Retaining Wall Design - SESOC

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ABSTRACT

In the absence of a recognised or accepted national standard, and in order to provide clarity around the technical basis for their retaining wall software, some time ago SESOC embarked on the development of two design guides for these, namely the:

- Cantilever Timber Pole Wall Design Guide, and the
- Concrete Retaining Wall Design Guide.

The goal was for a consolidated and coherent methodology for static/gravity design, covering a range of common scenarios, including water table, sloped walls, retained slope, pole spacing effects, shear key, etc – as well as a clear and consistent set of load factors.

In addition to static design, dynamic aspects also must be handled, with a number of challenges in order to present a methodology which is both robust as well as suitable for use by the typical structural practitioner.

This presentation will (briefly) cover these design guides.

1 INTRODUCTION

1.1 Software Origins

It was by happenstance, back in the 1990s, that SESOC became involved in software, as a result of the considerable enthusiasm of one of our early members, Esli Forrest. He initially developed the Soils program, later followed by further work.

Upon taking responsibility for the SESOC Software portfolio circa 2010, it was the first author’s particular question and concern regarding the SESOC Soils program – “What is the Technical Basis ?”, that has prompted this initiative and design guides, and as a result now, this introductory conference paper.

This paper can, of necessity, merely introduce some of the basic concepts underpinning the two design guides, which each run to 50 pages plus. And so, the following pages are intended to provide an insight to the scope, methodology, and some of the challenges, using snips from the original design guides, etc.

Also, in many cases, these may be partial extracts from the much more extensive content of the design guides. And so, for expediency reasons, the reader is asked to overlook the ‘…’ or “etc’ when just some of the key points are presented herein.

1.2 Background

The Soils program provides three main areas of capability, with sub-categories under each of these, as follows :

• Shallow Foundations :	• Pad footings, Strip footings
• Deep Foundations :	• Piles (free and restrained head)
• Retaining :	• Cantilever Pole retaining walls • Reinforced Concrete retaining walls

The program is broadly based on B1/VM4, though of necessity implementing a number of aspects beyond that document.

While the technical basis is well established and documented for the piles and footings, arguably this is less so for the retaining walls design aspect, particularly for a pseudo-static structural mechanics approach.

In particular, the absence of a national standard or widely accepted industry guideline, or even substantive worked examples (ie covering the considerable range of design variations encountered in practice) – as well as an apparent diversity of approach in the Geotech space, left SESOC in the unenviable position of having provided some software without a robust and documented technical basis.

Further to discussion with various people from the Geotech fraternity, it became evident that a national standard and/or guideline was unlikely in a reasonable timeframe.

With respect and acknowledgement to the two (relatively recent) MBIE retaining wall design examples, as well as various national seminars by the late Mick Pender, Brabha Pathmanathan, Kevin McManus, et al, we observe the multiplicity of combinations and permutations of soil type, static and dynamic loading, water table level, vertical or sloped wall, horizontal or sloping retained slope, virtual back of wall, front of wall slope, etc, many of which have not been adequately addressed, if at all.

And so, several years ago now, SESOC embarked on a journey to prepare documentation to serve as a technical basis for the software, with - in hindsight, little knowledge of the effort this would take.

1.3 Scope

It must be noted that the two design guides have been prepared, primarily, as a robust technical basis for the software.

In this regard, we have intentionally constrained the scope to what a competent structural engineer 'should' be able to reasonably undertake – with suitable Geotech input as appropriate.

In other words, we've sought to cover the majority of low rise, 'garden variety' retaining walls, with the higher, or more complex, or tied back, or displacement sensitive type structures to be handled by a professional Geotech practitioner.

1.4 Assumptions & Limitations

There are a number of assumptions and limitations which underpin both guides. Some of the key aspects are provided below :

Fundamental Assumptions

- Granular backfill
- Simple cantilever
- Not displacement sensitive

Geotech assumptions:

- Triangular pressure distribution
- Soil & pore water are homogenous
- . . . .

Geometry :

- <= 3.0m height
- Pole spacing <= 6D [CTP]
- Slope distance limits

Outside these .. you need to engage a Geotech ..

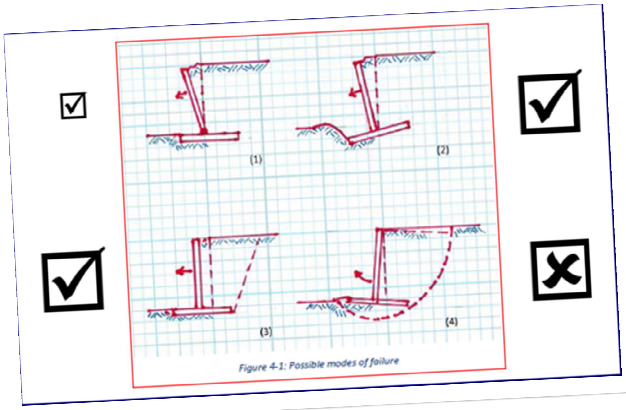
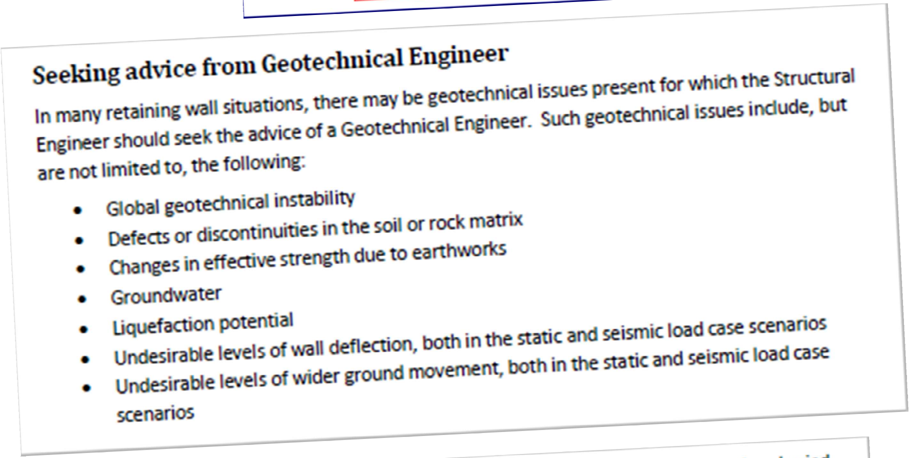


