Developing a Method for Prioritising Maintenance for Reinforced Concrete Reservoirs

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Declaration

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March 2015

STELLENBOSCH UNIVERSITY

Abstract

Faculty of Civil Engineering
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Master's of Science in Engineering

Developing a Method for Prioritising Maintenance for Reinforced Concrete Reservoirs

by Paul DUVENAGE

The Department of Water Affairs and Forestry infrastructure has shown a decline in condition from 2006 to 2011, according to the Infrastructure Report Card. With the increase in population, the additional demand placed on the already ageing infrastructure together with inadequate maintenance exacerbates the deterioration of these structures. Much has been done to improve the provision of basic water services to South Africans, however to ensure that basic water services remain intact, maintenance of the existing structures is of paramount importance.

The storage of potable water in a hygienic manner is essential to the water provision network, thus focus is placed on water reservoirs (in particular reinforced concrete water reservoirs). It has been identified that there is a lack of appropriate policies, practices, procedures and guidelines related to the maintenance of municipal water reservoirs.

The solution that this study proposes is to develop a maintenance prioritization method for reinforced concrete water reservoirs. This method specifically provides the user (i.e facility manager) with a systematic approach to assessing and allocating a condition value to the reservoir, which is used to prioritize maintenance activities. This method follows the approach used by the TRH/TMH manuals and bridge management systems that are implemented throughout South Africa. This method includes, the breakdown of essential reservoir components thus facilitating the development of future asset registers, the deterioration mechanisms that affect these reservoirs along with the appropriate identification methodologies and the percentage contributions of each component to the overall condition of the facility.

The research for the prioritization method is conducted by combining literature with feedback from industry professionals. The literature featured investigation of the components of concrete reservoirs and deterioration mechanisms that affect these components.

The results of the feedback from the industry professionals indicated that some of the components contribute more to the overall condition of the facility than others. This contribution is based on the importance of the component with regard to the provision of service and safety. Thus, in the case of a concrete reservoir, the walls are more essential to the provision of service and safety than the access components, thus its contribution percentage is higher. The research suggests that if the prioritization method could successfully be implemented, it will provide the users additional information that can be used to prioritise maintenance activities at both component and network level. Further, it may allow for the development of a comprehensive asset register of concrete reservoirs and may also aid in the financial planning related to the maintenance of these structures.

STELLENBOSCH UNIVERSITEIT

Opsomming

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Die Departement van Waterwese en Bosbou se infrastruktuur het n afname in kondisie gradering getoon van 2006 tot 2011 volgens die Infrastruktuur Verslag Kaart. Die toename in die bevolking veroorsaak bykomende druk op die reeds verouderende infrastruktuur wat tesame met swak instandhouding die agteruitgang van hierdie strukture vererger. Baie is gedoen om die voorsiening van basiese waterdienste aan Suid-Afrikaners te verbeter, maar dit is uiters noodsaaklik dat bestaande strukture in stand gehou word om te verseker dat basiese waterdienste beskikbaar bly.

Die berging van drinkwater op 'n higiëniese wyse is noodsaaklik vir die watervoorsieningsnetwerk met die gevolg dat daar op waterreservoirs, spesifiek gewapende beton waterreservoirs, gefokus word. Daar is vasgestel dat daar nie toepaslike praktyke, prosedures en riglyne met betrekking tot die instandhouding van van munisipale waterreservoirs bestaan nie.

Die oplossing wat deur hierdie studie voorgestel word, is om 'n onderhoud prioritisering metode vir gewapende beton waterreservoirs te ontwikkel. Hierdie metode bied spesifiek aan die gebruiker (reservoir bestuurder) 'n sistematiese benadering om 'n toestandwaarde ten opsigte van die reservoir te bepaal en toe te wys, wat gebruik word om instandhoudingsaktiwiteite te prioritiseer. Hierdie metode volg die benadering van die TRH/TMH en brug bestuur sisteme, wat geimplimenteer word reg deur Suid Afrika.

Hierdie metode sluit in die klassifiseering van hoof komponente van 'n gewapende beton reservoir wat die ontwikkeling van toekomstige bateregisters, die degenerasiemeganismes wat hierdie reservoirs beïnvloed tesame met die gepaste identifiseringsmeganismes en die bydrae volgens persentasie van elke komponent tot die algehele toestand van die fasiliteit, fasiliteer.

Die navorsing ten opsigte van die prioritiserings metode is uitgevoer deur literatuur met terugvoer van bedryfskundiges te kombineer. Die literatuur wat geraadpleeg is handel oor die ondersoek na die komponente van gewapende beton reservoirs en degenerasiemeganismes wat hierdie komponente beïnvloed.

Die studie dui aan dat, aan die hand van die bedryfskundiges se terugvoer, sommige komponente meer as ander tot die algehele toestand van die fasiliteit bydra. Hierdie bydrae is gebaseer op die belangrikheid van die komponent in terme van die voorsiening van dien ek veiligheid. Dus, is die geval van n beton reservoir, is die mure meer van beland as die toegans komponente in terme van voorsiening van diens en veiligheid. Die navorsing gee te kenne dat indien die prioritiserings metode suksesvol geïmplementeer kan word, dit die gebruiker bykomende inligting kan gee wat gebruik kan word om die instandhoudingsaktiviteite te prioritiseer op beide netwerk en komponente vlak. Verder, mag daar 'n omvattende bateregister van gewapende beton reservoirs ontwikkel kan word wat dus sal help met die finansiële beplanning rondom die instandhouding van hierdie strukture.

