Waterproofing of Concrete Foundations

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WATERPROOFING OF CONCRETE FOUNDATIONS

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Abstract: Successful waterproofing of concrete foundations prevents the degradation of environmental and health conditions and of building materials used in below-ground storeys, and extends the service life of concrete constructions. However, despite the important role of waterproofing systems for concrete foundations, and the fact that repairing them is either impractical or prohibitively expensive, there is very little useful information or discussion on membrane properties and the detailing required for a durable, watertight design. This paper presents a discussion of the requirements of waterproofing membranes and the auxiliary components used in waterproofing systems for concrete footings, mat-slabs and pile foundations, along with a schematic representation of suggested systems and their detailing. Flexibility and mechanical resistance are particularly important and reasonably well-documented properties of buried waterproofing membranes, but knowledge of their long-term durability presently relies mostly on empirical data. The cost analysis of some of the suggested waterproofing systems revealed significant differences which, along with the other data presented, should aid building designers and contractors with the design and installation of effective waterproofing solutions for concrete foundations.

Keywords: foundation; concrete; membrane; polymer; waterproofing; cost; GCL.

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INTRODUCTION

Inappropriate concrete quality and architectural features that result in increased potential for long-term contact with water mean that concrete structures usually require waterproofing systems to prevent water leakage and permeation (Feiteira et al. 2011, Morgado et al. 2011). Additionally, concerns about durability, damage to finishes and furnishings or health and environment conditions in below ground facilities, or the aesthetic degradation of building elements, have made the waterproofing of reinforced concrete foundations against ground moisture a desirable feature (Ellsworth 2004, Bredenberg 1995, Leivo and Rantala 2005). The most common phenomena affecting the durability of concrete foundations arise from the contact between concrete and surface water or groundwater containing acids, sulphate salts or chloride ions which may change the microstructure and chemical composition of concrete and/or promote the corrosion of reinforcement steel.

Whatever the particular watertightness requirements of a reinforced concrete foundation, they should be considered and fully assessed at the design stage (Klein 2007), as it is either impossible or extremely difficult - and very expensive - to access foundations after construction. Data on the existing groundwater regime is needed to assess the cheapest solution capable of ensuring the watertightness of concrete foundations, as waterproofing is key to prevent leakage through concrete only under hydrostatic pressure. If there is little or no hydrostatic pressure then damp-proofing, good drainage and appropriate concrete mix design may suffice to meet watertightness requirements in many situations. Damp-proofing aims at reducing water vapour transmission, which only retards moisture transmission through concrete. It is usually achieved with low thickness liquid-applied systems (ACI 1986). Drainage layers and pipes reduce the capillary flow from the subsoil but have been shown to be ineffective in several cases (Leivo and Rantala 2005).

Even the leakage of water through concrete foundations due to hydrostatic pressure can be significantly reduced through the use of good construction practices and careful mix design (Concrete Construction staff 1981), together with either high-performance concrete (Mehta 1992) or precast concrete elements. However, even though good quality concrete assures the durability of foundations with extended service life requirements, it may still allow moisture transfer to below-ground storeys, in which case waterproofing would be beneficial. Additionally, the durability of good quality concrete depends significantly on the absence of micro-cracking, achievable only with careful placing and curing and difficult to assure for some heavily reinforced elements of concrete foundations. Drainage can also assist the role of waterproofing systems by reducing the potential for hydrostatic pressure.

Because even the more thorough literature on below-grade concrete waterproofing (ACI 1986, BSI 2009, Henshell 2000, Kubal 2008) contains little discussion of particulars related to concrete foundations, waterproofing details are often simply left to the contractor. Therefore, in this paper, waterproofing systems and relevant details for the most common types of concrete foundations are suggested, and their associated costs and the fitness of a number of waterproofing products are also analysed. The data presented here should aid building designers in achieving effective waterproofing solutions for concrete foundations and highlight the importance of their informative role when dealing with owners.

CASE STUDIES

Even though anomalies often result from inexistent or improper foundation water-proofing, actual failure cases are seldom reported in the literature. Leivo and Rantala (2005) reported a survey of several cases of moisture-related anomalies in slab-on-ground structures. It was concluded that a large portion of these structures presented degraded building materials and environmental conditions (odour, mould growth and visible moisture) in the interior spaces, due essentially to design flaws leading to ineffective waterproofing against capillary flow from the foundations.

