EMBEDDED RETAINING WALL DESIGN IN ACCORDANCE WITH AUSTRALIAN DESIGN STANDARD AS5100.3-2017

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https://doi.org/10.56295/AGJ6124

ABSTRACT

Australian Standard AS5100 is often specified as the technical standard for embedded retaining walls in Australian infrastructure projects. The authors have identified compatibility issues between strength and stability-based criteria in AS5100 and Strength Factor analysis methods adopted by commonly used software packages. AS5100 adopts a Limit State Design approach requiring a reduction factor to be applied to passive restorative forces; whereas the Strength Factor method used in commonly adopted software such as WALLAP (Strength Factor Method option) and PLAXIS, applies a single reduction factor to all values of soil strength in the active and passive zones. The fundamental difference creates challenges for designers attempting to demonstrate compliance with AS5100 when using the widely adopted software packages.

Using a typical cantilever wall example and a range of commonly adopted soil parameters, the authors demonstrate equivalency between these methods by ascertaining the minimum Strength Factor required to achieve equal (or longer) embedment depths compared with the stipulated reduction factor per AS5100.

1 BACKGROUND

Embedded retaining walls are a common type of retaining structure to support excavations in soil and rock. Adherence to Australian Standard AS5100 – Bridge Design is commonly stipulated in the technical specifications for the design of retaining walls in Australian infrastructure projects.

The authors have identified challenges faced by designers to prove the attainment of strength and stability-based criteria in AS5100, due to the inherent incompatibility with analysis methods adopted by commonly used software packages such as WALLAP (Strength Factor Method) and PLAXIS. In this context, strength and stability-based assessments pertain to the embedded length of the pile, i.e. the length of the pile below the excavated ground surface.

For geotechnical strength (failure) and / or stability-based assessments AS5100 adopts a Limit State Design approach, requiring reduction in the restoring forces and increase of applied forces with load factors. Commonly used design software such as WALLAP (Strength Factor Method), PLAXIS2D and PLAXIS3D employ the Strength Factor method which progressively apply a single reduction factor to all values of soil strength in both the active and passive zones until a state of failure or instability is reached. The calculation methods of AS5100 and common design software are seemingly incompatible, i.e. FOS (factors of safety) calculated from WALLAP (Strength Factor Method) and / or PLAXIS are not equivalent to the FOS (inverse of load factors) stipulated in AS5100.

The incompatibility between AS5100 and design software has created inefficiencies in practice. Many designers have to perform duplicate calculations to prove that the embedded wall designs are satisfactory using their adopted design software and then verifying compliance with AS5100 Limit State Design approach. This has resulted in design inefficiencies and re-work in tight working schedules.

This paper aims to review the requirements of AS5100 and ascertain design “equivalent FOS” that are compatible with current modelling software / approaches. Note that this paper focuses on geotechnical strength design only. Structural design and serviceability should also be considered but are not included in this paper.

2 WHAT IS AN EMBEDDED RETAINING WALL

An embedded retaining wall is one that penetrates the ground at its base and obtains some lateral support from it (CIRIA C760). The wall may be freestanding or cantilever and may also be supported by structural members such as props, berms, ground anchors and slabs. Common retaining wall types include sheet piles, king post walls, contiguous bored pile wall, secant pile wall and diaphragm walls.

Cantilever embedded walls rely on an adequate embedment below the excavation level for their stability. For unpropped walls, the failure mechanism is likely to be rotational movement around the wall toe where the soil behind the wall will move to an active state while the resisting zone in front of the wall will provide passive support. Refer to Figure 1 for an illustration of the stress distributions around embedded walls extracted from CIRIA 760.

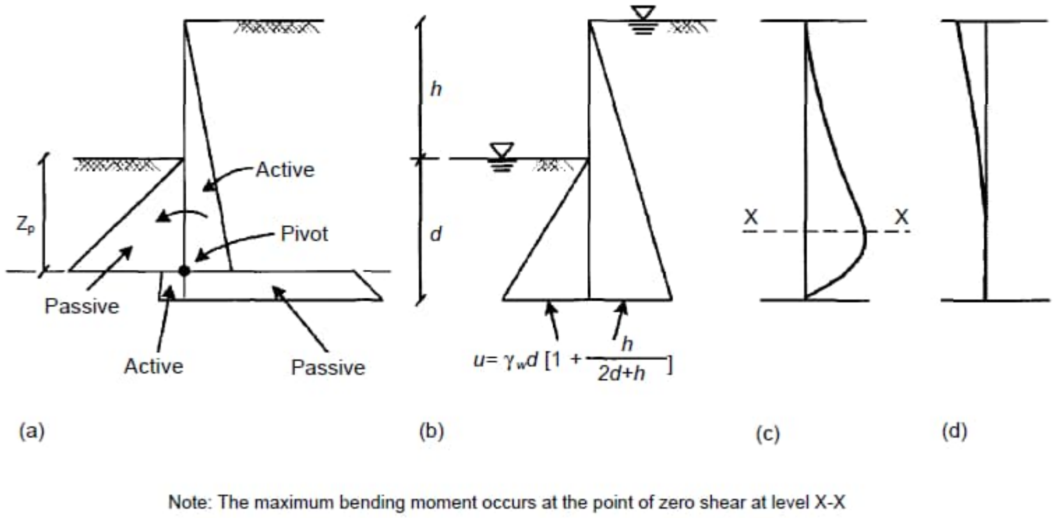


Figure 1: Idealised stress distribution for an unpropped embedded cantilever wall at failure: (a) effective stress; (b) pore water pressures; (c) wall bending moment distribution; (d) wall deflection (CIRIA 760)

3 METHODS OF ANALYSIS

3.1 OVERVIEW

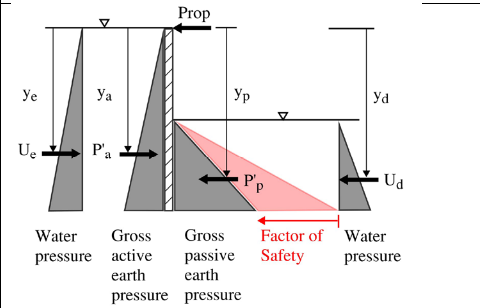
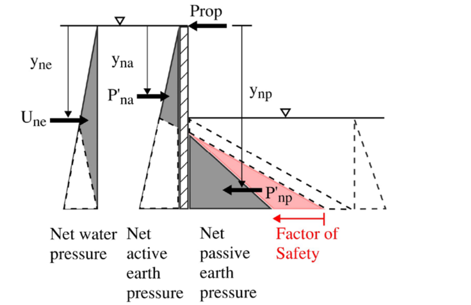
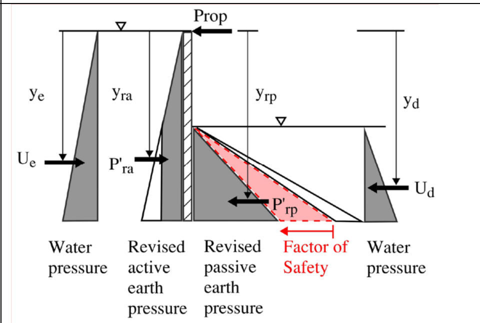
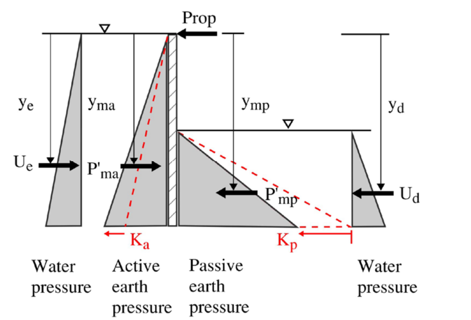
A brief history of embedded retaining wall stability design methods is summarised in Table 1. Some of these analysis methods are still in use today and form the basis for the geotechnical strength / stability assessments in commonly used design software.

4 OVERVIEW OF AS5100.3

The latest version of Australian Standard AS5100 Bridge Design was issued in March 2017, containing a total of nine separate parts. For the purposes of this paper, reference will be made mostly to Part 3 – Foundation and Soil-Supporting Structures (AS5100.3 – 2017) as this contains the design criteria for retaining walls. Reference will also be made to AS5100.3 Supplement 1 – 2008 which provides commentary and guidance to the application of AS5100.3 – 2004.

Note that an updated supplement is not currently available for AS5100.3 – 2017. The authors have undertaken a review of the design criteria in AS5100.3 – 2004 versus 2017 and identified no discernible differences. Hence, the authors consider use of AS5100.3 Supplement 1 – 2008 for the interpretation of AS5100.3 – 2017 remains adequate for the context of this paper.