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Abbreviations

AM	**A**sset **M**anagement
CoGTA	**Co**operative **G**overnance and **T**raditional **A**ffairs
CSIR	**C**ouncil for **S**cientific and **I**ndustrial **R**esearch
DWAF	**D**epartment of **W**ater **A**ffairs and **F**orestry
IDP	**I**nfrastructure **D**evelopment **P**lan
IIMM	**I**nternational **I**nfrastructure **M**anagement **M**anual
IRC	**I**nfrastructure **R**eport **C**ard
MFMA	**M**unicipal **F**inance **M**anagement **A**ct
NGO	**N**on **G**overnmental **O**rganisation
PFMA	**P**ublic **F**inance **M**anagement **A**ct
SABS	**S**outh **A**frican **B**ureau of **S**tandards
SAICE	**S**outh **A**frica **I**nstitute of **C**ivil **E**ngineering
SANS	**S**outh **A**frica **N**ational **S**tandards
TMH	**T**echnical **M**ethods for **H**ighways
TRH	**T**echnical **R**ecommendation for **H**ighways
VIP	**V**entilated **I**mproved **P**it latrine
WISA	**W**ater **I**nstitute of **S**outhern **A**frica
WRC	**W**ater **R**esearch **C**ommission
WRS	**W**ater **R**etaining **S**tructures
WSA	**W**ater **S**ervice **A**uthority
WSDP	**W**ater **S**ervice **D**evelopment **P**lan
WSIAM	**W**ater **S**ervice **I**nfrastructure **A**sset **M**anagement
WSP	**W**ater **Services** **P**rovider

Dedicated to Rose-Mari Duvenage, my mother, for always believing in me and encouraging me to follow my dreams...
(1960 - 2011)

Chapter 1

Introduction

This chapter provides a general introduction to the research study, a motivation and the key objectives of the study, thus facilitating easy navigation throughout the remainder of the document.

Background is provided regarding the current state of concrete water retaining infrastructure and the management thereof in South Africa. From this, a problem has been identified. The problem statement is formulated and a motivation is given for the research into this field.

1.1 Background

In South Africa, the design of reinforced concrete water retaining structures have been based on provisions provided by both the Euro codes and British Standards, as a South African design code for water retaining structures (WRS) does not exist at present. Recently a new design code, SANS 10100 Part 3 - *Design of Concrete Liquid Retaining Structures* has been developed and is in the process of being certified and published by the South African National Standards (SANS). With the new design code for WRS, management and maintenance policies that conform to the design philosophies of the new design code are essential for the continued operation and maintenance of water services infrastructure. This also applies to existing structures that were constructed based on the older codes.

Bulk storage of water in a hygienic manner is essential to piped water supply systems. This storage is achieved by means of water reservoirs. Various different materials and methods are used for the construction of water reservoirs, which include [Still and Butler, 2011]:

- Steel reinforced concrete.
- Plastic.
- Fibreglass.
- Fibre cement.
- Plastered brick masonry, reinforced with steel.
- Brick masonry in combination with reinforced steel.
- Plastered stone masonry, reinforced with steel.
- Earth lined with a rubber membrane and covered with a floating membrane.
- Corrosion protected steel with or without plastic or rubber membrane liners.
- Timber reinforced with steel.
- Ferrocement.

South Africa has an average weighted infrastructure age of 39 years [SAICE, 2011]. Re-commissioning of existing infrastructure, given the current average infrastructure age, may require careful management and maintenance. Many municipalities do not have the capacity to properly maintain these structures as they age and become more maintenance intensive [CSIR, 2007]. The CSIR [2007] adds that gross shortcomings in many municipal maintenance policies and practices can be found and that the lack in capacity may be a key contributing factor.

Infrastructure asset management is a well-researched and documented field with principles established and set out in the International Infrastructure Management Manual [IIMM, 2011]. An understanding of the infrastructure and its requirements is needed to implement these principles. Numerous initiatives have been set in motion to aid in the implementation of these principles. These initiatives include [IIMM, 2011]:

- Improvement of technical skills in a number of municipalities.

- Improvement of Municipal Capacity to Manage Infrastructure (a pilot study commissioned by COGTA and funded by the European Union).
- Development of a Water Service Infrastructure AM Strategy (WSIAM) by the DWA.

Despite the development of these initiatives many municipalities will not be able to improve their maintenance policies and practices without direction and assistance, and needs to be improved if municipal infrastructure maintenance is to be adequate [CSIR, 2007].

1.2 Problem Statement

In South Africa asset management of pavement and road structural infrastructure (i.e bridges) is performed according to asset management principles set out in the [IIMM, 2011]. Key components of an asset lifecycle strategy include the operation and maintenance activities as well as the condition monitoring of the asset. TRH and draft TMH manuals describe the design, construction and maintenance procedures for pavement surfaces and the road structures respectively and aid in the scheduling of maintenance. The TMH 9 main objective is to assess the condition at network level and schedule maintenance for the use in management systems [TMH 9, 1992]. The TRH 22 provides guidelines for the implementation of pavement management systems [TRH 22, 1994].

Similar to the TRH and TMH manuals, bridge management systems (BMS) provide a systematic method for the management of bridge and road structures alike. There are many different types and versions of bridge management systems, however most systems revolve around the concepts of condition assessment and maintenance activities [Nordengen et al., 2000].

These manuals and systems provide the user with a set of tools that can be used to managed and maintained these infrastructure and detail the inspection process, key components that require attention and the greatest risks faced by the infrastructure. It also includes a condition rating, which is based on risk. This risk is based on the probability of failure multiplied by the impact. It is important to know the condition and performance information of an asset as it drives future programs [IIMM, 2011].

Currently no similar document exists that provide such tools or methods for concrete water retaining structures, and more specifically reinforced concrete reservoirs. The condition assessments of these structures are based on the discretion and experience of the inspector, generally an external consultant, and his/her professional opinion. In municipalities that have limited resources and capacity, the condition assessment data may be inadequate to properly maintain these structures. The absence of such a document leads to a lack of uniformity with regard to inspection methodology, uniformity of data, quality of data and remedial actions.

Absence of such a document can be attributed to the following factors:

- Lack of understanding with respect to the behaviour of concrete reservoirs and their components.
- Lack of knowledge regarding deterioration patterns related to concrete reservoirs and related components.
- Lack of knowledge regarding the factors that influence material deterioration of concrete reservoirs.
- Lack of knowledge regarding the risks associated with concrete reservoirs.

