Changes in Retaining Wall Design

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Changes in retaining wall design

The changes made in the Codes of Practice for retaining wall design over the last 50 years are reviewed by Rodney McDermott, based on a final year project at the University of Ulster

This report summarises the findings of a comparison between the design philosophies of water retaining and non-water retaining codes of practice (codes) in relation to retaining wall design. The comparison was built upon an extensive final year BEng (Hons) project at the University of Ulster which compared codes in terms of design philosophy, treatment of durability and influence on construction techniques. This involved comparing nine relevant codes spanning from 1957 to 2006 as shown in Fig 1.

The comparative *in situ* retaining wall design focused on the determination of the wall root width (h) and the root reinforcement (A_s) as illustrated in Fig 2. In terms of physical requirements, the results are shown in Table 1 whilst Table 10 compares the results in terms of economy.

In all cases the designs were based on the use of Grade 35 concrete (with equivalent cylinder strength in EC 2 designs) and high yield deformed reinforcement.

For the purposes of this comparison, the retaining wall was designed for two loading scenarios:

- Reservoir full – no backfill in place
- Backfill in place – reservoir empty

Within the various codes, a number of changes were made which resulted in varying dimensions and areas of reinforcement for the retaining wall. The most influential changes in the Codes related to Factors of Safety, Reinforcement, Crack Control, Span Depth Ratio and Triangular Loading.

Factors of Safety

The first of the codes considered was CP 114 (BSI, 1948) which was introduced in April 1948, replacing the London County Council By-laws of 1938, and revised in 1957. This code did not cover prestressed concrete which was addressed separately in CP 115 (BSI, 1959).

CP 114 assumes that steel and concrete are elastic within the specified range of permissible values which are provided in Clause 303 and Clause 304 respectively. A Factor of Safety (FoS) against failure is achieved solely by limiting these permissible stresses for the estimated working loads. Concrete stresses are limited to approximately 33% of the cube strength while steel stresses are limited to approximately 50% of the yield strength. For this reason, the elastic or modular ratio method is sometimes referred to as 'permissible stress design'.

The fact that stress–strain relationship for concrete changes with time is taken into account by the selection of a modular ratio, $m = 15$. This is based on a single value of long-term modulus of elasticity which allows for creep effect. However, no account is taken of the many other factors which have an influence.

In the 1957 version of CP 114 (BSI, 1957), the Load Factor Method (LFM) was introduced as an alternative design method. This was due to the

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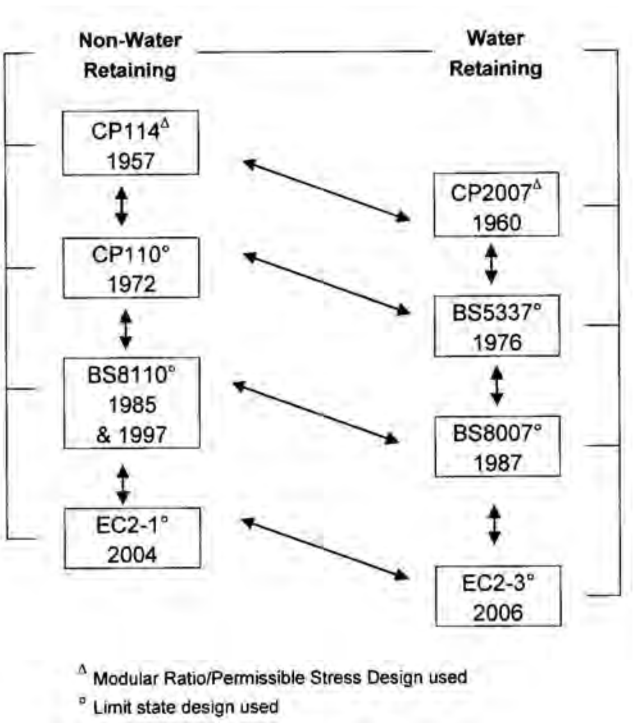

