Design of Liquid Retaining Concrete Structures

3rd edition

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Preface

In 2010, a new suite of design codes was introduced into the UK. As such, the British Standard Codes of Practice 8110 *Structural Use of Concrete* and 8007 *Design of Concrete Structures for Retaining Aqueous Liquids* were replaced by Eurocode 2 (BS EN 1992-1-1) and Eurocode 2 Part 3 (BS EN 1992–3), respectively, both with accompanying UK specific National Application Documents. The guidance provided by these new codes is quoted as being much more theoretical in its nature and is therefore fundamentally different to the traditional step-by-step guidance that has been offered for many years in the UK by the British Standards. The approach of these new replacement codes is therefore a step change in design guidance, requiring much more interpretation.

The third edition of this book, whilst adopting a similar structure to the first two editions, has attempted to reflect this more theoretical approach. The new codes represented an opportunity to improve the guidance, based on a greater depth of research and practical experience gained over the last two decades. Unfortunately, the improvements are not as extensive as would have been hoped, partly because much research to corroborate some of the proposed new theory is still ongoing. In order to accommodate this position, the book offers an insight into some of the remaining shortcomings of the code and the potential improvements to the efficiency of design and possible innovations that are possible and which can hopefully be included in the planned revision of the codes in 2020.

JPF and AJM

Acknowledgements

I met Andrew Beeby for the first time in 1997; later, in 1999 the opportunity arose for me to join the Structures Group at the University of Leeds; I took up the position because Andrew was the head of that group. I have always felt privileged to have been able to call Andrew my mentor, a role which continued even after he retired; at which point in time I could more accurately and proudly call him my friend. I have never known anyone more insightful. His passing in 2011 was an extremely sad time. He was a true gentleman, possessing rare qualities; I give my thanks for his guidance, knowledge, motivation and friendship.

I would also like to thank all the engineers and researchers who have contributed to the better understanding of this fascinating topic of water retaining structures, past and present.

JPF, Leeds

Structural engineering is a fascinating subject and I acknowledge with grateful thanks all those who have influenced my education, training and development as an engineer throughout my career. I am grateful to Matt Kirby for permission to use the photograph reproduced in Figure 1.2. My contribution to this book is dedicated to my family and especially to my father Geoffrey H. Martin (1929–2013).

AJM, Copenhagen

We are both very grateful to Bob Anchor for this opportunity to produce the third edition of his book. His contribution to the design of water retaining structures is now into its fifth decade – an outstanding achievement.

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Chapter 1
Introduction

1.1 Scope

It is common practice to use reinforced or prestressed concrete structures for the storage of water and other aqueous liquids. Similar design methods may also be used to design basements in buildings where groundwater must be excluded. For such purposes as these, concrete is generally the most economical material of construction and, when correctly designed and constructed, will provide long life and low maintenance costs. The design methods given in this book are appropriate for the following types of structure (all of which are in-line with the scope of Part 3 of Eurocode 2, BS EN 1992-3, 2006): storage tanks, reservoirs, swimming pools, elevated tanks (not the tower supporting the tank), ponds, settlement tanks, basement walls, and similar structures (Figures 1.1 and 1.2). Specifically excluded are: dams, structures subjected to dynamic forces, and pipelines, aqueducts or other types of structure for the conveyance of liquids.

It is convenient to discuss designs for the retention of water, but the principles apply equally to the retention of other aqueous liquids. In particular, sewage tanks are included. The pressures on a structure may have to be calculated using a specific gravity greater than unity, where the stored liquid is of greater density than water. Throughout this book it is assumed that water is the retained liquid unless any other qualification is made. The term 'structure' is used in the book to describe the vessel or container that retains or excludes the liquid.

The design of structures to retain oil, petrol and other penetrating liquids is not included (the code (BS EN 1992-3, 2006) recommends reference to specialist literature) but the principles may still apply. Likewise, the design of tanks to contain hot liquids (> 200°C) is not discussed.