Table 1: Embedded retaining wall analysis methods, based on Clayton, C.R.I et al (2013)

Method	Name	Description	Relevant Equations	Illustration	Comments and Notes
1	Civil Engineering Code of Practice No. 2, 1951 (CP2) (= AS5100.3)	• Published by Institution of Structural Engineers in 1951 • Apply single factor of safety (minimum 2.0) onto gross passive earth pressures	$FOS = \frac{P_p' y_p}{P_a' y_a + U_e y_e - U_d y_d}$		• Follows calculation methodology in AS5100.3 Supplement 1 – 2008, i.e. applies reduction factor to passive resistance only. Refer Section 5.5 • Burland et al. (1981) criticised the factors of safety on gross pressures when applied to undrained conditions as the method rendered inconsistent embedded lengths, i.e. longer embedment depths were required for lower factors of safety • Superseded by BS8002 in 1994, British Standards Institution published new code of practice for earth retaining structures to replace CP2 This stability assessment method is adopted in WALLAP (CP2 option).
2	BSC Piling Handbook	• British Steel Corporation published Piling Handbook in 1997 (blue book). • Apply factor of safety to net passive earth pressure	$FOS = \frac{P_{np}' y_{np}}{P_{na}' y_{na} + U_{ne} y_{ne}}$		Burland et al. (1981) and Potts and Burland (1983) found that the factor of safety using the BSC method was very low compared with other calculated methods. For these reasons, the net pressure method has fallen out of favour in modern times
3	Burland Potts Method (Revised Method)	• Published by Potts and Burland (1983) • Attempt to counteract undesirable features of gross and net pressure methods (Method 1 and 2 respectively) • Effective earth pressures on both sides of the wall are reduced by an equal amount (by ignoring the hatched areas) so that the active earth pressures below formation level remain constant	$FOS = \frac{P_{rp}' y_{rp}}{P_{ra}' y_{ra} + U_e y_e - U_d y_d}$		• More complicated than the other methods and has not been used widely in UK practice (and to the author's knowledge hardly at all outside the UK). • With the publication of BS 8002 and Eurocode 7, use of the revised method has waned
4	Strength Factor Method	• In 1994 BS8002 introduced Mobilisation Factor, M, which reduces soil strength (drained or undrained) in the active and passive regions to a "design value". This is analogous to a "factor of safety, FOS" • Active earth pressures are increased; passive pressures are decreased.	$design\ c' = \frac{c_r'}{M}$ $design\ \phi' = tan^{-1}\left[\frac{tan\ \phi_r'}{M}\right]$ $design\ c_u = \frac{c_{ur}}{M}$ Where, $M = FOS$		• Supersedes CP2 (Method 1) in accordance with BS8002 • BS8002:1994: M = 1.2 for effective stress, and 1.5 for total stress parameters – applied to representative peak strength of soil • Stability assessment methods adopted in the following software programs have Strength Factor method functionality: ○ WALLAP – Strength Factor Method ○ PLAXIS – Phi/C reduction (Safety method) ○ RocScience – Shear Strength Reduction (SSR) In WALLAP / PLAXIS / RocScience, the Strength Factor is employed whereby the strength parameters are reduced by a factor, and by which all values of cohesion and tan phi must be reduced to bring about a state of limiting equilibrium, i.e. failure.

5 DESIGN METHODOLOGY ACCORDING TO AS5100.3

5.1 OVERVIEW

AS5100.3 adopts a limit state design method, whereby reduced restorative forces must exceed magnified destabilising loads. All strength-based assessments for the pile length must adhere to Equation 2.3.3(2) in AS5100.3, reproduced below in Equation 1.

$$\phi_g R_{u.g} \geq E_d \quad (1)$$

Where the terms of Equation 1 are presented in Table 2.

Table 2: Terms in Equation 1

Symbol	Description	Details	Reference in AS5100.3 – 2017
E_d	Design Action Effect	Design effect imposed by loading, e.g. soil, surcharge on slope of ground surface, compaction pressures	Cl 2.3.3(d), Cl3.3.3, Cl8.3.2
ϕ_g	Geotechnical Strength Reduction Factor		Table 8.3.1 (A)
$R_{u.g}$	Ultimate geotechnical strength	• Passive resistance only • Use unfactored values for material parameters	Cl2.3.3(d)

Details of each input into Equation 1 are described in the sections below.

5.2 DESIGN ACTION EFFECT, E_d

According to AS5100.3, for soil-supporting structures (i.e. where the loads are imposed predominantly from the soil) load factors on the Design Action Effect, E_d, shall be 1.0 for geotechnical strength design. Given that design effects include the imposed loads, this pertains to any destabilising load, including (but not limited to) active pressures imposed by the soil.

5.3 GEOTECHNICAL STRENGTH REDUCTION FACTOR, ϕ_g

The reduction in restorative forces is governed by the Geotechnical Strength Reduction Factor, ϕ_g. A summary of the ϕ_g values stipulated in AS5100.3 is provided in Table 3.

Table 3: Geotechnical Strength Reduction Factors, ϕ_g, for retaining walls and abutments. Extracted from AS5100.3 Table 8.3.1(A)

Bearing Failure	Overturning, sliding and global stability	
	Permanent structures	Temporary structures
0.30 – 0.45	0.45 – 0.55	0.45 – 0.70

** selection of value adopted for design should be based on the method of assessment of ultimate geotechnical strength pertaining to quality of ground investigation undertaken*

Assessment of strength / stability for an embedded retaining wall pertains to overturning failure, and or global stability failure. As such, the relevant ϕ_g according to AS5100.3 Table 8.3.1(A) should be as per Table 4 below. The FOS for these reduction factors can be calculated from the inverse of each value. These inversed values will be referred to as FOS_{AS5100} here forth.

Table 4: Geotechnical Strength Reduction Factors (ϕ_g) and corresponding FOS in accordance with AS5100.3

Design case	ϕ_g	Inverse of ϕ_g (FOS_{AS5100})
Temporary structures	0.45 – 0.70	1.43 – 2.22
Permanent structures	0.45 – 0.55	1.82 – 2.22

5.4 ULTIMATE GEOTECHNICAL STRENGTH

According to Cl2.3.3(d) of AS5100.3, the ultimate geotechnical strength is equal to the passive resistance on the retaining wall, determined using unfactored material parameters. It is upon the passive resistance that the Geotechnical Strength Reduction Factor, ϕ_g, is applied.

5.5 AS5100.3 SUPPLEMENT 1 – 2008 EXAMPLE CALCULATIONS

Within the appendices of AS5100.3 Supplement 1 – 2008 are a set of example calculations for an anchored pile wall demonstrating the limit equilibrium approach and limit state analysis in accordance with AS5100.3. The geometry of the problem is shown in Figure 2.

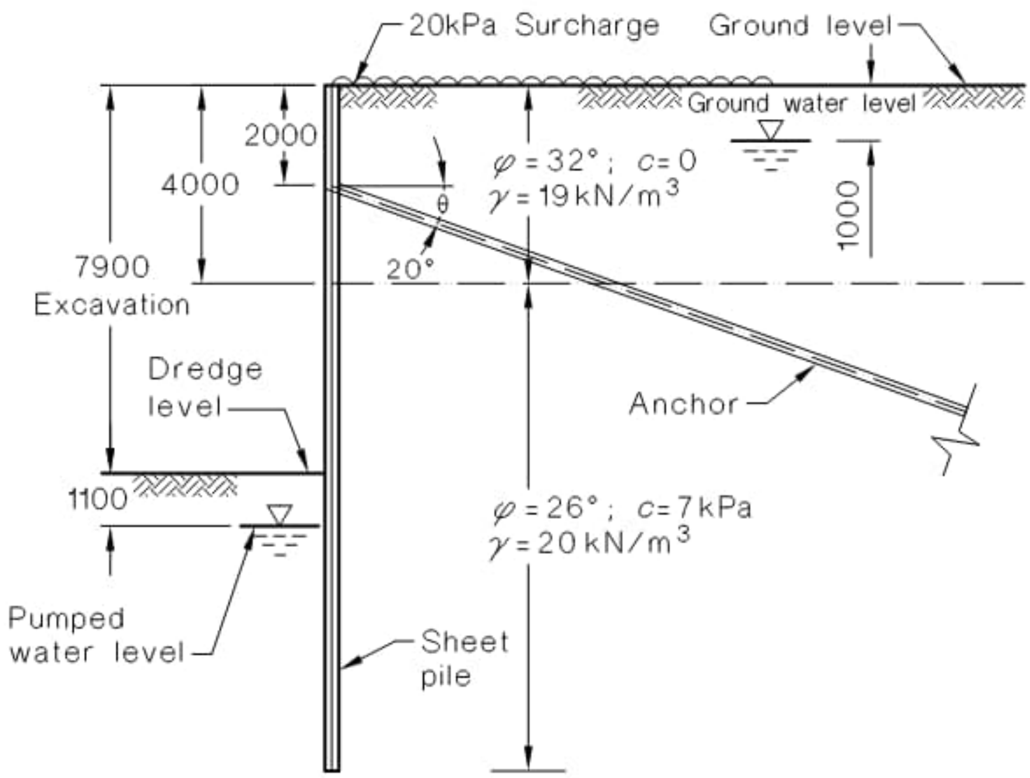


Figure 2: Embedded retaining wall example (extracted AS5100.3 Supplement 1 – 2008, millimetres)

The calculations summarised below have been extracted from the Limit Equilibrium (LEM) approach within the Supplement, which does not take into account interaction between pile, soil and flexibility of anchor and construction stages. Finite Element Modelling (FEM) and pseudo-FEM can take these details into account and are discussed in the Supplement. Reproduction of the LEM approach is used herein for transparency in the analytical application of AS5100.3.

