

# EMBEDDED RETAINING WALLS – STREAMLINING DESIGN GUIDANCE

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## ABSTRACT

The behaviour of an embedded retaining wall is dependent on the stiffness, and ultimately strength, of the soil and the structure. Geotechnical and structural engineering skills are required to design the wall efficiently. Current design codes do not present a consistent approach to the design of embedded walls to accommodate this soil-structure interaction and interpretation of design requirements can vary between designers. Areas of difference between the current codes, and the relationship between the codes and current practice, will be explored. Particular emphasis will be placed on the opportunity to accommodate Australian design issues within the current re-drafting of the CIRIA C580 report “Embedded retaining walls – guidance for economic design” with a view to increasing the relevance of this document to our retaining wall designs.

## 1 INTRODUCTION

An embedded retaining wall is one in which the lateral support of the wall is primarily provided by the passive earth pressure mobilised in front of the element of the wall extending below excavation level. Typically the retaining wall may be constructed from sheet piles, bored piles or diaphragm wall panels. For these embedded structural elements, the forces acting on the wall, and the resulting actions to which the structure needs to be designed, are determined from the interrelation of the soil and the structure.

Many technical papers and text books have been written on the theory of earth pressure distribution, limit state design v soil-structure interaction and applying factors to the design of retaining walls to various codes. Within the geotechnical community, the complexity of embedded retaining wall design is understood, but too often, the final design of retaining walls is left to a single, simplified expression for an earth pressure distribution behind a wall that is plugged into a structural analysis with no further reference to the mechanics of soil behaviour. Using simplified earth pressure distributions may make life simpler for the wall designer, but does not reflect the behaviour of the soil during the excavation process, particularly for multi-propped excavation systems. The simplified approach can lead to over design of anchors/props and does not allow the designer to consider the impact of uncertainty in parameter selection.

There are elements of our current retaining wall codes that do not adequately support the coordination of geotechnical and structural design for embedded retaining walls and the wider acceptance of retaining wall design guidance presented within the CIRIA C580 report may help to bridge this gap.

## 2 CIRIA C580 EMBEDDED RETAINING WALLS – GUIDANCE FOR ECONOMIC DESIGN

The CIRIA report C580 was published in 2003 and captured the best practice design guidance from the UK retaining wall industry, including consultants, contractors and client bodies. From the background of numerous design guidelines and codes of practice providing disparate advice on the design of embedded retaining walls, the aim of the report was to develop a “coherent and authoritative publication” that collated “the best ideas and experience”. C580 is widely used in the UK and is also one of the main design references for embedded retaining walls in Hong Kong.

The design guidance provided in C580 accommodates the selection of wall types, prediction of ground movements, wall design for stability, strength and serviceability and the design of support systems.

In response to advances in the design and construction methods in the past decade, CIRIA are currently planning a revision to C580 to update the best practice presented. As part of the revision process, there is also an aspiration to develop areas of the report to increase the applicability beyond the current focus on stiff clays to potentially include soft clays and weak rocks. Funding is currently being secured from the Land Transit Authority in Singapore and the Hong Kong Government to support the development of C580 in these areas to increase the relevance to their environments. The purpose of this paper is to increase awareness of C580 as a design guidance document, in the context of potentially conflicting design codes for embedded retaining walls in Australia, and identify any areas where there could be benefit in active participation in the preparation of the revised report.

### 3 DESIGN FOR STABILITY AND STRENGTH

For the design of an embedded retaining wall system, the depth of embedment below excavation level needs to be determined to address the following:

- The wall is sufficiently deep to support any applied vertical load
- The wall is sufficiently deep to provide an adequate groundwater cut-off (if relevant)
- The global stability of potential failure mechanisms below the toe of the wall is ensured
- The lateral stability of the wall and any propping system is ensured

It is the final design requirement, relating to the lateral stability of the embedded retaining wall that is discussed within this paper.

#### Lateral Stability

The design of retaining walls in Australia is commonly carried out in accordance with one of two Australian Standards – AS4678 or AS5100. The approach adopted within each of these standards with respect to the ultimate limit state design of a retaining wall is different, and can potentially lead to unrealistic designs, as concluded by Day et al (2007) in their assessment of geotechnical limit state design in Australia. In the case of embedded retaining wall design, where soil-structure interaction is prevalent, the inconsistencies between the design approaches are particularly acute.

