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A Commentary on the Use of the CECP2 and BS8002 Methods for the Analysis and Design of Cantilever Sheet Piles

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ABSTRACT

The application of conventional as well as limit state design methods to the analysis and design of retaining walls of the cantilever sheet pile type was undertaken using the CECP2 and BS8002 codes. The main aim of the investigation was to determine the suitability and consistency of the afore-mentioned code procedures to cantilever sheet pile analysis and design in both cohesive and cohesionless soils. It was found that the CECP2 and BS8002 codes produced results that were in close agreement for embedded walls in cohesionless soils. However for walls in cohesive soils the conventional CECP2 method was found to produce largely varying results, while the limit state design approach of BS8002 yielded quite consistent answers. As a consequence it was concluded that for cantilever sheet piles in cohesive soils the BS8002 design method may be more appropriate in contrast to the traditional CECP2 approach; for cohesionless soils either of the two methods should prove satisfactory. The study also noted that in all cases it was necessary to carefully select the design soil parameters and determine the most critical geometrical loading and groundwater conditions.

KEY WORDS: Cantilever, pile, design, analysis, cohesive, cohesionless, factor, safety.

INTRODUCTION

The use of retaining wall structures in construction has undergone a significant increase in recent decades due to the increased level of development and construction all over the world. This has necessitated the need to develop appropriate methods of analysis and design for these structures in order to cope with the ever increasing demand and evolving technological innovations. Hence various design methods have been developed to solve problems associated with earth retaining structures. One of such conventional methods is that represented by the CECP2 code [1] which has been applied in a number of variant forms to numerous cases involving the analysis and design of retaining walls. However, while such conventional methods have been in use for a very long time and have provided satisfactory results, they have frequently been found not to be totally accurate and to possess some shortcomings [2].

The limit state design method which currently is very widely used and accepted is a rational approach which can be said to have yielded positive results in the last four decades particularly in regards to structural engineering design problems. The limit state design procedure aims at providing an acceptable probability that a structure will not reach a limit state during its working life [3, 4]. The introduction of the code of practice for earth retaining structures BS8002 [5] by the British Standards Institution using the new design philosophy appears to be a radical departure from the approach of previous conventional methods like that represented by the CECP2 code. This has generated a lot of controversy in respect to the design of earth retaining structures.

It is in light of the above that the present study on cantilever sheet piles was carried out. The main aim was to compare and contrast the results of analysis and design of embedded walls using both the CECP2 and BS8002 methods. In this regard it was not considered practical to carry out case studies of existing walls nor model tests, and the approach that was adopted for the current study was mainly theoretical. The values of design soil parameters employed were mostly assumed ones. However these values could be said to be good representations of those actually obtained in local practice.

LITERATURE REVIEW

Several design methods have traditionally been used in the design of small to medium sized embedded or sheet pile retaining walls. A succinct summary of these methods is given by Burland et al [2]. One approach involves the use of a multiplying factor to increase the computed depth of penetration determined from stability assessment based on limit equilibrium method of analysis.

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Another approach is the gross pressure method which involves factoring the gross passive pressure diagram. Yet another approach is the net available passive resistance method where the factor of safety is applied to the moment of the net available passive resistance. This method partially overcomes the anomaly in the gross pressure method with regard to the factor of safety which reduces with increasing depth of penetration.

Another procedure, the strength factor method, applies a factor of safety to reduce the strength parameter values of the soil. It is equivalent to the procedure used in slope stability calculations. The resultant effect is to increase K_a and reduce K_p the active and passive pressure coefficients respectively, and modify the distribution of earth pressure relative to that obtained using the gross pressure method. Two additional procedures are also noted by Burland et al [2] namely, the nett pressure method and the end fixity method. However it is worthwhile stating here that all of the afore-mentioned methods despite their different shortcomings and their having been found not to be totally accurate nor reliable are still employed in the design of retaining wall structures and have provided fairly satisfactory results in a great number of cases.