Figures 1 and 2 show additional and extremely palpable evidence of the importance of waterproofing concrete foundations. In these cases, total disregard of the need for waterproofing mat-slab foundations placed below the water table led to clear leaking into the inside of below-ground floors and degradation of building materials due to salt crystallization. Figure 1 additionally shows that junctions between mat-slabs and vertical walls present high leaking potential and that particular attention should be given to these singularities. Other cases exist where waterproofing systems were installed but leaking was also present. However, the cause of failure in those cases, which could range from poor installation to accidental perforation, is often impossible to determine due to the inaccessibility of foundations.

Also due to inaccessibility, field evidence of the influence of waterproofing on the durability of concrete foundations is not known to be documented. Nevertheless, improved durability was surely a major reason for buildings with extended service life, such as the Nelson-Atkins Museum, Kansas City (Ellsworth 2004) and the Champalimaud Foundation, Lisbon (Figures 5 and 9 shown in the following sections) to require extensive and careful waterproofing.

WATERPROOFING MATERIALS FOR CONCRETE FOUNDATIONS

Several materials can be used in waterproofing systems for concrete foundations. Liquid-applied systems require a particularly thorough surface preparation and skilled workmanship to ensure a consistent minimum cover thickness (Steele and Steele 1999), which is why they are not often used to waterproof buried concrete elements, where accessibility before or after backfilling is limited and extended service lives are required. There are some exceptions where waterproofing systems based on liquid products have been used in below-grade concrete walls of important buildings (Ellsworth 2004).

Most concrete foundations waterproofing works thus require either bituminous or synthetic prefabricated membranes. Some of the synthetic geomembranes commonly used for waterproofing are listed in Table 1, along with their most relevant properties for foundation waterproofing. High flexibility is required for detail work on complex concrete shapes such as footings, which require very low bending radius. It also enables the factory welding of different panels, which reduces the risk of seam failure since the resulting large sheets can be folded for transport to the construction site. The sheets would otherwise be supplied in rolls. Punching resistance and stress cracking resistance are desirable because they prevent potential damage from mechanical action during installation on concrete casting or after backfilling. Stress cracking is the brittle failure of a membrane at an applied constant stress lower than its tensile strength at yield and it can be caused by several factors such as cyclic temperature variations, the presence of chemical agents, UV oxidation and, most importantly, fatigue (Scheirs 2009). Membranes should also support high elongation at break, so that they can resist any potential cracking of concrete. Table 1 also lists the welding methods usually available for each membrane type. More accurate data should be sought with the manufacturer, since such important data as the minimum radius of bending of a membrane is not usually available and depends on the manufacturing source.

As it is either very difficult or impossible to repair buried geomembranes used in foundation waterproofing, and as they guarantee the proper operation of buildings with design service lives of several decades, their durability is a major concern. However, the lifetime prediction of membranes is complex (Peggs 2003) and depends on more properties than those listed in Table 1, aggravated by the fact that membrane composition has a significant influence on durability and may vary significantly from manufacturer to manufacturer (Koerner et al. 2005). It is clear that additional extensive research and testing is also needed in order to more accurately assess the long-term performance of geomembranes, as current service life prediction relies essentially on empirical data (Rollin 2004).

Furthermore, degradation mechanisms may affect the properties listed in Table 1 differently, resulting in the resistance to ageing being as critical for the system's performance as those properties. As the synthetic geomembranes used in foundation waterproofing are not exposed during their service lives, ultraviolet light (UV) exposure, a major degradation mechanism, is avoided. But polyolefins (polyethylene and polypropylene) and all co-polymers containing ethylene or propylene fractions in their formulation, such as those in HDPE (high-density polyethylene), fPP (flexible polypropylene) and EPDM (ethylene propylene diene monomer), are susceptible to oxidation resulting from the loss of antioxidants and chemical reactions with oxygen, which ultimately reduces the tensile performance of these geomembranes (Koerner et al. 2005). PVC, meanwhile, is affected by plasticiser depletion, usually due to UV exposure but reportedly also due to direct contact with certain substances of which concrete is a particularly relevant example (Scheirs 2009). As plasticiser is added to the formulation of PVC to impart flexibility, its depletion implies a return to brittle behaviour and a higher potential for membrane failure.