1.2 General design objectives

A structure that is designed to retain liquids must fulfil the requirements for normal structures in having adequate strength, durability, and freedom from excessive cracking or deflection. In addition, it must be designed so that the liquid is not allowed to leak or percolate through the concrete structure. In the design of normal building structures, the most critical aspect of the design is to ensure that the structure retains its stability under the applied (permanent and variable) actions. In the design of structures to retain liquids, it is usual to find that if the structure has been proportioned and reinforced so that the liquid is retained without leakage (i.e. satisfying the Serviceability Limit State, SLS), then the strength (the Ultimate Limit State, ULS requirements)

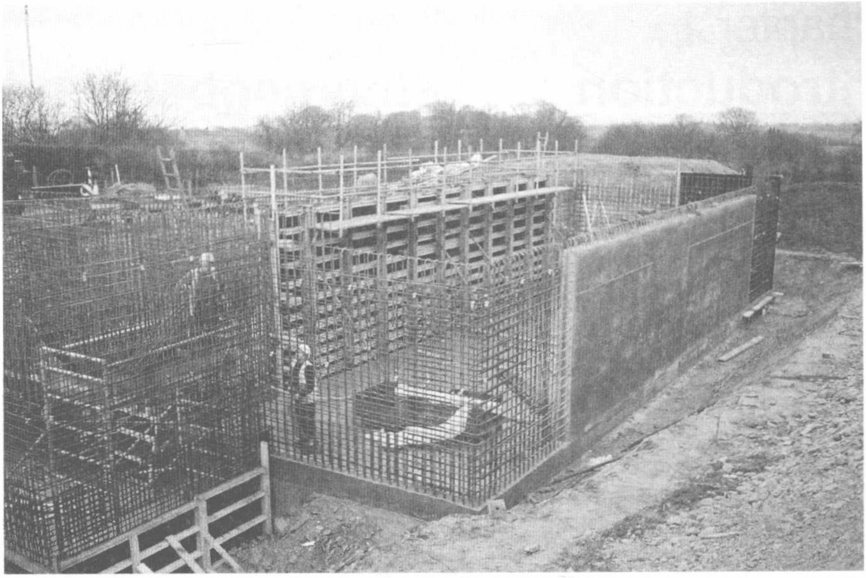

Figure 1.1 *A tank under construction* (Photo: J.P. Forth/A.P. Lowe).

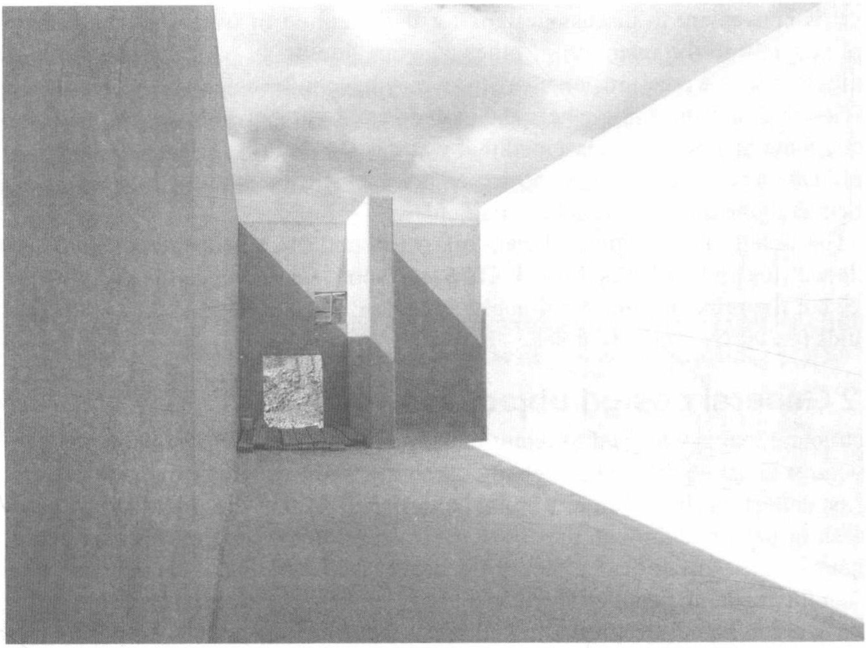

Figure 1.2 *A concrete tank (before construction of the roof) illustrating the simplicity of the structural form* (Photo: M.J. Kirby).

is more than adequate. The requirements for ensuring a reasonable service life for the structure without undue maintenance are more onerous for liquid-retaining structures than for normal structures, and adequate concrete cover to the reinforcement is essential. Equally, the concrete itself must be of good quality, and be properly compacted: good workmanship during construction is critical.

