Int. J. of GEOMATE, Sept., 2015, Vol. 9, No. 1 (Sl. No. 17), pp. 1395-1402
Geotech., Const. Mat. and Env., ISSN:2186-2982(P), 2186-2990(O), Japan

ANCHORED WALL DESIGN: COMPARING THE GLOBAL AND PARTIAL FACTORS OF SAFETY INCORPORATING THE AUSTRALIAN STANDARDS

Hadi Khabbaz[1] and Ye Aung[2]

[1,2] Centre for Built Infrastructure Research, University of Technology, Sydney (UTS), NSW, Australia

ABSTRACT: A versatile and user-friendly model has been developed for evaluating the factor of safety of anchored sheet-pile structures, using both global factors of safety (GFS) and partial factors of safety (PFS) methods, abiding AS 4678 standard, an Australian standard for retaining wall design. The developed model is aimed to determine the following features: (i) depth of embedment, (ii) total wall height for determining the amount of material required, (iii) the length of anchor, (iv) the anchor force and (v) the maximum moment acting on the sheet-pile wall. Key findings are highlighted based on the design calculations. This study incorporates different design scenarios including layered soil, line loads and uniformly distributed surcharge loads to draw comparisons between the GFS and PFS methods. Many examples are used to validate the outputs of the program. The results indicate that the PFS method is preferred for design strength and safety aspects, whereas the GFS method is adopted for cost effectiveness and simplicity of design calculations. The limitations of the Australian standard AS 4678-2002 are discussed in order to identify the superiority of one method over another.

Keywords: Anchored walls, Global Factor of Safety (GFS), Partial Factor of Safety (PFS)

1. INTRODUCTION

Retaining walls are one of the most important types of engineering structures. The main purpose of the retaining wall is to withstand the forces exerted by the retained ground and to transmit these forces safely to the foundation, as expressed in [1]. This paper focuses mainly on the design of anchored sheet-pile walls. Nowadays, anchored walls are widely used in highway construction projects for stabilisation of excavations and embankments. This paper presents the main steps of developing a graphical user interface program employing MATLAB software for the design of the earth-retaining structures, particularly anchored sheet-pile walls. The two most common methods of calculations of the factors of safety are incorporated, namely the global factor of safety (GFS) and the partial factor of safety (PFS).

2. FACTOR OF SAFETY METHODS: GFS AND PFS

The GFS method has traditionally been used to analyse the stability of retaining walls. It depends not only on the factor of safety, but also on the list of the following factors: (i) the probability of failure, (ii) the use of appropriate soil parameters and (iii) the determination of loading conditions. According to [2]:

$$Factor\ of\ Safety = \frac{Resisting\ Actions}{Destabilising\ Actions} \tag{1}$$

Typical global factors of safety for the three major retaining wall failure modes are considered based on the suggestions provided by [3], [4]. These factors are shown in Table 1.

Table 1 Global factors of safety

Failure Modes	*Factor of Safety*
Overturning about the toe	2
Sliding on the base	1.5
Excessive pressure on soil	3

In contrast to the GFS method, the PFS method takes into account of different adjustment factors for loading and material properties, commensurate with different reliabilities and consequences, in compliance with the Australian Standard AS 4678-2002, as stated in [3].

Reference [6] incorporates the structural classification factor, Φ_n, ranging from 0.9 to 1.1 depending on the importance level of the structure or consequences of failure. The approach must satisfy the following condition:

$$\Phi_n R^* \geq S^* \tag{2}$$

where,

Φ_n = the structural classification factor
R^* = the design strength parameters obtained by reducing the characteristic strength values of the soil using different partial factors of safety
S^* = the design action effects obtained by using factored-up disturbing actions

According to [6], various combinations of partial load factors are provided in Tables 2 to 4.

Table 2 Load factors (PFS method)

Load Factor	*Strength*	*Stability*	*Serviceability*
Dead load of wall and contained soil	1.25	0.8	1
Dead load of earth pressure behind wall	1.25	1.25	1
Dead load of fill in front of wall	0.8	0.8	1
Water pressures on either side of wall	1	1	1
Live load on top of wall and contained soil	1.5	0	0.7 or 0.4*
Live load on backfill behind wall	1.5	1.5	0.7 or 0.4*
Live load on fill in front of wall	0	0	0

* 0.7 for long term case and 0.4 for short term case

The surcharge loading effects are also adjusted by using a factor of 1.5, provided that the minimum live load of 5 kPa must be applied to all the structures. This indicates that the minimum surcharge loading of 7.5 kPa must be applied according to the standard.