In this example simplified distributions of active and passive pressures are assumed, using the nomenclature in Table 5.

Table 5: Nomenclature used in example extracted from AS5100.3 Supplement 1 – 2008. Refer to Figure 2 and Figure 3

Symbol	Description	Distance offset from anchor
$P_a^{'}$	Total effective active force	y_a
U_e	Total water load on active (retained) side	y_e
$P_p^{'}$ $(= R_{u.g})$	Total effective passive force	y_p
U_d	Total water load on passive (dredged) side	y_d

Taking moments about the anchor point, the depth of penetration needs to satisfy Equation 2. Note that in accordance with Cl2.3.3(d), the passive resistance should be factored by ϕ_g.

$$\phi_g \, P_p^{'} y_p \geq \; P_a^{'} y_a + \; U_e y_e - U_d y_d \quad \textbf{(2)}$$

The pressures must be assessed and iterated for various pile depths until Equation 2 is satisfied.

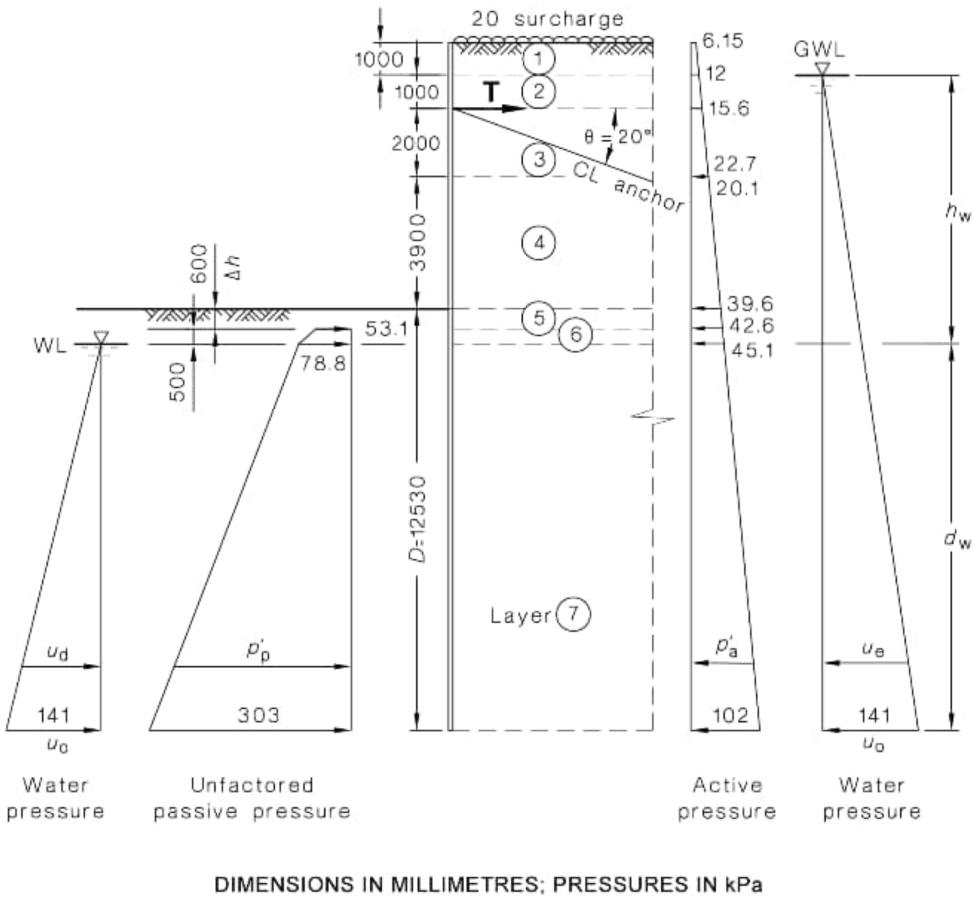


Figure 3: Embedded retaining wall example – calculated pressures (AS5100.3 Supplement 1 – 2008)

6 COMPARING ANALYSIS METHODS WITH AS5100.3 APPROACH

Of the analysis methods in Table 1, Method 1 (CP2) is equivalent to the LEM method outlined in AS5100.3 Supplement 1 – 2008. Their equivalency can be seen in equation for Method 1 from Table 1 versus Equation 2 from AS5100.3 summarised below. The equations are inverse of each other, i.e. FOS in Method 1 is relayed inversely as a reduction factor ϕ_g in Equation 2. The methods are identical in that the Strength Factor or Reduction Factor is applied to the gross passive resistance only.

$$FOS = \frac{P_p' y_p}{P_a' y_a + U_e y_e - U_d y_d}$$

Method 1 equation (CP2)

$$\frac{1}{FOS_{AS5100}} = \phi_g \geq \frac{P_a' y_a + U_e y_e - U_d y_d}{P_p' y_p}$$

Equation 2 (AS5100.3) rearranged

Methods 2, 3 and 4 adopt different means of applying the Strength / Reduction factors compared with the example in AS5100.3 Supplement 1 – 2008. As these analysis methods differ fundamentally from the AS5100.3 approach, results obtained using these methods do not demonstrate compliance with AS5100.3 criteria.

Method 4 (Strength Factor) is currently utilised within all commonly used software to assess FOS's for wall embedment depths such as WALLAP (Strength Factor Method), PLAXIS and RocScience. For wall designs using these (or similarly structured) software, engineers are required to use alternate means of demonstrating compliance with AS5100.3 criteria. This creates additional effort and cost in the design process.

7 SATISFYING AS5100.3 USING CURRENT ANALYSIS METHODS

7.1 GENERAL

Whilst the analysis methods within popular design software differs from that specified in AS5100.3, the sections below describe the method by which the authors derived "equivalent FOS's" using Strength Factor analyses (Method 4), i.e. FOS_{SF}, which match or exceed embedded pile lengths calculated using CP2 (ϕ_g, FOS_{AS5100}) per AS5100.3 (Method 1). Equivalency was not sought for Methods 2 and 3, as these are not commonly used design approaches.

7.2 ANALYSIS METHODOLOGY

Firstly, a list of the variables which were expected to have a significant impact on the geotechnical strength / stability of embedded walls was generated, including ranges of values that are typically encountered, as noted below. Refer to Figure 4 for an illustrated sketch of the noted variables.

- Soil strength, ϕ' (range = 24^o to 38^o)
- Retained height, H (range 2m to 7.5m)
- Surcharge pressure, q (range 0kPa to 50kPa)
- Water table height, W (range 0m to full retained height)

A parametric assessment was then undertaken where for each combination of the variables a geotechnical strength / stability assessment was performed using the CP2 method (using WALLAP CP2 option per AS5100.3) to establish the required embedment depth.

Then, for each combination of variables, WALLAP (Strength Factor Method) and PLAXIS were used to perform geotechnical strength assessments using the same variables **and total pile length** per AS5100.3, to determine the "equivalent" factor of safety utilising the Strength Factor method, i.e. FOS_{SF}.

Details of the variables used in each of the parametric models and assessment steps are provided in Table 6 and Table 7.

