STRUCTURAL RELIABILITY OF RETAINING WALLS DESIGNED TO AS 4678 FOR PERMANENT, IMPOSED AND SEISMIC LOADS

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ABSTRACT

Part 1 – External Stability

AS 4678-2002 *Earth retaining structures* may be used to design gravity retaining walls (including reinforced soils, segmental gravity retaining walls and cantilever retaining walls). This paper compares the structural reliability of retaining walls designed to AS 4678, to those designed using other codes, British Code of Practice CP2 and the National Concrete Masonry Association (USA) method of designing reinforced soils.

Part 2 – Earthquake

AS 4678 Appendix I sets out the options for designing retaining walls for earthquake, based on a classification method consistent with AS 1170.4-1993 (which is now superseded) and simplified rules. Some combinations lead to non-conservative design, but only where "failure would result in not more than moderate damage and not more than minimal loss of access", or "failure would result in moderate damage and loss of services" with low or medium seismicity.

PART 1 – EXTERNAL STABILITY

1. Background

The design of gravity retaining walls (including reinforced soils, segmental gravity retaining walls and cantilever retaining walls) was previously governed principally by overturning about the toe. However, using AS 4678-2002, design for forward sliding or bearing now often governs the design process. Most structures in cohesive soils have difficulty in meeting the sliding (external design) limit state, for the types of soil parameters commonly assumed by Australian design engineers. This Part examines in detail the implications of external design for sliding, overturning and bearing, common to all gravity retaining wall systems; and compares the results to similar analyses using the Civil Engineering Code of Practice No 2 (1951) and National Concrete Masonry Association (USA) method

Theoretical designs of retaining walls were compared, using ultimate load design to AS 4678, working stress design to CP 2 and working stress design to NCMA. An idealized structure was selected that best mimics reinforced soils, segmental gravity retaining walls and cantilever retaining walls. This requires constant structure density (20 kN/m^3), idealized soil block (also 20 kN/m^3), near vertical face, and embedment of H/15. The variables tested are different heights, soil types, slopes, and water table. The following are not considered in this paper; slope of the retaining wall face, footings that extend in front of the wall face, reduced density of no-fines segmental gravity walls, and keys under footings.

2. Benchmark

In order to test AS 4678, it is necessary to adopt benchmarks of acceptable designs, which have a long history of satisfactory performance, and can be justified by a combination of theory and experience. British code of Practice No 2 [1]fits this criterion, and has been selected.

[1] Code of Practice No 2 was published in 1951, reprinted in 1975, and the methods described therein remained in common use to the turn of the century. Thus, for over fifty years it has provided the basis of design of most retaining walls in the English speaking world, including Australia. Whilst there are sound reasons to deviate from the working stress methods of Code of Practice No 2, to cater for uncommon consequence of failure or uncommon levels of workmanship, it still remains an acceptable starting point for the benchmarking process for the most common situations.

3. Walls Analysed

External design considerations are common for all types of gravity walls, including:

- Concrete Segmental Reinforced Soil Structures
- Concrete Segmental Gravity Walls (with or without no-fines concrete)
- Reinforced Concrete Cantilever Gravity Walls, with a substantial heel under the retained fill.

The following idealized structure, which best fits all three types, has been analyzed.

- The assumed shape of the gravity structure is a parallelogram, with horizontal base and horizontal top, with slightly sloping front face and parallel rear surface. Both front and rear faces are at 1.43^{o} (1 in 40) to vertical.
- Density of the gravity structure is a uniform value, approximating the average density of the soil and concrete, and taken as 20 $kN.m^3$ [2]
- Embedment of the structure is taken as the exposed height divided by 15[3].
- Minimum imposed (live) load of 1.5 kPa, except in Load Case 3. , where a minimum of 10 kPa is specified.[4]

For wall designed to AS 4678, the minimum values of imposed (live) surcharge are:

Classification	Height	Backfill Slope Horizontal : Vertical	
		Steeper than 4:1	4:1 of flatter
B, C	Any	2.5 kPa	5.0 kPa
A	≤1.5 m [Note 1]	1.5 kPa	2.5 kPa
Notes Classification A retaining walls must be equal to or less than 1.5 m high.			

- Because the purpose of the analysis is to determine the broad effects of the various design standards, possible pragmatic construction expedients to make the structures more economic should be ignored. For example, the following expedients, although considered to be “good engineering” would not be assumed:
  - Excavation and replacement of weak foundation material (Soil type .2 and .3)
  - Draining the water table (Load case 4.)
  - Sloping the face more than the 1.43^{o} (I in 400 of the idealized structure

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[2] If the face is vertical and density of gravity structure is assumed equal to the density of retained soil, the benchmark designs will be quite accurate for Concrete Segmental Reinforced Soil Structures, Concrete Segmental Gravity Walls (without no-fines concrete) and Type 1 Reinforced Concrete Cantilever Gravity Walls (no significant toe and the heel extending under the fill). However, the benchmark designs will be a little non-conservative for Concrete Segmental Gravity Walls (with no-fines concrete), and quite non-conservative for Type 2 Reinforced Concrete Cantilever Gravity Walls (a large toe and no heel under the fill).These two cases should be considered independently.

[3] Reinforced soils generally require embedment of total height / 20.
Low height segmental gravity walls may be built with zero embedment.
Type 1 cantilever walls often require 300 + mm depth to cover the footing.
The selected compromise embedment is exposed height / 15.

[4] Although CP2 and the NCMA method do not specify a minimum imposed (live) load, it is impossible to have a “zero imposed load” case. There will always be at least some (perhaps unspecified) imposed (live) load that a designer must consider. Failure of a designer to formally assume at least some value for imposed (live) surcharge would leave the designer exposed in any potential litigation, and a competent designer using CP2 or the NCMA method would always adopt some value. AS 4678 assumes a general minimum of 5 kPa (except in low risk walls). In this analysis, a much more optimistic minimum value of 1.5 kPa has been assumed.

Walls Analysed							
1,600 mm total height (1,500 mm clear height + 100 mm embedment) – Low consequence of failure 3,200 mm total height (3,000 mm clear height + 200 mm embedment)) – Normal consequence of failure 4,800 mm total height (4,500 mm clear height + 300 mm embedment)) – Normal consequence of failure 6,400 mm total height (6,000 mm clear height + 400 mm embedment)) – High consequence of failure							
Case	Slope	Surcharge kPa	Water Table	Internal Friction φ °	External Friction δ °	Cohesion C kPa	Soil Type
1.1	Level	1.5	No	35	20	0	Cohesionless soil, moist
1.2	Level	1.5	No	20	0	7.2	Silt with friction and cohesion
1.3	Level	1.5	No	0	0	14.3	Cohesive non-fissured clay
2.1	1 in 4	1.5	No	35	20	0	Cohesionless soil, moist
2.2	1 in 4	1.5	No	20	0	7.2	Silt with friction and cohesion
2.3	1 in 4	1.5	No	0	0	14.3	Cohesive non-fissured clay
3.1	Level	10.0	No	35	20	0	Cohesionless soil, moist
3.2	Level	10.0	No	20	0	7.2	Silt with friction and cohesion
3.3	Level	10.0	No	0	0	14.3	Cohesive non-fissured clay
4.1	Level	1.5	Yes	35	20	0	Cohesionless soil, moist
4.2	Level	1.5	Yes	20	0	7.2	Silt with friction and cohesion
4.3	Level	1.5	Yes	0	0	14.3	Cohesive non-fissured clay
Consequence of failure							AS 4678 Structure Class
Low Consequence - Failure results in minimal damage & loss of access							A
Normal Consequence - Failure results in moderate damage & loss of service							B
High Consequence - Failure results in significant damage or risk to life							C
The soil properties and water table to be checked are from Appendix D of Code of Practice CP 2							