Table 3 Soil shear strength parameters (PFS method)

Soil or Fill Properties: c' and ϕ'					
		Fill Class I (98%)	*Fill Class II (95%)*	*Uncont-rolled Fill*	*In-situ Soil*
Strength	$\phi_{u\phi}$	0.95	0.90	0.75	0.85
	ϕ_{uc}	0.90	0.75	0.50	0.70
Service-ability	$\phi_{u\phi}$	1.00	0.95	0.90	1.00
	ϕ_{uc}	1.00	0.85	0.65	0.85
Soil or Fill Property: C_u					
Strength	ϕ_{uc}	0.60	0.50	0.30	0.50
Service-ability	ϕ_{uc}	0.90	0.80	0.50	0.75

Table 4 Structural classification factors (PFS method)

Classification	*Examples of structures*	φ_n
A	Where failure would result in significant damage and loss of access	0.9
B	Where failure would result in moderate damage and loss of services	1
C	Where failure would result in minimal damage and loss of access	1.1

3. MAJOR ASPECTS OF AS 4678 STANDARD

As 4678 [6] does not refer to the common earth pressure coefficients, K_o, K_a and K_p and uses the modified parameters c* and Φ* to describe a soil. It is not applicable to walls less than 800 mm high [6]. According to [7], it takes into account of the effect of proposed construction on the adjoining ground and the effective drainage system associated with the wall.

4. DESIGN OF ANCHORED SHEET-PILE WALLS – PROPOSED METHOD

4.1 Free Earth Support Method

The major assumption is that the base of the pile is relatively free to move (Fig. 1). This means that the passive resistance is mobilised on one face only. This method often provides a cost-effective solution by giving smaller depth of embankment but larger bending moments compared to the fixed earth support method.

4.1.1 Assumptions

The main assumptions are: [8], (i) sheeting is rigid compared to the soil; however, if anchor yields for some exceptional cases, it is normally sufficient to give full active pressure at the top of the wall, provided that the active earth pressures occur over the full height of the retained soil, (ii) the depth of embedment of the sheet-pile wall is assumed to be insufficient to provide fixity at the bottom end of the wall, (iii) the rotation of the sheet-pile wall is assumed to be about the point of attachment of the anchor, and (iv) the anchor does not yield.

These assumptions are essential in the development of the proposed model, considering the fact that this method is regarded as the most frequently used method in design practice, as suggested by [9].

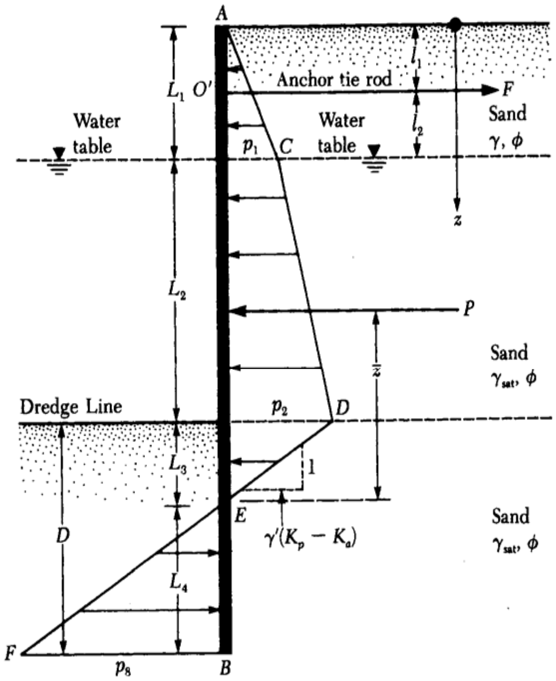

Fig. 1 Free earth support method for penetration of sandy soil [7].