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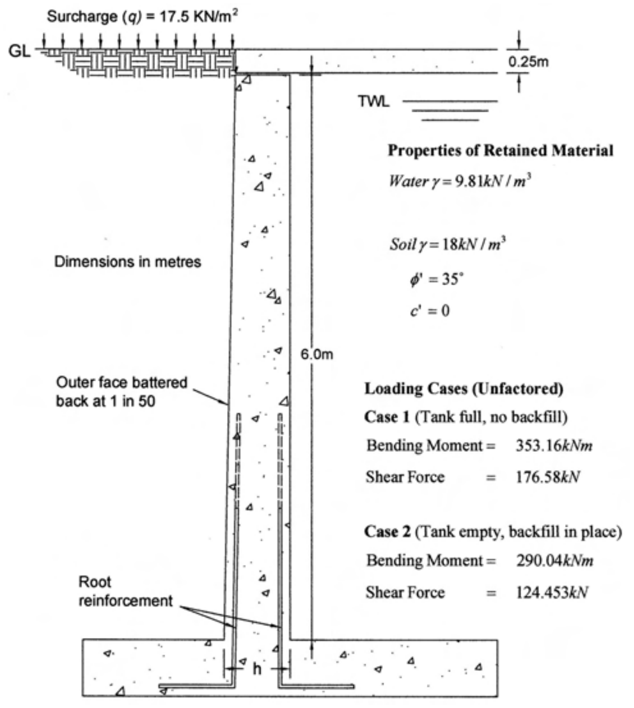

Fig 1. Comparison of Structural Concrete Codes / Fig 2. Section through retaining wall used in designs

main criticism of the modular ratio method as being too conservative. The LFM was a first attempt at Ultimate Limit State Design (ULSD) with sections considered at failure. Sections were designed for the working loads multiplied by a load factor, generally 1.8. A rectangular stress distribution of two-thirds the cube strength acting on a compression zone limited to 0.5 times the effective depth was used. The stress in the tensile reinforcement was limited to the appropriate permissible stress given in the code. This had the effect of increasing the factor of safety beyond 1.8.

According to Scott *et al.* (1965), the condition of balance (compression zone equal to 0.5 times the effective depth) in load factor design corresponds to the use of the 'economic percentage in the design according to elastic theory'. The load factor method only gave a 1% saving on the area of steel over the Modular Ratio Method for the root of the wall section chosen.

The requirements of CP 114 are deemed to form the basis of the water retaining code CP 2007 (BSI, 1960). However, some of the requirements of CP 114 have been modified, such as much-reduced permissible stresses in the steel. Reducing the permissible stress in the steel reduced the strain in the concrete which consequently reduced crack widths in the concrete. The backdrop to CP 2007 appears to be the *Code of Practice for the Design and Construction of Reinforced Concrete Structures for the Storage of Liquids* which was first published in 1938 (ICE, 1938). Unlike CP 114, CP 2007 also covered prestressed concrete design. The relationship between water retaining and non-water retaining codes still exists, as shown in Fig 1.

CP 110 introduced in 1972 (BSI, 1972) is commonly known as the 'unified code for structural concrete' as it covered both reinforced and prestressed concrete. It introduced the concept of Limit State Design (LSD) which has been carried through all the later reinforced concrete codes considered here.

The code subdivides limit state design into two categories:

- Ultimate Limit State which is concerned with providing an acceptable probability of ensuring that the structure does not collapse under the actions of defined loads (Cement and Concrete Association, 1972).
- Serviceability Limit State which considers deflection, cracking and vibration.

In order to satisfy the limit states, partial factors of safety were introduced for both loads and materials. Partial Factors of Safety for Loads (γ_f) increase the loads to take account of possible unusual increases in the actual load not covered in deriving the characteristic load, incorrect assumptions regarding stresses, and dimensional accuracy in construction. Various factors are used for serviceability and ultimate limit states and for various types of loads and combinations.

Design strengths for materials are determined by dividing the characteristic material strengths by the relevant Partial Factors of Safety for the Material (γ_m). These factors take account of the variability of materials and the limit state considered. Generally $\gamma_f = 1.0$ is used for serviceability limit state; values of γ_f for ultimate limit state are shown in Table 2

The γ_m value for concrete, at the ultimate limit state, has remained at 1.5 from CP 110 to Eurocode 2: Part 1 (EC 2-1). However, the corresponding γ_m values for steel have fluctuated from CP 110 to EC 2-1, as shown in Table 3.