Apart from the above, several notable investigations and developments in design methods have occurred over the past six decades [6–14]. These have also included work on the stability performance of earth retaining structures in service. Powrie [14] investigated embedded retaining walls analyzed on the basis of limit equilibrium stress distribution and treated parameters such as soil strength, soil-wall friction and factor of safety, all of which had generated controversies in the past. The aim of his investigation was to set out a rational basis for the selection of soil parameters and factor of safety for use in conventional limit equilibrium analysis of embedded retaining walls. He concluded that the success of the limit equilibrium method depended on the identification of the most onerous loading and geometrical conditions and the fullest consideration of groundwater effect. This was apart from the selection of appropriate soil parameters as well as an appropriate factor of safety. Furthermore he stated that the BS8002 procedures [5] should result in embedment depths which are sufficient to guard against excessive moments under working conditions, provided all the factors listed earlier are considered and the soil strength chosen with care.

The BS8002 code [5] differs from the conventional CECP2 code [1] and its variants in several important respects. Although it adopts the limit state philosophy it does not involve the use of partial factors, while CECP2 uses factors of safety. Also design according to BS8002 is not based upon the ultimate limit state but on the serviceability limit state. This according to Akroyd [15] is because the earth pressures should be those which occur at service. In contrast the code CECP2, although introduced before the evolution and adoption of the limit state philosophy embodied concepts that could be said to base designs on ultimate limit state principles whereby safety factors were utilized to guard against failure at the ultimate limit state. Furthermore the design method in BS8002 uses a fraction of the peak soil strength in earth pressure calculations while the CECP2 approach recommends the use of the actual strength. Additionally BS8002 also stipulates a compulsory 0.5 metres over-dig level or not less than 10% of the total height retained for cantilever walls, in order to provide for unforeseen and accidental events. Finally BS8002 also specifies an obligatory surcharge of $10KN/m^2$ to be applied to the surface of the retained soil to take account of incidental loading from construction plant, stacking of materials and traffic movement during and after construction.

It is in view of all the foregoing that the present study has been carried out. The study forms part of a broader and more general investigation on the analysis and design of embedded walls. For the current purpose the emphasis has been on cantilever sheet piles in both cohesive and cohesionless soils. On account of all the controversies noted in respect of analysis and design of earth retaining structures and the marked difference in the BS8002 and CECP2 methodologies, an investigation to compare and contrast the results of both codes in relation to cantilever walls has been embarked upon.

METHODOLOGY

General remarks

In order to arrive at a rational approach for the comparative study of the application of the conventional CECP2 and the limit state BS8002 methods to cantilever sheet pile analysis and design, the investigation was carried out on embedded walls in both cohesionless and cohesive soils, and a critical comparison of the results obtained by both methods was made. With reference to the CECP2 method and its variants, the two procedures adopted were firstly to increase the computed embedment depth by 20% to 40%, and then alternatively to apply a reduction factor of 1.5 to K_p (the coefficient of passive earth pressure) for cohesionless soils and to c (the cohesion term) for cohesive soils. For the purpose of the present study, analysis and design have been limited only to stability calculations.

Cantilever sheet pile in cohesionless soil

The pressure distribution diagram for a cantilever sheet pile in cohesionless soils in the absence of water in the backfill based on the conventional method is shown in Figure 1. It is assumed the soil below the dredge line has the same angle of shearing resistance ϕ as the backfill above the dredge line. In order to ensure safety and stability using the CECP2 approach, the following equation from Bowles [16] is adopted:

$$Y^4 + \frac{Y^3\bar{p}'_p}{C} - \frac{Y^2 8R_a}{C} - Y\left[\frac{6R_a}{C^2}\left(2\bar{y}C + \bar{p}'_p\right)\right] - \frac{6R_a\bar{y}\bar{p}'_p + 4R_a{}^2}{C^2} = 0 \qquad (1)$$