Based the assumptions made by the Free Earth Support method, Eq. (3) – (13) have been analysed and incorporated into the developed model.

$$\theta_{a*} = sin^{-1}\left(\frac{\sin\beta}{\sin\Phi}\right) - \beta + 2\eta \tag{3}$$

$$K_{A*} = \frac{\cos(\beta-\eta)\sqrt{1+sin^2\Phi-2\sin\Phi cos\theta_a}}{cos^2\eta(\cos\beta+\sqrt{sin^2\Phi-sin^2\beta})} \tag{4}$$

$$\theta_{p*} = sin^{-1}\left(\frac{\sin\beta}{\sin\Phi}\right) + \beta - 2\eta \tag{5}$$

$$K_{P*} = \frac{\cos(\beta-\eta)\sqrt{1+sin^2\Phi+2\sin\Phi cos\theta_a}}{cos^2\eta(\cos\beta-\sqrt{sin^2\Phi-sin^2\beta})} \tag{6}$$

The length of Anchor is determined using Sine rule, i.e. Eq. (7).

$$\frac{L}{\sin\theta_1} = \frac{y_1}{\sin\theta_2} \tag{7}$$

The other three unknowns, "y_1, θ_1, θ_2", can be determined from simple geometric equations.

Lateral earth pressures are calculated from Eq. (8) and (9).

$$\sigma_{a*} = K_{a*}\,[\sigma_v'] \tag{8}$$

$$\sigma_{p*} = K_{p*}\,[\sigma_v'] \tag{9}$$

Primarily, the total lateral earth pressure force is determined from the area of the pressure distribution obtained. Since the pressure distribution is mainly of a triangular shape, Eqs. (10) and (11). If the pressure distribution in a rectangular shape, simply use Eq. (12) and (13).

$$[P_{a*}] = [1/2]\,K_{a*}\,[\gamma][H^2] \tag{10}$$

$$[P_{p*}] = [1/2]\,K_{p*}\,[\gamma][H^2] \tag{11}$$

$$[P_{a*}] = K_{a*}\,[\gamma][H] \tag{12}$$

$$[P_{p*}] = K_{p*}\,[\gamma][H] \tag{13}$$

Where,

K_{A*} = the active earth Pressure coefficient
K_{P*} = the passive earth Pressure coefficient
σ_v' = the vertical Effective overburden pressure
σ_{a*} = the active earth pressure
σ_{p*} = the passive earth pressure
P = the lateral Earth Pressure force
γ = the unit weight of soil in kN/m^3
H = the height of the corresponding pressure distribution

5. DESIGN MODEL

MATLAB software was utilized in order to design the computer program that could generate the design outcomes for four major types of earth-retaining structures using both GFS and PFS method, abiding As 4678 [6].

Detailed flow charts have been prepared to be able to identify the major variables and limitations that need to be taken into account in order to determine the scope of the proposed model. Design assumptions have been made, without compromising the usefulness of the model. The whole project has been broken down into small sections that could easily be tested and modified until the program could be deemed to have the capacity to generate desired accurate outcomes. The outcomes generated by the developed model have then been analysed and verified by both hand-written calculations and PLAXIS software.

The developed model has been prioritised to be user-friendly, along with three major attributes including speed, reliability and versatility. The preview of major user-interfaces can be seen in Fig. 2.

The developed model is aimed to determine the following features: (i) depth of embedment, (ii) total wall height for determining of the amount of material required, (iii) the length of anchor, (iv) the anchor force and (v) the maximum moment acting on the sheet-pile wall.

The "Inputs" interface page of the developed model has properly been designed and a snapshot of it can be seen in Fig. 3.