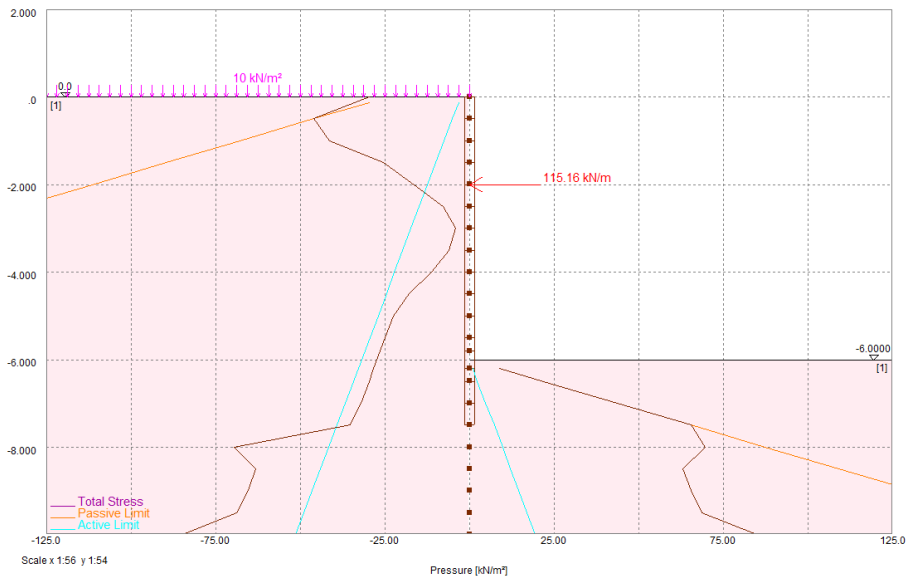
The design approach adopted within AS4678 is tailored to the design of gravity walls where the elements of force acting on the retaining wall can be most readily separated into actions and reactions, and factors then applied to each component of force. The design is essentially focusing on limit equilibrium calculations with full active and full passive pressures developing. This situation may be applicable to simple cantilevered embedded retaining walls, but for propped excavations, the mobilisation of earth pressure is strongly dependent on the relative stiffness of the soil, the wall and the lateral support system and the various elements of force cannot be separated in the same way as a gravity retaining wall scenario. The requirements of AS4678 are not conducive to the efficient design of embedded retaining walls.

Within AS5100.3, the guidance provided for soil-supporting structures is more accommodating of embedded retaining wall design. The design requirements recognise the interaction between the soil and the structure, but the factors applied to the design are focused on reducing the resistance forces, and not a fundamental consideration of the soil behaviour in response to the soil-structure interaction. This method of factoring earth pressure resistance forces does not address fundamental soil properties and, by focusing solely on resistance forces, the sensitivity of the analysis to other elements of the retaining wall system may be lost.