where Y is the distance from the centre of rotation O or point of zero pressure of the pile to its base, R_a is the resultant force of all the forces above O and Figure 1 identifies all the other terms. Equation (1) is used in computing the required embedment depth D which is given by

$$D = Y + a \qquad (2)$$

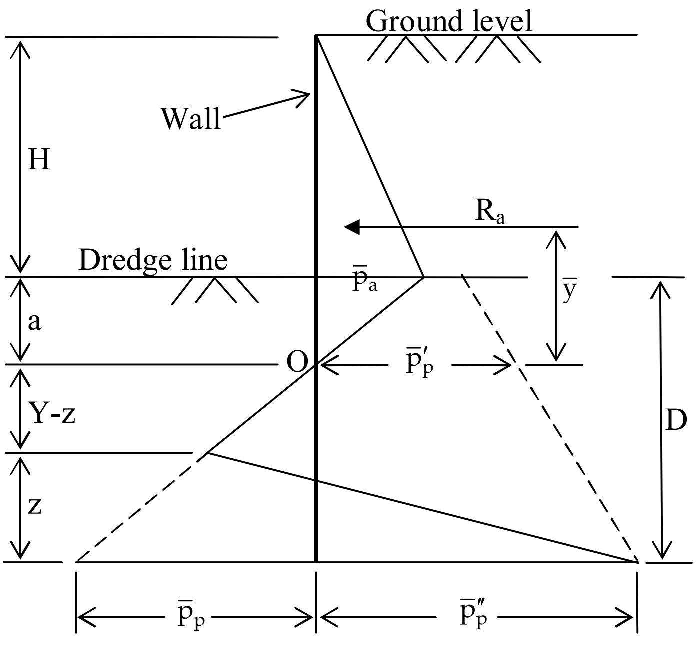
The total required length of pile is (H+D). To ensure stability the calculated embedment depth is increased by 20% to 40% or a safety factor of 1.5 is applied to the K_p term.

The idealized pressure distribution diagram for the BS8002 method is shown in Figure 2. BS8002 only requires that the restoring moment should just equal or be only marginally greater than the overturning moment for the worst credible loading condition. In the design, the mobilized soil strength, ϕ_{mob} is used. Also a surcharge of 10 KN/m^2 on the retained soil is applied and an unplanned excavation of not less than 0.5m or 10% of the retained height is assumed. All that is now needed is to assume an embedment depth and carry out the moments check mentioned earlier.

Cantilever sheet pile in cohesive soil

The pressure distribution diagram in this case is shown in Figure 3. Often the piling is driven in a clay or silty soil and then backfilled with a free draining granular soil on account of the uncertain response of clay and the need to contain a fill on which a structure will be constructed . From Figure 3 and following Bowles [16], the distance from the base of the pile to the point at which the passive pressure in front of the wall becomes uniform is given by

$$z = \frac{D(4c - \bar{q}) - R_a}{4c} \qquad (3)$$



$$a = \frac{\bar{p}_a}{\gamma(K_p - K_a)} = \frac{\bar{p}_a}{C}$$

$$\bar{p}_p = CY$$

$$\bar{p}_p = \gamma HK_p + \gamma aK_p - \gamma aK_a$$

$$\bar{p}''_p = \bar{p}'_p + CY$$

Figure 1. Pressure distribution diagram for cantilever sheet pile in cohesionless soil, using the conventional method