Figure 4-1: Possible modes of failure

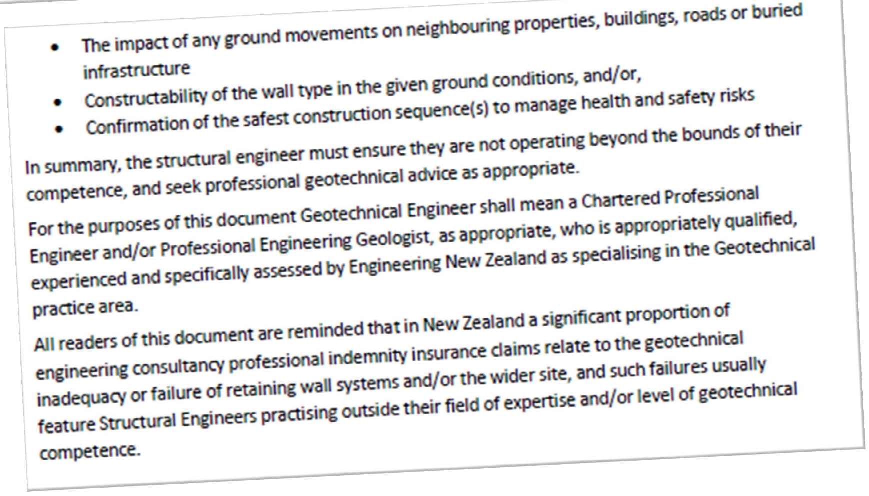
Partial extracts from the relevant content :



Seeking advice from Geotechnical Engineer

In many retaining wall situations, there may be geotechnical issues present for which the Structural Engineer should seek the advice of a Geotechnical Engineer. Such geotechnical issues include, but are not limited to, the following:

- Global geotechnical instability
- Defects or discontinuities in the soil or rock matrix
- Changes in effective strength due to earthworks
- Groundwater
- Liquefaction potential
- Undesirable levels of wall deflection, both in the static and seismic load case scenarios
- Undesirable levels of wider ground movement, both in the static and seismic load case scenarios



- The impact of any ground movements on neighbouring properties, buildings, roads or buried infrastructure
- Constructability of the wall type in the given ground conditions, and/or,
- Confirmation of the safest construction sequence(s) to manage health and safety risks

In summary, the structural engineer must ensure they are not operating beyond the bounds of their competence, and seek professional geotechnical advice as appropriate.

For the purposes of this document Geotechnical Engineer shall mean a Chartered Professional Engineer and/or Professional Engineering Geologist, as appropriate, who is appropriately qualified, experienced and specifically assessed by Engineering New Zealand as specialising in the Geotechnical practice area.

All readers of this document are reminded that in New Zealand a significant proportion of engineering consultancy professional indemnity insurance claims relate to the geotechnical inadequacy or failure of retaining wall systems and/or the wider site, and such failures usually feature Structural Engineers practising outside their field of expertise and/or level of geotechnical competence.

1.5 Editorial Basis

These guides are, intended, in effect as "Retaining Wall Design for Structural Engineers", written **for** structural engineers .. **by** structural engineers .. *but with Geotech input.*

The **Design philosophy** is based on Static pressure blocks (i.e a structural mechanics approach) using **LFRD** but optionally with F.o.S

The methodology includes a wide range of variations as encountered in 'typical' retaining wall design

Including :

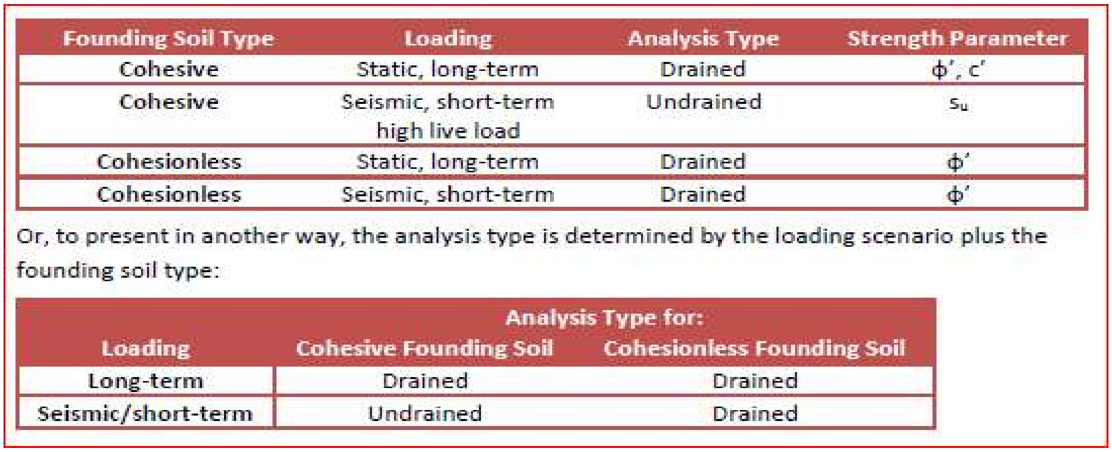
- Soil types : cohesive & cohesionless
- Loading : static + seismic
- Water table : none, at GL, or above GL
- Retaining wall : vertical or sloped
- Retained soil : horizontal or sloped
- Full design methodology
- CTP : pole spacing effects
- RCW : virtual back of wall
- RCW : positional effect of key

But Excluding :

- Construction detailing
- Displacement sensitive structures
- Displacement calcs
- Etc

1.6 Analysis Basis vs Soil Classification and Loading

The following table (extract) shows the interaction between the soil type and loading conditions, and how this affects the calculation process.