BS 5337 (BSI, 1976) which superseded CP 2007 in 1976 was the sister code to CP 110. It included three design options for water retaining structures:

- the limit state design method;
- the alternative design method which was similar to that of CP 2007 (provision is made to use the most recent version of CP 114);
- the limited stress method using limit state design and elastic theory.

For the limit state design method, the partial factors of safety used were those in CP 110. However, earth and water loads were taken as imposed loads with the unjustifiably high partial factor of safety of 1.6.

CP 110 was replaced in 1985 by the more economical BS 8110 (BSI, 1985). Part of the reason for this improved economy was due to the significant reduction in the partial safety factor for earth and water loads from 1.6 to 1.4 the revised version, BS 8110 (BSI, 1997) states that $\gamma_f = 1.4$ should still be used for water in circumstances where the maximum credible water level cannot be clearly identified but allows for a further reduction to $\gamma_f = 1.2$ where the maximum water level can be identified, as is the case in the majority of circumstances. All comparative designs used a 6m depth of water in order to conform to Clause 2.3 in BS 8007 which states that 'for ultimate limit state conditions, liquid levels should be taken to the tops of walls assuming that the liquid outlets are blocked' (BSI, 1987). Comparisons of the wall design to each of the BS 8110 versions are shown in Table 1.

BS 8110 (1997) also made a significant change to the partial factor of safety for steel, reducing the value $\gamma_m = 1.15$ used in BS 8110 (1985) and the superseded CP 110 to 1.05. Beeby (1994) provided analysis of 10 330 test results on high yield steel which indicated a 95% of yield

Table 1: Summary of results

Non-Water Retaining Codes			Water Retaining Codes		
Code	**h§(mm)**	**A$_s$ (mm^2/m) Both faces**	**Code**	**h§(mm)**	**A$_s$ (mm^2/m) Both faces**
CP 114† (1957)	655	6233	CP 2007 (1960)	925	9,360
CP 110 (1972)	740	4315	BS 5337 (1976)	750	4,540
BS 8110 (1985)	660	4071	BS 8007 (1987)	660	4,967*
BS 8110 (1997)	670	3400			
EC 2-1 (2004)	610	3916	EC 2-3 (2006)	610	5,744

* Change in formula for calculating crack width from that given in BS 5337.
† Load factor and modular ratio method gave almost the same results.
§ The value of h refers to h_{bottom}.
h_{top} will be 120mm less in each case due to the outer wall face being battered back at 1 in 50.

Table 2: Ultimate limit state partial safety factor for loads (γ_f) used in comparative design of retaining walls

Loading combination	**Code**	**Load type**					
		Dead		**Imposed**		**Earth & Water Pressure**	**Wind**
		Adverse	**Beneficial**	**Adverse**	**Beneficial**		
Dead & imposed	CP 110	1.40	–	1.60	0.00	As imposed load§	–
	BS 8110*	1.40	1.00	1.60	0.00	1.20 (1.40)	–
	EC2	1.35	1.00	1.50	0.00	1.35	–

Note: *EC2/EC0 refers to dead load as permanent load and imposed load as variable load.*

* The version of BS 8110 referred to in Tables 2 and 3 are the 1997 version with the bracketed information referring to BS 8110 (1985)

§ Explicitly given in Clause 4.2, BS 5337 except for the earth covering on reservoir roofs which may be taken as dead load

Table 3: Partial factors (γ_m) for material for the ultimate limit state

Design situation	**Code**	**Material**		
		Concrete	**Reinforcing**	**Prestressing**
Normal	CP 110	1.5	1.15	–
	BS 8110	1.5* 1.25◊ 1.4‡	1.05 (1.15)	1.05
	EC2	1.5	1.15	1.15

* = flexure or axial load; ◊ = shear stress; ‡ = bond strength

strengths of 490N/mm² or above.

BS 8007 omitted the alternative design methods for water retaining structures in BS 5337 which it replaced in 1987 and is based mainly on the limit state approach of BS 8110. However, a few elements of the limited stress approach remained. A factor of safety of not less than 1.1 was recommended in BS 8007 against uplift.