According to Schiers (2009), the term HDPE is used by the industry for geomembranes that are actually made of a medium density polyethylene, as regular HDPE would be too stiff. The regular, stiff HDPE is used to manufacture the dimpled sheets often used as an air gap or drainage layer for below-grade concrete walls. Waterstops are flexible elements embedded across and along the connections of concrete structures to prevent leaking, and are widely prescribed in the design of foundation waterproofing systems (Laning 1993).

Prefabricated bituminous sheets used for waterproofing are usually modified with APP (atactic polypropylene) or SBS (styrene-butadiene-styrene) polymers and a variety of synthetic mats and scrims to improve their mechanical resistance. Bituminous sheets are also characterized by lower flexibility when compared to most synthetic membranes, which makes them less suited to waterproof concrete elements requiring extensive detailing. As bitumen has inherent oxidation stability and the synthetic reinforcement is embedded and protected from the usual degradation mechanisms, the service life of modified bituminous membranes can be expected to be higher than that of geosynthetics (Schiers 2009).

Sodium bentonite has also been used in a variety of formats for waterproofing applications. Water uptake causes sodium bentonite to swell to several times its original volume, thus filling any cracks in concrete elements. However, while geomembranes allow inspection before backfilling or concrete casting to confirm watertightness, bentonite waterproofing solutions are not watertight until water reaches them, after the concrete foundation is backfilled (Bredenberg 1995).

As there are several kinds of waterproofing membranes, each with its intrinsic strengths and weaknesses, their suitability for a particular type of concrete foundation is analysed in the next section, and waterproofing solutions for the most common concrete foundation types are also described.

WATERPROOFING OF CONCRETE FOUNDATIONS

Footings

Footing trenches are confined spaces and extensive folding is required to shape a waterproofing membrane to a concrete footing's geometry, so it is recommended that the most flexible membranes available should be used to waterproof them. To minimise stress-related damage and punching of the waterproofing coat during concrete casting, it is recommended that geotextile sheets are installed both before and after its placement, as shown in Figure 3. Figure 4 shows the legend generally used for all the schematic representations shown in this paper. The outer geotextile has an additional drainage function and prevents direct contact between the soil components and the waterproofing coat, thus reducing any related degradation. The three coats should be moulded to the trench, covering it and being fixed to the walls and the bottom of the trench over the blinding concrete. After concrete casting, the waterproofing system should be folded around the top of the concrete footing only after proper curing is achieved. This will prevent the encapsulation of any excess water available for cement hydration. Further folding details and particulars are given below.

Prefabricated footings are also available, and as they do not require trench excavation the folding details are less complex. Figure 5 shows the field implementation of a waterproofing system for prefabricated column footings based on a bentonite geosynthetic clay liner (GCL).

The cross-section schematic representation of the waterproofing system shown in Figure 5 applies to all types of concrete footings, including wall, combined and strap footings. However, it is difficult to waterproof strap footings because of the significant seaming and folding required to mould the waterproofing coat to the more complex geometry of this type of footing. If strap footings are mandatory, bentonite GCLs may be the best waterproofing solution since they do not require field seaming and can self-heal.

If there is a below-grade slab, continuity between footing and slab waterproofing systems should be assured. Slab waterproofing representations are shown in the next section.

Mat-slabs

Mat-slab foundations are reinforced concrete slabs which distribute the building loads over the entire floor area to minimise the pressure transmitted to the soil. Either positive side (the hydrostatic pressure side) or negative side (the opposite side) waterproofing can be installed on this type of foundation, but negative side waterproofing (on the slab surface furthest from the soil) strictly stops water from reaching the slab floor covering but does not prevent slab degradation, and so it cannot be used to waterproof mat-slabs below or near the water table. The procedure for positive side waterproofing is similar to that for concrete footings, with the waterproofing coat protected from mechanical damage by a layer of geotextile on both sides, as shown in Figure 6. As mat-slabs are continuous, large, flat surfaces, folding is only needed at their outer edges and so it is not essential for their waterproofing coat to be flexible. Further details of the interface between mat-slab and walls are shown below. Nevertheless, as discussed previously, the greater flexibility of certain geomembranes used as waterproofing coats does allow factory seaming and so there is less potential for failure along the extensive seams required for the waterproofing of large mat-slabs. Figure 7 shows a negative side waterproofing system implemented in the field on a large mat slab foundation using a PVC geomembrane, including thermal welding of seams resulting from detailing work.