Founding Soil Type	Loading	Analysis Type	Strength Parameter
Cohesive	Static, long-term	Drained	ϕ', c'
Cohesive	Seismic, short-term high live load	Undrained	s_u
Cohesionless	Static, long-term	Drained	ϕ'
Cohesionless	Seismic, short-term	Drained	ϕ'

Or, to present in another way, the analysis type is determined by the loading scenario plus the founding soil type:

	Analysis Type for:	
Loading	Cohesive Founding Soil	Cohesionless Founding Soil
Long-term	Drained	Drained
Seismic/short-term	Undrained	Drained

1.7 Soil Pressure

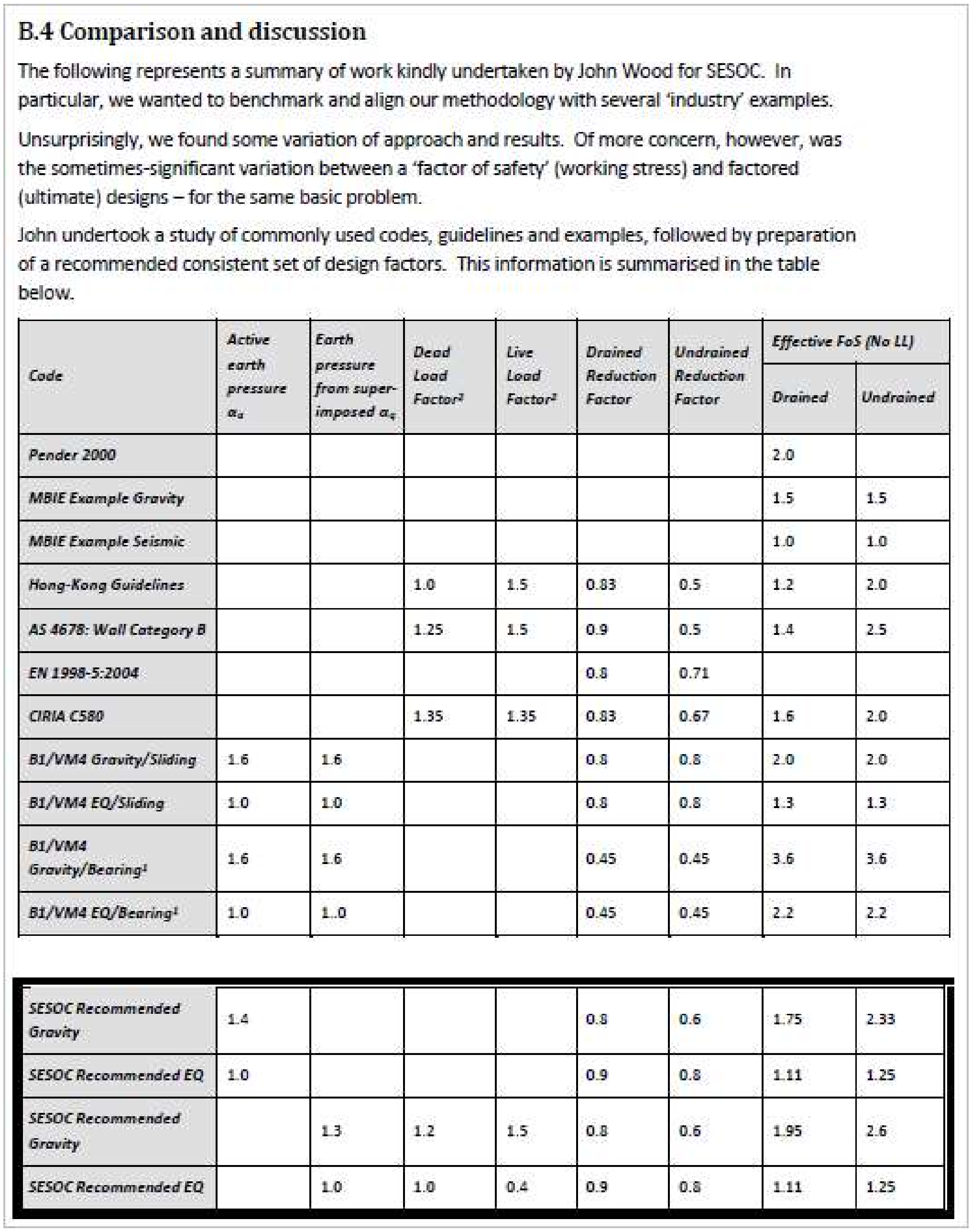
We have sought to present a single, coherent, soils model, conservative (but not too conservative), across a range of parameters with, ideally, a 'closed form solution' for implementation in the software. Ideally, also, a model that will readily accommodate vertical as well as sloping retaining systems, plus horizontal as well as sloping retained sites, with or without surcharge loading, and compatible with the seismic model.