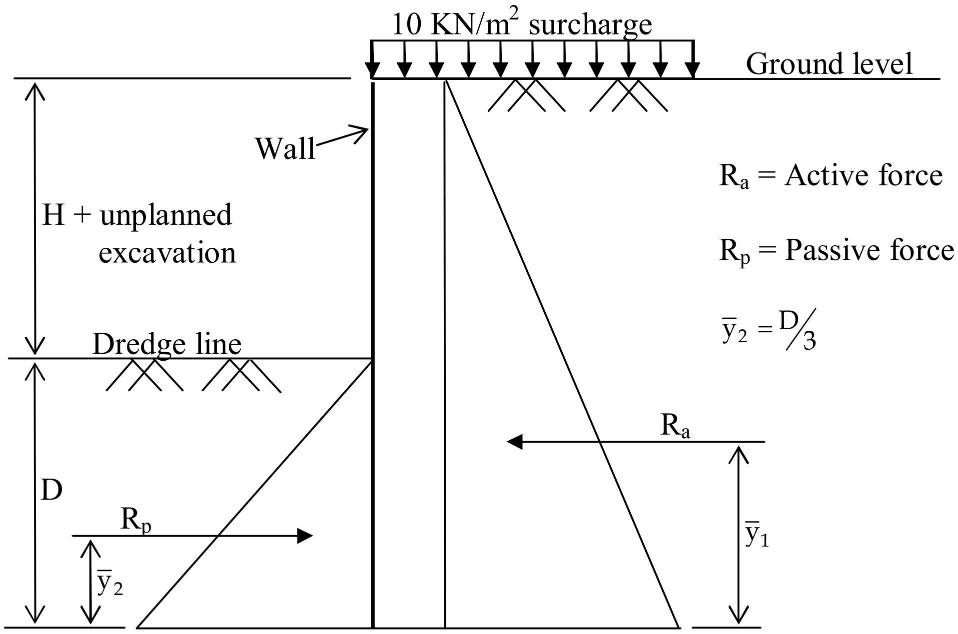


Figure 2. Pressure distribution diagram for cantilever sheet pile in cohesionless soil, using the BS8002 method

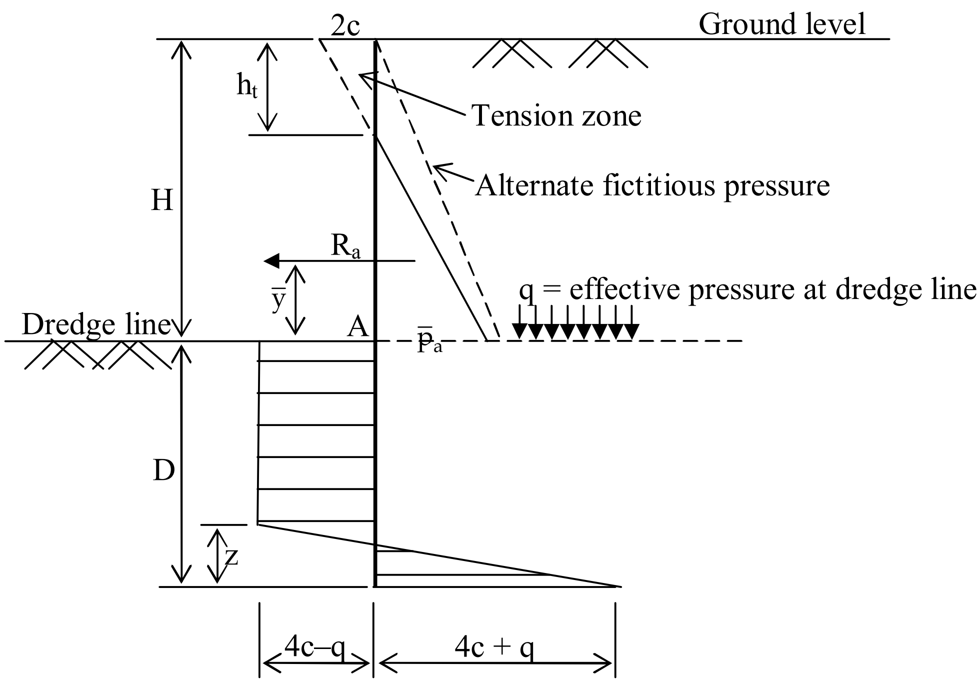


Figure 3. Pressure distribution diagram for a cantilever sheet pile in cohesive soil