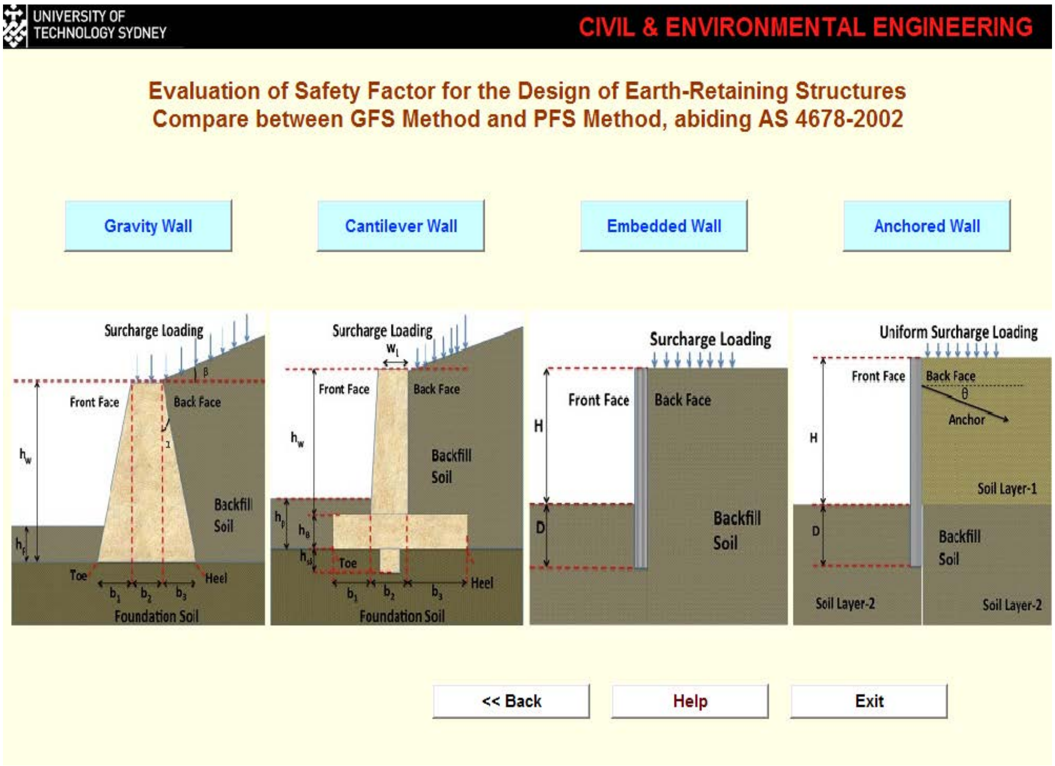

Fig. 2 A snapshot of the main page of the developed model using the graphical user interface in MATLAB