The South African Institution for Civil Engineers (SAICE) infrastructure condition audit was performed initially in 2006 and scored the DWAF infrastructure a "D+" [SAICE, 2006]. The audit was performed again in 2011 and found the DWAF infrastructure condition to be a "D-" [SAICE, 2011]. This indicates a decline in infrastructure condition. This decline along with the absence of appropriate maintenance policies and practices highlights the problem.

Steel reinforced concrete reservoirs are static infrastructure that require very little mechanical and chemical operation. This focuses the problem on the factors that influence the civil components and subcomponents of the facility.

To address this problem the research study investigates the factors influencing the deterioration of concrete reservoirs with the aim of identifying the critical aspects of reservoir management and provide a method for the prioritization of maintenance. This method provide users ,with limited resources and capacity, sufficient information to implement the method and obtain reliable data, which can be used for the prioritization of maintenance activities. The research follows a similar systems approach as that of the TRH/TMH manuals and BMS systems. The economic benefits of using a systems approach for the maintenance and management of infrastructure has been proven by many authorities [Nordengen et al., 2000]. This serves as motivation for research into this area of study.

1.3 Research Question

In order to develop a maintenance prioritization method, key concepts need to be addressed, thus the research question for this study reads as follows:

"What deterioration mechanisms affect steel reinforced concrete reservoirs and how can the maintenance of the affected components be prioritized?"

In order to perform this investigation, the question is broken up into measurable sub-questions. The sub-questions are as follows:

- What are the components of this infrastructure?
- What distress/deterioration mechanisms do these components encounter?
- What are the risks associated with these mechanisms?
- How can the maintenance of the affected components be prioritized?

Each question will be investigated and the results will be detailed in this document. A brief description of the proposed research methodology provides insight into the process involved in answering these questions.

1.4 Objectives of the Study

The primary goal of this study is to develop a method of prioritising maintenance for steel reinforced concrete reservoirs. This method will provide additional information to the user/owner to aid in the planning and scheduling of maintenance activities.

The main objectives of this study can be summarised in the following list:

- Define the components of a reinforced concrete reservoir (this definition must be applicable to the majority of reservoirs).
- Identify the common distresses that affect these structures.
- Identify the common identification methodologies and rank them according to the technical skill required to execute the methodology.
- Quantify the importance value attributed to each component of a reservoir with regard to maintenance and reservoir service delivery.
- Synthesize all the findings of the study to develop a method for prioritising maintenance activities for reservoirs.

1.5 Chapter Overviews

1.5.1 Chapter 1: Introduction

Chapter 1 serves as an introduction to the research study and outlines the problem statement as well as providing a motivation for research into the area of study. It suggests a possible solution to the problem as well as defining the key objectives of the research study. A summary of each chapter ends the introduction.

1.5.2 Chapter 2: Research Design and Methodology

Chapter 2 provides a detailed description of the research methodology followed throughout the study. It also describes the scope and limitations of the study.

1.5.3 Chapter 3: Literature Study

Chapter 3 provides a background on the water infrastructure industry in South Africa. It also describes the current infrastructure situation in South Africa and highlights the possible causes. It reviews and compares international and national maintenance regimes and highlights good asset management practices.

1.5.4 Chapter 4: Reservoirs Component Breakdown

Chapter 4 reviews previously designed concrete reservoir's technical drawings together with the guidance of the draft SANS 10100 design code and interviews with design professionals to identify the different components of a reservoir.

1.5.5 Chapter 5: Reservoir Deterioration Factors

Chapter 5 investigates the different deterioration mechanisms that affect the different components of a concrete reservoir. The chapter is divided into three main sections, with each of the sections focussing on a specific material type, namely concrete, steel, synthetics.

1.5.6 Chapter 6: Quantify Component Importance

Chapter 6 details the data gathering process by means of the questionnaire. This includes the conversion of the average data to percentages. This data represent the contribution of each component towards the overall condition of the asset to which it relates, as well at the asset contributions towards the overall facility condition.

1.5.7 Chapter 7: Prioritization Method

Chapter 7 uses the findings from each chapter as building blocks for the development of the prioritization method. This method includes the general information required to apply it as well as a fictitious example of the prioritization calculation process.

1.5.8 Chapter 8: Findings, Conclusions and Recommendations

Chapter 8 discusses the findings of the research and compares them to the research objectives. From these findings, conclusions are drawn as well as highlighting key shortcomings that affected the research. Recommendations are made for further study into this area of study.

Chapter 2

Research Design and Methodology

2.1 Introduction

This chapter describes the research design and methodology of the study. It also includes the scope and limitations of the study.

2.2 Research Approach

To achieve the key objectives defined in chapter 1, research is performed into the fields of water services infrastructure, material deterioration, asset maintenance and management, condition assessment techniques as well as component importance.

The research consists of three main techniques namely: literature investigation, interviews with professionals and specialists, and the use of a survey. Each of these techniques will be applied to address the relevant aspects of the study. The following sections describe the use of each technique.

2.2.1 Background Investigation

An initial background study is performed by means of a detailed literature investigation into the state of South Africa's water infrastructure, maintenance practices internationally and locally, and infrastructure asset management principles.

Investigating the state of South Africa's water infrastructure provides a context for the study and helps to formulate the problem statement. By researching international and local maintenance practices, key difference are highlighted which may be used to aid in the development of the prioritization method. Investigating asset management practices highlights the key management principles and ensures that the research conforms to these accepted principles.

The purpose of this background investigation is to provide information regarding the related factors of the proposed solution to the problem and to steer the remainder of the research.

2.2.2 Component Breakdown

Performing the component identification of a reservoir is aided by using two of the three research techniques, literature review and interviews. Inspection of detailed technical design drawings from previously designed and constructed reservoirs provides a starting point for the component identification. Existing Eurocodes and British standards along with the new draft design code SANS 10100 Part 3 - *Design of concrete liquid retaining structures*, also aid in the identification of these components.

Additionally, interviews are conducted with engineering practitioners who have experience with reservoir design. These interviews provide insight into the most important components of reservoirs and also aid in the component identification. A site visit allowed a visual interpretation of the information supplied by the above-mentioned sources.

The identification of the components ensures universal applicability with regard to other reinforced concrete structures. Thus not all reservoirs are equally sized or operate in the same manner, however they all share similar fundamental design actions on a component level.