Potable water from moorland areas may contain free carbon dioxide or dissolved salts from the gathering grounds, which attack normal concrete. Similar difficulties may occur with tanks that are used to store sewage or industrial liquids. After investigating by tests the types of aggressive elements that are present, it may be necessary to increase the cover, the cement content of the concrete mix, use special cements or, under 'very severe' (BS EN 1992-1-1, 2004; BS 8500-1, 2006) conditions, use a special lining to the concrete tank.

1.3 Fundamental design methods

Historically, the design of structural concrete was based on elastic theory, with specified maximum design stresses in the materials at working loads. In the 1980s, limit state philosophy was introduced in the UK, providing a more logical basis for determining factors of safety. 2011 has seen the introduction of the new Eurocodes; BS 8110 and BS 8007 have been withdrawn, and in their place is a suite of new codes, including specifically BS EN 1992-1-1:2004 (Eurocode 2 Part 1 or EC2) and BS EN 1992-3: 2006 (Eurocode 2 Part 3 or EC2 Part 3) and their respective National Annexes. The new Eurocodes continue to adopt the limit state design approach. In ultimate design, the working or characteristic actions are enhanced by being multiplied by *partial safety factors*. The enhanced or ultimate actions are then used with the failure strengths of the materials, which are themselves modified by their own partial factors of safety, to design the structure.

Limit state design methods enable the possible modes of failure of a structure to be identified and investigated so that a particular premature form of failure may be prevented. Limit states may be 'ultimate' (where ultimate actions are used) or 'serviceability' (where service actions are used).

Previously, when the design of liquid-retaining structures was based on the use of elastic design (BS 5337), the material stresses were so low that no flexural tensile cracks developed. This led to the use of thick concrete sections with copious quantities of mild steel reinforcement. The probability of shrinkage and thermal cracking was not dealt with on a satisfactory basis, and nominal quantities of reinforcement were specified in most codes of practice. It was possible to align the design guidance relating to liquid-retaining structures with that of the Limit State code BS 8110 Structural Use of Concrete once analytical procedures had been developed to enable flexural crack widths to be estimated and compared with specified maxima (Base *et al*., 1966; Beeby, 1979) and a method of calculating the effects of thermal and shrinkage strains had been published (Hughes, 1976).

Prior to the introduction of BS 8007 in the 1980s, BS 5337 allowed designers to choose between either elastic or limit state design. It has often been said 'A structure does not know how it has been designed'. Any design system that enables a serviceable structure to be constructed safely and with due economy is acceptable. However, since BS 8007 was introduced in the UK, limit state design has been used consistently and perhaps more successfully for the design of liquid-retaining structures and, although it has now been withdrawn, there is no reason why this trend cannot continue with the introduction of these new Eurocodes, which continue to utilise this limit state design philosophy.

1.4 Codes of practice

Guidance for the design of water-retaining structures can be found in BS EN 1992-3 which provides additional guidance, specific to containment structures, to that found in BS EN 1992-1-1 (BS EN 1992-3 does not provide guidance on joint detail). This approach is not unusual as the superseded code BS 8007 also provided additional rules to those found in the over-arching Structural Use of Concrete code, BS 8110. However, whereas BS 8110 contained both guidance on the philosophy of design and the loads and their combinations to be considered in design, a different approach is adopted in the Eurocodes. BS EN 1992-1-1 is itself supported by the Eurocode (BS EN 1990:2002–commonly referred to as Eurocode 0) Basis of Structural Design and Eurocode 1(BS EN 1991–10 parts) Actions on Structures. BS EN 1990 guides the designer in areas of structural safety, serviceability and durability–it relates to all construction materials. BS EN 1991 actually supersedes BS 6399 Loading for Buildings and BS 648 Schedule of weights of building materials. All Eurocodes and their individual Parts are accompanied by a National Annex (NA) / National Application Document (NAD), which provide guidance specific to each individual state of the European Union, i.e. the UK National Application Document only applies to the UK. Values in these National Annexes may be different to the main body of text produced in the Eurocodes by the European Committee for Standardization (CEN).