The geotextile layer under the waterproofing coat is sometimes replaced by dimpled HDPE sheets. These sheets have the added benefit of functioning as a drainage layer, either installed with the dimples facing the waterproofing coat or the other way, in which case they have to be installed over a geotextile to prevent soil from blocking the drainage layer and also to create an air gap. However, HPDE sheets should only be considered as a protection layer of waterproofing systems placed under mat-slabs if the load they are subjected to is less than their strength, as to minimize the risk of dimples collapsing.

Pile heads and caps

The construction process of piles makes it hard to waterproof them entirely (Penteado and Brito 2012), so the waterproofing of pile foundations aims strictly at providing a water barrier between the top of the pile head and the structure above. Thus, waterproofing does not increase the durability of this kind of foundation. Because piles to which the waterproofing coat has to be shaped typically have a round cross-section, only bentonite-based solutions, which do not require seaming, or the most flexible waterproofing geomembranes listed in Table 1 are recommended for the waterproofing of pile heads.

Figure 8 shows the cross-section of the waterproofing system of a single pile head, whose waterproofing coat sits between two protecting geotextile layers, as recommended for the waterproofing systems of the types of foundation discussed earlier. The continuity of the waterproofing system at the top of the pile head is secured with watertight cement grout cast over sound concrete, exposed after removal of the debris and loose concrete. A waterstop should be installed at the interface between the pile head and the adjoining concrete slab as a redundant measure to prevent leaking through the singularity at the interface between cement grout and the waterproofing coat. A waterstop with a proper configuration in this junction may also function as a cant strip to prevent both the bending of the membrane at a sharp angle and any damage that might result.

Pile heads connected by a pile cap block are waterproofed in a similar manner, with the different coats of the waterproofing system being extended beyond the edges of the underside of the pile cap block to be cast over the previously placed blinding concrete. After concrete casting and proper curing, the pile cap is completely encased by the coats of the waterproofing system. Figure 9 shows a series of pile cap blocks encased in a GCL waterproofing system which, as discussed previously, removes the need for extra geotextile layers to protect them from mechanical damage.

An alternative solution to assure continuity of waterproofing systems at the top of a pile head consists of covering the area with a galvanised steel plate connected to the waterproofing coat through a flanged joint, as shown in Figure 10. Rebars are welded to both sides of the steel plate for connection to the pile head and for lap splicing, on the upper surface. This solution eliminates the singularities at the interface between cement grout and the two waterproofing coats and the rebars of the solution shown in Figure 8.

The top of the pile head has to be drilled to receive the connecting rebars welded to the galvanised steel plate. Once the steel plate is fixed to the pile head, the waterproofing coat is laid on top of the plate, with an additional ring of the same material. Both coats of waterproofing membrane have to be perforated for the mechanical flanged connection to be secured with metal screws. These screws fasten a final metal ring to the bottom steel plate to form a tight seal with the clamped membrane. A field implementation of this solution is shown in Figure 11.

FINISHING DETAILS AND PARTICULARS

Details and particulars of waterproofing systems require special care, as they are singularities with high potential for failure. Therefore, their design should be as simple as possible in order to minimize seams and folds, particularly for the complex shapes of footing foundations. It is also of extreme importance to take special provisions that avoid labour-induced perforation of the waterproofing layers, as it is known to be their main cause of failure (Peggs 2003). Details on the dimensions of laps should also be sought with the manufacturer, as they depend on the surface roughness. While a local source advises a minimum of 10 cm for bentonite GCLs, irregular surfaces should need lapping as high as half the width of the bentonite sheet. Another local specialist suggested a minimum of 12 cm width lapping for PVC membranes over regular, clean surfaces and up to 20 cm for increasing surface roughness.

The details and particulars of membrane folding and meeting points of different structural elements are covered in this section.