In general, (with particular and significant input by the last named contributor in the acknowledgements), we have landed on the following :

- Active pressure : K_a is calculated using Coulomb's failure wedge approach, adjusted for wall friction and non-horizontal backfill and non-vertical soil-wall interface. K_{ae} is calculated based on Mononobe-Okabe theory
- Passive pressure : K_p and K_{pe} values are based on the closed-form 'stress plasticity' formulation by Mylonakis et al 2007 [1].

1.8 Load Factors

Within industry there appears to be a multiplicity of load factors used, as per the analysis of various documents below, which we have sought to consolidate in to a single coherent whole.



B.4 Comparison and discussion

The following represents a summary of work kindly undertaken by John Wood for SESOC. In particular, we wanted to benchmark and align our methodology with several 'industry' examples.

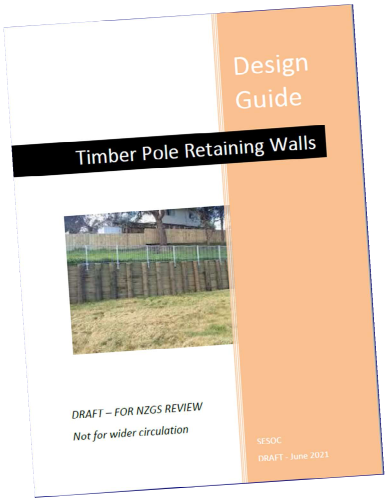
Unsurprisingly, we found some variation of approach and results. Of more concern, however, was the sometimes-significant variation between a 'factor of safety' (working stress) and factored (ultimate) designs – for the same basic problem.

John undertook a study of commonly used codes, guidelines and examples, followed by preparation of a recommended consistent set of design factors. This information is summarised in the table below.

Code	*Active earth pressure α_a*	*Earth pressure from super-imposed α_q*	*Dead Load Factor*[2]	*Live Load Factor*[2]	*Drained Reduction Factor*	*Undrained Reduction Factor*	*Effective FoS (No LL)*	
							Drained	*Undrained*
Pender 2000							2.0	
MBIE Example Gravity							1.5	1.5
MBIE Example Seismic							1.0	1.0
Hong-Kong Guidelines			1.0	1.5	0.83	0.5	1.2	2.0
AS 4678: Wall Category B			1.25	1.5	0.9	0.5	1.4	2.5
EN 1998-5:2004					0.8	0.71		
CIRIA C580			1.35	1.35	0.83	0.67	1.6	2.0
B1/VM4 Gravity/Sliding	1.6	1.6			0.8	0.8	2.0	2.0
B1/VM4 EQ/Sliding	1.0	1.0			0.8	0.8	1.3	1.3
B1/VM4 Gravity/Bearing[1]	1.6	1.6			0.45	0.45	3.6	3.6
B1/VM4 EQ/Bearing[1]	1.0	1..0			0.45	0.45	2.2	2.2
SESOC Recommended Gravity	1.4				0.8	0.6	1.75	2.33
SESOC Recommended EQ	1.0				0.9	0.8	1.11	1.25
SESOC Recommended Gravity		1.3	1.2	1.5	0.8	0.6	1.95	2.6
SESOC Recommended EQ		1.0	1.0	0.4	0.9	0.8	1.11	1.25

Extract from the Appendices of the CTP Design Guide

2 CTP: CANTILEVER TIMBER POLE WALL



Design Guide

Timber Pole Retaining Walls

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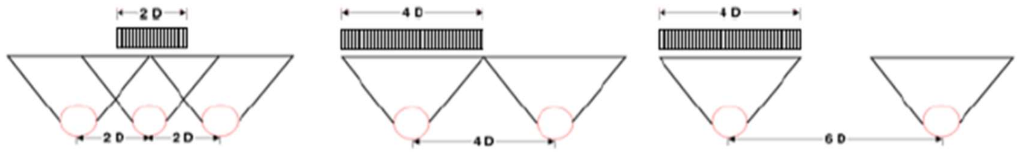
The following is some brief commentary along with a number of graphics outlining some of the key points in terms of the technical basis of the guide.

2.1 Pole Spacing Effect

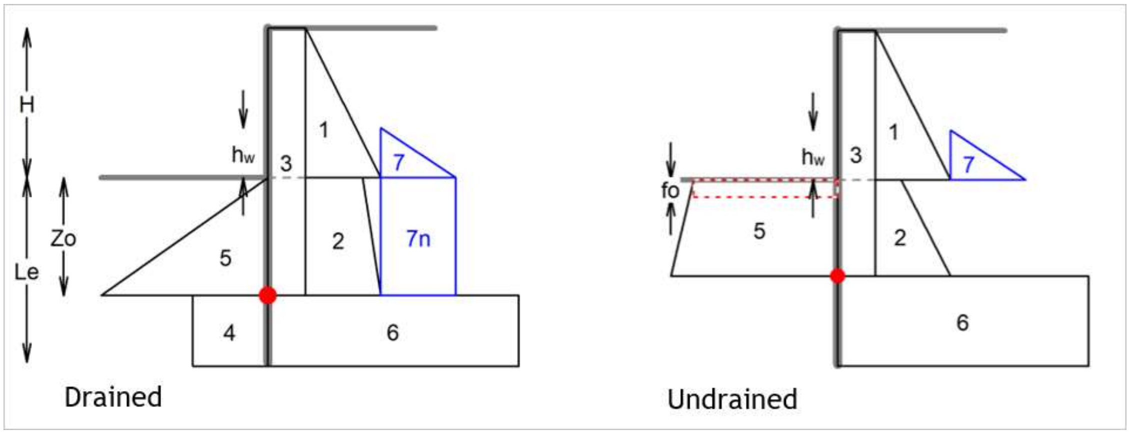
- Simplified approach
- Above ground: full contributory area between poles transferred to pole
- Below ground soil: assumes a maximum effective pressure width of $4D_c$ i.e. EFW = MIN[Sp, $4D_c$]
- Below ground water: based simply on the width of the pole D_c