There are two distinct differences between BS 8110/BS 8007 and the new Eurocodes, which will immediately be apparent to the designer. Eurocodes provide advice on structural behaviour (i.e. bending, shear etc.) and not member types (i.e. beams etc.). Also, Eurocodes are technically strong and fundamental in their approach–they do not provide a step-by-step approach on how to design a structural member.

1.5 Impermeability

Concrete for liquid-retaining structures must have low permeability. This is necessary to prevent leakage through the concrete and also to provide adequate durability, resistance to frost damage, and protection against corrosion for the reinforcement and other embedded steel. An uncracked concrete slab of adequate thickness will be impervious to the flow of liquid if the concrete mix has been properly designed and compacted into position. The specification of suitable concrete mixes is discussed in Chapter 2. Practically, the minimum thickness of poured in-situ concrete for satisfactory performance in most structures is 300 mm. Thinner slabs should only be used for structural members of very limited dimensions or under very low liquid pressures.

Liquid loss may occur at joints that have been badly designed or constructed, and also at cracks or from concrete surfaces where incomplete compaction has been achieved. It is nearly inevitable that some cracking will be present in all but the simplest and smallest of structures. If a concrete slab cracks for any reason, there is a possibility that liquid may leak or that a wet patch will occur on the surface. However, it is found that cracks of limited width do not allow liquid to leak (Sadgrove, 1974) and the problem for the designer is to limit the surface crack widths to a predetermined size. Cracks due to shrinkage and thermal movement tend to be of uniform thickness (although this does depend on the uniformity of the internal restraint) through the thickness of the slab, whereas cracks due to flexural action are of limited depth and are backed up by a depth of concrete that is in compression. Clearly, the former type of crack is more serious in allowing leakage to occur.

An important question is whether or not the cracks formed from the two cases mentioned above (Early Thermal and Loading) are additive. It is accepted that long-term effects may be complementary to early thermal cracking and in these instances steps are taken to reduce the limiting crack width for early deformations. However, currently there is no suggestion or process by which cracking resulting from early-age effects should be added to that resulting from structural loading. It has to be said that no problems have been recognised specific to this; however, it does not mean that it is not occurring. In fact, recent investigations by the author into shrinkage curvature have suggested that both extension of early age cracks and new cracks can occur on loading (Forth *et al.*, 2004).

Before considering whether or not early-age cracking is additive with cracking from structural loading it is worth clarifying the conditions of external restraint to imposed deformation, which can result in this early-age cracking. This external restraint results from either end or edge (base) restraint. Figure 1.3 illustrates the two forms of restraint. These two types of restraint are really limiting forms of restraint. In practice, the situation is somewhat more complicated and the actual restraint is either a combination of these two forms or, more likely when early thermal movements are being considered in a wall, one of edge restraint (Beeby and Forth, 2005).

An example of where both forms of restraint exist can be found by considering a new section of concrete cast between two pre-existing concrete wall sections and onto a pre-existing concrete base. At the base, edge restraint will dominate (see Figure 1.4–Zone 2). However, further up the wall away from the base, edge restraint will become less significant and end restraint will become more influential. At a point within the height of the wall, end restraint will dominate and edge restraint becomes insignificant (see Figure 1.4–Zone 1). The position and significance of the two restraint conditions

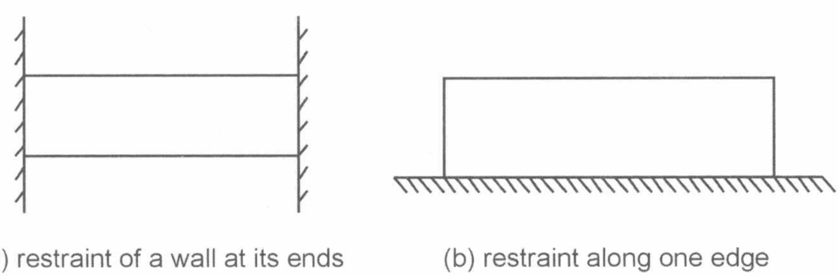

Figure 1.3 *External end and edge (base) restraint.*

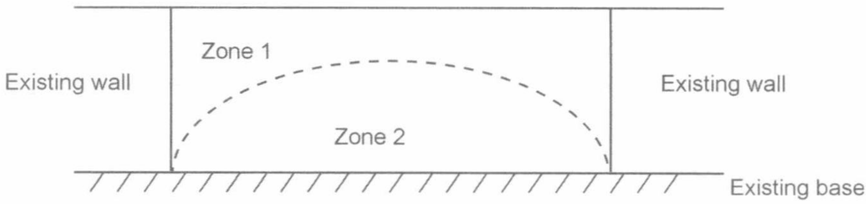

Figure 1.4 *Approximate regions of domination of end (Zone 1) and edge (Zone 2) restraint in an infill wall.*

is obviously dependent on the height, cross section and length of the concrete section as well as the concrete base.

