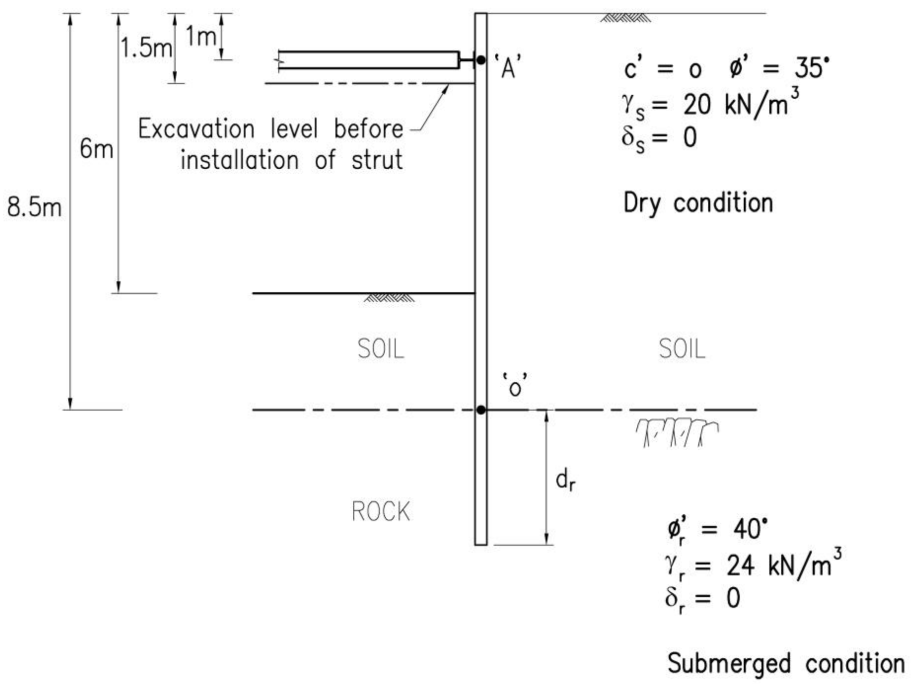


Figure 6: Details of worked example

4.1 Stage 1- Cantilever Stage

To assess the rock socket length required for this cantilever stage of excavation, the magnitude of *M* and *V* at the rock head can be obtained by considering force and moment equilibrium of soil pressures above point ‘O’. An overall factor of safety of 2 is applied to the passive resistance of soil on the excavation side. By considering limiting force equilibrium, the magnitude of *V* is calculated to be –46.5 kN. By considering limit moment equilibrium about point ‘O’, the value of *M* is obtained as –44.9 kNm. Since there are two equations available based on limiting force and moment equilibrium for solving *V* and *M*, the solution is unique. As the calculated values of *V* and *M* are both negative, the passive resistance offered by the soils on the excavation side will be sufficient to achieve the required factor of safety without a rock socket for Stage 1 excavation.

4.2 Stage 2 - Excavation After Installation of Strut

By taking moment about point ‘A’ at the strut level, the relation between *M* and V can be obtained using Eq.3 and the results are presented in Figure 7. As explained earlier, negative values of *M* should be selected for calculating the corresponding values of *V* because the sign conventions in Geoguide 1 as described in Figure 3 are adopted. When the restoring moment for preventing kickout failure is smaller (i.e. *M* being less negative), the shear force *V* needed to maintain limiting equilibrium will naturally be higher.

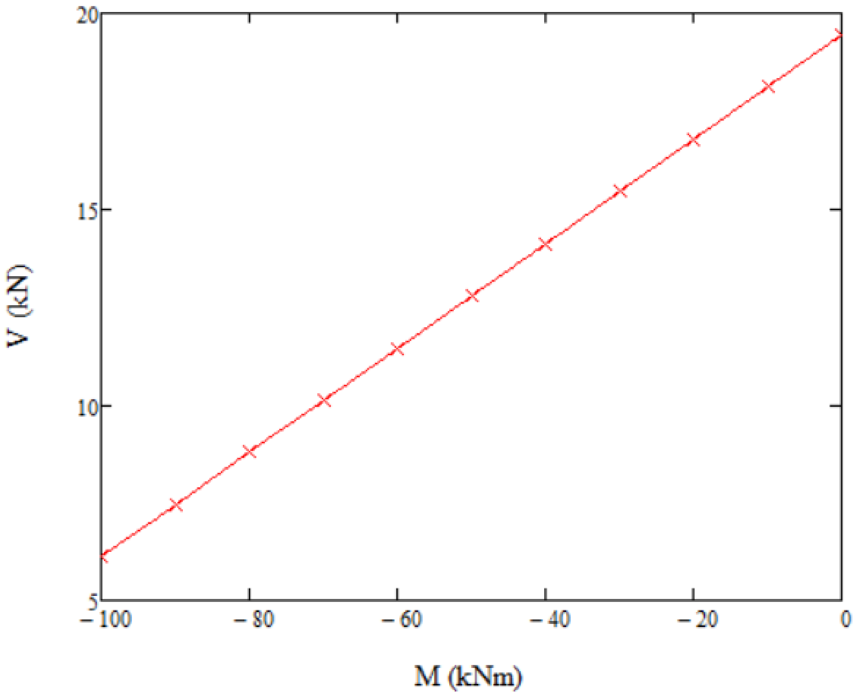


Figure 7: Relationship between *M* and *V*

Using the selected value of *M* and calculated value of *V* shown in Figure 7, the required rock socket length for each of these pairs of *M* and *V* can be obtained using the formulas in Figure 3. The results are presented in Figure 8 with the calculated values of required rock socket length d_r plotted against the selected values of *M*.