EC 2-1 (BSI, 2004), which will eventually replace BS 8110, reduces the partial factors of safety for ultimate dead and imposed loads from 1.4 to 1.35 and 1.6 to 1.5 respectively. However it increases the partial factor of safety for earth and water, loads, where the levels could be reasonably easily determined, from 1.2 in BS 8110 (1997) to 1.35.

The partial factor of safety for steel has also been increased from 1.05 to 1.15 but this is offset by an increase in characteristic yield strength (see below Reinforcement section).

Eurocode 2: Part 3 (EC 2-3) (BSI, 2006) which deals with liquid retaining structures uses the same factors of safety for ultimate limit design.

Reinforcement

High tensile steel was used in all comparative designs. In the CP 114 and CP 2007 designs, the most notable differences are the permissible stresses in the steel and concrete and this has a significant bearing on the satisfactory root width (h) (see Table 4).

The reduced permissible stresses in CP 2007 gave a 41.2% increase in wall root thickness and 50.2% extra reinforcement.

CP 110 Table 3 used a characteristic yield strength of 460N/mm² for high yield steel bars up to and including 16mm diameter, but this is reduced to 425N/mm² for bars exceeding 16mm diameter. The bars chosen for all comparative designs exceeded 16mm diameter requiring the use of 425N/mm² in the designs to CP 110 and BS 5337.

Design to BS 8110 and BS 8007 used a characteristic yield strength of 460N/mm² for all high yield steel bar sizes.

EC 2-1 does not give mild steel strengths as Clause 3.2.2(3)P states that the application rules for design and detailing are valid for a specified yield range f_{yk} = 400-600N/mm². EC 2 refers to BS EN 10080 (BSI, 2005) in terms of reinforcement which gives f_{yk} = 500N/mm². This was the value used in the EC 2 designs although the higher characteristic yield strength is off set by the increase in partial factor of safety. BS 8110 (1997) gives a design yield strength of 460/1.05 ≈ 438.1 N/mm² while EC 2: Part 1 gives 500/1.15 ≈ 434.8 N/mm².

Crack control

Crack control in CP 114 and CP 2007 was assumed to be achieved by limiting the permissible stresses. However, Hughes (1977), reports that experience has shown that structures designed to CP 2007 (1960) can exhibit cracking because of shrinkage and early thermal movement in the immature concrete.

From CP 110 onward, all non-water retaining codes provide formulae for calculating crack widths (w) although for routine work, crack width was deemed to have been controlled by the use of reinforcement rules. Whilst CP 110 and both versions of BS 8110 give a maximum w = 0.3mm; EC 2-1 implies a maximum w = 0.4mm.

The water retaining codes give more detailed information on the requirements for w.

The change in BS 8110 (1997) in partial factor of safety for steel from 1.15 to 1.05 has the effect of increasing service steel stress requiring a reduction in the maximum reinforcement spacing.

BS 5337 attempted to improve upon the problems in CP 2007 mainly in two ways:

- the code permits three different types of design as referred to previously.
- by providing the designer with greater flexibility. This is achieved by introducing three classes of exposure with three corresponding maximum crack width values as shown in Table 5.

The exposure conditions were revised in BS 8007 as were the maximum design surface crack widths, w, as follows:

- severe or very severe exposure = 0.2mm
- critical aesthetic appearance = 0.1mm

The fundamental differences between the approach to crack width of BS 5337 and BS 8007 was in the calculation of the strain due to the stiffening effect of concrete between the cracks. This resulted in a larger average strain at the surface hence a closer spacing of bars, and increased reinforcement area were required to give an acceptable crack width in BS 8007 design.

EC 2-3 provides four classes of structure as follows:

- Class 0: Some degree of leakage acceptable
- Class 1: Leakage limited to a small amount. Some surface damp patches acceptable
- Class 2: Minimal leakage. Appearance not to be impaired by staining
- Class 3: No leakage permitted.