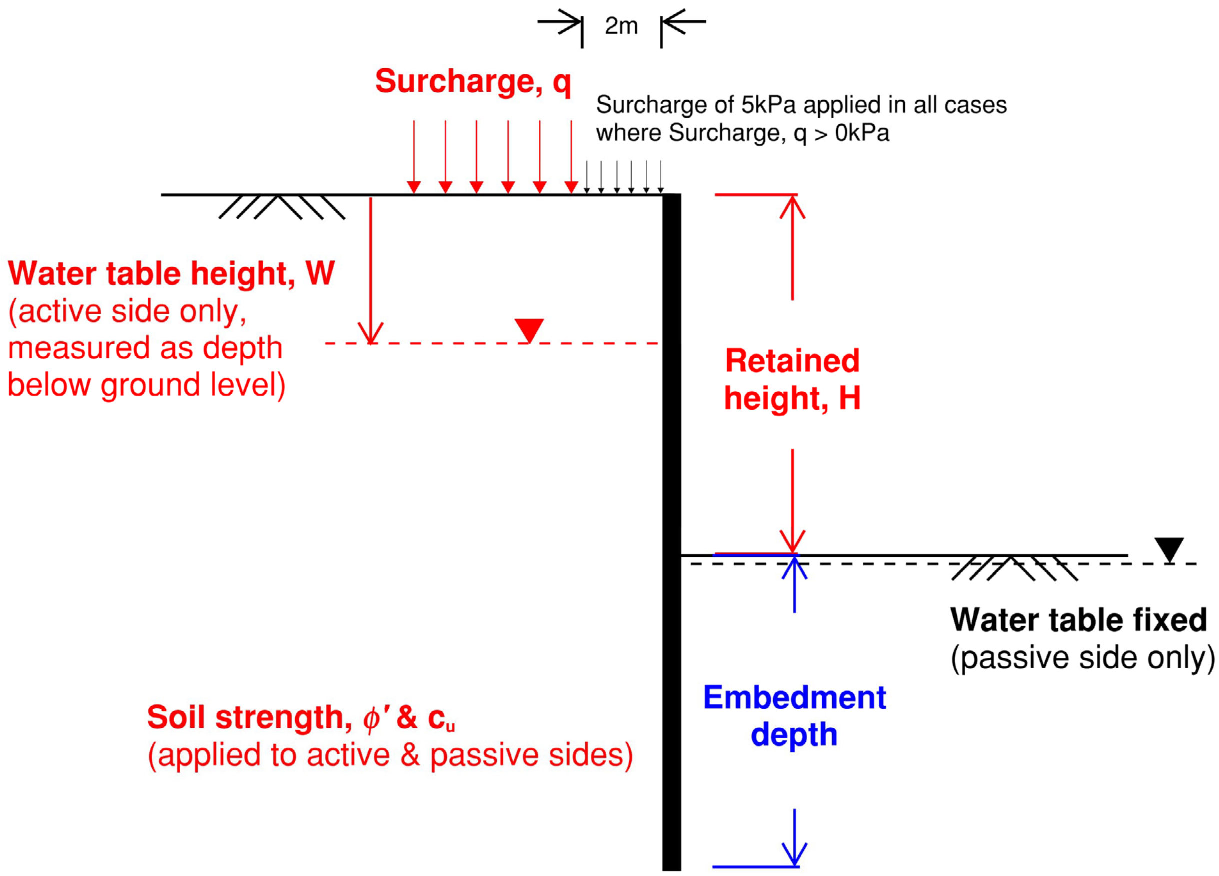


Figure 4: Embedded retaining wall parameters for parametric modelling. Black text = fixed conditions, Red text = parametric variables, Blue text = calculated variable

Table 6: Parametric modelling variables

Tested variable	Range of tested variable	Variables to fix
Soil strength, ϕ'	ϕ' = 24°, 26°, 28°, 30°, 32°, 34°, 36°, 38°	• Soil strength, c' = 5kPa • Retained height = 7.5m • Surcharge = 20kPa • Water level (active) = 1mbgl
Retained height, H	H (m) = 2, 4, 6, 7.5	• Soil strength, c' = 5kPa • Soil strength, ϕ' = 35° • Surcharge = 20kPa • Water level (active) = 1mbgl
Surcharge, q	q (kPa) = 0, 10, 20, 30, 40, 50	• Soil strength, c' = 5kPa • Soil strength, ϕ' = 35° • Retained height = 7.5m • Water level (active) = 1mbgl
Water table (active), W – measured relative to formation level on active side	W (m) = 0, 1.5, 3, 4.5, 6, 7.5	• Soil strength, c' = 5kPa • Soil strength, ϕ' = 35° • Retained height = 7.5m • Surcharge = 20kPa

Table 7: Parametric modelling analysis steps

Step	Assessment Method	Software	Embedment assessment method	Details
1	Method 1	WALLAP *	CP2 (equivalent to AS5100.3)	Select a test variable, e.g. soil strength, ϕ', and apply the first value in the test range. Ensure other variables are fixed
2				Assess necessary embedment depth to achieve ϕ_g per AS5100.3, refer Table 4
3	Method 4	WALLAP	Strength Factor	Replicate the same model from Steps 1 & 2, but select Strength Factor method for analysis
4				Determine FOS achieved (FOS_{SF}) for the same embedment depth of pile calculated using CP2, i.e. Step 2
5	Method 4	PLAXIS2D	Strength Factor (Finite Element)	Replicate the same model from Steps 1 & 2, Run Phi/C reduction (Safety) on the model
				Determine FOS achieved (FOS_{SF}) for the same embedment depth of pile calculated using CP2, i.e. Step 2
6	Repeat Steps 1 – 5 inclusive for next value within the range of test variables, until embedment depths have been calculated for all values within the range			
7	Repeat Steps 1 – 6 inclusive for next test variable, until embedment depths have been calculated for all test variables			

* Note WALLAP software includes options to undertake CP2 analysis methods as well as Strength Factor Methods

7.3 ASSUMPTIONS

The following assumptions were made in the parametric assessments:

- Assessments did not account for the reduction in passive resistance in front of the wall equivalent to 10% of the height above the nominal ground level (minimum of 0.5m), per Clause 8.3.1 in AS5100.3
- Groundwater was modelled assuming hydrostatic groundwater conditions and balanced by interpolating the water pressures linearly based on the groundwater level assigned on each side of the wall separately.
- Assessment was undertaken for geotechnical strength design only. Note that a complete retaining wall design should also include serviceability assessments and structural design, i.e. bending moments and shear forces

7.4 EMBEDDED WALL PROPERTIES

The structural properties of the embedded wall adopted the properties noted below. These properties remained constant in all analyses and were selected to ensure the geotechnical strength solution was not impacted by these properties in any way, i.e. provision of a very stiff wall member. These properties are provided for reference only.

- Construction Material = Contiguous Bored Pile Wall
- Young's Modulus, E = 32,800,000 kPa
- Pile diameter = 1.2m
- Pile spacing = 2.1m centre to centre

7.5 ANALYSIS OUTCOMES

A complete summary of all the parametric modelling outcomes is provided in Table 8. For each parametric model, graphs were plotted to illustrate the calculated outcomes provided in the Appendices. An example is shown in Figure 5.