Effective pressure widths for below-ground soil pressures

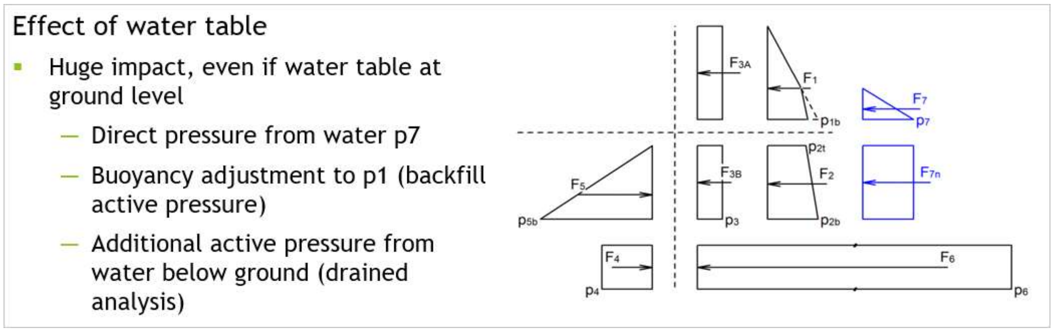
2.2 Pressure Blocks :

- Embedded pole rotates about point Zo below ground
- 1, 2: active pressure due to retained soil
- 3: active pressure due to superimposed loading
- 4: active pressure occurring due to pole rotation
- 5, 6: passive pressure resisting rotation



Sample structural mechanics pressure block diagram from the CTP guide.

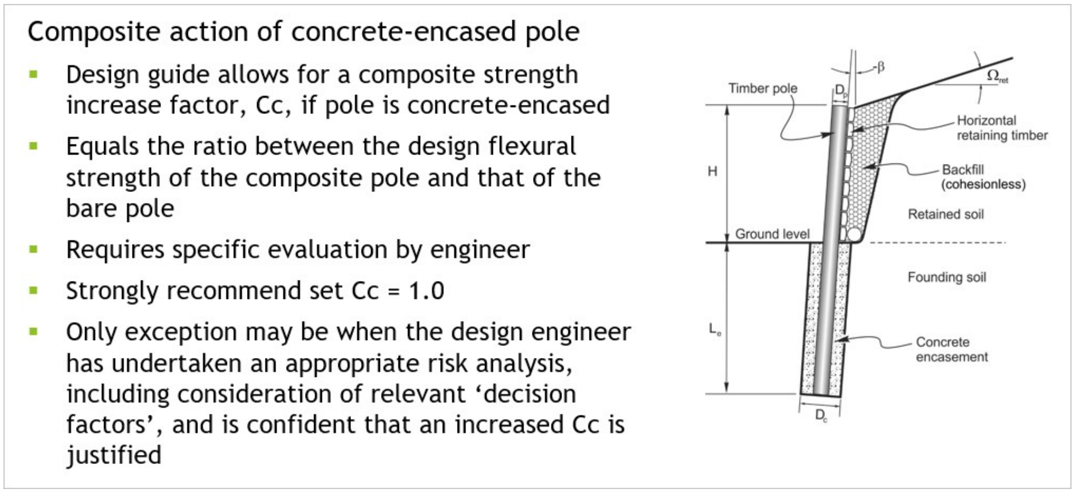
2.3 Water Table



Effect of water table

- Huge impact, even if water table at ground level
  - Direct pressure from water p7
  - Buoyancy adjustment to p1 (backfill active pressure)
  - Additional active pressure from water below ground (drained analysis)

2.4 Composite Action :

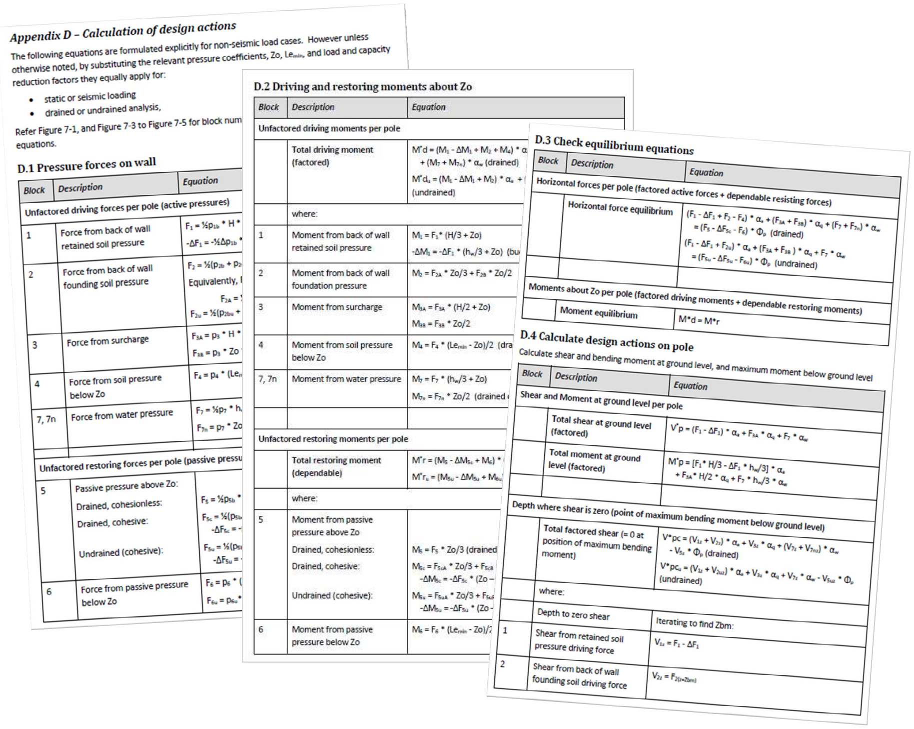


Composite action of concrete-encased pole

- Design guide allows for a composite strength increase factor, Cc, if pole is concrete-encased
- Equals the ratio between the design flexural strength of the composite pole and that of the bare pole
- Requires specific evaluation by engineer
- Strongly recommend set Cc = 1.0
- Only exception may be when the design engineer has undertaken an appropriate risk analysis, including consideration of relevant 'decision factors', and is confident that an increased Cc is justified