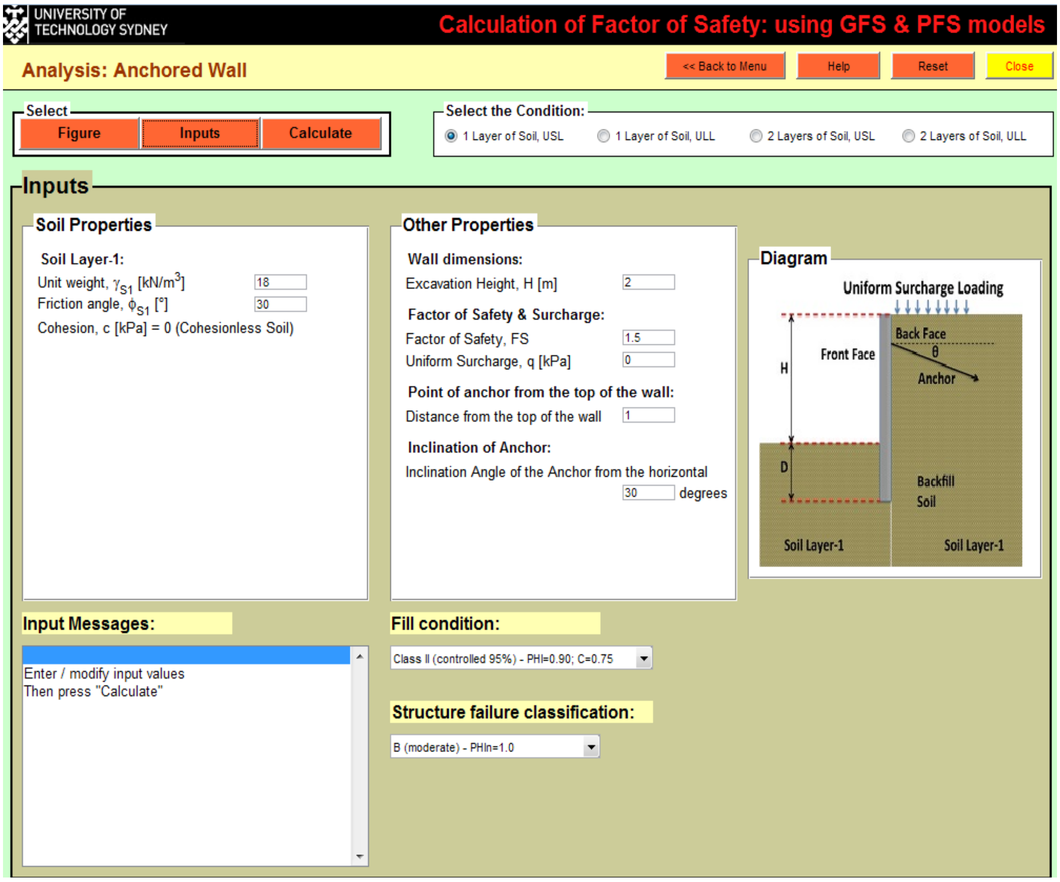

Fig. 3 A snapshot of the "Inputs" page of the model for an anchored wall

5.1 Model Global Assumptions

Major assumptions that have an impact on the whole model have been identified and made, as suggested by comprehensive analyses of the provided references: (i) all types of retaining walls are assumed to be rigid. This means that the active and passive earth pressures are uniformly distributed for simplified calculations, (ii) Rankine's theory has been adopted in favour of Coulomb's theory, as the latter tends to over-estimate the lateral earth pressure coefficients, (iii) all the backfill materials are assumed to be cohesionless in drained conditions, (iv) in determining the passive lateral earth pressure coefficients, the soil in front of the wall is assumed to be frictionless and at zero angle to the ground surface, (v) the surcharge value, which is an input by the user is only considered in evaluating the disturbing actions of the wall, not for the resisting actions, (vi) this program also applies the Hansen's theory in evaluating the ultimate and allowable bearing capacities of the foundation soil.

5.2 Model Local Assumptions

In contrast to global assumptions, these assumptions, only affecting anchored walls, are also identified: (i) the material for the sheet-pile wall is assumed to be steel, (ii) the sheet-pile wall that can be analysed by this model is assumed to have free earth support condition at the end support, (iii) as a result, the design of the anchored sheet-pile wall assumes that the sheet pile being installed is stable as well as the thrust, the passive resistance and the pull in the anchorage tie-rods. The wall deformations have been ignored due to serviceability considerations, according to [10]; (iv) there is no water table in the analysis, which indicates that the granular soil is used and the water table is well below the wall base; (v) the strict equilibrium of a sheet pile wall is assumed for all the foregoing calculations, which utilize the active and passive earth pressure coefficients, determined using the previous assumptions; (vi) the installed anchor is assumed not to be yielded under most circumstances; (vii) however, if anchor yields for some exceptional cases, it is normally sufficient to give full active pressure at the top of the wall, provided that the active earth pressures occur over the full height of the retained soil, (viii) the rotation of the sheet-pile wall is assumed to be about the point of attachment of the anchor; and (ix) the soil existing in front of the wall is assumed to be horizontal.

6. TEST RESULTS

The design outcomes obtained by both GFS and PFS methods are tabulated along with the percentage difference between the two most popular methods for the evaluation of factor of safety, shown in Table 5 and Fig. 4.

Table 5 Sample preview of a particular test case scenario – (anchored wall, Test Case 1)

Key Design Outcomes	*GFS*	*PFS*	*% Diff*
Resultant Active lateral earth pressure force [kN]	61.6	124.1	101.6
Resultant Passive lateral earth pressure force [kN]	41.1	98.9	140.9
Depth of Embedment [m]	1.5	2.3	52.9
Total Wall Height [m]	4.5	5.3	17.7
Anchor Force [kN]	20.5	25.2	22.9
Required Anchor Length [m]	1.8	2.3	30.1
Location of maximum moment from the top [m]	2.6	2.4	-8.5
Maximum moment acting on the wall [kNm]	-14.7	-14.5	-1.8