BS EN 1992-3 provides restraint factors, R for various wall and floor slab placing sequences (this figure is reproduced from BS 8007). Diagrammatically it attempts to describe the combination of the two types of external restraint described above, i.e. end and edge restraint, although the restraint factor, R is really only based on the structural model of a member restrained at its end against overall shortening.

On the matter of whether or not early age cracking can be compounded by load cracking, consider the example of a horizontal slab between rigid end restraints (Fig. L1 (b) of BS EN 1992-3). Due to end restraint conditions, a slab between rigid restraints will produce a primary crack, parallel to the rigid restraints most likely midway between the restraints. This is also the most likely position of a crack to form from structural loading. So although further investigations are required to confirm the presence of combined cracking, clearly in this case the opportunity exists.

In the case of a wall cast on a base, if the wall is sufficiently long then even without the restraint offered by adjacent wall panels a primary vertical crack may develop due to the edge restraint of early age movement. Structurally the wall will behave as a cantilever and structural cracking will therefore be horizontal in nature. In such a case, it is clear that early age cracking is not compounded by structural cracking. Taking this example one step further and considering Fig. L1 (d) of BS EN 1992-3, which illustrates a wall restrained at its base and by adjacent wall panels, diagonal cracks are predicted to occur at the base of the wall and near its ends. It is unsure as to whether these diagonal cracks would influence the formation and behaviour of structural cracking; further investigation is required.

As mentioned above, no problems have been identified that can be specifically explained by this potential combination of early-age and structural cracking. This could be because fortuitously, the code guidance for the design of water-retaining structures results in an over-estimation of steel required to resist imposed deformations. For edge-restrained situations, the crack width depends on the restrained imposed strain and not the tensile strength of the concrete (Al Rawi and Kheder, 1990). The amount of horizontal reinforcement is entirely dictated by that needed to control early thermal cracking (restraint to early thermal movement). Traditional detailing used about 0.2% of anti-crack reinforcement, whereas BS 8007 tended to require at least twice this amount (because of the intended use of the structure and the better control of crack widths required in water-retaining structures). The Eurocodes appear to require between 0.3 and 0.4%. These all relate to restraint of early thermal movement which, as discussed earlier, is based on the end restraint condition and not edge restraint. The question is one of whether this amount of steel is actually necessary.

1.6 Site conditions

The choice of site for a reservoir or tank is usually dictated by requirements outside the structural designer's responsibility, but the soil conditions may radically affect the design. A well-drained site with underlying soils having a uniform safe bearing pressure at foundation level is ideal. These conditions may be achieved for a service reservoir near to the top of a hill, but at many sites where sewage tanks are being constructed, the subsoil has a poor bearing capacity and the groundwater table is near to the surface. A high level of groundwater must be considered in designing the tanks in order to prevent flotation (Figure 1.5), and poor bearing capacity may give rise to increased settlement. Where the subsoil strata dip, so that a level excavation intersects more than one type of subsoil, the effects of differential settlement must be considered (Figure 1.6). A soil survey is always necessary unless an accurate record of the subsoil is available. Typically, boreholes of at least 150 mm diameter should be drilled to a depth of 10 m, and soil samples taken and tested to determine the sequence of strata and the allowable bearing pressure at various depths. The information from boreholes should be supplemented by digging trial pits with a small excavator to a depth of 3–4 m.

The soil investigation must also include chemical tests on the soils and groundwater to detect the presence of sulphates or other chemicals in the ground that could attack the concrete and eventually cause corrosion of the reinforcement (Newman and Choo, 2003). Careful analysis of the subsoil is particularly important when the site has previously been used for industrial purposes, or where groundwater from an adjacent tip may flow through the site. Further information is given in Chapter 2.