4. Reliability Indices

In order to compare the various design options, hypothetical Reliability Indices have been calculated for lognormal distributions of load and resistance, given by the following:

$$\text{Reliability index, } \beta = \frac{\{ (R_{mean} / S_{mean}) [(1 + V_S^2) / (1 + V_R^2)]^{0.5}\}}{\{\ln[(1 + V_S^2)(1 + V_R^2)]^{0.5}\}}$$

R_{mean}

- For sliding, this is the calculated mean sliding resistance at working loads.
- For bearing, this is the calculated mean bearing capacity (assuming rectangular distribution, Terzagghi method and Vesic modification factors) at working loads.
- For overturning, this is the product of:

  The calculated mean bearing capacity (assuming rectangular distribution, Terzagghi method and Vesic modification factors) at working loads, and

  The lever arm, x" = B / 2 – B / (2 x 2 x 6)$^{0.5}$

  = 0.295 B

S_{mean}

- For sliding, this is the calculated forward sliding force at working loads.
- For bearing, this is the calculated vertical downwards force at working loads.
- For overturning, this is the product of calculated forward sliding force at working loads multiplied by the appropriate lever arms.

V_R The coefficient of variation of the resistances. This is assumed to be equal to the coefficient of variation of the relevant foundation soil property (i.e. internal friction angle or cohesion of the foundation).

V_S The coefficient of variation of the loads causing instability (i.e. Sliding, overturning or bearing failure). This is assumed to be equal to the combined coefficients of resistance of the variations of the relevant retained soil property (i.e. internal friction angle and/or cohesion of the foundation), the weighted values of permanent loads and imposed loads.

5. Determination of Coefficients of Variation for Calculation of Reliability Indices - Resistance

It is assumed that the $V_{R,}$ the coefficient of variation of the resistances, is made up of two components:

- The coefficient of variation of the relevant foundation soil property (i.e. internal friction angle or cohesion of the foundation); and
- The coefficient of variation of the relevant analysis method.

Coefficient of variation of internal friction angle of the foundation, $V_{r\ found\ \varphi}$

The principal design properties for a foundation soil are its internal and external friction angles. AS 4678 Table D4 provides for four broad soil types.

AS 4678 Table D4 – Soil Classification

Soil Group	Typical soils in group	Cohesion c' kPa	Internal friction φ' (degrees)	<u>Range</u> Mean
Poor	Soft & firm clay of medium to high plasticity, silty clays, loose variable clayey fill, loose sandy silts	0 to 5	17 to 25	0.39
Average	Stiff sandy clays, gravelly clays, compact clayey sands and sandy silts, compact clay fill (Class 2)	0 to 10	26 to 32	0.21
Good	Gravelly & compacted sands, controlled crushed sandstone & gravel fills (Class 1), dense well graded sands	0 to 5	32 to 37	0.14
Very good	Weak weathered rock, controlled fills (Class 1) of road base, gravel, recycled concrete	0 to 25	36 to 43	0.18

The design is based on a "conservative estimate of the mean" strength. Although individual parts of the soil in proximity to each other may vary widely, the <u>mean</u> strength of the soil operating on a particular part of the wall would be subject to relatively little variation. On the basis of the tables above, it is reasonable to assume a 20% coefficient of variation of the "conservative estimate of the mean" internal and external friction angle.

Coefficient of variation of cohesion of the foundation, $V_{r\ found\ c}$

Because cohesion is more variable than friction angle, a value of 30% for coefficient of variation of the "conservative estimate of the mean" cohesion is assumed.

Coefficient of variation of analysis method

The designs are based on Coulomb or Rankine methods, considered to be quite accurate. A value of 10% for coefficient of variation assumed.

Coefficient of variation of the resistances

The combination of coefficient of variation of the resistances is based on the following formula.

$$V_R = (V_{r\ found}^2 + V_{R\ anal}^2)^{0.5}$$

6. Determination of Coefficients of Variation for Calculation of Reliability Indices - Loads

It is assumed that the $V_{S,}$ the coefficient of variation of the loads, is made up of three components, the most important of which is the soil property

- The coefficient of variation of the relevant foundation soil property (i.e. internal friction angle or cohesion of the foundation); and
- The coefficient of variation of any externally applied permanent loads.
- The coefficient of variation of any externally applied live loads.

Coefficient of variation of internal friction angle of retained soil, $V_{S\ reta\ \varphi}$

The principal design properties for a retained soil are its internal and external friction angles. Although the soil type may be different from the foundation soil, the approach to the coefficient of friction can be the same. On this basis, it is reasonable to assume a 20% coefficient of variation of the "conservative estimate of the mean" internal and external friction angle.

S_{reta} / S = the proportion of total loads associated with the retained soil

Coefficient of variation of the permanent loads, $V_{S\ perm}$

The applied dead loads are upper bounds of the loads applied. i.e. conservative values. A value of 10% for coefficient of variation of the permanent loads is assumed.

S_{perm} / S = the proportion of total loads associated with the external permanent loads

Coefficient of variation of imposed loads, $V_{S\ imp}$

The applied imposed loads are upper bounds of the loads applied. i.e. conservative values. A value of 10% for coefficient of variation of the permanent loads is assumed.

S_{imp} / S = the proportion of total loads associated with the externally imposed loads

Coefficient of variation of loads

The combination of coefficient of variation of the loads is based on the following formula.

$$V_R = [(V_{S\ reta} .\ S_{reta} / S)^2 + (V_{R\ perm} .\ S_{perm} / S)^2 + (V_{R\ imp} .\ S_{imp} / S)^2]^{0.5}$$

7. Use of Reliability Indices

Reliability indices may be used as a guide when setting the load factors and resistance factors in design standards, although caution is required when determining and applying the criteria. As a guide, the following recommendations from ISO 2394 Table E1 have been included in this paper.

ISO 2394 Table E1 Target β-values (life-time, examples)				
Relative costs of safety measures	Consequences of failure			
	Small	Some	Moderate	Great
High	0	A 1.5	2.3	B 3.1
Moderate	**1.3**	**2.3**	**3.1**	C 3.8
Low	2.3	3.1	3.8	4.3

Some suggestions are:

A: for serviceability limit states, use β = 0 for reversible and β = 1.5 for irreversible limit states.

B: for fatigue limit states, use β = 2.3 to β = 3.1, depending on the possibility of inspection.

C: for ultimate limit states, use the safety classes β = 3.1, 3.8 and 4.3.

The choice of target reliability indices should depend upon calibration of the reliability model. The values given in ISO 2394 are predicated on the use of the same or similar reliability models for various building systems.

Criteria used to Examine Reliability Indices

In the absence of clear guidelines, the following Reliability Indices have been adopted for purposes of examining the apparent reliability of the structures analyzed in this paper.