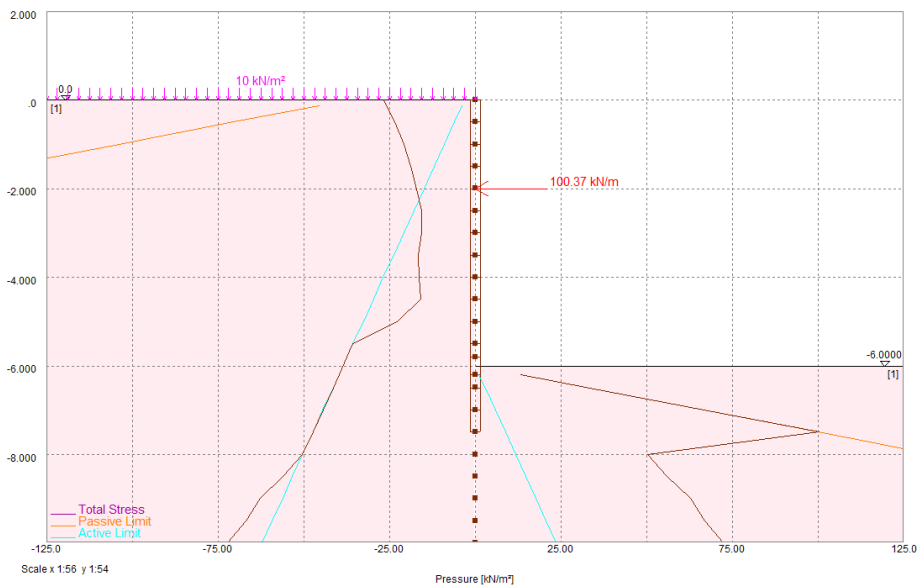
In practice, many designers are now adopting the design approach detailed within CIRIA C580 for the design of stability for embedded retaining walls. In essence, the ULS stability design to C580 considers moderately conservative soil strength parameters and applies a factor of 1.2 to effective stress parameters ( $\tan \phi$  and  $c'$ ) and a factor of 1.5 to total stress parameters ( $c_u$ ). The resulting earth pressure limits are calculated within the design calculations for these factored strength parameters, considering the impact of lower strengths in areas of both active and passive earth pressure behaviour.

The example of an embedded retaining wall designed to both AS5100.3 and CIRIA C580 is presented in Figure 1 to consider the difference in the wall design for stability. In both cases, the analysis has been carried out to ensure that convergence can be achieved for the wall toe depth specified using the pseudo finite element program *OasysFREW*.

The passive resistance below excavation level for each analysis is shown to be fully mobilised and, for the CIRIA C580 example, it can be seen that the active pressure limit behind the wall is higher than the AS5100.3 analysis. In terms of stability, for this single prop wall the results are broadly similar for the AS5100.3 and CIRIA C580 approaches. The design for the strength of the same retention system is now considered.



a) AS5100.3 Stability analysis (factored  $k_p$ )



b) CIRIA C580 ULS Method A: soil strength factored

Figure 1: Earth pressure profiles

**Strength**

The design for structural strength of the retaining wall system, including prop forces where applicable, described in AS5100.3 is broadly similar to one part of the methodology described within CIRIA C580. To AS5100.3, the soil-structure interaction analysis is carried out with all loads and load combinations, including soil strength parameters, unfactored to determine the design action effects imposed through the soil ( $S_e$ ). This value is then multiplied by 1.5 to determine the ULS  $S^*$  value for the structural design. The guidance in CIRIA C580 is similar, with a factor of 1.35 applied to the unfactored design action effects.

The additional element within CIRIA C580 guidance is that the ULS structural forces are then compared with the design action effects derived from the ULS stability analysis, described above, and the larger of the two action effects adopted for the structural design.

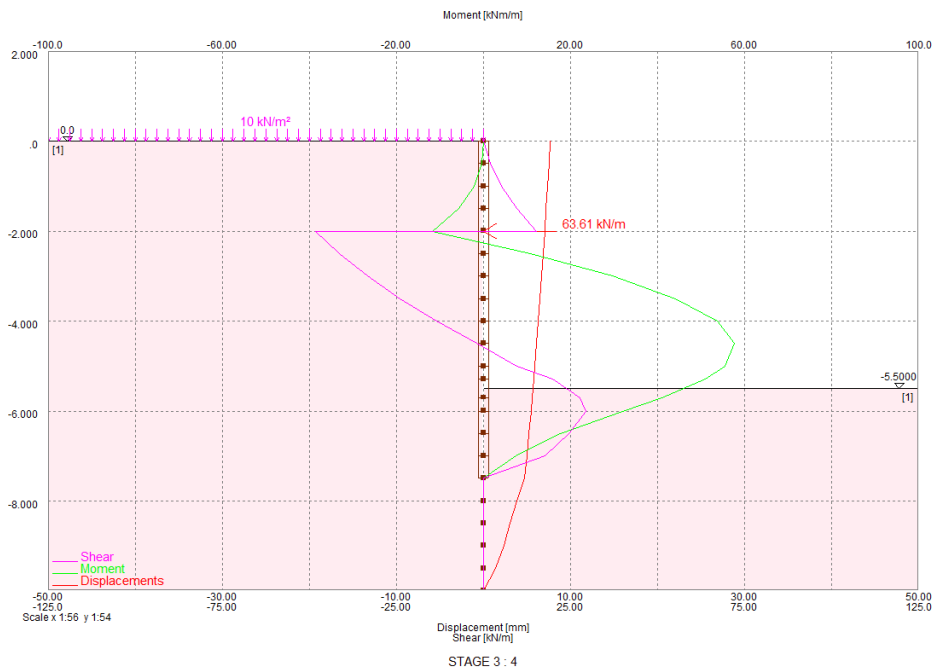
To consider the variation of bending moments, shear forces and prop forces for these conditions, output from *OasysFREW* for the single prop wall example are provided in Figure 2 for the unfactored condition and the CIRIA C580 ULS condition. A summary of the S\* values derived from the AS5100.3 and CIRIA C580 approaches is provided in Table 1.