The components of reservoirs are categorized according to the following categories:

- High-level component function
- Material properties
- Relevant subcomponents

2.2.3 Deterioration Mechanisms

A detailed literature investigation is conducted into the deterioration mechanisms that affect the various materials used in the construction of these structures. This literature consists of case studies, journal articles, books as well as technical manuals and specifications from leading industry material manufactures.

The literature investigation identifies the deterioration mechanisms as well as the common identification techniques used to identify each. This allows the condition of the structure to be determined based on the mechanism present. This determination forms the basis of the prioritization method as it allows maintenance to be prioritized based on the current condition of the component in question.

The purpose of identifying the deterioration mechanisms and identification methodologies is to develop the building blocks of the prioritization method and to provide users with limited resources and capacity reference information needed to apply the method.

2.2.4 Component Importance

The identification of the importance of each component is the determining factor in the development of the prioritization method. It allows the ranking of components based on its importance, thus prioritizing the maintenance requirements associated with each.

The use of a survey is the main method of gathering the relevant data with regard to the importance of each component. A survey was distributed to the working group members of the Draft SANS - 10100 design code and was used to identify the contributions of each component to the overall condition of the facility. This working group consists of specialists with expertise in the fields of hydraulic structure design, reservoir post tensioning and construction.

The components of the survey, the choice of respondents, related questions and the results are discussed in detail in chapter 6.

2.3 Scope and Limitations of Study

2.3.1 Scope

The scope of this study is divided into two areas of research, namely the infrastructure and the lifecycle activity. By defining these two areas the study can be focused in order to achieve the research objectives.

Defining Infrastructure Scope

Water retaining structures can be highly variable with regard to the size, design, purpose of the structure, operating processes, construction techniques and materials used. Due to this variability, a clear scope definition is required to focus the study. Both water treatment works and wastewater treatment works have mechanical and chemical procedures used in the day-to-day operation of the facility. By contrast reservoirs often have very few procedures other than storing water in a hygienic manner. The scope of the study is limited to water reservoirs.

A significant portion of municipal and public infrastructure reservoirs are constructed using reinforced concrete. The scope is therefore focused further onto reinforced concrete water reservoirs. This scope definition will allow focus to be placed on the civil engineering components of the structure and not on the processes related to the water services infrastructure.

It is envisaged that a similar research process be developed by others for other water infrastructure types, such as water treatment work and wastewater treatment works.

Defining Lifecycle Scope

Lifecycle management is a key principle of asset management. The lifecycle approach is all encompassing and follows the cradle to grave principle. This means that it includes every aspect of an asset from its inception to its decommissioning [National Treasury, 2008].

Infrastructure asset lifecycle cost occur in four main phases namely, initiation and planning, acquisition, operation and maintenance and disposal as illustrated in figure 2.1 [National Treasury, 2008]. The time and cost related to each phase may vary.

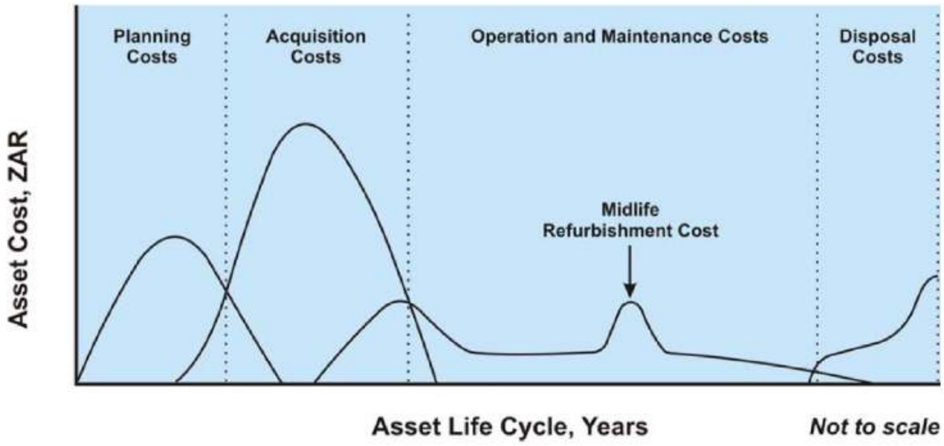


FIGURE 2.1: Typical Lifecycle cost of Water Infrastructure [National Treasury, 2008].

The scope of the study is limited to the operation and maintenance phase, as this is where deficiencies in policies and practices have been identified. The IIMM [2011] defines maintenance as the actions necessary for retaining an asset as near as practicable to its original condition, but excluding renewal and rehabilitation. An important part of operation & maintenance is asset condition monitoring. The monitoring of an asset relates closely to the O&M activities, in that the performance relates to the asset's ability to meet a defined level of service [IIMM, 2011]. Additionally, the condition reflects the asset's physical state and dictates the maintenance requirements [IIMM, 2011]. Asset condition monitoring is thus included into the scope.

With focus being placed on providing information regarding the prioritization of maintenance activities for existing structures, the phases related to the initiation and development of new structures as well as the disposal of existing structures are also excluded from this study.

2.3.2 Limitations

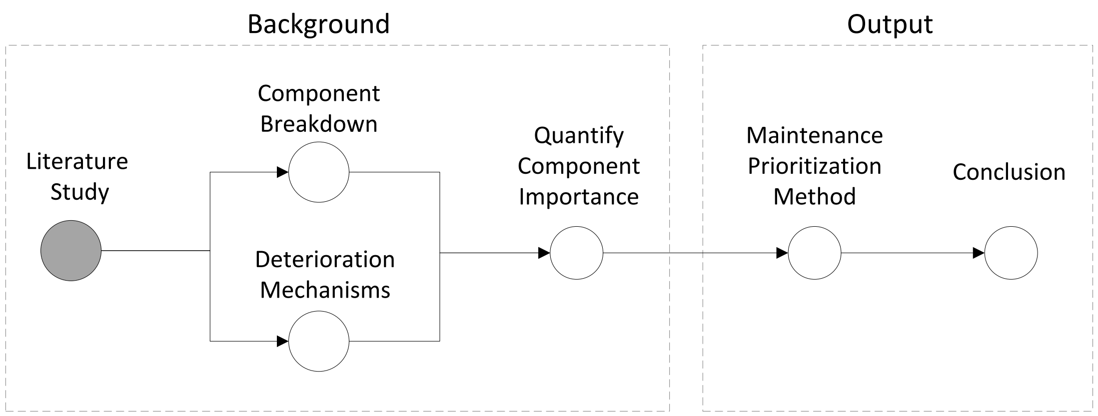
In order to achieve the primary goal of developing a maintenance prioritization method, research is needed into current maintenance practices and the state of infrastructure in South Africa. However the lack of documentation and record keeping is a key limitation of this study. International regimes are incorporated in order to formulate a concept of water reservoirs maintenance practices. This can be measured against local practices to incorporate any potential differences.