Structure Classification AS 4678 Table 1.1	Reason for selecting the particular Target Reliability Index, β	Target Reliability Index, β
A	Where failure would result in minimal damage or loss of access. Retaining walls not higher than 1.5 m, and supporting only minor structures, such as garden sheds or similar.	1.3
B	Where failure would result in moderate damage or loss of access. This is applicable to most common applications.	2.3
C	Where failure would result in significant damage or risk to life. Retaining walls supporting highways, bridges, hospitals, high rise buildings and the like.	3.1

8. Tabulated Results

For each of the walls analysed, the Reliability Indices, β, and the Volume of Retaining Structure is tabulated.

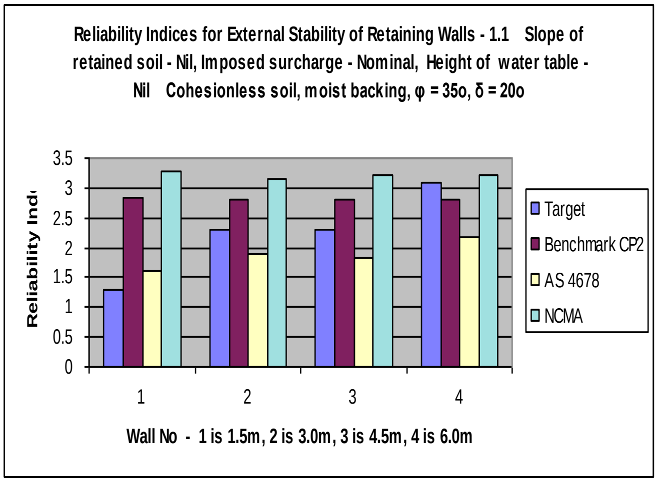
- The Reliability Index is a measure of the safety.
- The Volume of Retaining Structure is a measure of the economy of the retaining wall.

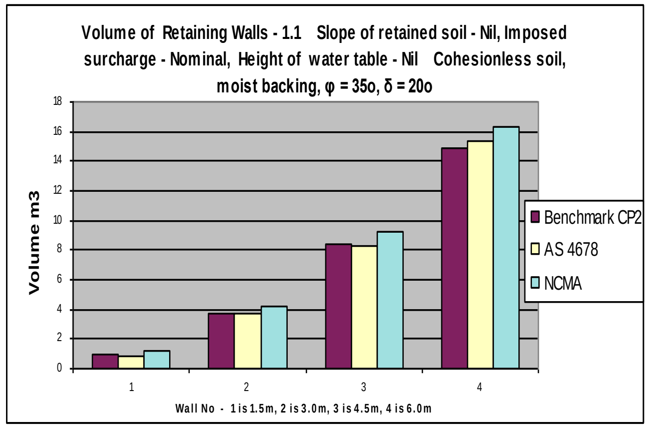
In very broad terms, for any particular height, a wide structure leads to greater safety (higher Reliability Index) and lesser economy (higher Volume). However, this simple relationship is complicated by the fact that Reliability Index can be the minimum of sliding, bearing or overturning, and Volume is affected by both structure width and bearing pad depth. The following principles have been employed when interpreting the tabulations of calculated structure length (depth into the embankment) and bearing pad thickness for the four load case, three soil types and four wall heights.

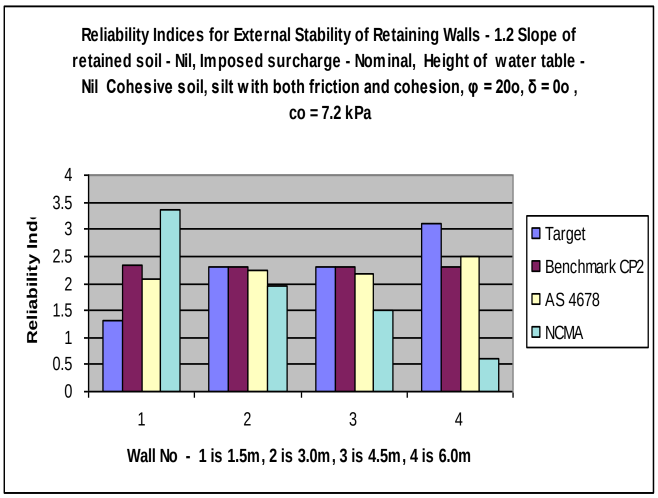
1. The target Reliability Indices represent the ideal for one set of assumed coefficients of variation of loads and soil properties. They can be used as a guide, but must be tempered by engineering judgement.
2. If the calculated Reliability Index is higher than the target or other methods, then the level of safety is higher (i.e. the design is more conservative).

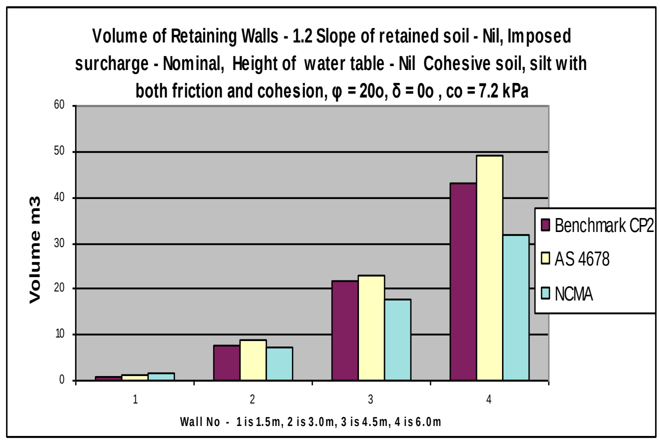
   If the calculated Reliability Index is lower than the target or other methods, then the level of safety is lower (i.e. the design is more liberal).
3. The economy of a structure is broadly indicated by the calculated volume, determined as follows.

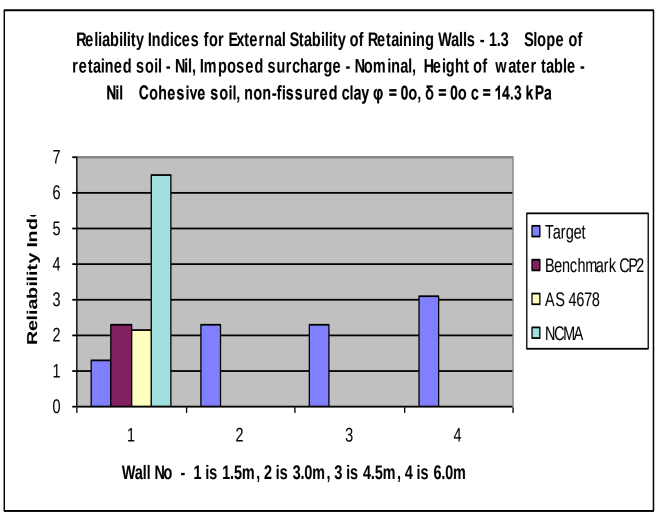
   Volume = (Height x Calculated length) + (Bearing pad thickness x Calculated Length)
4. Broadly speaking, as the length of the structure (depth into the embankment) is decreased, the safety is reduced and the economy is increased.
5. There are complications to Comment 4 above. Although the length may be reduced, this may cause a need for increased bearing pad thickness, thus reducing the impact on economy. Overall safety is the minimum of sliding, bearing and overturning. Any can govern.
6. The calculated structure lengths (depth into the embankment) and bearing pad thicknesses are intended to demonstrate what is possible, not what is good design.