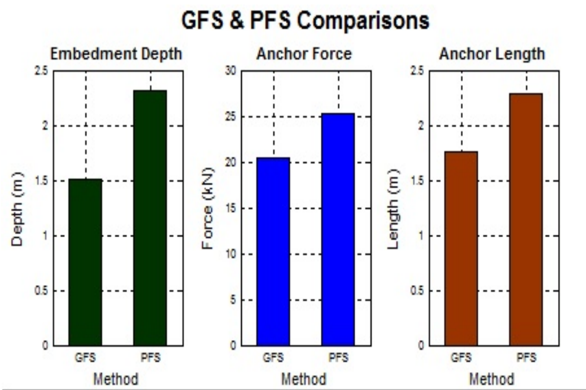

Fig. 4 Sample preview of the comparisons between GFS and PFS methods

7. VALIDATION

The results, generated by the developed model, have been validated by hand calculations and using PLAXIS software to assess the reliability of the developed model. Design inputs for one layer of soil subjected to uniform surcharge loading is shown in Table 6, while the design outputs for one layer of soil subjected to uniform surcharge loading are given in Table 7. The developed model calculations have been compared to PLAXIS results, which are depicted in Table 8, Fig. 5 and Fig 6.

Table 6 Design inputs for one layer of soil subjected to uniform surcharge loading

Anchored Wall	*Design Inputs*	*Values*
Soil Properties	Unit Weight, Υ_{S1} [kN/m3]	18.00
	Friction angle, φ_{S1} [°]	30.00
	Cohesion, c [kPa]	0.00
Other Properties	Excavation Height, H [m]	3.00
	Factor of Safety, FS	1.50
	Uniform Surcharge, q [kPa]	10.00
	Point of anchor from the top of the wall [m]	1.00
	Inclination angle of anchor from the horizontal [°]	30.00
Fill Condition	φ_{φ}	0.90
	φ_{c}	0.75
Structural Failure	φ_{n}	1.00

Table 7 Design outputs for one layer of soil subjected to uniform surcharge loading (anchored wall, Test Case 1)

Key Design Outcomes	*GFS*	*PFS*	*% Diff*
Resultant Active lateral earth pressure force [kN]	81.8	139.5	70.1
Resultant Passive lateral earth pressure force [kN]	51.8	91.9	77.5
Depth of Embedment [m]	1.7	2.2	27.7
Total Wall Height [m]	4.7	5.2	10
Anchor Force [kN]	30.0	47.6	58.5
Required Anchor Length [m]	1.9	2.2	16.8
Location of maximum moment from the top [m]	2.7	2.8	4.9
Maximum moment acting on the wall [kNm]	-19.3	-33.7	74.8

Table 8 Comparing developed model calculations to PLAXIS results

Anchored Wall	*One Layer of Soil subjected to Uniform Surcharge Loading*		
Key Design Outcomes	MATLAB model	PLAXIS software	Difference (%)
Anchor Force [kN]	40.14	44.12	10%
Maximum Moment [kNm]	24.25	21.25	12%

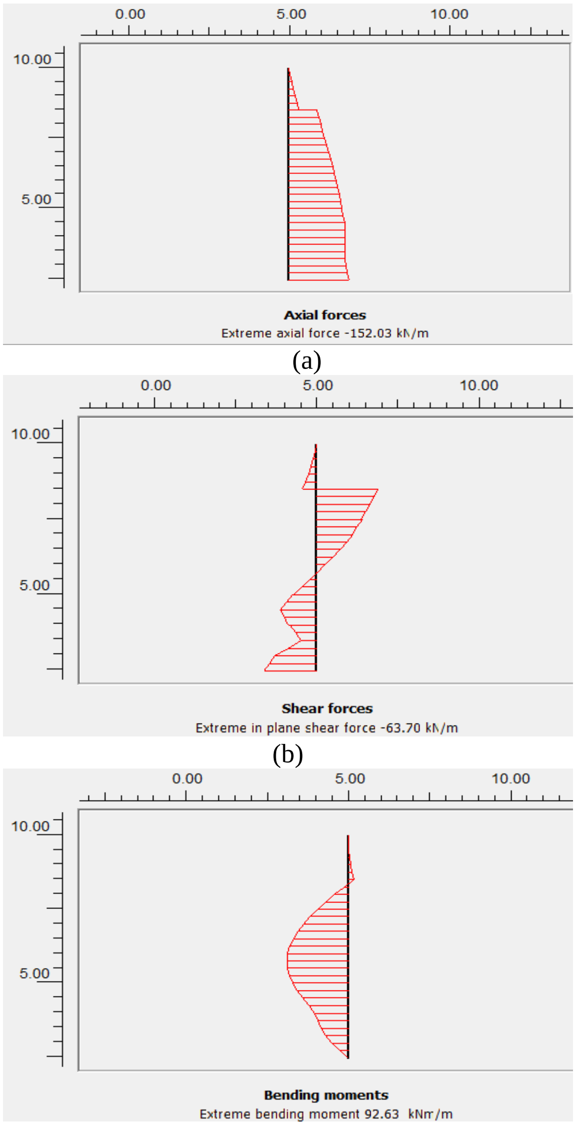

Fig. 5 Model results validated by PLAXIS software (a) axial forces, (b) shear forces and (c) bending moments