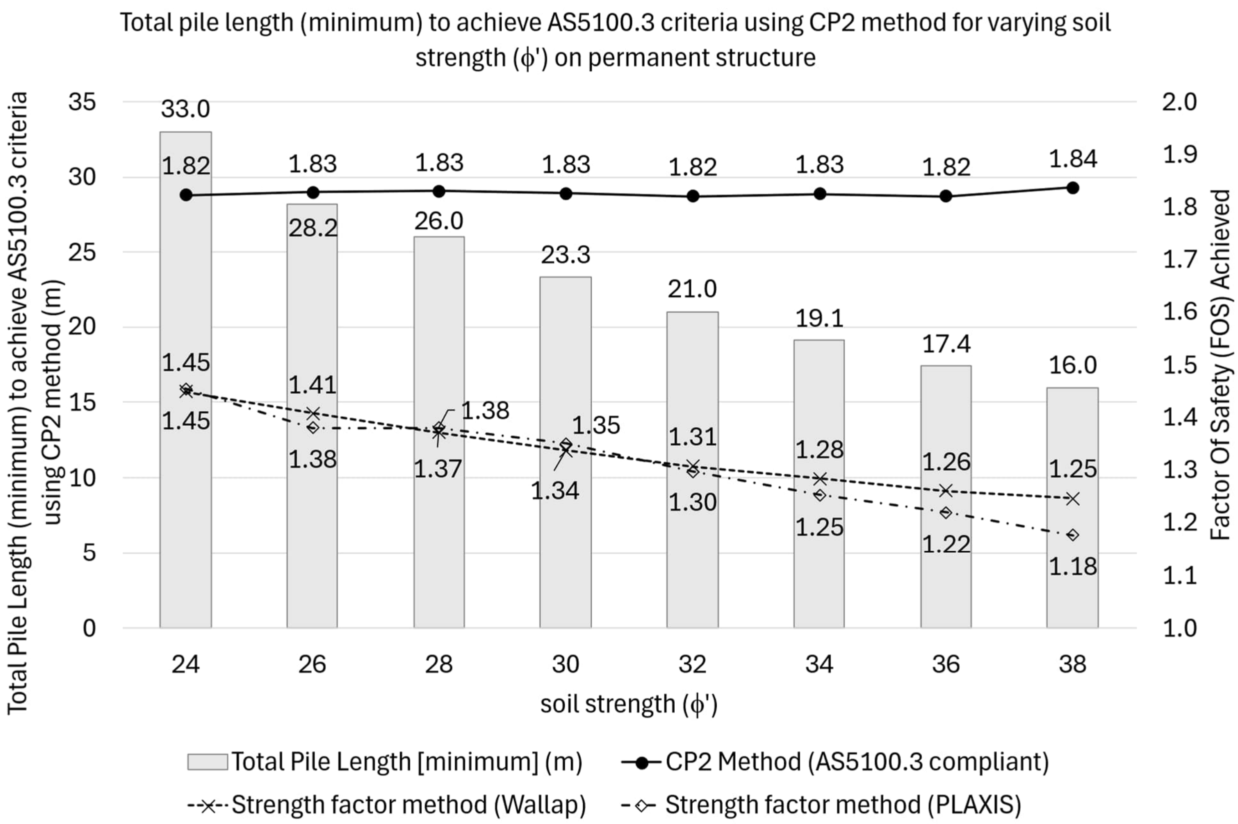


Figure 5: Example of plotted output from parametric model

Table 8: Outcomes of parametric modelling – varying effective soil strength, retained height, surcharge magnitude, water table height

Tested variable	Target FOS_{AS5100}		Equivalent FOS_{SF} using Strength Factor method (based on required pile length to achieve FOS_{AS5100})									
Soil strength, ϕ'		Test variable value (ϕ'), deg	24°	26°	28°	30°	32°	34°	36°	38°	-	Equivalent FOS_{SF}
	1.43	**Total pile length to attain FOS_{AS5100} per AS5100.3 (m)**	**27.4**	**24.6**	**22.2**	**20.2**	**18.5**	**16.9**	**15.6**	**14.4**		-
		Strength Factor (WALLAP)	1.23	1.21	1.19	1.18	1.17	1.15	1.14	1.13		1.13 – 1.23
		Strength Factor (PLAXIS Phi/C)	1.25	1.22	1.19	1.17	1.14	1.11	1.07	1.05		1.05 – 1.25
	1.82	**Total pile length to attain FOS_{AS5100} per AS5100.3 (m)**	**33**	**28.2**	**26**	**23.3**	**21**	**19.1**	**17.4**	**16**		-
		Strength Factor (WALLAP)	1.45	1.41	1.37	1.34	1.31	1.28	1.26	1.25		1.25 – 1.45
		Strength Factor (PLAXIS Phi/C)	1.45	1.38	1.38	1.35	1.30	1.25	1.22	1.18		1.18 – 1.45
Retained height, H		Test variable value (H), m	2	4	6	7.5	-	-	-	-	-	Equivalent FOS_{SF}
	1.43	**Total pile length to attain FOS_{AS5100} per AS5100.3 (m)**	**2.7**	**7.8**	**13.3**	**16.1**	-	-	-	-	-	-
		Strength Factor (WALLAP)	1.10	1.13	1.15	1.15	-	-	-	-	-	1.10 - 1.15
		Strength Factor (PLAXIS Phi/C)	1.12	1.15	1.09	1.07	-	-	-	-	-	1.07 - 1.15
	1.82	**Total pile length to attain FOS_{AS5100} per AS5100.3 (m)**	**2.8**	**8.6**	**14.8**	**18.1**	-	-	-	-	-	-
		Strength Factor (WALLAP)	1.14	1.23	1.27	1.27	-	-	-	-	-	1.14 -1.27
		Strength Factor (PLAXIS Phi/C)	1.24	1.26	1.23	1.24	-	-	-	-	-	1.15 - 1.27
Surcharge, q		Test variable value (q), kPa	0	10	20	30	40	50	-	-	-	Equivalent FOS_{SF}
	1.43	**Total pile length to attain FOS_{AS5100} per AS5100.3 (m)**	**15.7**	**16**	**16.1**	**16.3**	**16.5**	**16.7**	-	-	-	-
		Strength Factor (WALLAP)	1.15	1.15	1.15	1.15	1.15	1.15	-	-	-	1.15
		Strength Factor (PLAXIS Phi/C)	1.11	1.08	1.07	1.07	1.07	1.06	-	-	-	1.06 - 1.11
	1.82	**Total pile length to attain FOS_{AS5100} per AS5100.3 (m)**	**17.6**	**17.9**	**18.2**	**18.4**	**18.6**	**18.8**	-	-	-	-
		Strength Factor (WALLAP)	1.28	1.28	1.28	1.28	1.27	1.27	-	-	-	1.27 - 1.28
		Strength Factor (PLAXIS Phi/C)	1.24	1.23	1.22	1.20	1.19	1.19	-	-	-	1.19 - 1.24

Tested variable	Target FOS_{AS5100}		Equivalent FOS_{SF} using Strength Factor method (based on required pile length to achieve FOS_{AS5100})									
Water table (active), W – measured relative to formation level on active side		Test variable value (W), m	0	1.5	3	4.5	6	7.5	-	-	-	Equivalent FOS_{SF}
	1.43	**Total pile length to attain FOS_{AS5100} per AS5100.3 (m)**	**18.5**	**16.9**	**15.5**	**14.3**	**13.3**	**12.6**	-	-	-	-
		Strength Factor (WALLAP)	1.16	1.15	1.13	1.12	1.11	1.10	-	-	-	1.10 - 1.16
		Strength Factor (PLAXIS Phi/C)	1.01	1.03	1.07	1.10	1.09	1.10	-	-	-	1.01 - 1.10
	1.82	**Total pile length to attain FOS_{AS5100} per AS5100.3 (m)**	**20.6**	**18.8**	**17.1**	**15.6**	**14.4**	**13.5**	-	-	-	-
		Strength Factor (WALLAP)	1.29	1.27	1.25	1.22	1.20	1.19	-	-	-	1.19 - 1.29
		Strength Factor (PLAXIS Phi/C)	1.11	1.13	1.16	1.19	1.18	1.16	-	-	-	1.11 - 1.19

8 DISCUSSION OF ANALYSIS OUTCOMES

For parametric models with the same modelled conditions and same embedded wall length,

- CP2 (AS5100.3 compatible) assessment outcomes consistently derived higher FOS compared with the Strength Factor assessments, i.e. FOS_{AS5100} was consistently greater than FOS_{SF}
- The Strength Factor values from both WALLAP and PLAXIS using Strength Factor methods were very similar

The "equivalent FOS" results using Strength Factor methods of analyses (FOS_{SF}) have been summarised in Table 9. Note that this "equivalency" is only relevant for the parameters discussed within this paper.

Table 9: AS5100.3 design criteria and corresponding equivalent FOS using Strength Factor methods (FOS_{SF}) for the same embedment depth. Summarised from Table 8

	AS5100.3 Criteria		**Strength Factor method ***
Design case	ϕ_g	**FOS_{AS5100}**	**Equivalent FOS (FOS_{SF})**
Temporary structures	0.45 – 0.70	1.43 – 2.22	1.01 - 1.25
Permanent structures	0.45 – 0.55	1.82 – 2.22	1.11 - 1.45

* assessed using Strength Factor method in WALLAP and PLAXIS

9 FUTURE WORK

When this paper was being written, amendment 1 to Part 3 of AS5100.3 – 2017 (Amd 1:2023 Bridge Design Foundation and Soil Supporting Structures) was released in December 2023. Major changes in this amendment affecting stability analysis of retaining walls relate to the range of ϕ_g factor for design of temporary and permanent structures. These are summarised in Table 10.

Table 10: Comparison of design criteria between AS5100.3 – 2017 and AS5100.3 Amd 1:2023

	Comparison of AS5100.3 Criteria	
Design case	ϕ_g **AS5100.3 – 2017**	ϕ_g **AS5100.3 Amd 1:2023**
Temporary structures*	0.45 – 0.70	0.54 – 0.78
Permanent structures	0.45 – 0.55	0.45 – 0.65

*Amd 1:2023 does not provide a ϕ_g for temporary structures but provides guidance that the adopted ϕ_g may be multiplied by a factor of up to 1.2. Provided rages in Table 10 for temporary structures is based on a factor of 1.2 applied to ϕ_g for Permanent Structures.

For simplicity, the analysis undertaken as part of this paper has been based on ϕ_g as per AS5100.3 – 2017 and not the amendment. In authors' view, the conclusions made in this paper remain valid.

10 CONCLUSIONS

The following conclusions can be drawn:

- For geotechnical strength and stability design of embedded retaining walls, AS5100.3 follows a limit state design approach which imposes a reduction factor (geotechnical strength reduction factor, ϕ_g) to the gross passive earth pressure. This approach is analogous to the CP2 method.