Folding of membranes around footings

The perspective representation of the folding scheme shown in Figure 12 should be self-explanatory, except for some details provided below. The line pattern represents the geotextile layer for mechanical protection, while the lighter shade of the membrane being folded represents the outer side, nearest the backfill, and the darker shade represents the side next to the concrete element’s surface. For a clearer presentation, the geotextile layer between the waterproofing coat and the soil backfill shown in the cross-section representation of Figure 3 is not shown in the perspective representation of Figure 12. Another simplification is that the geotextile layer shown in Figure 12 between the concrete surface and the waterproofing coat only covers the underside and the vertical faces of the footing, while in Figure 3 the upper surface of the footing is also covered. These are the critical locations for this layer of mechanical protection, which is required to protect the waterproofing membrane from the concrete casting.

While the mechanical protection layer can be cut to shape, synthetic waterproofing membranes should be kept intact and be folded instead. For this, a large square section of the waterproofing membrane to be used should be centred with the area receiving the concrete cast. This square section should be sufficiently large to enclose the entire footing after folding, as suggested in Figure 12. Folds should be mechanically fixed or welded and, if required, the details at the junction between footing and column can be executed according to the directions suggested previously.

GCLs, however, do not require folding and can be cut to shape because the expansive nature of bentonite effectively seals the resulting seams. Nevertheless, reinforcement with bentonite paste is recommended at the edges of the concrete element, where sections of GCL may meet.

Junction between footing and column

If continuity of the waterproofing system is required between footing and column, then, as with any structure where a concrete slab is not directly cast against the footings, the detailing of the junction between the two elements requires particular care. Figure 13 shows a suggestion for the complete waterproofing of both footing (shown in Figure 12) and column, including detailing for this junction. The waterproofing membrane should be cut as shown in Figure 13, tightly fixed to the column and welded to the waterproofing coat of the footing. To guarantee a watertight design, patches should also be welded across the lower part of the vertical edges of the column, extending into the waterproofing coat of the footing.

Junction between mat-slab and vertical element

The design of the interface between the waterproofing systems of below-grade mat-slab foundations and those of below-grade concrete walls also requires special care to assure watertight continuity. Figure 14 shows the suggested finishing details for the waterproofing systems at this junction, based on either vertical or horizontal seaming.

The correct positioning of the waterproofing coat on walls over the waterproofing coat of the mat-slab on a vertical seam (Figure 14 a) minimises the likelihood of damage during backfilling operations. For both the examples in Figure 14 the lap seam should have a minimum overlap that varies with the type of waterproofing coat used, so as to provide proper mechanical resistance.

COST ANALYSIS

A cost analysis yielded the average costs listed in Table 2 for several of the waterproofing systems for concrete foundations discussed. Cost calculation was based on average material prices and estimated productivity, labour costs and equipment costs in Portugal and so these parameters and the final costs will differ in other markets.

Despite cost being a critical parameter for decision-making in construction processes, the choice of a particular waterproofing system must nonetheless ensure fitness for the intended purpose and foundation type and consider the particular requirements of the respective building in terms of expected service life and health and environmental conditions, as discussed.

CONCLUSIONS

Concrete foundations must be waterproofed to guarantee the required health and environmental conditions, to prevent the degradation of building materials in below-ground storeys, and to extend the service life of concrete constructions. A variety of waterproofing membranes is currently available to be applied to concrete foundations, but there is little information in the relevant literature on their fitness for this particular use and on installation techniques and details. Data on the durability of buried waterproofing membranes is particularly sparse and based mostly on empirical observations and it is clear that more extensive testing and research is still needed in order to improve the knowledge on the membranes' long-term performance. Due to the inaccessibility after backfilling, which renders repairs impractical, the successful waterproofing of concrete foundations demands that detailing and specification of an appropriate waterproofing membrane are considered at the design stage of construction projects. Despite this, they are often left for the contractor to decide. In this respect, building designers should take a more active informative role when dealing with owners, highlighting the benefits of waterproofing systems and the importance of their respective detailing.