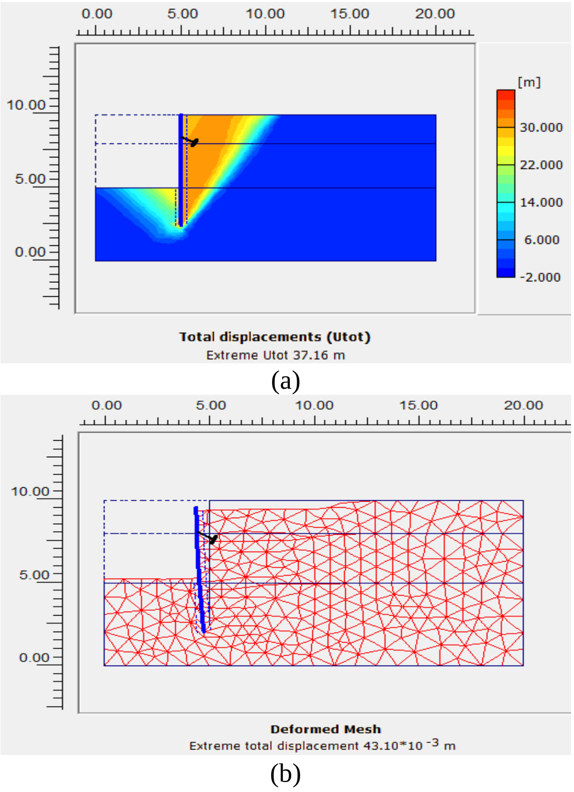

Fig. 6 Model results validated by PLAXIS software (a) total displacements and (b) deformed mesh

8. ADVANTAGES AND DISADVANTAGES OF GFS AND PFS METHODS

8.1 Probability of Failure – Safety Margin

It is quite obvious that PFS method, abiding [6], provides more conservative design as echoed by [11]. This is due to PFS method taking into account of trivial probabilities of failure by applying partial factors of safety to the major design parameters. Using un-factored strengths could potentially result in the under-designed wall, in which the GFS method needs to rectify.

8.2 Design Cost-Effectiveness

Considering the costs, GFS method is deemed to be more favourable as the calculated design results in much smaller steel-section. This means that the costs associated with the extent of complexity of sheet-pile and anchor installation are going to be reduced proportionally.

8.3 Simplicity of Design Calculation

In this case, GFS method, compared with PFS method, is determined to be much simpler and less vulnerable to the calculation errors in the design of Earth-retaining structures.

8.4 Design Consideration

PFS method considers additional design considerations: (i) consideration of the subsurface variability across the site, (ii) the quality and reliability of the soil strength data, (iii) the longevity of the retaining structure, (iv) environmental effects, such as proper drainage system, and (v) confidence in the magnitude of surcharge loading. Both literature (e.g. [12] and [13]) and developed model results indicate that PFS method is more advantageous than GFS method, when it comes to the safety aspects of the earth-retaining structures.

8.5 Designer's Perspective

As safety factor is incorporated only in one stage of the design calculations, GFS design is extremely vulnerable to failure unless the designer has sufficient experience to select the vital safety factor values.

PFS method, however, has its own adjustment factors set by the standard (AS 4678) [6], regarding the relevant types of earth-retaining structure, as explained in [6]. The standard adopts an ultimate limit state approach in determination of earth pressures, resisting forces and bending moments.

Therefore, it can be concluded that the reliance on the experience of the engineer is much reduced with the adoption of PFS method.

9. KEY FINDINGS BETWEEN GFS AND PFS METHODS

Table 9 mainly describes the advantages of each method over the other with respect to specific design criteria. Since both of these methods have their own advantages and disadvantages, the adoption of one method over another mainly depends on the design requirements as well as the designer's expertise and interest.