2.5 Design Guidance :

In addition to the technical background, and (hopefully) gradual immersion of the reader from broad concepts progressively leading on to more and more technical detail, the CTP also provides detailed and explicit formulation of all the calculations of design actions and pressures, through to the ultimate calculation of forces, moments and the crucial stability checks.



Appendix D – Calculation of design actions

The following equations are formulated explicitly for non-seismic load cases. However unless otherwise noted, by substituting the relevant pressure coefficients, Zo, Le$_{min}$, and load and capacity reduction factors they equally apply for:

- static or seismic loading
- drained or undrained analysis,

Refer Figure 7-1, and Figure 7-3 to Figure 7-5 for block num equations.

D.1 Pressure forces on wall

Block	*Description*	*Equation*
Unfactored driving forces per pole (active pressures)		
1	Force from back of wall retained soil pressure	$F_1 = \tfrac{1}{2}p_{1b} * H *$ $-\Delta F_1 = -\tfrac{1}{2}\Delta p_{1b} *$
2	Force from back of wall founding soil pressure	$F_2 = \tfrac{1}{2}(p_{2b} + p_2$ Equivalently, $F_{2A} =$ $F_{2u} = \tfrac{1}{2}(p_{2bu} +$
3	Force from surcharge	$F_{3A} = p_3 * H *$ $F_{3B} = p_3 * Zo$
4	Force from soil pressure below Zo	$F_4 = p_4 * (Le$
7, 7n	Force from water pressure	$F_7 = \tfrac{1}{2}p_7 * h$ $F_{7n} = p_7 * Zo$
Unfactored restoring forces per pole (passive pressu		
5	Passive pressure above Zo: Drained, cohesionless: Drained, cohesive: Undrained (cohesive):	$F_5 = \tfrac{1}{2}p_{5b} *$ $F_{5c} = \tfrac{1}{2}(p_{5b}$ $-\Delta F_{5c} = -$ $F_{5u} = \tfrac{1}{2}(p_{5u}$ $-\Delta F_{5u} = -$
6	Force from passive pressure below Zo	$F_6 = p_6 * ($ $F_{6u} = p_{6u} *$

D.2 Driving and restoring moments about Zo

Block	*Description*	*Equation*
Unfactored driving moments per pole		
	Total driving moment (factored)	$M^*d = (M_1 - \Delta M_1 + M_2 + M_4) * \alpha$ $+ (M_7 + M_{7n}) * \alpha_w$ (drained) $M^*d_u = (M_1 - \Delta M_1 + M_2) * \alpha_a +$ (undrained)
	where:	
1	Moment from back of wall retained soil pressure	$M_1 = F_1 * (H/3 + Zo)$ $-\Delta M_1 = -\Delta F_1 * (h_w/3 + Zo)$ (bu
2	Moment from back of wall foundation pressure	$M_2 = F_{2A} * Zo/3 + F_{2B} * Zo/2$
3	Moment from surcharge	$M_{3A} = F_{3A} * (H/2 + Zo)$ $M_{3B} = F_{3B} * Zo/2$
4	Moment from soil pressure below Zo	$M_4 = F_4 * (Le_{min} - Zo)/2$ (dra
7, 7n	Moment from water pressure	$M_7 = F_7 * (h_w/3 + Zo)$ $M_{7n} = F_{7n} * Zo/2$ (drained
Unfactored restoring moments per pole		
	Total restoring moment (dependable)	$M^*r = (M_5 - \Delta M_{5c} + M_6) *$ $M^*r_u = (M_{5u} - \Delta M_{5u} + M_{6u}$
	where:	
5	Moment from passive pressure above Zo Drained, cohesionless: Drained, cohesive: Undrained (cohesive):	$M_5 = F_5 * Zo/3$ (drained $M_{5c} = F_{5cA} * Zo/3 + F_{5cB}$ $-\Delta M_{5c} = -\Delta F_{5c} * (Zo -$ $M_{5u} = F_{5uA} * Zo/3 + F_{5u}$ $-\Delta M_{5u} = -\Delta F_{5u} * (Zo -$
6	Moment from passive pressure below Zo	$M_6 = F_6 * (Le_{min} - Zo)/2$

D.3 Check equilibrium equations

Block	*Description*	*Equation*
Horizontal forces per pole (factored active forces + dependable resisting forces)		
	Horizontal force equilibrium	$(F_1 - \Delta F_1 + F_2 - F_4) * \alpha_a + (F_{3A} + F_{3B}) * \alpha_q + (F_7 + F_{7n}) * \alpha_w = (F_5 - \Delta F_{5c} - F_6) * \Phi_p$ (drained) $(F_1 - \Delta F_1 + F_{2u}) * \alpha_a + (F_{3A} + F_{3B}) * \alpha_q + F_7 * \alpha_w = (F_{5u} - \Delta F_{5u} - F_{6u}) * \Phi_p$ (undrained)
Moments about Zo per pole (factored driving moments + dependable restoring moments)		
	Moment equilibrium	$M^*d = M^*r$