Flexibility is a particularly important property of synthetic geomembranes if they are used in waterproofing solutions for concrete footings and pile heads, due to the geometry of these types of foundations. The extensive folding and patching required at the junction between footing and column, in particular, requires a synthetic geomembrane with high flexibility and can benefit from the self-healing properties and seamless application of bentonite GCLs. However, the effectiveness of waterproofing solutions based on GCLs cannot be assured before backfilling as it depends on clay expansion due to water absorption. The large flat surfaces of mat-slabs can more easily accommodate poor flexibility, as folding is limited to the interface between slab and vertical elements. Nevertheless, highly flexible membranes allow large factory seamed sheets to be folded and transported to the construction site, thus reducing the potential for failure along the extensive seaming required for the waterproofing of mat-slabs. Even though waterproofing aims at increasing the durability of concrete foundations, the waterproofing of concrete pile foundations strictly prevents water from entering the building, and do not protect the piles below the caps. The same holds true for the negative side waterproofing of mat-slabs. Layers of geotextile sheets are used for the mechanical protection of waterproofing membranes during backfilling and concrete casting in all the waterproofing solutions presented, whose description benefited from the detailed schematic representations shown. Finally, a cost analysis of some of the suggested waterproofing systems revealed significant differences that should be considered during the design stage, but not forgetting suitability for the intended use and the particular requirements of the building in question.

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REFERENCES

ACI - American Concrete Institute (1986). *A guide to the use of waterproofing, dampproofing and decorative barrier systems for concrete*, ACI, Detroit, USA.

Bredenberg, A. (1995), “Waterproofing options for concrete foundations.” *Concrete Construction*, 40(5).

BSI - British Standards Institution (2009). *Code of practice for protection of below ground structures against water from the ground - BS 8102*, BSI, London, UK.

Concrete construction staff (1981). “Waterproofing: who needs it?” *Concrete Construction*, 26(4).

Ellsworth, H. (2004). “Finding the right waterproofing system.” *Concrete Construction*, 49(2).

Feiteira, J., Grandão Lopes, J. and de Brito, J. (2011). “Mechanical performance of liquid-applied roof waterproofing systems." *Journal of Performance of Constructed Facilities*, doi:10.1061/(ASCE)CF.1943-5509.0000314.

Henshell, J. (2000). "Manual of below-grade waterproofing systems." John Wiley and Sons, New York, USA.

Klein, K. (2007). "Proactive waterproofing." *Concrete Construction*, 52(3).

Koerner, R. M., Hsuan, Y. and Koerner, G. (2005). *Geomembrane lifetime prediction: unexposed and exposed conditions*, GRI White Paper #6, Geosynthetic Institute, Folsom, PA, USA.

Kubal, M. T. (2008). *Construction waterproofing handbook*, McGraw-Hill, New York, USA.

Laning, A. (1993). "Flexible waterstops." *Concrete Construction*, 38(5).

Leivo, V. and Rantala, J. (2005). "Typical moisture failures of slab-on-ground structures in Finland." *Practice Periodical on Structural Design and Construction*, 10(2), 98-101.

Mehta, K. (1992). "High-performance concrete durability affected by many factors." *Concrete Construction*, 37(5), 367-370.

Morgado, F., Grandão Lopes, J., de Brito, J. and Feiteira J. (2011). "Portuguese irrigation canals: lining solutions, anomalies and rehabilitation." *Journal of Performance of Constructed Facilities*, 26(4), 507-515.

Peggs, I. (2003). "Geomembrane liner durability: contributing factors and the status quo." Geosynthetics: protecting the environment, Dixon, N., Smith, D. M., Greenwood, J. R. and Jones, D. R. V., eds., Thomas Telford, London, UK.

Penteado, M. L. and de Brito, J. (2012). "Expert knowledge-based selection methodology for optimizing the construction of concrete piles." *Journal of Performance of Constructed Facilities*, 26(1), 95-103.

Rollin, A. (2004). “Long term performance of polymeric geomembranes.” *57th Canadian Geotechnical Conference - GeoQuebec 2004*, Quebec, Canada.

Sadlier, M. and Frobel, R. (1997). *Geomembrane properties - A comparative perspective*, *1st Australia-New Zealand Conference on Environmental Geotechnics - GeoEnvironment 97*, Melbourne, Australia.

Scheirs, J. (2009). *A guide to polymeric geomembranes. A practical approach*, John Wiley and Sons Ltd, West Sussex, UK.