Reservoirs are generally distributed in varying locations within municipalities. Due to limited resources only a limited number of reservoirs have been visited. Inspection of reservoirs within one municipality does not accurately represent the condition of all reservoirs throughout South Africa. For this reason and the lack of maintenance records, information taken from extensive condition audits performed, by reputable bodies, throughout South Africa is the primary method of gauging the condition of the water service industry. These audits are however high-level and do not report specifically on the condition of reinforced concrete reservoirs, however it does provide a general condition index.

Using the design code working group as the target audience provides expert opinion on the importance of each component, however as the working group only consists of twenty people, the sample size limits the accuracy of the information gathered.

Chapter 3

Literature Study



3.1 Introduction

With political focus on new infrastructure delivery rather than the maintenance of existing structures, facilities may not be receiving the required maintenance to ensure acceptable service delivery standards are adhered to [SAICE, 2011]. However, political focus alone is not responsible for serviceability failure, lack of knowledge, skills and funding all contribute. Infrastructure is ageing in South Africa and many facilities are reaching their design life end. Effective management and maintenance protocols are thus required.

This chapter provides a background to South African infrastructure and the management thereof, as well as a review of literature regarding the management principles employed in other infrastructure fields. This provides a benchmark by which the development of a maintenance prioritization method may be approached.

The first section of the chapter provides a broad overview of the current water infrastructure situation in South Africa. This includes the current state of water infrastructure, as well as possible causes for the current condition of water infrastructure. Condition data per sector is highly fragmented, incomplete, generally outdated and inconsistent, thus making the data unreliable [Boshoff, 2009]. Furthermore, no comprehensive database of national infrastructure condition and age exists [CSIR, 2007]. Therefore, it was assumed that the condition of the water infrastructure industry as a whole reflects the condition of the service reservoirs.

This overview provides insight into the distresses faced by water retaining structures in South Africa. This overview will shed light on the condition of concrete reservoirs. The background provides a context for the current condition of South African water based infrastructure.

The second section of this chapter focuses on current maintenance philosophies and practices with respects to concrete reservoirs, both nationally and internationally. An investigation is performed into inspection and maintenance regimes from the USA and UK. Investigation into national and international inspection and maintenance programmes may highlight key differences which can be incorporated in South Africa.

The third section of this chapter reviews the management principles set out in the International Infrastructure Management Manual 2011. Lifecycle asset management is a key principle and specific focus is placed on the two components of this principle, namely assessing asset condition and developing maintenance strategies and plans. The use of these principals and practices will act as a template for the development of a maintenance prioritization method.

3.2 Water Infrastructure in South Africa

The Department of Water Affairs and Forestry (DWAF) governs and regulates water related services in South Africa. They are responsible for much of the bulk resource infrastructure, while municipalities and water services provides are responsible for local water quality and water provision [SAICE, 2011]. Municipalities provide asset-based services to households, businesses, governmental institutions and all other communities. Potable water and sanitation are among the asset-based services provided.

"South Africa ranks as one of the most water-scarce countries in the world" [DBSA, 2012]. Due to this scarcity, emphasis is placed on water storage. Thus it is important that the water storage infrastructure that is in place operates at its highest level.

Water infrastructure in South Africa can be divided into two main categories namely water abstraction and water conveyance infrastructure, with local water treatment and distribution falling under the latter [SAICE, 2011].

Reservoirs are an integral part of the reticulation system, and fall under the conveyance category of the water value chain as illustrated in figure 3.1.

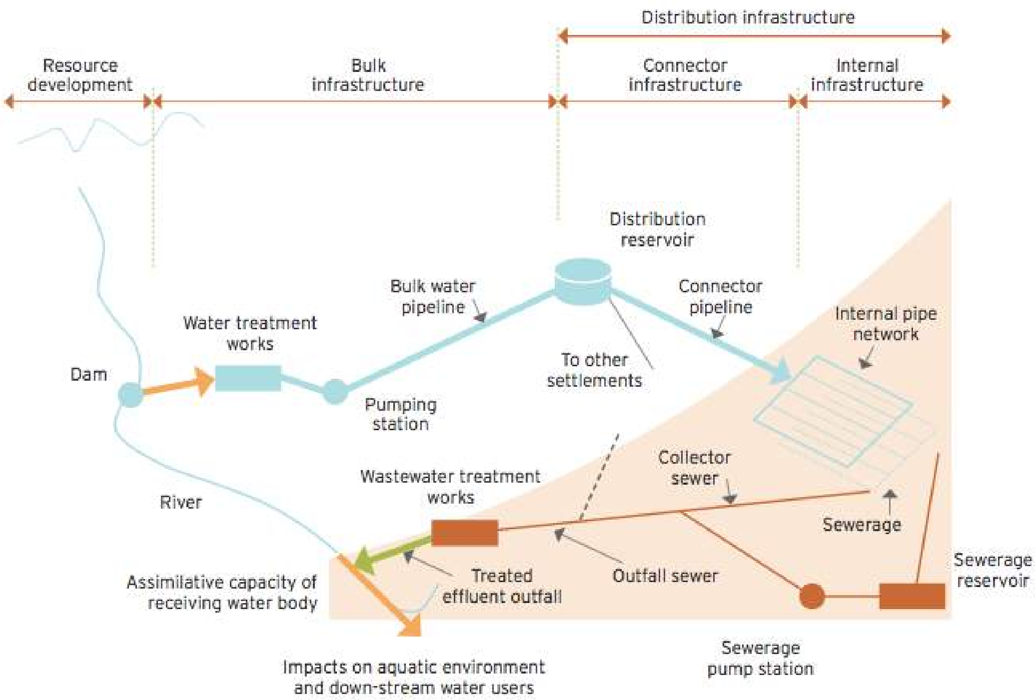


Figure 3.1: Components of water sector infrastructure [Balzer, 2011].