For equilibrium the sum of the moments about the base of the pile is zero, that is

$$R_a(\bar{y}+D)-\frac{D^2}{2}(4c-\bar{q})+\frac{z^2}{3}(4c)=0 \tag{4}$$

Substituting equation (3) into equation (4) and rearranging yields

$$D^2(4c-\bar{q})-2DR_a-\frac{R_a(12c\bar{y}+R_a)}{2c+\bar{q}}=0 \tag{5}$$

The computed embedment depth D from equation (5) may be increased by 20% to 40% or as an alternative, the cohesion, c, used in the equation may be divided by a factor of safety in the range 1.5 to 2.0, thereby increasing the computed depth. For the current study, designs for both the CECP2 and BS8110 methods were carried out on the assumption that the sheet pile was driven into cohesive soil of angle of shearing resistance $\phi = 0^o$ and backfilled with granular material.

RESULTS

The results obtained from the analysis and design of cantilever sheet piles in both granular and cohesive soils are presented in Tables 1 and 2 respectively. With reference to the two design methods under investigation, every attempt has been made to keep the design parameters the same in order to aid the comparison.

Table 1. Results of design of cantilever sheet piles in cohesionless soils

Method used	Design parameters	Embedment depth, D (m)	Factor of safety	Total length of pile (m)
Conventional (CECP2) **(a) Increasing computed depth by 30%**	Retained height H = 3.0 m γ =21 KN/m^3 Design ϕ = 30^o δ = 20^o	2.70	1.60	5.70
(b) Reducing K_p by a factor (i.e. using K_p/1.5)		2.58	1.30	5.58
BS8002 approach based on taking different trial depths and checking equilibrium	Retained height = 3.5 m (i.e. 3.0 m + 0.5m unplanned excavation) γ =21 KN/m^3 Design ϕ = 25.7^o δ = 19.8^o	3.0	1.00	6.5
		3.5	1.29	7.0
		4.0	1.58	7.5
		4.5	1.88	8.0

Table 2. Results of design of cantilever sheet piles in cohesive soils

Method used	Design parameters	Embedment depth, D (m)	Factor of safety	Total length of pile (m)
Conventional (CECP2) **(a) Increasing computed depth by 30%**	Retained height H = 6.0 m γ =17.3 KN/m^3 for granular backfill Design ϕ = 30^o c = 57.5 KN/m^3 below dredge line	3.95	1.25	9.95
(b) Reducing the cohesion term (i.e. using c/1.5)		5.64	1.60	11.64
BS8002 approach based on taking different trial depths and checking equilibrium	Retained height = 6.5 m (i.e. 6.0 m + 0.5m unplanned excavation) γ = 17.3 KN/m^3 Design ϕ = 25.7^o δ = 19.8^o	4.72	1.00	11.22
		5.00	1.06	11.50
		5.50	1.15	12.00
		6.00	1.25	12.50
		6.20	1.28	12.70
		6.50	1.33	13.00

DISCUSSION

The results in Table 1 for the cantilever sheet pile in cohesionless soil reveal that the use of the BS8002 design method gives a slightly higher depth of penetration than the conventional CECP2 method. For the latter, increasing the computed depth by 30% gives a factor of safety (F.S.) of 1.6 and depth of 2.70 m, while on the other hand factoring the passive pressure coefficient K_p gives a depth of 2.58 m and a F.S. of 1.3 against overturning. The F.S. values, particularly when applying a reduction factor to K_p appears low when compared to what is often stipulated in practice, i.e. 2.0. This would imply that in practical situations the embedment depth may still have to be increased further.