Steele, J. & Steele, C. (1999). “Performance criteria for coatings on concrete in chemical exposures.” *Journal of protective coatings & linings*, 16(7), 29-35.

TABLES

Table 1 - Properties of commonly used geosynthetic membranes used in concrete foundations (Scheirs 2009 citing Sadlier and Frobel 1997)

Membrane	HDPE	PVC	fPP	EPDM
Flexibility for detail work	Fair	Excellent	Excellent	Good
Uniaxial elongation	Excellent	Good	Excellent	Good
Multiaxial elongation	Poor	Excellent	Excellent	Good
Stress cracking resistance	Fair	Good	Does not occur	Does not occur
Punching resistance	Fair	Excellent	Excellent	Good
Seaming method	Thermal	Thermal or solvent bonding	Thermal	Vulcanizing tape seams

Table 2 - Average estimated cost of some of the waterproofing systems for concrete foundations

Foundation	Description of waterproofing system	Total cost
Footing	Mechanically fixed PVC waterproofing membrane and 2 polyester geotextile layers (300 g/m^2) as mechanical protection	23.82 €/unit
	Mechanically fixed EPDM waterproofing membrane and 2 polyester geotextile layers (300 g/m^2) as mechanical protection	21.87 €/unit
	Mechanically fixed GCL	15.11 €/unit
Mat-slab	Positive side waterproofing with mechanically fixed PVC waterproofing membrane and 2 polyester geotextile layers (300g/m^2) as mechanical protection	20.16 €/m^2
	Positive side waterproofing with mechanically fixed PVC waterproofing membrane and dimpled HPDE and polyester geotextile (300 g/m^2) layers as mechanical protection and drainage	18.19 €/m^2
	Positive side waterproofing with mechanically fixed EPDM waterproofing membrane and 2 polyester geotextile layers (300 g/m^2) as mechanical protection	25.33 €/m^2
Pile head	Waterproofing of ø0.50 m pile head with PVC waterproofing membrane, PVC water-stop and grout	58.47 €/unit
	Waterproofing of ø0.50 m pile head with PVC waterproofing membrane and flanged joint seam system	656.11 €/unit

FIGURE CAPTIONS

Figure 1 - Water leaking through a mat-slab foundation lacking waterproofing

Figure 2 - Salt crystallization on building materials and finishes due to the absence of a waterproofing system for the concrete foundations

Figure 3 - Cross-section representation of a waterproofing system for concrete footings

Figure 4 - Legend used for all the schematic representations shown

Figure 5 - Field implementation of a waterproofing system of prefabricated column footings based on a bentonite GCL

Figure 6 - Cross-section representation of a positive side waterproofing system for mat-slab concrete foundations

Figure 7 - Field implementation of a negative side waterproofing system for a large mat-slab foundation based on a PVC waterproofing coat, showing detailing and thermal welding of seams

Figure 8 - Schematic cross-section of a waterproofing system for single pile heads with adjoining concrete slab

Figure 9 - Pile cap blocks encased in a GCL waterproofing system

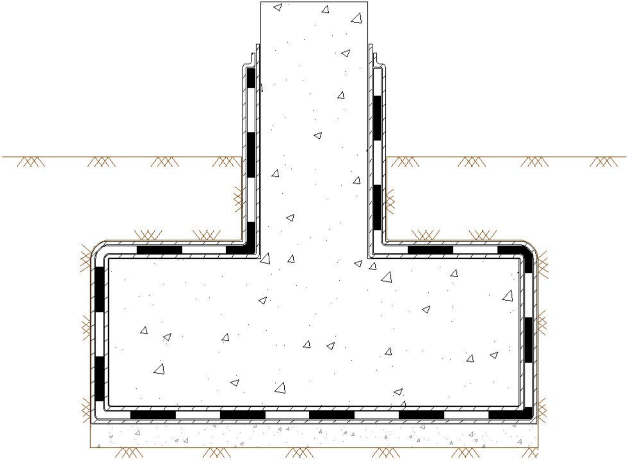
Figure 10 - Schematic cross-section of a waterproofing solution for pile heads based on a flanged joint