- Commonly adopted embedded wall software such as WALLAP (Strength Factor Method) and PLAXIS follows the Strength Factor method which progressively applies a single reduction factor to all values of soil strength in both the active and passive zones until a state of failure or instability is reached
- Due to the incompatibility of the analysis methods, Factors of Safety (FOS) attained using Strength Factor methods (FOS_{SF}) are not equivalent to the FOS (inverse of load / reduction factors) stipulated in AS5100 (FOS_{AS5100})
- For a defined set of parametric variables and assumptions, the authors have ascertained "equivalent FOS" using Strength Factor analyses (Method 4), i.e. FOS_{SF}, to match (as closely as possible) the minimum embedded lengths calculated using CP2 / AS5100.3 (Method 1) which satisfy reduction factors of ϕ_g per AS5100.3, i.e. FOS_{AS5100}. For all parametric models with the with the same modelled conditions and same embedded wall length, CP2 (AS5100.3 compatible) assessment outcomes consistently derived higher FOS compared with the Strength Factor assessments, i.e. FOS_{AS5100} was consistently greater than $FOS_{SF.}$ Note that the "equivalent FOS" values achieved are only applicable for the variables and assumptions covered within this paper, i.e. these values may not be applicable in a universal sense.
- For problems with variables beyond those covered by this paper, it is the authors' opinion that AS5100.3 (CP2) assessments should be undertaken in the first instance to ensure attainment of the prescribed project criteria before embarking on Strength Factor methods using more commonly used software.
- It is essential that designers recognise the different methods available for embedded wall stability assessment and understand that FOS is defined differently across these methods.
- This paper addresses the criteria from AS5100.3 – 2017 and AS5100.3 Supplement 1 – 2008 only.
- This paper addresses geotechnical strength and stability analyses only. Serviceability and Structural design are not covered herein but should always be considered for all retaining wall designs

CRediT authorship contribution statement

Idy Li: Writing - original draft. **Jawad Zeerak:** Writing - original draft. **Jackson Ho:** Writing - original draft.

11 REFERENCES

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CIRIA C760 (2017) Guidance on embedded retaining wall design
Clayton C.R.I, Woods R.I, Bond A.J, Milititsky J (2013) Earth Pressure and Earth-Retaining Structures, Third Edition, CRC Press
PLAXIS Connect Edition V22.01 (2022) Finite element code for soil and rock analyses, Version 22, Bentley

12 APPENDICES

Graphs of all parameter models

- Tested variable, Soil strength, ϕ' (range = 24° to 38°)
- Retained height, H (range 2m to 7.5m)
- Surcharge pressure, q (range 0kPa to 50kPa)
- Water table height, W (range 0m to full retained height)

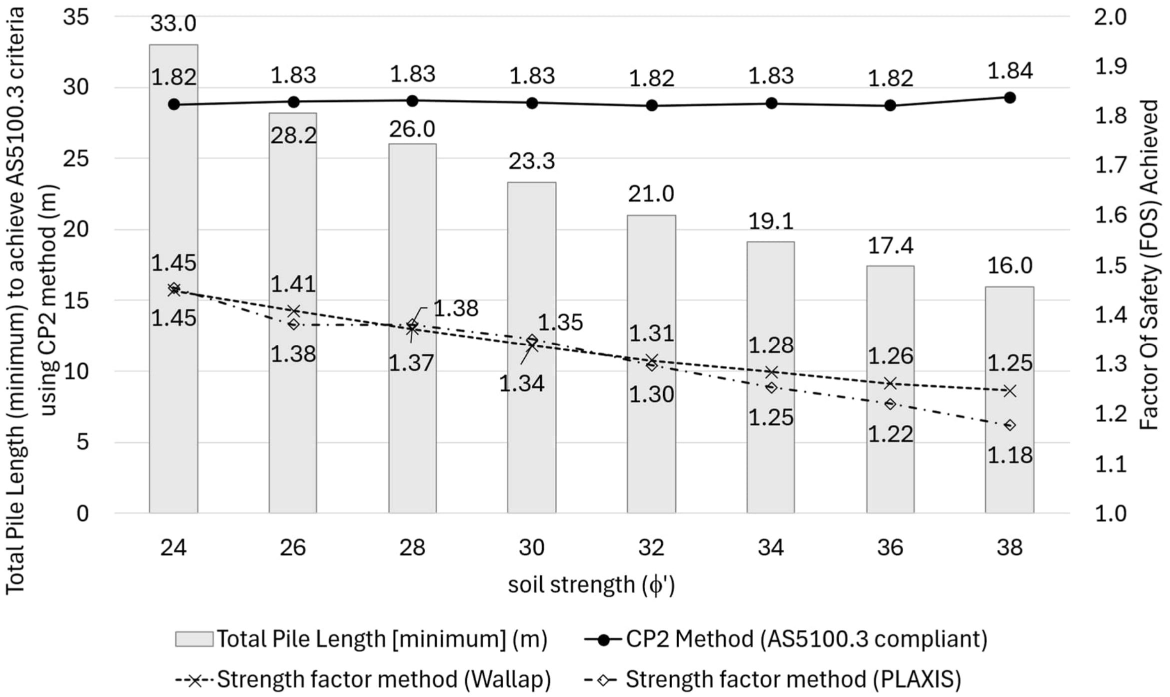

Figure 6: Total pile length (minimum) to achieve AS5100.3 criteria using CP2 method for varying soil strength (ϕ) on permanent structure

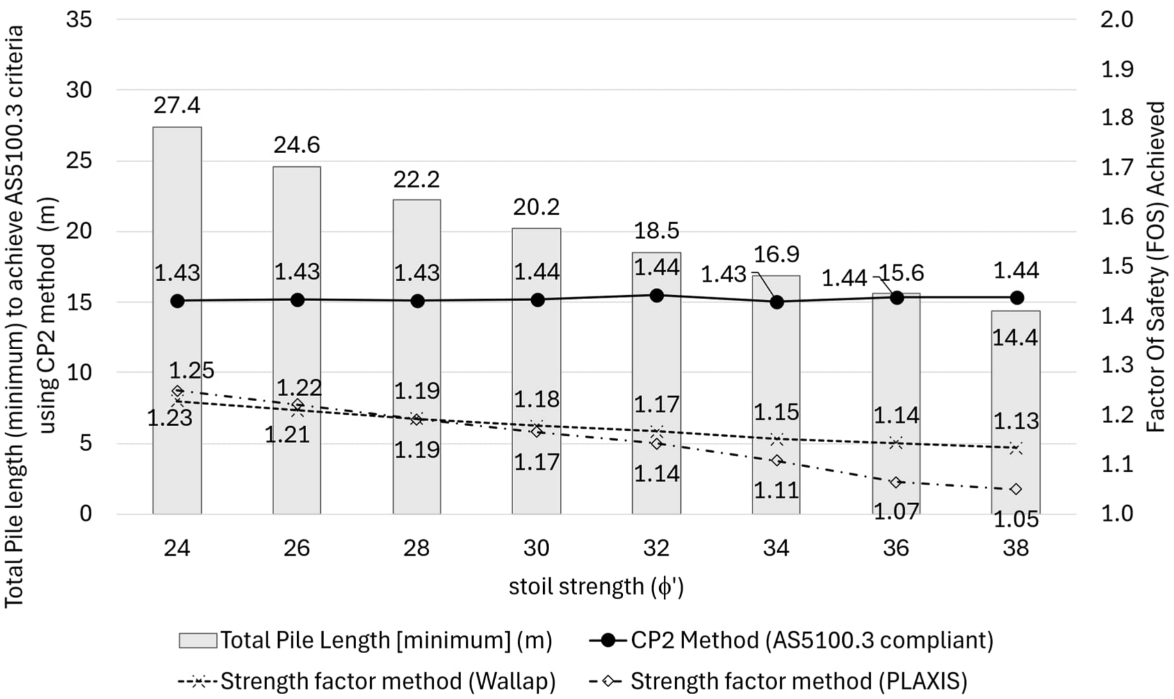

Figure 7: Total pile length (minimum) to achieve AS5100.3 criteria using CP2 method for varying soil strength (ϕ) on temporary structure