3.2.1 Types of Water Infrastructure in South Africa

Due to the scarcity of water in South Africa, the storage of water is essential to the provision of water services, as reservoirs act as a buffer to fluctuating demands. The infrastructure required in the water services system, known as water services infrastructure, can be divided into the following components [DBSA, 2012]

- Regional bulk water services.
- Local wastewater and water treatment services.
- Internal distribution and reticulation network services.

Bulk infrastructure includes raw water abstraction facilities, water treatment plants, reservoirs and distribution pipelines [DBSA, 2012]. The services that this infrastructure provides can be supplied across municipal borders.

It is estimated that South Africa's water and wastewater treatment industry consists of over 800 water treatment plants and approximately 2000 wastewater treatment works [DBSA, 2012].

The internal distribution and reticulation network, illustrated in figure 3.1, is the responsibility of Water Service Authorities (WSAs). In some cases, the WSAs may delegate the responsibility to the water service providers (WSPs). These responsibilities include the operation and maintenance of the facilities in question.

3.2.2 Institutional frameworks, Regulatory Authorities and Policies.

The water sector is governed and regulated by various authorities. These authorities operate within a predefined institutional framework. This framework comprises of a hierarchical structure of liability from one authority to another. Figure 3.2 illustrates the stakeholders in the South African water sector according to the Development Bank of Southern Africa.

FIGURE 3.2: Stakeholders in the South African water sector [DBSA, 2012].

Government is represented by the (DWAF) and related agencies. Apart from providing bulk water infrastructure, the responsibility of these entities is to oversee the water sector at regional and national level [DBSA, 2012].

Consulting and contracting industries comprise the bulk of the private sector. The contracting industry is responsible for the construction of the infrastructure, while the consulting industries undertake the development activities. These activities include, but are not limited to, planning, feasibility studies, design, monitoring and management of these facilities [DBSA, 2012].

The Water Institution of Southern Africa (WISA) is the most notable professional body in Southern Africa. WISA's aim is to share water related knowledge, by means of conferences, workshops, training programmes and seminars [DBSA, 2012]. NGO's participate in community water projects, of which the Mvula Trust is the largest in Africa [DBSA, 2012].

Policies and Legislation

There are many legislative and policy oriented documents put in place to govern and regulate the water service industry. These documents define key attributes of the water service industry that aid in the provision of services. The development and application of asset management principles through the water services development plan (WSDP) are key requirements of these statues. Numerous statues directly or indirectly require asset management of infrastructure [WSIAM, 2011]. Specific legislation include [WSIAM, 2011]:

- Municipal Systems Act (Act 32 of 2000).
- Municipal Structures Act (Act 117 of 1998).
- Municipal Finance Management Act (MFMA) (Act 56 of 2003) - Specific to Municipalities. Public Finance Management Act (PFMA) (Act 1 of 1999) - Specific to Water Boards (national government business enterprises).

The Municipal Systems Act sets out the rights of the communities and individuals, duties of the personnel and core processes to be followed within municipal systems. Additionally it requires that municipalities prepare integrated development plans (IDPs) [WSIAM, 2011].

The Municipal Structure Act defines the organizational structure. It highlights the municipal functions, powers and relating systems [WSIAM, 2011]. The Municipal Finance Management Act defines financial management and accounting processes. Legislation and strategy documents pertaining specifically to the water sector includes [WSIAM, 2011]:

- Water Services Act (act 108 of 1997) - requires WSAs to prepare WSDP.
- The National Water Act (Act 36 of 1998).
- Strategic Framework for Water Services (DWA et al 2003).
- National Water Resource Strategy (DWA 2004).
- Occupational Health and Safety Act (Act 85 of 1993).
- National Environment Management Act (Act 107 of 1998).
- Environment Conservation Act (Act 73 of 1989).
- National Health Act (Act 61 of 2003).
- Disaster Management Act (Act 57 of 2002).

3.2.3 Current State of Water Infrastructure in South Africa

The CSIR has been conducting research into the state and performance of municipal infrastructure since 2001. The main obstacle faced is the lack of record of any formal broad-based audit or studies into the state of municipal infrastructure [CSIR, 2007]. The CSIR's study focused on the state of infrastructure, its maintenance and underlying cause for the state of maintenance. Improving maintenance of municipal infrastructure was the main goal. This would be facilitated by the identification of measures that could be taken to achieve improved maintenance [CSIR, 2007]. The investigation was a challenge due to the vast amount of municipal infrastructure and poor records thereof, however distinct patterns were revealed that allowed credible conclusions to be drawn for broad categories of municipalities [CSIR, 2007]. "Many municipalities do not have the basics in place" and "there are gross shortcomings in the maintenance policies and practices" are some of the conclusions drawn from this study [CSIR, 2007].

These findings are supported by a study performed by the Water Research Commission (WRC) in 2013 into the municipal water service delivery challenges. This study found that many municipalities are "unable to address backlogs in infrastructure asset maintenance and rehabilitation" [WRC, 2013].

In the water sector, there are extreme disparities in the performance and condition of the infrastructure, as well as with the documentation thereof [SAICE, 2011]. This disparity has been mitigated by the introduction of the "Blue Drop and Green Drop" Water Quality Regulation Strategy. It is the key initiative that monitors potable water management and maintenance, with "Blue Drop" monitoring the quality of water management and "Green Drop" monitoring the quality of treated wastewater management. As focus is placed on reservoirs that store potable water, only the "Blue Drop" initiative is of concern. The SANS 241 drinking water code provides water quality regulations to municipalities and any other public service provider.