Table 9 Key findings comparing GFS and PFS methods

Design Criteria	*GFS Method*	*PFS Method*
Safety		☑
Design Strength		☑
Simplicity of Design Calculations	☑	
Compatibility with other design codes		☑
Cost-effectiveness	☑	
Designer's perspective		☑
Designer's experience & judgment	☑	

10. CONCLUSIONS

A user friendly program, using MATLAB software, was developed for the design of earth-retaining structures, including gravity walls, cantilever walls, embedded walls and anchored sheet-pile walls in particular. The global factor of safety (GFS) and the partial factor of safety (PFS) methods were used to evaluate active and passive earth pressures, which are crucial in design calculations. Four major design scenarios, for which the developed model can be used, were arbitrarily created by taking into account of the literature background to reflect the real-world design situations. The three major attributes of the developed model, embracing speed, reliability and versatility, were then uncompromised with the support of available information.

The results indicate that PFS method, abiding the AS 4678 Australian standard, tends to provide more conservative design compared to the traditional GFS method. The use of multiple adjustment factors in the PFS method indicates the fact that it takes into account various uncertainties associated with the design. The applications of fill and structure classification as well as the multiplication of strength and load factors reflect the supremacy of the PFS method in considering the safety factor of the Anchored structures. However, the variations of many different parameters produce dramatic changes in both GFS and PFS methods, hence making it difficult to achieve accurate determination on the percentage differences between GFS and PFS methods.

11. ACKNOWLEDGMENT

The authors would like to acknowledge Erikas Datenis efforts, UTS former undergraduate student, developed the initial model for retaining wall design, which was a foundation to carry on the anchored sheet-pile walls section.

12. REFERENCES

[1] Castillo E, Minguez R, Reran AR and Fernandez-Canteli A, "Design and sensitivity analysis using the probability-safety-factor method". An application to retaining walls, Elsevier Ltd, Spain, 2003, pp. 159-179.

[2] Kempfert H and Gebreselassie B, "Supported excavations in soft soil deposits", Excavations and foundations in soft soils, Springer-Verlag, 2006, pp. 149-152.

[3] Das BM, "Earth Anchors", Elsevier Science Publishers, Amsterdam, 1990.

[4] Day RA, Wong PK and Poulos, HG, "Fifteen years of geotechnical limit state design in Australia - Part 1, Soil retaining structures", in Proc. 10th ANZ Geomechanics Conf. 2011, pp. 596-601.

[5] Simpson B, "Partial factors of safety for the design of retaining walls", Geotechnique, Vol. 42, No. 1, 1992, pp. 131-136.

[6] AS 4678-2002, Australian Standard, "Earth-Retaining Structures", 2002.

[7] Shirley A, "An overview of AS 4678-2002 – Earth Retaining Structures", http://www.shirley.net.au/pdf/An_Overview_of_AS4678_Earth_Retaining_Structures.pdf, viewed August 2013.

[8] Rowe PW, "Anchored Sheet-Pile Walls", ICE Proceedings, Vol. 1, Issue. 1, 1952, pp. 27-70.

[9] Budhu M, "Foundations and Earth Retaining Structures", John Wiley & Sons, Inc., USA, 2008.

[10] Bilgin O and Erten MB, "Analysis of Anchored Sheet Pile Wall Deformations", Contemporary Topics in Ground Modification, Problem Soils, and Geo-Support, American Society of Civil Engineers, 2009.

[11] Wijaya J and Taiebat HA, "Factor of Safety in AS 4678-2002: Earth Retaining Structures", Australian Geomechanics Journal, Vol. 44, No. 4, 2009, pp. 27-32.

[12] Simpson B, "Partial factors: where to apply them?", LSD2000: International Workshop on Limit State Design in Geotechnical Engineering, Melbourne, Australia, 2000, pp. 1-10.

[13] Geotechnical Engineering Office, "Guide to Retaining Wall Design", Civil Engineering Department, Government Publications Centre, Hong Kong. 1993.

Int. J. of GEOMATE, Sept., 2015, Vol. 9, No. 1 (Sl. No. 17), pp. 1395-1402.
MS No. 4291 received on July 10, 2014 and reviewed under GEOMATE publication policies.

Corresponding Author: Hadi Khabbaz