Permissible crack width is also related to the hydrostatic head/root width varying linearly from 0.2mm at a hydrostatic head/root width ratio of 5

Table 4: Permissible reinforcement stress: CP 114 versus CP 2007

Permissible stress (N/mm²)			
Code	Concrete (N/mm²)	High yield deformed steel reinforcement	
		Liquid retaining face (N/mm²)	Outer face (N/mm²)
CP114	12.82	210#	210#
CP2007	11.67	82.8∅	138§°

bar Ø > 20mm. However, for bar Ø < 20mm, permissible stress = max. 230N/mm²
∅ value is 60.6% less than the CP 114 value
§ value is 34.3% less than the CP 114 value
° for members with h > 229mm

Table 5: BS 5337 exposure class and maximum crack widths (w)

Exposure class (to BS 5337)	Description	Maximum w
A	Exposed to a moist or corrosive atmosphere or subject to alternate wetting and drying	0.1mm
B	Exposed to continuous or almost continuous contact with liquid	0.2mm
C	Not exposed to liquid nor to moist or corrosive conditions	0.3mm

Table 6: Basic Span/effective depth ratios

Code	s/d ratio for cantilevers. Rectangular sections
CP 110	7 Table 8
BS 8110	7 Table 3.9
EC 2	6-8 Table 7.4N

Table 7: Triangular loading modification factor

	h_{top}/h_{bottom}								
	1.0	**0.9**	**0.8**	**0.7**	**0.6**	**0.5**	**0.4**	**0.3**	
Triangular loading	1.25	1.19	1.13	1.06	1.00	0.92	0.85	0.78	Modification factor

N.B. shading denotes that values originate from Clause 2.2.3.4, BS 8007

Table 8: Cost of concrete for the wall stem of a 40m × 40m square reservoir

Concrete rate = £96.00m^3

Code	Concrete per linear m of wall (m^3)	Cost per m run of wall (£)	Perimeter wall 160 m (£)	Code	Concrete per linear m of wall (m^3)	Cost per m run of wall (£)	Perimeter wall 160m (£)
CP 114 (1957)	3.57	342.72	54 835.20	CP 2007 (1960)	5.19	498.24	79 718.40
CP 110 (1972)	4.08	391.68	62 668.80	BS 5337 (1976)	4.14	397.44	63 590.40
BS 110 (1985)	3.60	345.6	55 296.00	BS 8007 (1987)	3.60	345.60	55 296.00
BS 110 (1997)	3.66	351.36	56 217.60				
EC 2-1 (2004)	3.30	316.8	50 688.00	EC 2-3 (2006)	3.30	316.80	50 688.00

and below to 0.05 at a ratio of 35 and above. For this comparison study the EC 2-3 crack width was limited to under 0.2mm for similarity given the value of 0.2mm (maximum w) chosen in BS 5337 and compulsory in BS 8007 designs.

Span depth ratio

CP 114 provided a basic maximum span/depth ratio of 12 for a cantilever slab which was reduced depending on the level of permissible stresses in the concrete and steel. A much lower ratio was dictated by the greatly reduced permissible stresses permitted by CP 2007. CP 110 and subsequent codes changed the calculation of span/depth ratios which dictates h.

Beal (1983) commented on the change as follows: 'While the treatment of deflection in CP 110 has been generally welcomed as an improvement on the rather rough-and-ready span/depth rules in CP 114, it is very cumbersome to apply in practice. The designer cannot check the span/depth ratio until section design is almost complete and, if a problem arises, he/she has little guide as to what scope there is for solving it by redesigning with a reduced steel stress'.

The basic span/effective depth ratios shown in Table 6 for CP 110 and BS 8110 are modified by factors related to service stresses in the tensile and compressive reinforcement. The change in BS 8110 (1997) in partial factor of safety for steel from 1.15 to 1.05 had the effect of increasing service steel stress thus reducing the modification factor for span/depth ratio and increasing the corresponding root width in the design.

The EC 2-1 calculation of span/depth ratios varies from that in BS 8110 (1985/1997) which varied only slightly to CP 110 (1972) in that the formulae used takes into account the type of element and concrete strength as well as the tensile and compressive reinforcement ratios. The EC 2-1 and EC 2-3 designs were the most slender overall having h values of approximately 9.0% less than that required in BS 8110 (1997).