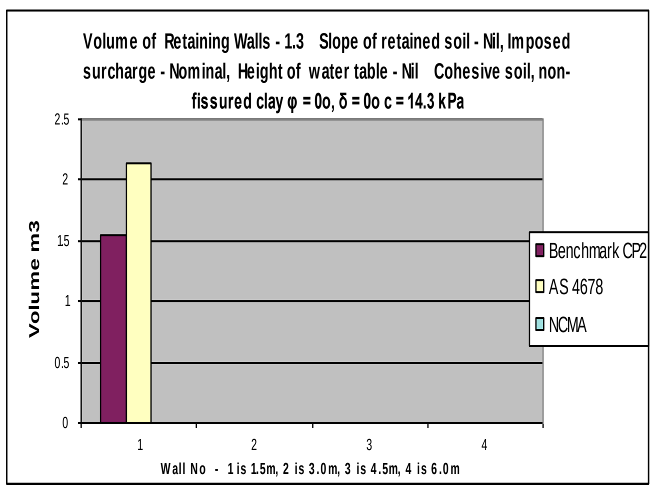

Reliability Indices for External Stability of Retaining Walls - 1.1 Slope of retained soil - Nil, Imposed surcharge - Nominal, Height of water table - Nil Cohesionless soil, moist backing, φ = 35o, δ = 20o
Reliability Ind
0
0.5
1
1.5
2
2.5
3
3.5
1
2
3
4
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m
Target
Benchmark CP2
AS 4678
NCMA

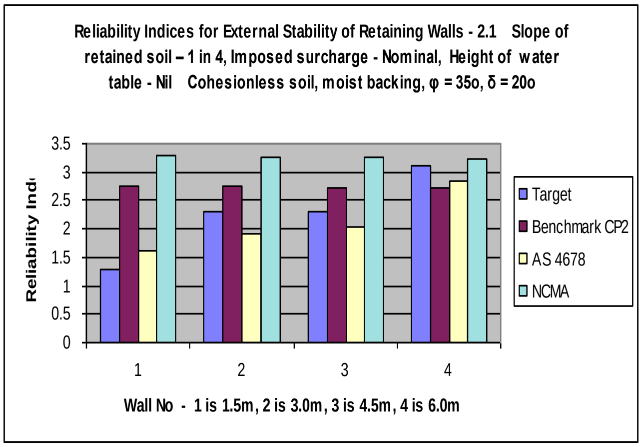

Volume of Retaining Walls - 1.1 Slope of retained soil - Nil, Imposed surcharge - Nominal, Height of water table - Nil Cohesionless soil, moist backing, φ = 35o, δ = 20o
Volume m3
0
2
4
6
8
10
12
14
16
18
1
2
3
4
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m
Benchmark CP2
AS 4678
NCMA

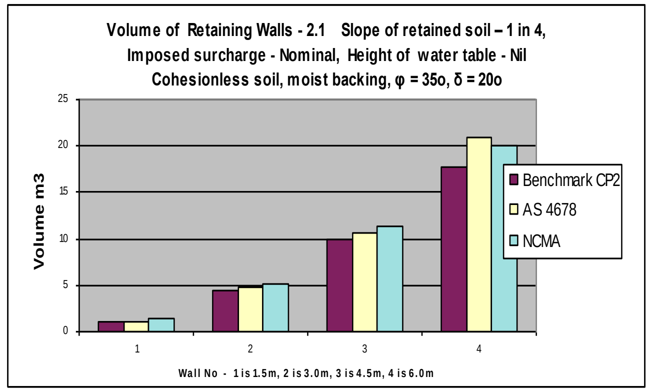

Reliability Indices for External Stability of Retaining Walls - 1.2 Slope of retained soil - Nil, Imposed surcharge - Nominal, Height of water table - Nil Cohesive soil, silt with both friction and cohesion, φ = 20o, δ = 0o , co = 7.2 kPa
Reliability Ind
0
0.5
1
1.5
2
2.5
3
3.5
4
1
2
3
4
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m
Target
Benchmark CP2
AS 4678
NCMA

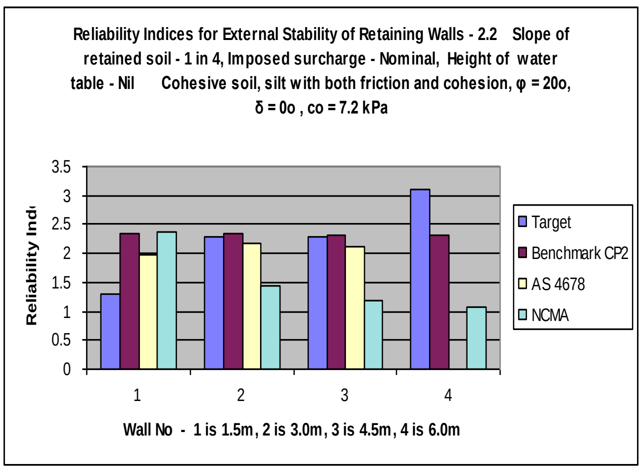

Volume of Retaining Walls - 1.2 Slope of retained soil - Nil, Imposed surcharge - Nominal, Height of water table - Nil Cohesive soil, silt with both friction and cohesion, φ = 20o, δ = 0o , co = 7.2 kPa
Volume m3
0
10
20
30
40
50
60
1
2
3
4
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m
Benchmark CP2
AS 4678
NCMA

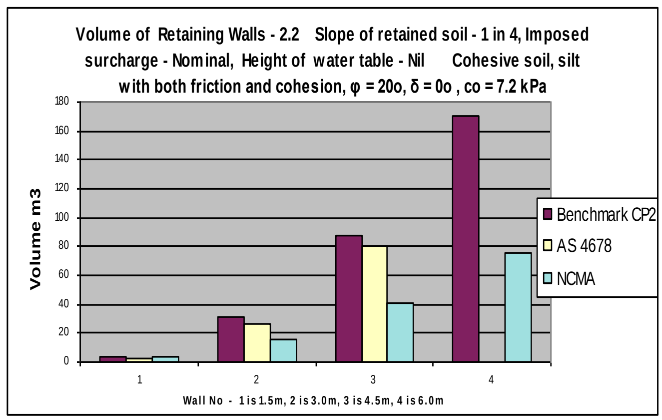

Reliability Indices for External Stability of Retaining Walls - 1.3 Slope of retained soil - Nil, Imposed surcharge - Nominal, Height of water table - Nil Cohesive soil, non-fissured clay φ = 0o, δ = 0o c = 14.3 kPa
Reliability Ind
0
1
2
3
4
5
6
7
1
2
3
4
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m
Target
Benchmark CP2
AS 4678
NCMA