The BS8002 method on the other hand has taken care of the most onerous loading conditions and, not surprisingly, the values obtained for the embedment depth are higher than for the conventional method. With the BS8002 method it is observed that the F.S. increases with increase in embedment depth. Figure 4 shows the trend of this increase. The linear variation tends to lend credence to the view that the BS8002 design methodology is quite rational. For the present design the ideal embedment depth according to BS8002 is that which results in a F.S. of 1.0, and this occurs at a depth of 3.0 m.

For the design of cantilever sheet piles in cohesive soils the results in Table 2 show that the use of the conventional method embodied in CECP2 and BS8110 [1, 4] gives two largely varying answers. Increasing the computed depth by 30% gives an embedment depth of 3.95 m and a F.S. of 1.25; this F.S. should be considered low by all accounts. Alternatively factoring the cohesive term by 1.5, gives a depth of 5.64 m and a F.S. of 1.6. It is obvious that there is a large difference in embedment depth depending on which course of action is followed

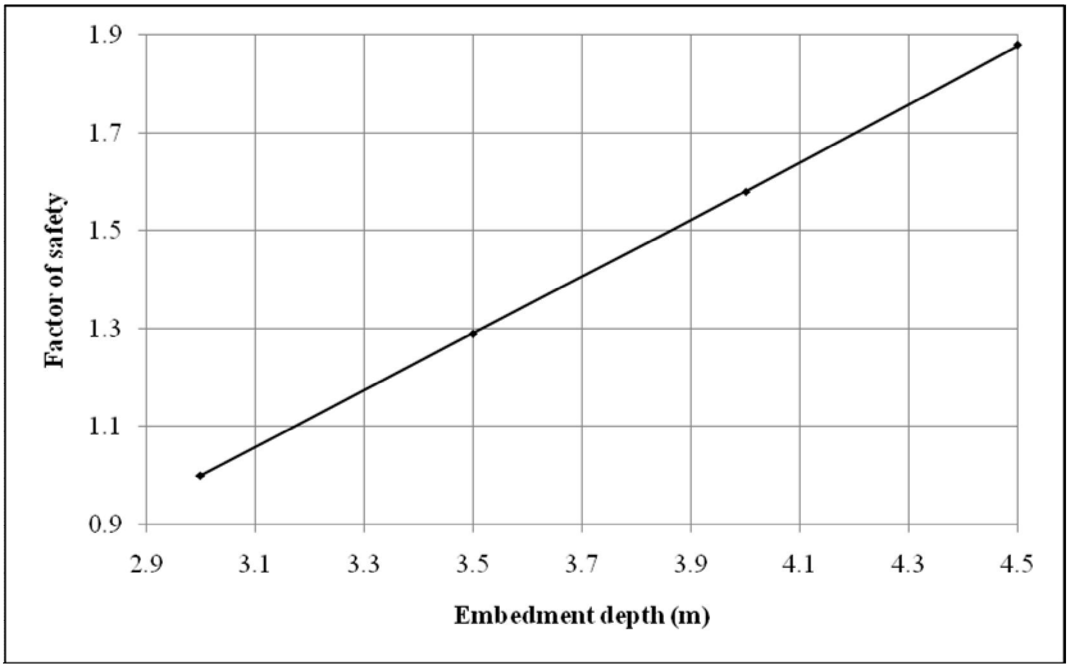


Figure 4. Variation of safety factor with embedment depth in cohesionless soils - BS8002 method