In limit state codes the effect of compressive reinforcement was not considered when modifying the basic span/depth ratios in the comparative designs

BS 8007 recognises that reservoir walls are usually tapered for aesthetic and economical reasons. Clause 2.2.3.4 states that for triangular loading on a cantilever wall, a net reduction factor should be applied to the basic span/depth ratio if the thickness at the top of the wall is less than 0.6 times the thickness at the base. This reduction factor can be assumed to vary linearly between 1.0 and 0.78 where the thickness at the top varies between 0.6 and 0.3 times the thickness at the

Table 9: Cost of wall starters/root reinforcement for a 40m × 40m square reservoir

Reinforcement rate = £27.00/1000mm^2 of root reinforcement

Code	A_s (mm^2)	Cost per m run of wall (£)	Perimeter wall 160 m (£)	Code	A_s (mm^2)	Cost per m run of wall (£)	Perimeter wall 160m (£)
CP 114 (1957)	6233	168.29	26 926.56	CP 2007 (1960)	9360	252.72	40 435.20
CP 110 (1972)	4315	116.50	18 640.80	BS 5337 (1976)	4540	122.58	19 612.80
BS 110 (1985)	4071	109.92	17 586.72	BS 8007 (1987)	4967	134.11	21 457.60
BS 110 (1997)	3400	91.80	14 688.00				
EC 2-1 (2004)	3916	105.73	16 917.12	EC 2-3 (2006)	5744	155.09	24 814.08

Table 10: Performance of codes in comparison with EC 2: Part 1

Code	Accumulated variable costs (£)	Performance related to EC2 (Part 1) (%)
Non-Water Retaining Codes		
CP 114 (1957)	81 761.76	+20.94
CP 110 (1972)	81 309.60	+20.27
BS 8110 (1985)	72 882.72	+7.81
BS 8110 (1997)	70 905.60	+4.88
EC2: Part 1 (2004)	67 605.12	Benchmark for comparison
Water Retaining Codes		
CP 2007 (1960)	120 153.60	+77.73
BS 5337(1976)	83 203.20	+23.07
BS 8007 (1987)	76 753.60	+13.53
EC 2: Part 3 (2006)	75 502.78	+11.68

bottom.

The information in BS 8007 (Clause 2.2.3.4), which is given as a reduction factor can also be interpreted to give an increased modification factor where h_{top}/h_{bottom} is greater than 0.6 (See Table 7). This was also demonstrated in the work of Batty (1991).

While it is recognised that this modification factor was only introduced in BS 8007 (1987), it is also recognised that pre-BS 8007 practising engineers were using modification factors based on triangular loading to achieve the most economical designs. The triangular loading modification factors were used for all limit state designs in this comparative study.

Comparison of design economy

Although the percentage differences in root width and reinforcement between the codes could be calculated from Table 1, it was decided to put the information in 'real terms' by using competitive rates for the reinforcement and concrete and comparing the construction costs of a retaining wall to form the perimeter of a typical 40m × 40m reservoir. The costs relate to the root reinforcement and wall stem concrete only and are shown in Tables 8 & 9.

Costs were based on a supply and fix price of £860.00/t for reinforcement and a rate for supplying and placing concrete of £96.00/m^3. Formwork areas vary only slightly and formwork costs were not considered in the cost comparison.

Calculation of reinforcement costs were based on the assumption of a starter bar (root reinforcement) of 4m overall length including embedment length in the base. This gives a root reinforcement rate of £27/1000mm^2 of reinforcement.

The summary of findings in Table 1 and the economic comparison in Table 10 are a result of keeping the root width of the wall to a credible minimum, but not the minimum possible root width. The minimum possible root width does not always give the most economical results due to increases in the steel when considering that the steel reinforcement is proportionately more expensive when compared to concrete.

The ±% in Table 10 is a measure of the overall performance of each code in relation to EC 2-1 which has been chosen as the benchmark.

\+ = increased cost/lower economical design

Conclusion

In this code comparison research every revised code included in this comparison yielded savings in terms of economy.

EC 2-1 is approximately 5% more economical than BS 8110 (1997). The water retaining codes generally give an average increase of approximately 7.2% on cost when compared with their respective non-water retaining partnering code (excluding CP 2007 which was very uneconomical). There is also a definite convergence in water retaining and non-water retaining code design philosophies.

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