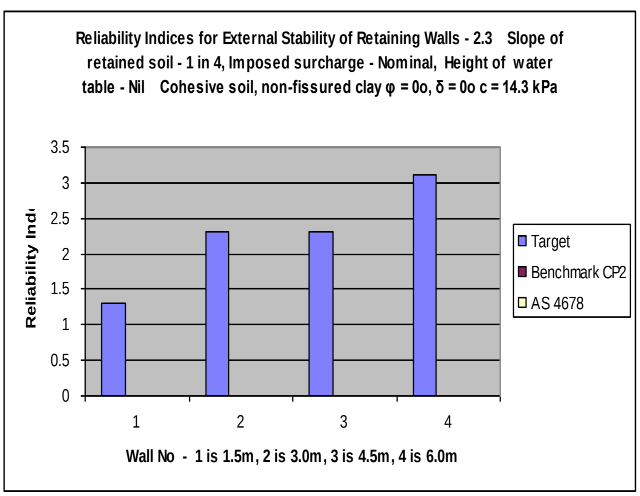

Volume of Retaining Walls - 1.3 Slope of retained soil - Nil, Imposed surcharge - Nominal, Height of water table - Nil Cohesive soil, non-fissured clay φ = 0o, δ = 0o c = 14.3 kPa
Volume m3
0
0.5
1
15
2
2.5
1
2
3
4
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m
Benchmark CP2
AS 4678
NCMA

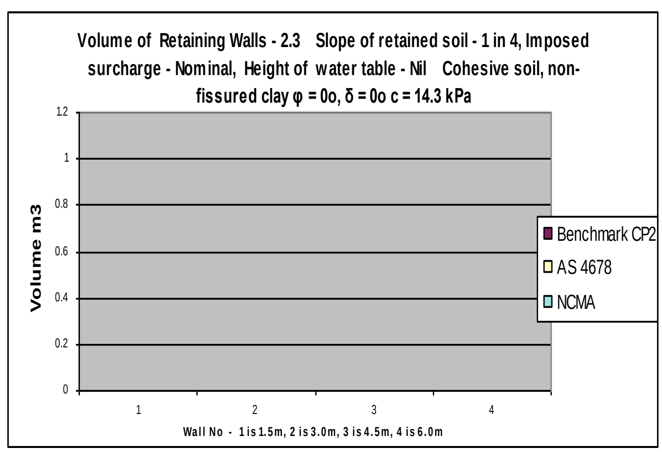

Reliability Indices for External Stability of Retaining Walls - 2.1 Slope of retained soil – 1 in 4, Imposed surcharge - Nominal, Height of water table - Nil Cohesionless soil, moist backing, φ = 35o, δ = 20o
Reliability Ind
Target
Benchmark CP2
AS 4678
NCMA
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m

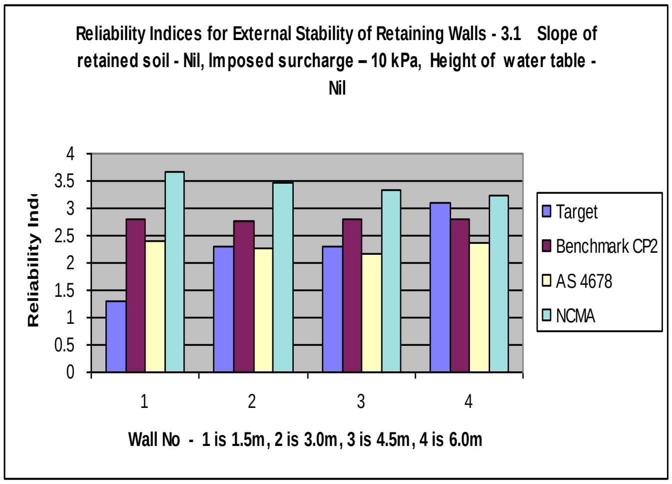

Volume of Retaining Walls - 2.1 Slope of retained soil – 1 in 4, Imposed surcharge - Nominal, Height of water table - Nil Cohesionless soil, moist backing, φ = 35o, δ = 20o
Volume m3
Benchmark CP2
AS 4678
NCMA
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m

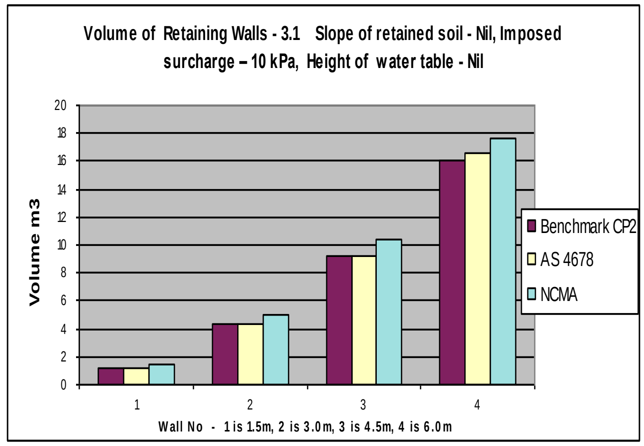

Reliability Indices for External Stability of Retaining Walls - 2.2 Slope of retained soil - 1 in 4, Imposed surcharge - Nominal, Height of water table - Nil Cohesive soil, silt with both friction and cohesion, φ = 20o, δ = 0o , co = 7.2 kPa
Reliability Ind
Target
Benchmark CP2
AS 4678
NCMA
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m

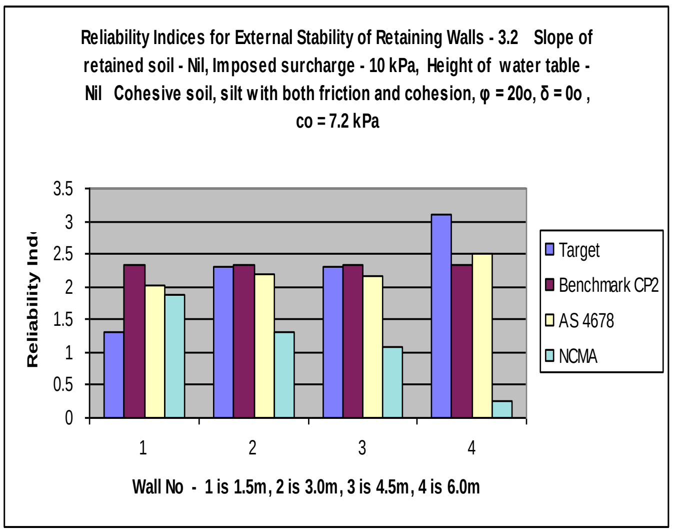

Volume of Retaining Walls - 2.2 Slope of retained soil - 1 in 4, Imposed surcharge - Nominal, Height of water table - Nil Cohesive soil, silt with both friction and cohesion, φ = 20o, δ = 0o , co = 7.2 kPa
Volume m3
Benchmark CP2
AS 4678
NCMA
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m

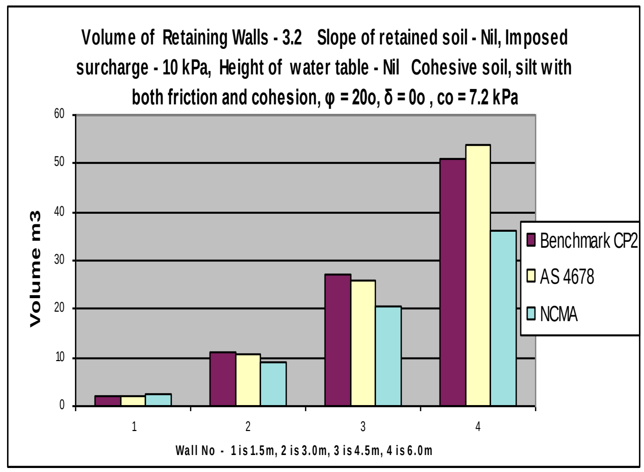

Reliability Indices for External Stability of Retaining Walls - 2.3 Slope of retained soil - 1 in 4, Imposed surcharge - Nominal, Height of water table - Nil Cohesive soil, non-fissured clay φ = 0o, δ = 0o c = 14.3 kPa
Reliability Ind
Target
Benchmark CP2
AS 4678
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m