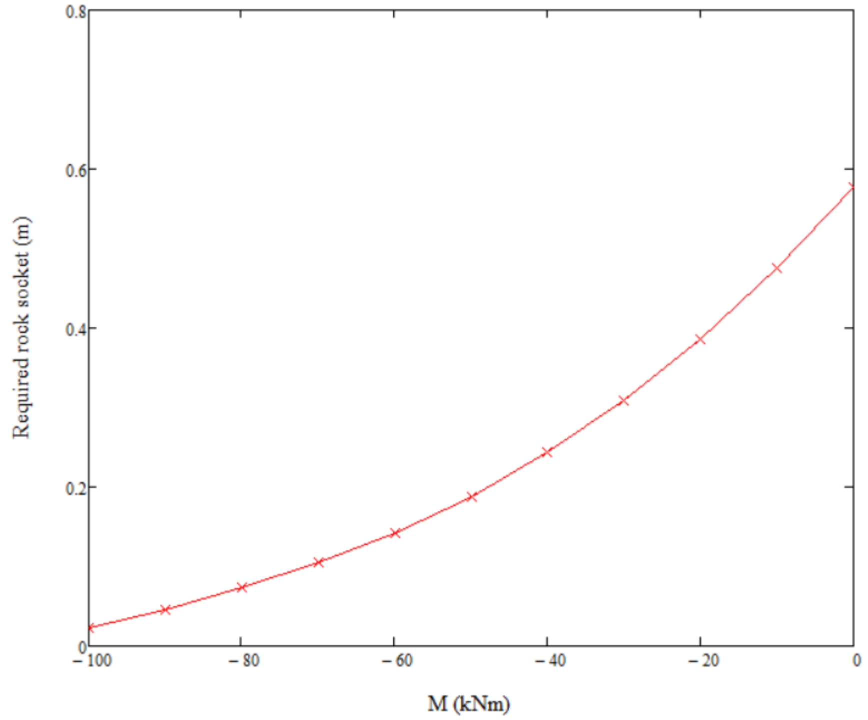


Figure 8: Required socket length for selected combinations of *M* and *V* for Stage 2 works

The required socket length is larger when the resisting moment is lower (i.e *M* being less negative). For design purpose, *M* can be taken as zero for simplicity of analysis and to be conservative. This gives a required socket length of 0.58m for this worked example for Stage 2 excavation. As the required rock socket for Stage 2 works is more critical than Stage 1 works, the design rock socket for the entire ELS works should be taken as 0.58m for this worked example.

5 Discussions

The design checking for kickout stability of embedded wall is routinely performed by geotechnical engineers in Hong Kong when designing ELS works. The proposed method provides a consistent way in which the overall FOS (*F*) is applied to both the passive resistance in soils and in rock for an embedded wall partially socketed in rock.

The paper will end by presenting some Author's views regarding the current practice of ELS design in Hong Kong.

- The procedures for design checking in the current practice or the modified procedures discussed in this paper may be regarded as complex rules to force designers to provide a certain minimum embedment length for the embedded wall. The soil pressure distributions based on full active and passive pressure under limiting equilibrium state considered in the analyses are purely assumptions. They do not reflect the real distributions of earth pressure for propped embedded walls.
- The required minimum overall FOS for ELS design used in Hong Kong is high, particularly for private development projects regulated by the BD. The GCO Publication No.1/90 recommends a factor of safety of higher than 1.5 while the BD tends to prefer a higher overall FOS of 2.0.

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The author has compiled the following summary of percentages of BD approved ELS designs prepared by his firm for private development projects between year 2000 and 2009.

Table 1. Summary of overall FOS used for ELS design

Year	Proportion of designs based on overall FOS =1.5	Proportion of designs based on overall FOS =2.0
2000	0	100%
2001	10%	90%
2002	24%	76%
2003	0	100%
2004	15%	85%
2005	0	100%
2006	74%	26%
2007	37%	63%
2008	17%	83%
2009	0	100%

It can be observed from the above table that a design overall FOS of 1.5 was still acceptable to the BD for a reasonable percentage of ELS designs until the late 2000s. The requirement of an overall FOS of 2.0 was formally stated in Practice Note APP-57 issued by the BD in 2012 (BD, 2012). Limit state structural codes generally recommend load factors between 1.4 and 1.6. For checking of embedment length against hydraulic failure, the design factor of safety is commonly taken as 1.5. Such values are significantly less the minimum overall FOS of 2.0 required for kickout failure. Collapse of ELS works is controlled by the weakest link which is likely to be structural failure of the embedded wall or struts rather than insufficient passive resistance of soil/rock to prevent kickout failure.

As discussed by Li (2010), construction problems arising from ELS works are often caused by over-conservatism in design requiring long embedment length to be provided to achieve the required FOS against kickout failure. Perhaps, reviewing the minimum overall FOS required for ELS design is more critical than developing a consistent procedure for determining the socket length of rock-socketed embedded walls.

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