The Blue Drop initiative is used to measure the performance of municipal services and provide a benchmark to which all water service providers should strive to. Blue Drop categories of evaluation are as shown below:

- Water Safety and Planning (35%) - This section consists of risk assessments, operational and compliance monitoring and incident management.

- DWQ Process Management & Control (8%) - This sections consists of the compliance to regulation and record keeping protocols.
- Drinking Water Quality Verification (30%) - This section monitors the water quality, both microbial and chemical.
- Management, Accountability & Local Regulation (10%) - This section consists of adhering to service level agreements and the publication of facility performance.
- Asset Management (14%) - This section requires compliance to predefined asset management techniques and procedures.
- Water Use Efficiency & Water Loss Management (3%) - This section consists of strategy and future programme planning.

For a more detailed description of the Blue Drop requirements see Appendix B.

Blue drop status is awarded to municipalities that achieve at least 95% in the Blue Drop Certification Programme (BDC) score sheet. According to SAICE [2011] to date, only 37% of municipalities have asserted "Blue Drop" status.

Since 1994, the percentage of South Africans that have access to basic water services increased from 59% to over 80% [SAICE, 2011]. The increase of water provision infrastructure is due to the sustained political preference for directing financial resources at the creation of new assets [Boshoff, 2009]. This political preference however is frequently at the expense of maintaining existing infrastructure [SAICE, 2011].

As mentioned above, capital renewal and insufficient maintenance exacerbates the deteriorating infrastructure condition. The DWA has estimated that to maintain current infrastructure will require R1.4 billion per annum [SAICE, 2011].

Due to the disparity and inconsistence of documentation practices, a sector-by-sector overview will be used to draw conclusions on the state of concrete reservoirs. It is therefore assumed that the current state of the water infrastructure industry as a whole represents the state of concrete reservoirs. The following section provides a sector-by-sector overview of the water infrastructure condition.

Water Treatment

The quality of water entering the reticulation system dictates the state and performance of the water treatment infrastructure. The standard for drinking water quality is set out in the SABS 241-2001. The most immediate cause for sub-par water quality is due to plant breakdown [CSIR, 2007]. Plant breakdown can be attributed to the following factors [CSIR, 2007]:

- Inappropriate plant.
- Faulty operating procedures.
- Lack of routine maintenance.
- Overload.
- Inadequate budgets and operator error.

A national scale survey to assess the compliance of municipalities with drinking water regulation requirements of the SABS 241-2001, revealed only 43% compliance [CSIR, 2007].

Water Reticulation

Water leakage is the most common problem experienced by reticulation systems [CSIR, 2007]. To determine the extent of the water leakage, 30 South African water services providers leakage data was compared to international norms. The average losses from international systems are approximately 16% [IWA, 2013]. Sixteen indicated leakage ratios higher than the average calculated by the International Water Association [CSIR, 2007].

Rand Water estimates that 27% of the water that it sells to local municipalities leaks away [CSIR, 2007]. Of this, 17% constitutes leakage from the municipal water systems and 83% from private properties [CSIR, 2007].

Wastewater Treatment

Similar to the SABS 241-2001 that dictate the standards of the water entering the reticulation system, the standard that dictate the quality of effluent exiting the treatment works is set out by the DWAF (Department of Water Affairs & Forestry). The quality of water being discharged from the treatment works is a representation of the performance of the facility. A survey conducted by the CSIR of municipalities in Gauteng reveals that many municipalities are not meeting the DWAF standards [CSIR, 2007]. Reasons for not meeting the required standards often include:

- Under budgeting for wastewater facility maintenance.
- Manager with insufficient understanding and knowledge of wastewater technology.
- Staff are not motivated to carry out duties with necessary care and energy.

Past neglect has been identified as a prime contributor to the current under performance of some older works [CSIR, 2007].

Sanitation

Spills from overloading and backlogs due to roots of trees, foreign objects, breakages and network deterioration are the most common problem experienced by waterborne sanitation reticulation systems [CSIR, 2007].

A sanitation sustainability audit was conducted by the DWAF, to ascertain the functionality of sanitation projects completed during 1994 - 2003 [DWAF, 2012]. The study revealed that:

- 28% of residential sanitation facilities are failing.
- 53% of municipalities have adequate maintenance capacity.
- 78% of municipalities that have VIPs, have no maintenance plans in place for them.

Infrastructure Report Card

As stated in section 1.2, the condition of DWAF infrastructure has declined from a "D+" to a "D-", from 2006 to 2011. The SAICE infrastructure report card (IRC) reports the finding from these condition audits and scores infrastructure condition according to a letter grade system. The grade classifications are indicated below:

- A - World Class.
- B - Fit for the future.
- C - Satisfactory for now.
- D - At risk.
- E - Unfit for purpose.

Additionally, the IRC scored the infrastructure in major urban areas a "C+" in 2006 [SAICE, 2006]. In 2011 urban infrastructure was found to have a score of "C+" [SAICE, 2011]. No change has occurred in urban infrastructure between the two audits, however with the decline in DWAF infrastructure, it would imply the overall condition of this infrastructure is at the more critical end of the at risk spectrum.

3.2.4 Causes of Current Conditions of Infrastructure

In South Africa there is a lack of infrastructure monitoring systems. These systems should monitor and record the condition of assets over time as well as the causes of varying condition levels [Boshoff, 2009]. The data from these monitoring systems provide historical condition data that can be used for the projection of future condition as well as maintenance scheduling. The lack of these systems causes uncertainty with regard to the average asset age data [Boshoff, 2009]. Due to this uncertainty, the causes of current municipal infrastructure condition, may be speculated, however are not known for certain. Normal deterioration patterns affect all infrastructures. Sub- standard maintenance regimes and insufficient renewal activities cause infrastructure condition to fall below serviceability standards [Boshoff, 2009].

According to Boshoff [2009] the state of affairs can be attributed to a number of factors that include, but are not limited to:

- Financial resource allocation towards the development of new assets, often at the cost of maintaining existing assets.