Table 1: Comparison of ULS structural forces for design

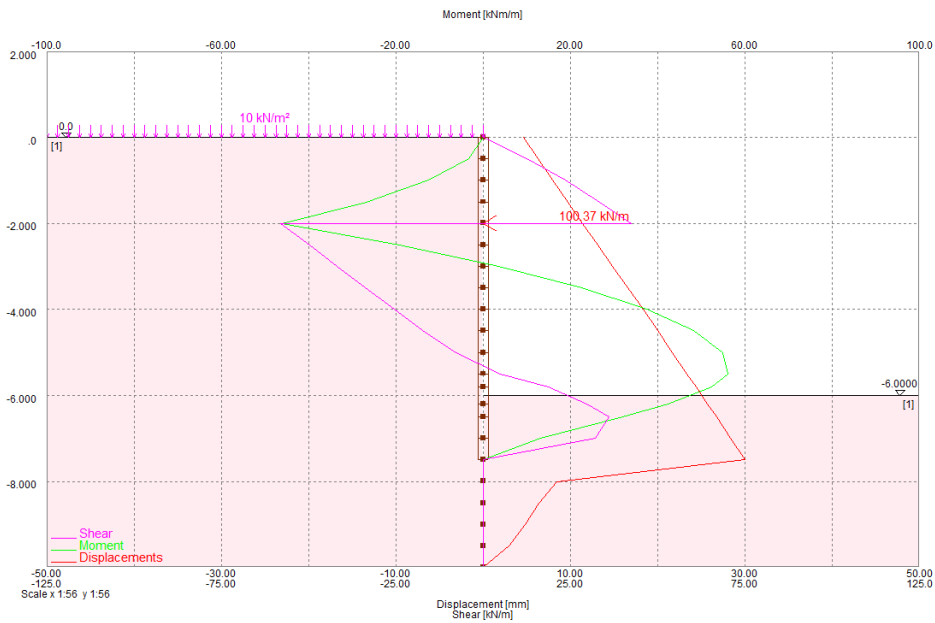
Analysis	Max bending moment (kNm/m)	Max shear force (kN/m)	Max prop force (kN/m)
CIRIA C580 ULS	56	58	100
Unfactored	58	48	63
ULS structural forces S* (AS5100.3) <i>[1.5 x unfactored analysis values]</i>	<b>87</b>	<b>72</b>	<b>95</b>
ULS structural forces (CIRIA C580) <i>[greater of 1.35 x unfactored analysis values and ULS analysis values]</i>	<b>78</b>	<b>65</b>	<b>100</b>

It can be seen from Table 1 that the AS5100.3 approach does not accommodate the structural forces resulting from the ULS analysis when designing the strength of the retention system. In this case, the design of the strut would be carried out for an S\* value of 95kN/m, but higher strut forces are estimated from the AS5100.3 stability analysis (Figure 1a) and the CIRIA C580 stability analysis (Figure 1b). In addition, designing the retaining wall from the unfactored bending moment profile (Figure 2a) would underestimate the negative bending moment values at the prop location identified in the ULS analysis (Figure 2b).