D.4 Calculate design actions on pole

Calculate shear and bending moment at ground level, and maximum moment below ground level

Block	*Description*	*Equation*
Shear and Moment at ground level per pole		
	Total shear at ground level (factored)	$V^*p = (F_1 - \Delta F_1) * \alpha_a + F_{3A} * \alpha_q + F_7 * \alpha_w$
	Total moment at ground level (factored)	$M^*p = [F_1 * H/3 - \Delta F_1 * h_w/3] * \alpha_a + F_{3A} * H/2 * \alpha_q + F_7 * h_w/3 * \alpha_w$
Depth where shear is zero (point of maximum bending moment below ground level)		
	Total factored shear (= 0 at position of maximum bending moment)	$V^*pc = (V_{1z} + V_{2z}) * \alpha_a + V_{3z} * \alpha_q + (V_{7z} + V_{7nz}) * \alpha_w - V_{5z} * \Phi_p$ (drained) $V^*pc_u = (V_{1z} + V_{2uz}) * \alpha_a + V_{3z} * \alpha_q + V_{7z} * \alpha_w - V_{5uz} * \Phi_p$ (undrained)
	where:	
	Depth to zero shear	Iterating to find Zbm:
1	Shear from retained soil pressure driving force	$V_{1z} = F_1 - \Delta F_1$
2	Shear from back of wall founding soil driving force	$V_{2z} = F_{2(z=Zbm)}$

3 RCW: REINFORCED CONCRETE WALL

3.1 Introduction

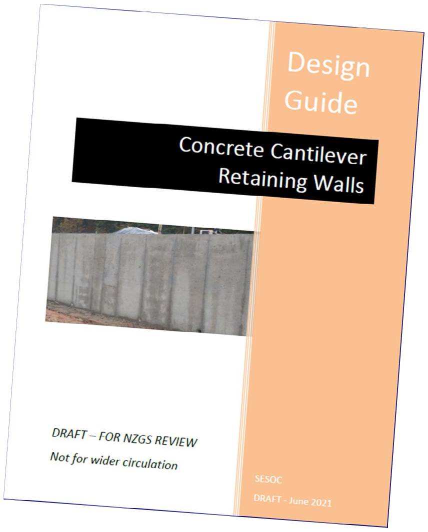
There are basically two (local) fundamental limit states :

- Overturning
- Sliding

And, typically, at least two load cases :

- Static (gravity)
- Dynamic (seismic)

.. with the following pseudo-static structural mechanics loads & pressure blocks



Design Guide

Concrete Cantilever Retaining Walls

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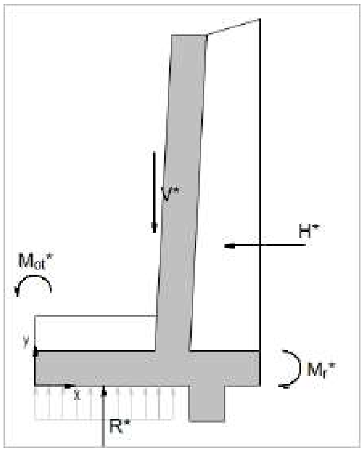
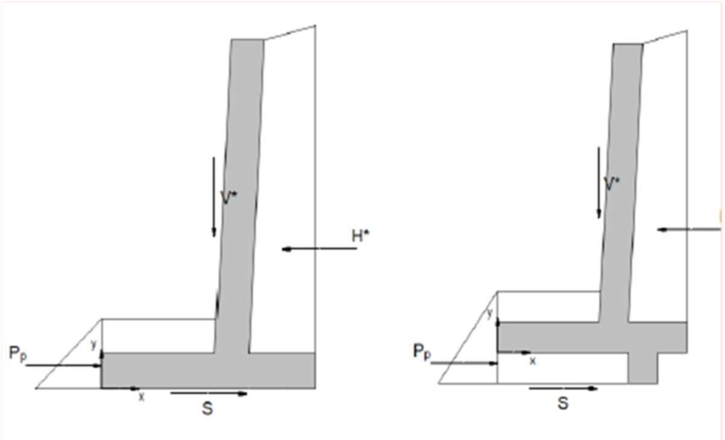
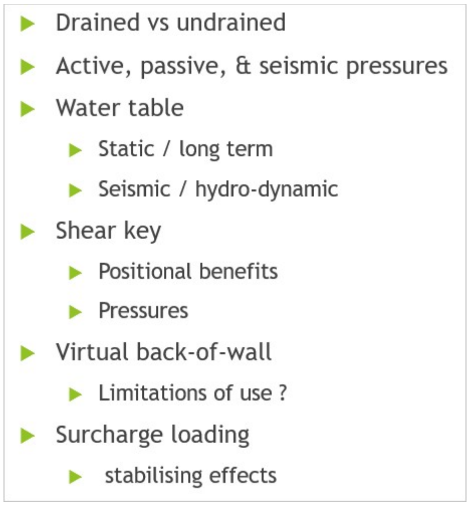




Force diagrams for sliding action

3.2 Further Details

However, behind these is a multiplicity of details, e.g.