When mining activity is suspected, a further survey may be necessary and a report from the mineral valuer or a mining consultant is necessary. Deeper, randomly located boreholes may be required to detect any voids underlying the site. The design of a reservoir to accept ground movement due to future mining activity requires the provision of extra movement joints or other measures to deal with the anticipated movement and is outside the scope of this book (Davies, 1960; Melerski, 2000). In some parts of the world, consideration must be given to the effects of earthquakes, and local practice should be ascertained.

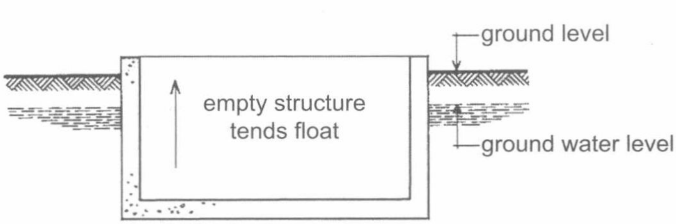

Figure 1.5 *Tank flotation due to ground water.*

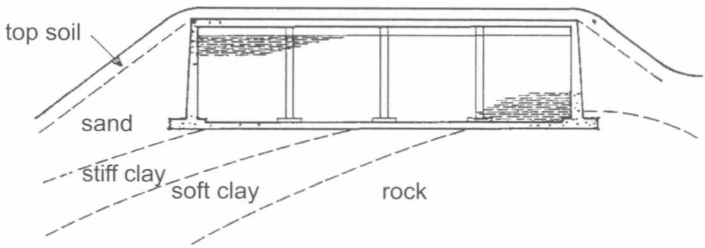

Figure 1.6 *Effect of varying strata on settlement.*

1.7 Influence of execution methods

Any structural design has to take account of the constructional problems involved and this is particularly the case in the field of liquid-retaining structures. Construction joints in building structures are not normally shown on detailed drawings but are described in the specification. For liquid-retaining structures, construction joints must be located on drawings, and the contractor is required to construct the works so that concrete is placed in one operation between the specified joint positions. The treatment of the joints must be specified, and any permanent movement joints must be fully detailed. All movement joints require a form of waterstop to be included; construction joints may or may not be designed using a waterstop (BS 8102:2009). Details of joint construction are given in Chapter 5. In the author's opinion, the detailed design and specification of joints is the responsibility of the designer and not the contractor. The quantity of distribution reinforcement in a slab and the spacing of joints are interdependent. Casting one section of concrete adjacent to another section, previously cast and hardened, causes restraining forces to be developed that tend to cause cracks in the newly placed concrete. It follows that the quantity of distribution reinforcement also depends on the degree of restraint provided by the adjacent panels.

Any tank that is to be constructed in water-bearing ground must be designed so that the groundwater can be excluded during construction. The two main methods of achieving this are by general ground de-watering, or by using sheet piling. If sheet piling is to be used, consideration must be given to the positions of any props that are necessary, and the sequence of construction that the designer envisages (Gray and Manning, 1973).

1.8 Design procedure

As with many structural design problems, once the member size and reinforcement have been defined, it is relatively simple to analyse the strength of a structural member and to calculate the crack widths under load: but the designer has to estimate the size of the members that he proposes to use before any calculations can proceed. With liquid-retaining structures, crack-width calculations control the thickness of the member, and therefore it is impossible to estimate the required thickness directly unless the limited stress method of design is used.

An intermediate method of design is also possible where the limit state of cracking is satisfied by limiting the reinforcement stress rather than by preparing a full calculation. This procedure is particularly useful for sections under combined flexural and direct stresses.

1.9 Code requirements (UK)

BS EN 1992-3 is based on the recommendations of BS EN 1992-1-1 for the design of normal structural concrete, and the design and detailing of liquid-retaining structures should comply with BS EN 1992-1-1 except where the recommendations of BS EN 1992-3 (and the UK National Annex) vary the requirements. The modifications that have been introduced into the Eurocodes mainly relate to:

- surface zones for thick sections with external restraint;
- surface zones for internal restraint only;
- the critical steel ratio, ρ_{crit};
- the maximum crack spacing, $S_{r,max}$;
- edge restraint.

These modifications are suitably discussed by Bamforth (2007), Hughes (2008) and Forth (2008).