The design approach for the strength of retention systems described within CIRIA C580 can be readily accommodated within Australian design practice, and is being used by geotechnical consultants on a project by project basis. Formal recognition of this methodology within the wider design profession would provide more clarity in the design of ULS loading conditions – such as overdig, traffic impact loads, extreme groundwater levels etc – and the accommodation of these actions in the structural design retaining wall systems.



a) Unfactored parameters



b) CIRIA C580 ULS Method A : soil strength factored

Figure 2: Bending moment, shear force and deflection profiles

**Deformations**

The acceptable movement of retention systems during excavation is often a defining factor in the design of retaining walls, which in turn puts great emphasis on the selection of stiffness parameters for the ground. In terms of design for stability of embedded retaining walls, the stiffness of the ground is not a critical factor, but when considering moments and forces for design derived from unfactored retaining wall analyses, stiffness of the ground is a significant input

parameter. Adopting lower bound values of soil stiffness will not necessarily result in a more onerous design and the need to define realistic stiffness parameters is fundamental for the economic design of embedded retaining walls.

The need for appropriate ground investigations and testing to provide a realistic assessment of insitu soil stiffness should be clearly articulated by the geotechnical engineer. Guidance provided within CIRIA C580 on this issue can provide substantiation, if required, to the wider design team and client bodies to justify any additional expense at the investigation stage.

#### **4 OBSERVATIONAL METHOD**

One of the strengths of CIRIA C580 is the scope within the document to provide advice on design methodologies with a view to achieving more economic designs. This type of design advice is not always applicable within more prescriptive design standards and codes. One example is the reference to the Observational Method within C580 which illustrates the benefit in raising awareness of this document within our industry.

The Observational Method is something that is widely used in mined tunnel design and construction, although not always referred to as such. The method is not routinely adopted in other areas of ground-related construction within Australia. In essence, the method requires two (or more) designs to be carried out, with each design reflecting possible geotechnical design parameters. The base design is carried out using conventional, moderately conservative, design parameters with the second design accommodating a more optimistic assessment of the geotechnical parameters. Each design is fully documented and checked by the approval authorities. Construction works commence on the basis of the “base” design with an extensive monitoring program implemented to check against the anticipated response to the excavation works. If the system is shown to be responding in line with the “more optimistic” parameters, then measures are put in place to scale down the structural capacity of the works to reflect the more optimistic design condition.

For the case of an embedded retaining wall, the base design would be that carried out using moderately conservative design parameters with conventional factors applied – in the case of CIRIA C580, this would mean factors of 1.2 on effective stress strength parameters and 1.5 on total stress strength parameters. A second design is then carried out using “most probable” soil parameters, using the same safety factors. The design of the wall itself, in terms of wall thickness, density of reinforcement etc, will be dictated by the design of the base case because the construction is initiated for this base case design. However, the installation of props as the excavation proceeds can be influenced by the movement of the wall during the excavation process, with significant savings to construction time as well as cost realised if the observed behaviour of the wall is more in line with the more optimistic soil parameters.

An example of the successful implementation of the Observational Method was for the cut and cover tunnels associated with Tseug Kwan O station in Hong Kong (Pan et al, 2001). In this instance, monitoring of the early stages of the tunnel construction demonstrated that the stiffness of the ground was higher than the base case design assumptions. The linear excavation process allowed for a refinement of the design for the latter stages of the construction works, with up to two levels of temporary props being omitted for the final lengths of tunnel excavation.

The Observational Method for embedded retaining wall construction can provide greatest benefits for the larger projects where the cost of the additional design effort and additional monitoring requirements can be compensated by the potential decrease in structural support and associated savings to construction program. The method is an example of wider design advice provided in CIRIA C580 and details of the methodology are presented in CIRIA 185.

#### **5 OTHER AREAS OF DESIGN GUIDANCE**

##### **5.1 WEAK ROCKS**

Designing retaining walls that extend into a weathered rock can present a dilemma – do you treat the embedment material as a stiff soil and apply soil mechanics principles, or do you treat the material as a rock and apply rock mechanics principle? Invariably the weathered rock will have overlying soils which can complicate the design further. This is a design scenario that is not addressed at present within CIRIA C580, but is an area that would be highly applicable to Australian practice.