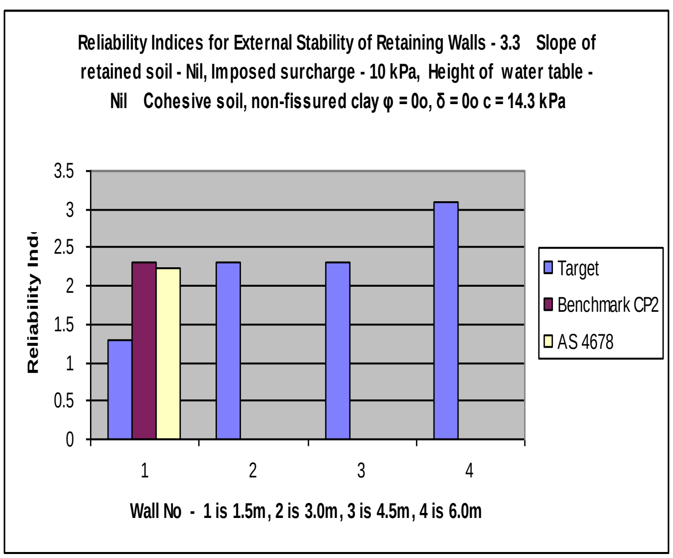

Volume of Retaining Walls - 2.3 Slope of retained soil - 1 in 4, Imposed surcharge - Nominal, Height of water table - Nil Cohesive soil, non-fissured clay φ = 0o, δ = 0o c = 14.3 kPa
Volume m3
Benchmark CP2
AS 4678
NCMA
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m

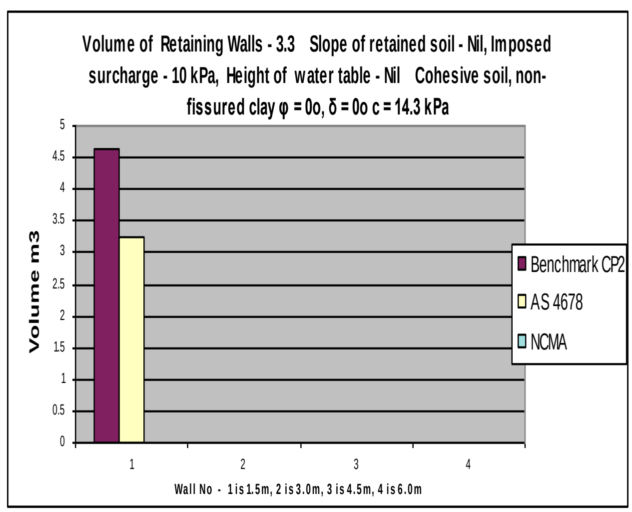

Reliability Indices for External Stability of Retaining Walls - 3.1 Slope of retained soil - Nil, Imposed surcharge – 10 kPa, Height of water table - Nil
Reliability Ind
0
0.5
1
1.5
2
2.5
3
3.5
4
1
2
3
4
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m
Target
Benchmark CP2
AS 4678
NCMA

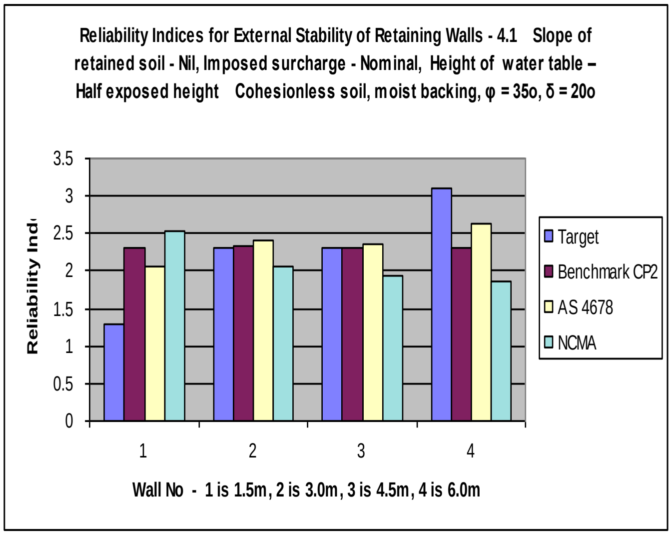

Volume of Retaining Walls - 3.1 Slope of retained soil - Nil, Imposed surcharge – 10 kPa, Height of water table - Nil
Volume m3
0
2
4
6
8
10
12
14
16
18
20
1
2
3
4
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m
Benchmark CP2
AS 4678
NCMA

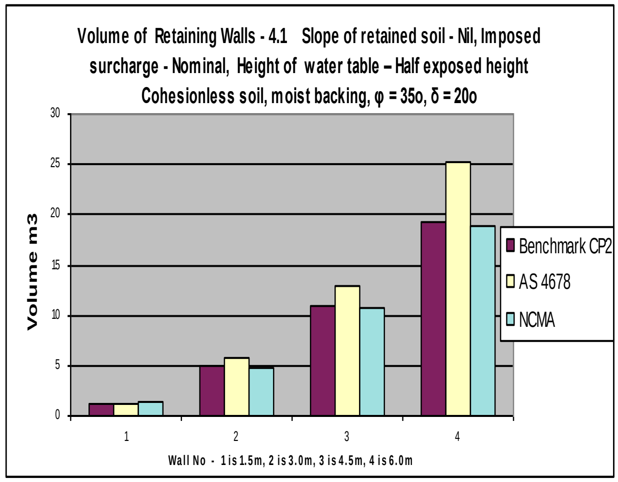

Reliability Indices for External Stability of Retaining Walls - 3.2 Slope of retained soil - Nil, Imposed surcharge - 10 kPa, Height of water table - Nil Cohesive soil, silt with both friction and cohesion, φ = 20o, δ = 0o , co = 7.2 kPa
Reliability Ind
0
0.5
1
1.5
2
2.5
3
3.5
1
2
3
4
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m
Target
Benchmark CP2
AS 4678
NCMA

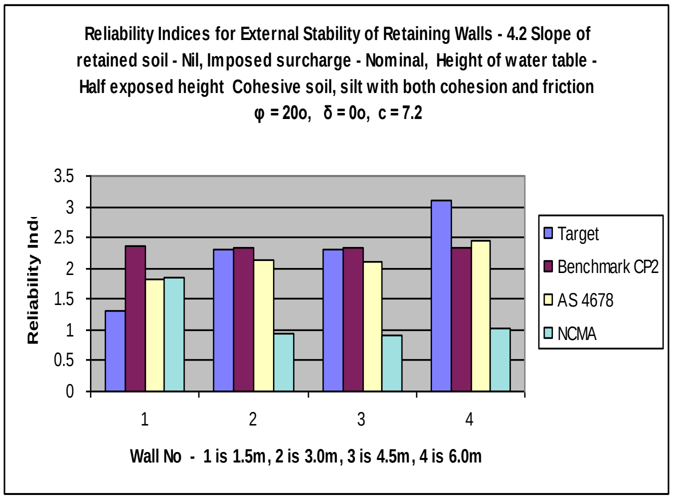

Volume of Retaining Walls - 3.2 Slope of retained soil - Nil, Imposed surcharge - 10 kPa, Height of water table - Nil Cohesive soil, silt with both friction and cohesion, φ = 20o, δ = 0o , co = 7.2 kPa
Volume m3
0
10
20
30
40
50
60
1
2
3
4
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m
Benchmark CP2
AS 4678
NCMA