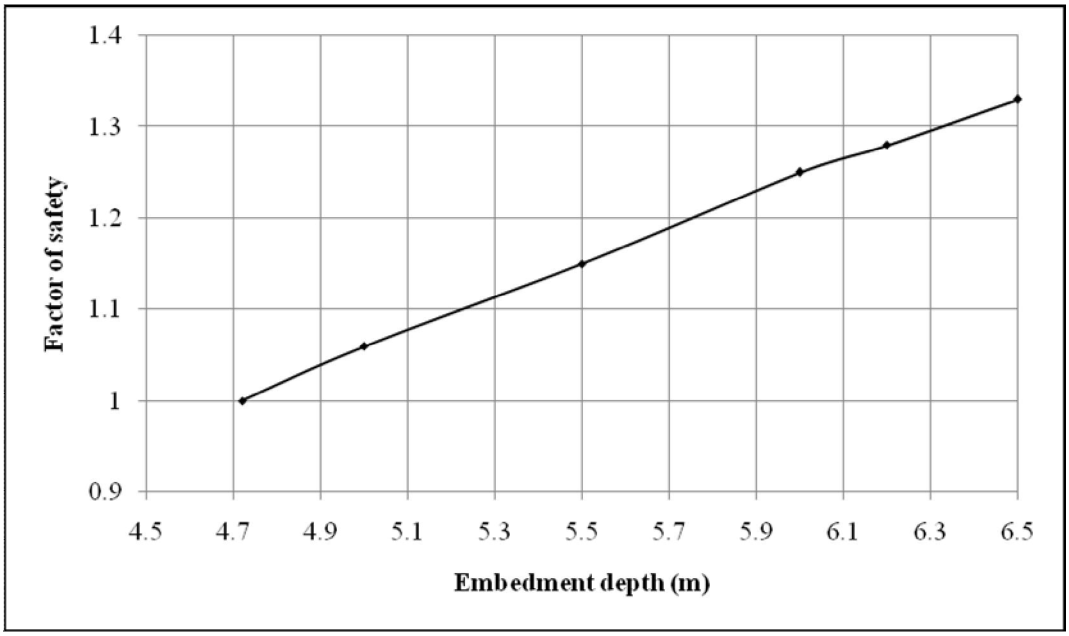


Figure 5. Variation of factor of safety with embedment depth in cohesive soils - BS8002 method

Use of the BS8002 method results in equilibrium being achieved at a depth of 4.72 m when restoring moments balanced the overturning moments. This depth appears to be just intermediate between the largely varying results obtained from the conventional approach. The relationship between the embedment depth and the F.S. for BS8002 is presented in Figure 5. Again it is apparent that the relationship is reasonably linear. Considering the fact that BS8002 adopts the most critical loading conditions in conjunction with other design criteria, it would appear that the code's design procedure is quite rational and appropriate for the sheet piles in cohesive soils.

In summary, it would appear that use of the two conventional procedures in cohesionless soils yield values of embedment depth which are quite close to each other. However for the design of cantilever sheet piles in cohesive soils, large disparities occur in the values of embedment depths and it then becomes a problem to determine which of the conventional procedures in CECP2 and BS8110 gives more accurate results. The BS8002 approach on the other hand appears to be particularly appropriate for walls in cohesive soils. Its value of ideal embedment depth is approximately intermediate between the largely varying results of the conventional methods.

CONCLUSIONS

The aim of the present study has been to investigate the applicability of the BS8002 limit state approach as well as the conventional procedures as embodied in CECP2 and to an extent BS8110 to the analysis and design of cantilever sheet piles. Based on the results of the study, the following conclusions can be drawn:

(1) The BS8002 design methodology appears to be a rational approach which takes into consideration the most onerous loading condition and deformation at service as its governing design criteria for cantilever sheet piles.

(2) For the design of cantilever sheet piles in cohesionless soils, the use of the conventional procedures embodied in CECP2 and BS8110 of either increasing the computed depth by a certain percentage or applying a reduction factor to K_p will yield similar results and produce lower embedment depths than those obtained using BS8002. However although the BS8002 procedure gives greater embedment depths and longer overall lengths of pile, it still yields an ideal embedment value (for F.S. = 1.0) in close proximity to those given by the conventional methods.

(3) For cantilever sheet piles in cohesive soils, the use of the conventional methods in CECP2 and BS8110 produce widely varying results in respect of embedment depths. In contrast the BS8002 design method gives more reliable and consistent results. Its values for ideal embedment depths are approximately intermediate between the widely varying results of the conventional procedures.

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