The approach to the design of embedded retaining walls in weathered rocks varies from designer to designer and can be largely dependent on the particular conditions at any one site. The example below is the approach adopted recently for a road-rail grade separation in Victoria.

The project involved the lowering of an existing train line below a 6-lane road to eliminate the level crossing. A total of 680m of bored pile retaining wall was designed to support the excavation for the lowered train line, with retaining heights ranging from 3m to 8m. Site constraints did not allow for any permanent tie backs and the wall was cantilevered

over the majority of the length of the site, with permanent propping provided at adjacent ground level in the area of the bridge deck across the road and the adjacent station building concourse.

The ground conditions comprised made ground over residual soils over weathered siltstone of the Melbourne Formation with a weathering profile from extremely weathered at 1.5m to 3m depth and generally highly weathered over the excavation depth, becoming moderately weathered below. In addition to the earth pressures, the design of the retaining walls had to accommodate lateral loads associated with the low to medium traffic containment barriers at the top of the wall.

In considering the design approach, a pure rock mechanics method was decided against for two reasons. Firstly, whilst advice on pressures acting on the back of retaining walls retaining jointed rock are provided by Morgan (1992), this approach does not directly provide the flexibility to accommodate the ULS traffic impact loads acting at the top of the wall and does not account for the beneficial effects of the embedment length of the wall below excavation level. Secondly, the site investigation information for the site did not provide sufficient detail to identify discontinuity orientation and spacings for the area. This is not a criticism of the extent of the site investigation, but rather that the highly weathered rock encountered over the excavation depth was not sufficiently structured to justify detailed discontinuity mapping.

The design approach therefore adopted soil mechanics principles, using the pseudo-finite element analysis program *OasysFREW*, with *PLAXIS* used to provide a design check for selected geometries.



Figure 3: Embedded retaining wall (to left) with traffic barrier for road-rail grade separation in Victoria

In deriving soil strength parameters to model the weathered rock profile, a series of rock wedge analyses were carried out to derive equivalent  $k_a$  values for a range of discontinuity orientations and infill conditions behind the wall. The resulting parameters for the highly weathered rock behind the retaining walls used in the design were effective stress parameters of  $\phi = 23^\circ$ ,  $c' = 5$  kPa. The resulting active earth pressure on the back of the wall with no surface surcharge and no lateral traffic impact loads was similar to that predicted using the Morgan (1992) method, but carrying out the design within *OasysFREW* enabled the additional elements of ULS loading to be easily introduced and streamlined the design of the structural elements of the wall and prop slabs throughout the project.

## 5.2 GROUND MOVEMENT DATABASE

One of the sections that are most referenced by designers within the CIRIA C580 document is the database of retaining wall movements and associated ground surface movements behind the wall. The results presented within the document accommodate measured movements from wall installation and excavation and provide both vertical and horizontal movements behind the wall. Within the current scope for the upcoming revision to the document the intent is to augment the database to accommodate more recent project examples as well as a wider variety of ground conditions and

construction methods. To increase the relevance of C580 to Australian practice, providing input to this area of the document update would be highly beneficial.

## 6 CONCLUSIONS AND RECOMMENDATIONS

Current design codes for retaining walls in Australia do not fully address the complexities of soil-structure interaction within an embedded retaining wall system. The codes support elements of industry practice where the retaining wall design is carried out as a beam element with a simplified earth pressure distribution acting on the back of the wall. This approach may be applicable for low height cantilever walls, but for deeper excavations and multi-propped systems, an understanding of the relationship between the soil and the retaining wall is required to establish earth pressures acting on the system and forces set up within the structural elements.

Elements of design guidance presented within CIRIA C580 can be directly applied to embedded retaining wall designs, in conjunction with AS5100.3, to more fully capture design conditions for both ULS and SLS considerations. An increased awareness, and acceptance, of the application of CIRIA C580 across both geotechnical and structural engineers for embedded retaining wall design will assist in streamlining design practice.

CIRIA C580 is in the process of being revised. One driver in increasing awareness of the document is to identify areas in which Australian practice could be introduced within the revision process to increase the relevance of the document to our work. Such areas may include embedded retaining wall design in soils on the hard soil/weak rock boundary and adding to the ground movement database.

## 7 REFERENCES

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