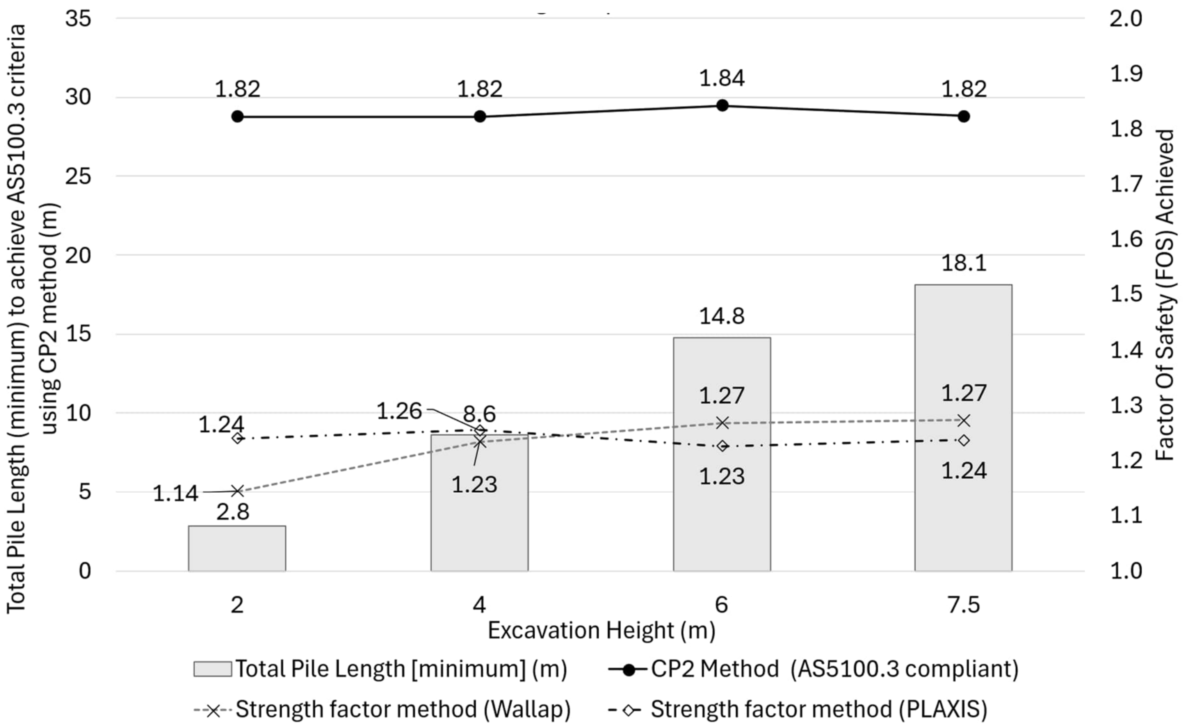

Figure 8: Total pile length (minimum) to achieve AS5100.3 criteria using CP2 method for varying excavation height on permanent structure

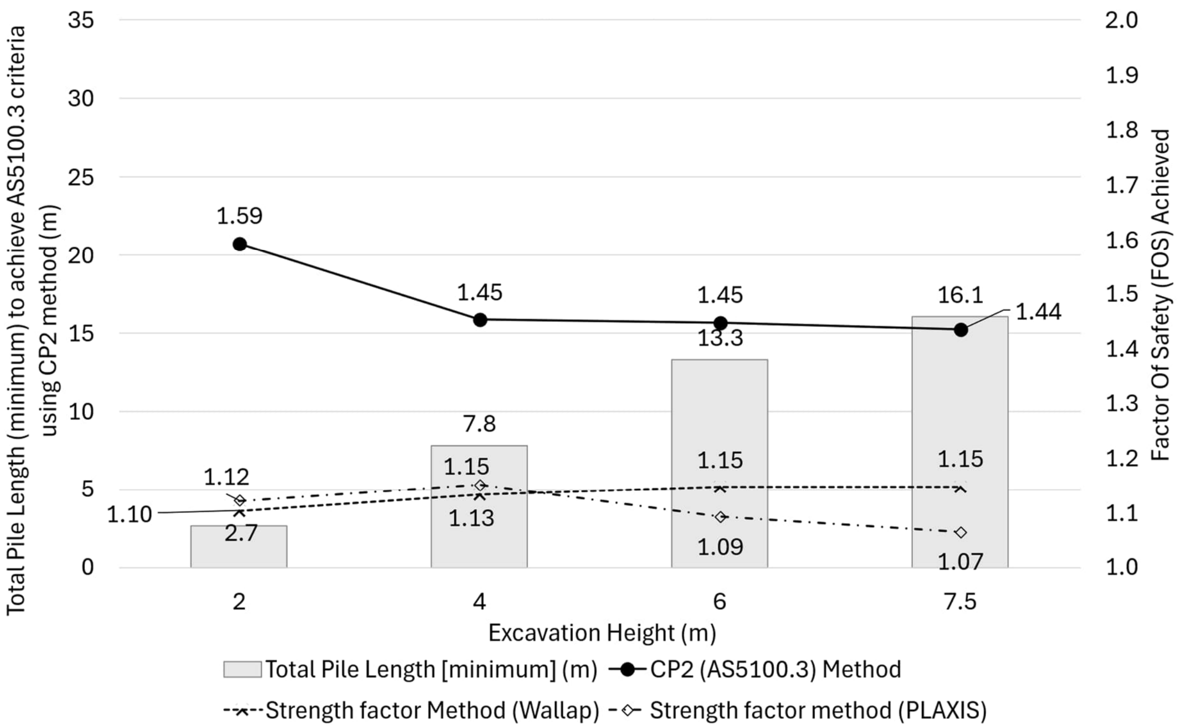

Figure 9: Total pile length (minimum) to achieve AS5100.3 criteria using CP2 method for varying excavation height on temporary structure

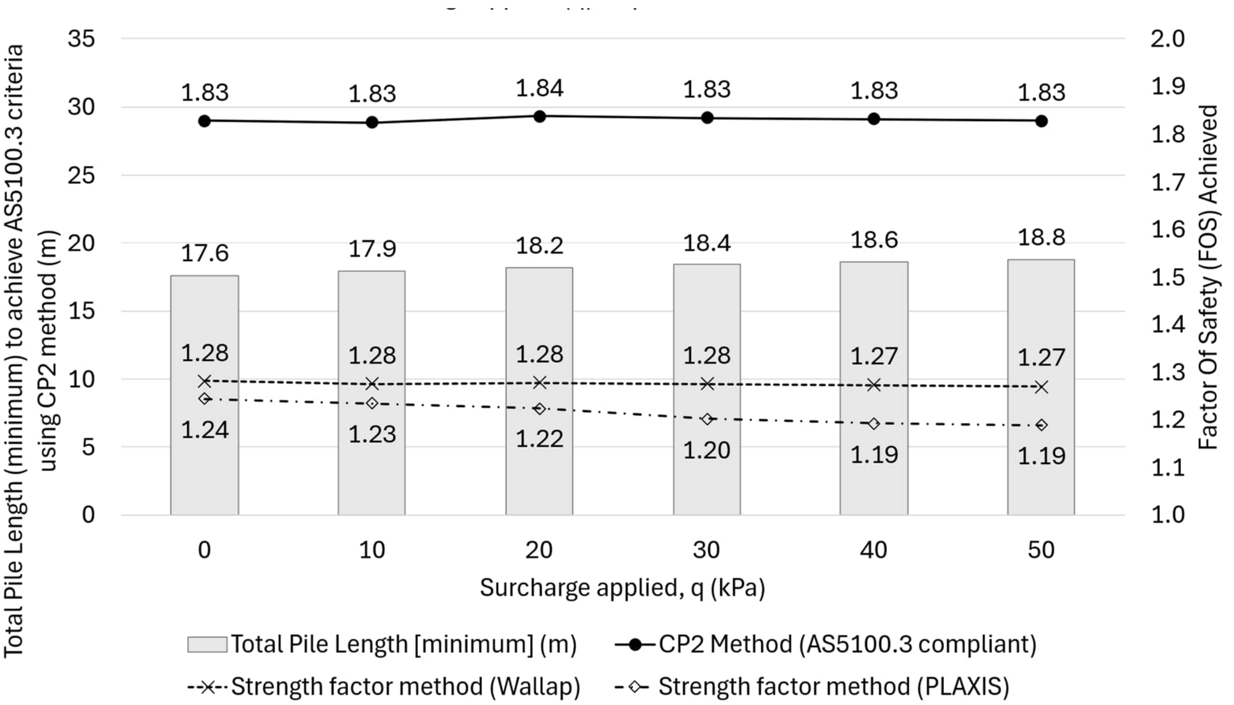

Figure 10: Total pile length (minimum) to achieve AS5100.3 criteria using CP2 method for varying surcharge applied (q) on permanent structure