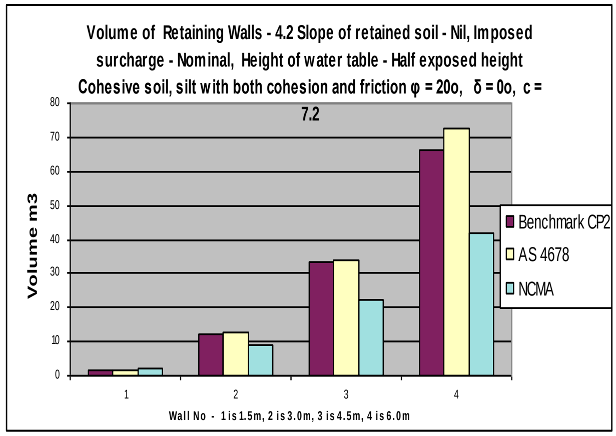

Reliability Indices for External Stability of Retaining Walls - 3.3 Slope of retained soil - Nil, Imposed surcharge - 10 kPa, Height of water table - Nil Cohesive soil, non-fissured clay φ = 0o, δ = 0o c = 14.3 kPa
Reliability Ind
0
0.5
1
1.5
2
2.5
3
3.5
1
2
3
4
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m
Target
Benchmark CP2
AS 4678

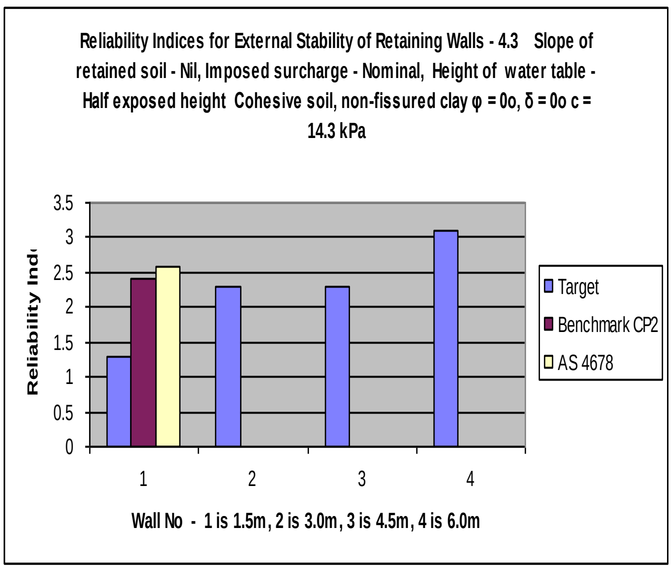

Volume of Retaining Walls - 3.3 Slope of retained soil - Nil, Imposed surcharge - 10 kPa, Height of water table - Nil Cohesive soil, non-fissured clay φ = 0o, δ = 0o c = 14.3 kPa
Volume m3
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
1
2
3
4
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m
Benchmark CP2
AS 4678
NCMA

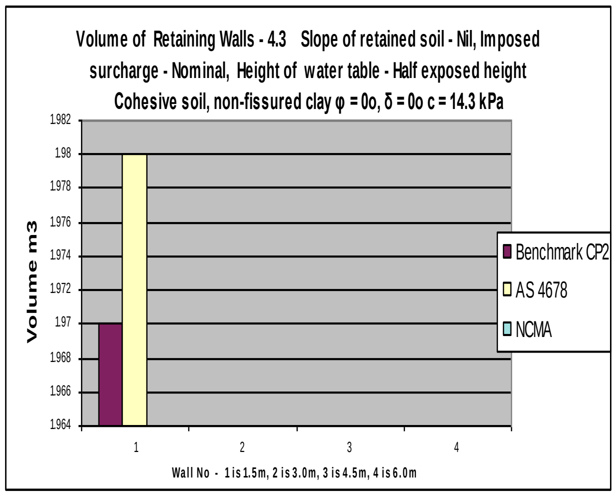

Reliability Indices for External Stability of Retaining Walls - 4.1 Slope of retained soil - Nil, Imposed surcharge - Nominal, Height of water table – Half exposed height Cohesionless soil, moist backing, φ = 35o, δ = 20o
Reliability Indi
Target
Benchmark CP2
AS 4678
NCMA
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m


Volume of Retaining Walls - 4.1 Slope of retained soil - Nil, Imposed surcharge - Nominal, Height of water table – Half exposed height Cohesionless soil, moist backing, φ = 35o, δ = 20o
Volume m3
Benchmark CP2
AS 4678
NCMA
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m


Reliability Indices for External Stability of Retaining Walls - 4.2 Slope of retained soil - Nil, Imposed surcharge - Nominal, Height of water table - Half exposed height Cohesive soil, silt with both cohesion and friction φ = 20o, δ = 0o, c = 7.2
Reliability Indi
Target
Benchmark CP2
AS 4678
NCMA
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m


Volume of Retaining Walls - 4.2 Slope of retained soil - Nil, Imposed surcharge - Nominal, Height of water table - Half exposed height Cohesive soil, silt with both cohesion and friction φ = 20o, δ = 0o, c = 7.2
Volume m3
Benchmark CP2
AS 4678
NCMA
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m


Reliability Indices for External Stability of Retaining Walls - 4.3 Slope of retained soil - Nil, Imposed surcharge - Nominal, Height of water table - Half exposed height Cohesive soil, non-fissured clay φ = 0o, δ = 0o c = 14.3 kPa
Reliability Indi
Target
Benchmark CP2
AS 4678
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m


Volume of Retaining Walls - 4.3 Slope of retained soil - Nil, Imposed surcharge - Nominal, Height of water table - Half exposed height Cohesive soil, non-fissured clay φ = 0o, δ = 0o c = 14.3 kPa
Volume m3
Benchmark CP2
AS 4678
NCMA
Wall No - 1 is 1.5m, 2 is 3.0m, 3 is 4.5m, 4 is 6.0m

9. Conclusions

1. The ultimate load limit state method of AS 4678 generally yields a more liberal design than the historical working stress method of Code of Practice CP 2.
2. The difference lies in the ability of AS 478 to take advantage of a stiff bearing pad to allow the point of rotation to approach the toe of the retaining wall and to spread the load deep into the foundation. The working stress method limits this reaction to within the middle third of the footing.
3. Load Case 1. (cohesionless soil) is limited by overturning for both methods, although AS 4678 has an advantage.
4. Load Case 2 (silt) show close relationship between both methods, generally limited by forward sliding.
5. Load Case 3 (non-fissured clay) cannot be sensibly designed in either case, because the clay foundation cannot prevent forward sliding. This leads to the logical conclusion that such foundations should replaced by material with high friction.
6. These observations lead to the following broad conclusions:
   - AS 4678 is not conservative when compared to traditional working stress methods. To the contrary, it is consistently more liberal.
   - Unlike traditional working stress methods, AS 4678 caters, to some extent, for the need for greater safety in structures with high consequence of failure and lower safety in structures with low consequence of failure.
   - There are some marginal savings in structure volume to be derived from using AS 4678, when compared to traditional working stress methods.
   - The difficulties in designing for cohesive soils derive not from AS 4678, but from the assumptions made in respect to soil properties.