- Drained vs undrained
- Active, passive, & seismic pressures
- Water table
  - Static / long term
  - Seismic / hydro-dynamic
- Shear key
  - Positional benefits
  - Pressures
- Virtual back-of-wall
  - Limitations of use ?
- Surcharge loading
  - stabilising effects

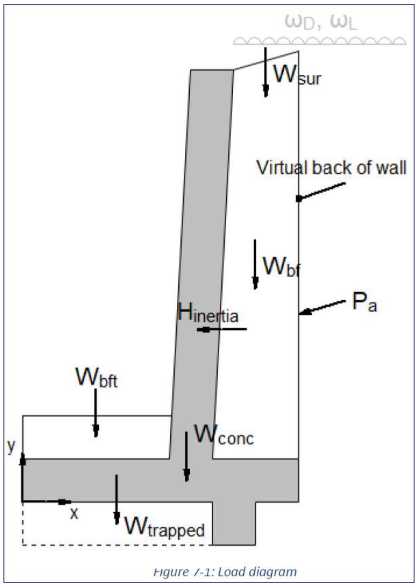


Figure 7-1: Load diagram

Including consideration regarding which components are providing stabilising actions, and which de-stabilising ? and the appropriate load factors for each, and which aspects we can (reasonably) ignore ?

This includes complexities around:

- Pressures and forces for sliding versus overturning, with and without key
- Water table pressures, especially in the vicinity of the footing
- etc

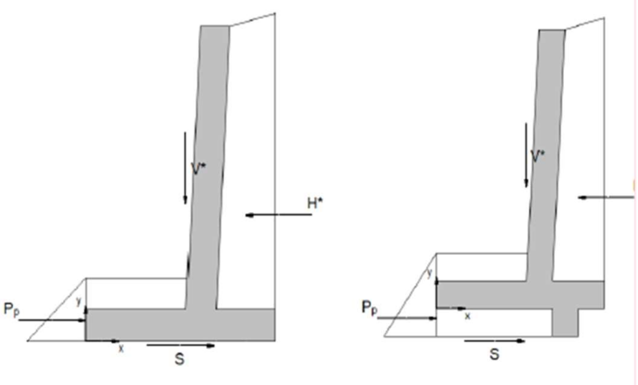


Figure 8-3: Force diagrams for sliding action

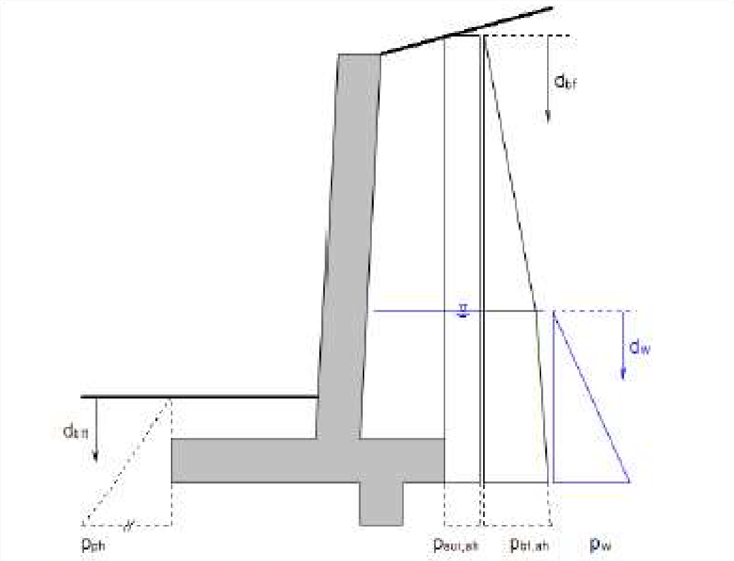


Figure 7-4: Horizontal pressure with water table (pressures under sliding conditions shown dashed) (refer to Figure 8-1 for additional nomenclature)

4 STATUS & ACKNOWLEDGEMENTS

Status: As at the time of writing (early Apr 2022), both documents are in draft format, and are with NZGS for formal review. We have received initial, positive feedback from the NZGS management committee, and the CTP design guide is now undergoing a detailed review by some experienced and senior Geotech practitioners.

Acknowledgements: Although numerous people from industry have provided valuable input at various times, particular acknowledgement must also be made to the following parties :

- Beca, for the first author's (unfunded) time and contribution, which has been quite substantial, and over several years
- My co-author, Allan McPherson, for his diligent efforts as the writer and pen-holder, as well as meticulous attention to detail

And last but not least :

- John Wood, for substantial input, as well as detailed review of these documents, and whose considered and thoughtful contributions have substantially strengthened and truly enhanced the quality of this initiative.

In parallel with the above NZGS review, SESOC have commissioned a University of Auckland PhD student to undertake a representative series of analytical models, in order to benchmark the proposed basic methodology – as well as the various combinations and permutations.

These are being carried out quite independently, yet following, as much as possible the philosophy espoused in the SESOC Design Guides – which, in turn, seek to also consolidate the various industry sources (from B1/VM4 and Mick Pender's Geotech 2000 series onwards) in to a single cohesive whole.

5 CONCLUSION

This paper provides a brief insight into the development process and current status of these two cantilever retaining wall design guides.

Although a process we would have preferred to be undertaken by others, in the absence of any form of national standard or similar, or timely expectation of such, SESOC felt it could no longer provide software without a robust and documented design methodology, hence the undertaking of these guides.

It is our hope that these guides will underpin future retaining wall work, in the wider sense, yet noting that the scope is deliberately restricted to 'residential', 'garden wall' type work. Very intentionally, the scope is limited to what a competent structural design professional 'should' be able to design (– with Geotech input as appropriate), and acknowledgement of the need of experienced Geotech professionals to undertake the broader spectrum of retaining walls - larger, tied back, more complex, stepped, etc.

6 REFERENCES

[1] Mylonakis, George & Kloukinas, Panos & Papantonopoulos, Costas. (2007). An alternative to the Mononobe–Okabe equation for seismic earth pressures. Soil Dynamics and Earthquake Engineering, 27. 957-969