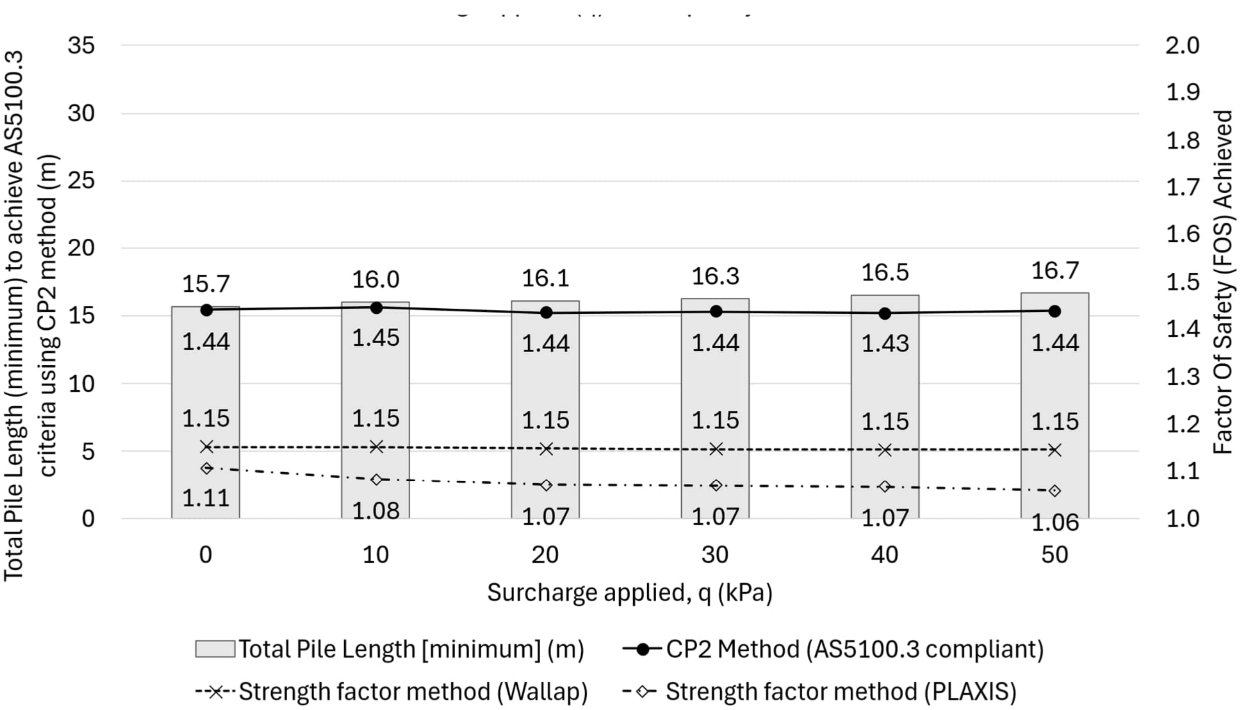

Figure 11: Total pile length (minimum) to achieve AS5100.3 criteria using CP2 method for varying surcharge applied (q) on temporary structure

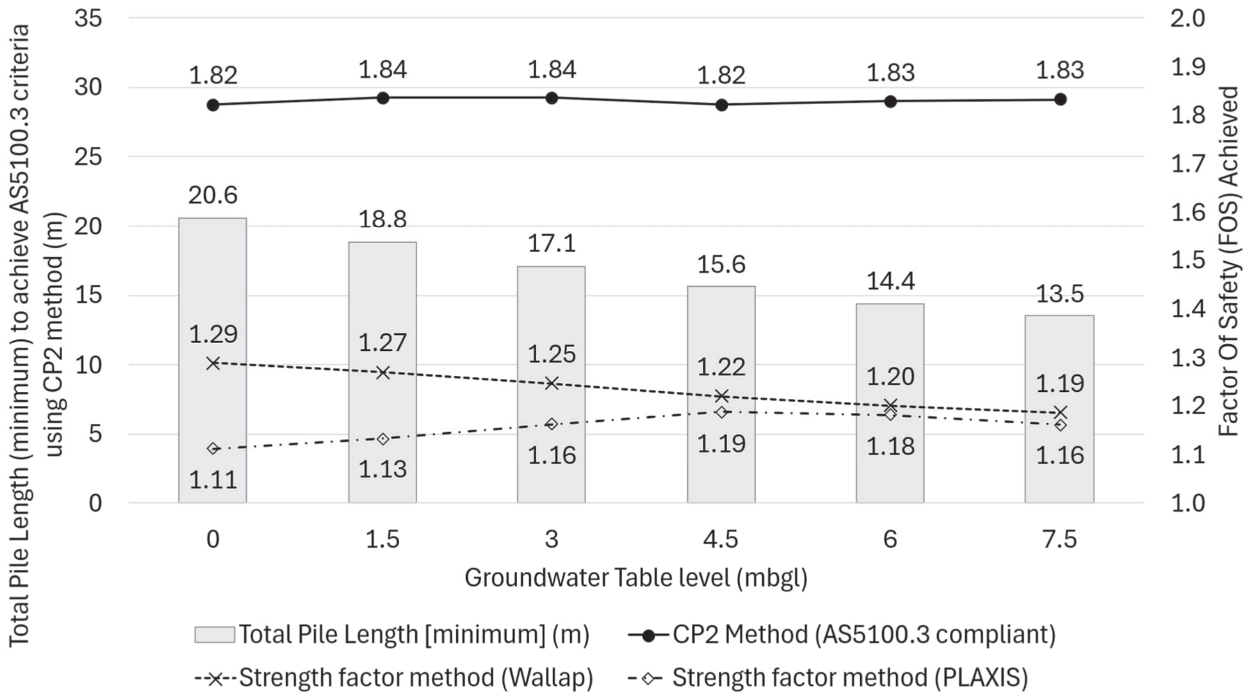

Figure 12: Total pile length (minimum) to achieve AS5100.3 criteria using CP2 method for varying groundwater table level on permanent structure

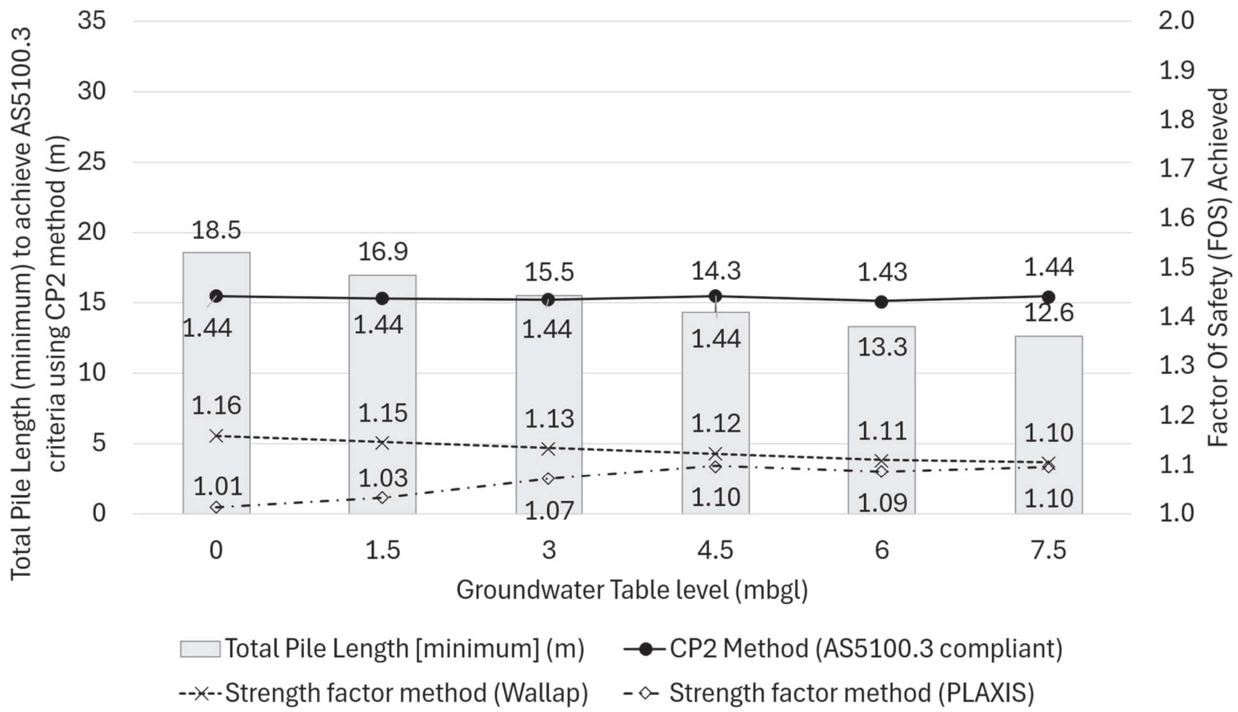

Figure 13: Total pile length (minimum) to achieve AS5100.3 criteria using CP2 method for varying groundwater table level on temporary structure