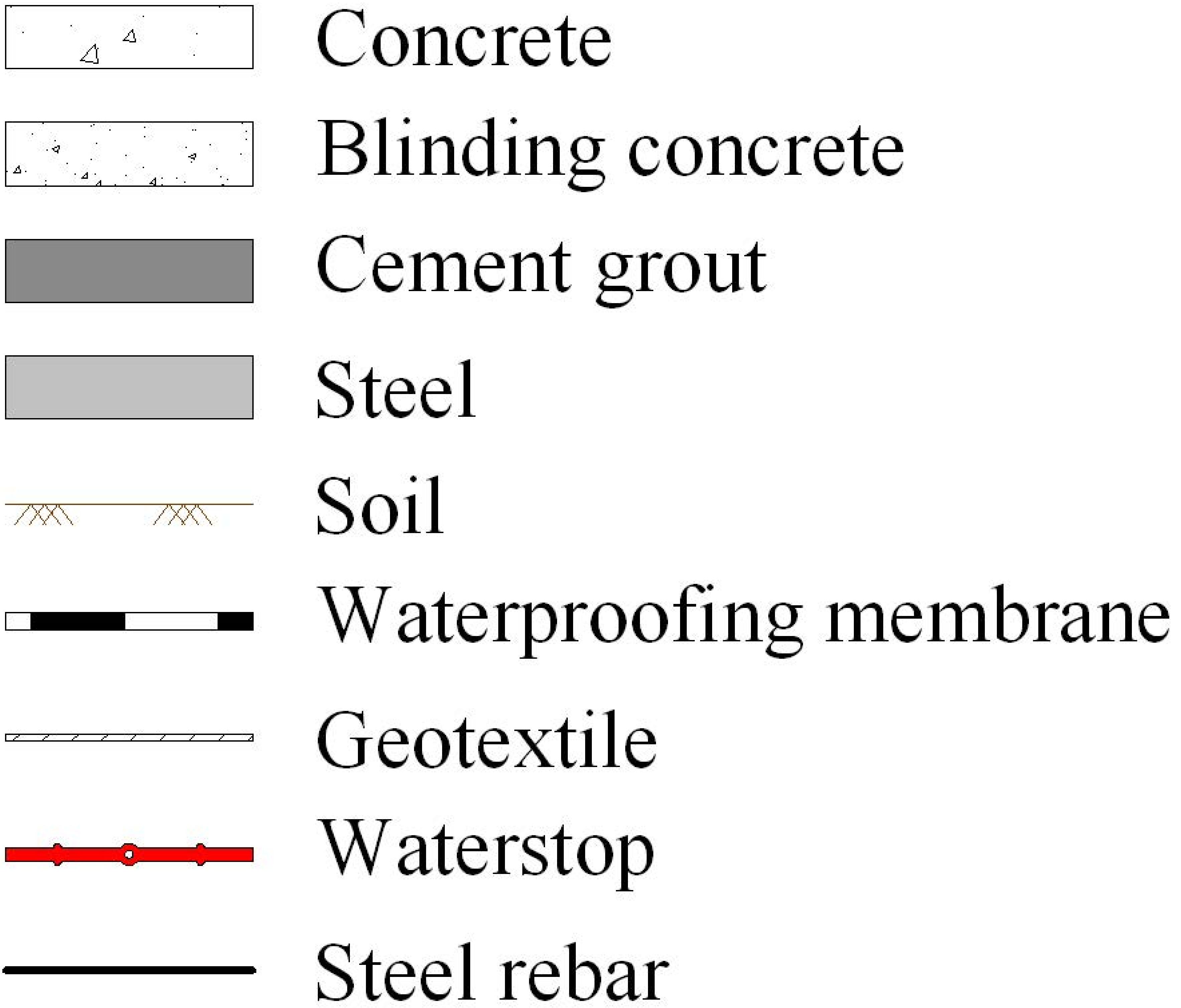
Figure 11 - Field implementation of the flanged joint detailed in Figure 7

Figure 12 - Folding of waterproofing membrane around footings

Figure 13 - Detailing of the junction between footing and column

Figure 14 - Finishing details of the interface between the waterproofing systems of mat-slab and below-grade concrete walls with vertical (a) or horizontal (b) seaming




Concrete
Blinding concrete
Cement grout
Steel
Soil
Waterproofing membrane
Geotextile
Waterstop
Steel rebar