10. References

AS 4678-2002 *Earth retaining structures*, Standards Australia

Civil Engineering Code of Practice No 2 (1951) *Earth Retaining Structures* Institution of Structural Engineers (UK)

Reinforced Concrete Masonry Cantilever Retaining Walls –Design and Construction Guide, Concrete Masonry Association of Australia, MA51, March 2005

Segmental Concrete Reinforced Soil Retaining Walls – Design and Construction Guide, Concrete Masonry Association of Australia, MA52, December 2004

Segmental Concrete Gravity Retaining Walls – Design and Construction Guide, Concrete Masonry Association of Australia, MA53, March 2005

11. Acknowledgements

Part 1 of this paper draws on the results of a desk-research project into the structural reliability of AS 4678, commissioned and funded by the Concrete Masonry Association of Australia, whose contribution is acknowledged and appreciated.

PART 2 – SEISMIC CONSIDERATIONS

1. AS 4678 Options

AS 4678 Appendix I sets out the options for designing retaining walls for earthquake. Briefly the procedure is:

- Determine the "Earthquake Design Category" using Table I3, which considers the "product of accelerations coefficient and site factor" (a measure of the seismicity) and the "structure classification" (which is a measure of the consequence of failure). This approach is consistent with that in AS 1170.4-1993 (which is now superseded).

- Depending on the Design Category, determine the design approach. There are three options given.
  - For low seismicity and low consequence of failure (A_{er} and B_{er}), a dead load factor of 1.25, the same as for static loads, may be used.
  - For increasing seismicity and consequence of failure (C_{er}), a dead load factor of 1.50 may be used.
  - For combinations of higher seismicity and consequence of failure (D_{er} and E_{er}), specific earthquake design to AS 4678 Clauses I8 to I22 must be used. Various analysis options are given. The Mononobe-Okabe method given in Clause I14 gives a simple solution, and has been used in the following analysis.

Table P2.1 provides a summary of the process described above, based on a combination of AS 4678 Tables I3 and I4.

Product of acceleration coefficient and site factor (*aS*)	**Table P2.1 - Design Category**		
	Structure classification		
	Type C **Failure would result in significant damage or risk to life**	**Type B** **Failure would result in moderate damage and loss of services**	**Type A** **Failure would result in not more than moderate damage and not more than minimal loss of access**
$aS \geq 0.2$ High seismicity	E_{er} Specific earthquake design to AS 4678 Clauses I8 to I22	D_{er} Specific earthquake design to AS 4678 Clauses I8 to I22	C_{er} Design for static loads with a dead load factor of 1.50
$0.1 \leq aS < 0.2$ Medium seismicity	D_{er} Specific earthquake design to AS 4678 Clauses I8 to I22	C_{er} Design for static loads with a dead load factor of 1.50	B_{er} Design for static loads with a dead load factor of 1.25
$aS < 0.1$ Low seismicity	C_{er} Design for static loads with a dead load factor of 1.50	B_{er} Design for static loads with a dead load factor of 1.25	A_{er} Design for static loads with a dead load factor of 1.25

2. Comparison of Specific Earthquake Design to the Options Given in AS 4678

Table P2.2 gives the effective dead load factor that would result from a rigorous determination of loads using AS 4678 Clauses I8 to I22; and compares them to the dead load factor that is permissible under a other combinations of AS 4678 Tables I3 and I4.

Product of acceleration coefficient and site factor (*aS*)	**Dead Load Factor for Design**		
	Structure classification		
	Type C **Failure would result in significant damage or risk to life**	**Type B** **Failure would result in moderate damage and loss of services**	**Type A** **Failure would result in not more than moderate damage and not more than minimal loss of access**
aS = 0.2 High seismicity	E_{er} Must use AS 4678 Clauses I8 to I22 giving the following: For $\phi = 25^o$ $\gamma = 1.69$ For $\phi = 30^o$ $\gamma = 1.70$ For $\phi = 25^o$ $\gamma = 1.73$	D_{er} Must use AS 4678 Clauses I8 to I22 giving the following For $\phi = 25^o$ $\gamma = 1.69$ For $\phi = 30^o$ $\gamma = 1.70$ For $\phi = 25^o$ $\gamma = 1.73$	C_{er} May use $\gamma = 1.50$ This is <u>non-conservative</u>, since the calculated values are: For $\phi = 25^o$ $\gamma = 1.69$ For $\phi = 30^o$ $\gamma = 1.70$ For $\phi = 25^o$ $\gamma = 1.73$
aS = 0.15 Medium seismicity	D_{er} Must use AS 4678 Clauses I8 to I22 giving the following For $\phi = 25^o$ $\gamma = 1.56$ For $\phi = 30^o$ $\gamma = 1.58$ For $\phi = 25^o$ $\gamma = 1.60$	C_{er} May use $\gamma = 1.50$ This is <u>a bit non-conservative</u>, since the calculated values are: For $\phi = 25^o$ $\gamma = 1.56$ For $\phi = 30^o$ $\gamma = 1.58$ For $\phi = 25^o$ $\gamma = 1.60$	B_{er} May use $\gamma = 1.25$ This is <u>non-conservative</u>, since the calculated values are: For $\phi = 25^o$ $\gamma = 1.56$ For $\phi = 30^o$ $\gamma = 1.58$ For $\phi = 25^o$ $\gamma = 1.60$
aS = 0.1 Low seismicity	C_{er} May use $\gamma = 1.50$ This is conservative, since the calculated values are: For $\phi = 25^o$ $\gamma = 1.45$ For $\phi = 30^o$ $\gamma = 1.46$ For $\phi = 25^o$ $\gamma = 1.47$	B_{er} May use $\gamma = 1.25$ This is <u>non-conservative</u>, since the calculated values are: For $\phi = 25^o$ $\gamma = 1.45$ For $\phi = 30^o$ $\gamma = 1.46$ For $\phi = 25^o$ $\gamma = 1.47$	A_{er} May use $\gamma = 1.25$ This is <u>non-conservative</u>, since the calculated values are: For $\phi = 25^o$ $\gamma = 1.45$ For $\phi = 30^o$ $\gamma = 1.46$ For $\phi = 25^o$ $\gamma = 1.47$

3. Conclusion

The only combinations that lead to non-conservative earthquake designs are those where "failure would result in not more than moderate damage and not more than minimal loss of access", or "failure would result in moderate damage and loss of services" in combination with low or medium seismicity situations. This should be considered this in the context of the other risks associated with the retaining walls being designed.

4. References

AS 4678-2002 *Earth retaining structures*, Standards Australia including those references cited in Appendix I.

ISO 2394 *General principles on reliability for structures,* 1998-06-01 International Standard.

Ghiocel, D. and Lungu,D. (1975), *Wind, Snow and Temperature Effects on Structures Based on Probabilitiy*, Abacus Press, UK.