- Primary focus on monitoring infrastructure delivery, as opposed to service delivery.
- Overloading of institutional capacity.
- Sub-standard designs.
- Sub-standard construction of facilities.
- Inadequate operating and maintenance practices, including exceeding facility's capacity.
- Lack of knowledge related to the criticality of assets and related factors.
- Poor assessment of maintenance requirements and financial implications thereof.
- The trimming of maintenance budgetary items when budget savings needs to be realised.
- A lack of technical and financial skills.
- No lifecycle planning for assets.
- Inadequate service levels and infrastructure solutions.
- Unachievable development plans.
- Inadequate cost recovery.
- Vandalism to the facilities and theft of property.

As can be seen various factors contribute to the current state of infrastructure and the maintenance thereof. It is important to know what these factors are in order to develop a strategy of addressing them.

3.3 Current Maintenance Regimes

Maintenance of infrastructure is required for a facility to reach its design life. During the operation & maintenance phase, the financial implications may be significant, particularly with short lived assets [IIMM, 2011]. This phase thus requires special attention to ensure maintenance requirements are continuously met.

3.3.1 International Regimes

By referring to two maintenance programs, one from the UK and the other from the USA, similarities in maintenance practices could be identified. The comparison of these two O&M regimes will serve as an example of international maintenance regimes, which can be compared to local regimes. Comparing local practices to international norms may highlight any potential differences. Should a difference in practices be identified and be applicable to the maintenance of local structures, it can be incorporated into the study and aid in the development of a prioritization method. Focus is placed on the inspection, deterioration identification, condition assessment and maintenance activities of these regimes, as they adhere to the approach taken by bridge and pavement management systems. The following sections provide a brief overview of international WRS maintenance regimes.

Inspection

The WSAs should have detailed records of the location of the service reservoirs along with detailed construction drawings if possible [EPA, 2011]. The detailed records should also include a log of previous inspection and cleaning activities. This information will aid the inspector in determining the severity of the identified issues.

A qualified inspector should perform the inspection of a service reservoir [RCSA, 2009]. The term qualified inspector may include the following [RCSA, 2009]:

- American Petroleum Institute (API) API 653 Certified tank inspector.
- NACE International Certified Coating Inspector.
- A Professional engineer with documented experience with atmospheric tanks.
- A Certified operator with documented experience with atmospheric tanks.

It should be noted that these qualified inspectors do not necessarily relate to concrete reservoir inspections.

Before an internal inspection can be conducted, the inspector should perform a perimeter investigation if possible [EPA, 2011]. The objective of the perimeter investigation is to ascertain the susceptibility of the facility for contamination. A detailed inspection of the fixtures associated with the reservoir must be conducted to ensure the reservoir is protected from contamination [RCSA, 2009]. Investigation of the vents, overflows and access hatches are the most critical [RCSA, 2009].

An exterior inspection is performed to assess the structural integrity of the reservoir and may include any signs of structural defects and weaknesses. Identification of corrosion, cracks, holes, deterioration of paint/exterior coating and any signs of wear is done. The severity of the external deterioration may indicate the condition of the structural integrity.

Once the external inspection is completed, an internal inspection may take place. There are three general options for the internal inspection of service reservoirs [EPA, 2011]:

- Fully drain the reservoir to allow inspector access (this may not always be an option, as the reservoir may be unable to be taken out of service for a period of time, due to water restrictions).
- Use certified SCUBA divers to perform a submerged inspection.
- Use remotely operated vehicles (ROV) to inspect and clean reservoirs.

The first option is the most popular method and is also most preferable as it allows for the most thorough cleaning of the reservoir [EPA, 2011]. If the WSAs decide to employ this method, notification to consumers should be done well in advance.

The interior of the reservoir should be inspected for corrosion, cracks, holes, pitting and any signs of deterioration that may cause contamination and loss of structural integrity [RCSA, 2009]. To check for water ingress through the roof, it is suggested that a roof flood test be performed [EPA, 2011]. The test is performed by flooding the roof area suspected of cracking and monitoring any signs of ingress [EPA, 2011]. Specific attention should be given to the joints and waterproofing of concrete reservoirs [RCSA, 2009].

The interior inspection must include an evaluation of the valve performance [EPA, 2011]. All associated valves and internal access components must be inspected for deterioration, specifically rust damage, and be regularly exercised to ensure proper operation [RCSA, 2009].

The inspection should also include the following:

- The appropriateness of the reservoir volume and detention times[EPA, 2011]. If the amount of water stored is sufficiently more than the demand it may result in stagnant water and/or loss of chlorine residual. Possible accumulated sediment may absorb some/all available chlorine and promote bacterial growth.
- The filling/drainage regime of the reservoir (does reservoir run dry en risk re-disturbance of settled solids) [EPA, 2011].
- A water quality analysis: Test results should indicate total coliform bacteria, total and free chlorine residual, physical parameter and volatile organic chemicals [RCSA, 2009]. This analysis should be performed in accordance with relevant authorities.
- An inspection of the cathodic protection system, if applicable.
- Verification that the reservoir is at least 15 m from nearest sewage disposal system and 7 m from the nearest watercourse or storm water drain [RCSA, 2009].
- An assessment of the reservoir's vulnerability to tampering, vandalism and other security issues [RCSA, 2009].
- An assessment of the required operation & maintenance activities needed to ensure continued level of service is maintained [RCSA, 2009].
- Confirmation that the reservoirs meet all necessary regulatory and statutory requirements [EPA, 2011].

Inspection frequency is dependent on the facility requirements and the available resources of the WSAs. Regulation only requires inspection once every 10 years, however it is recommended that atmospheric reservoirs be inspected every 3 - 5 years [[RCSA, 2009].

Quarterly inspection of vents, screens, overflow screens, access hatches and drain liners is recommended [RCSA, 2009].

Maintenance

Following the inspection, cleaning and disposal, it is the WSAs responsibility to ensure that the maintenance recommendations provided by the inspector are carried out [EPA, 2011].

Preventative maintenance is less expensive and is considered best practice. Preventative maintenance ensures no significant change in the reservoir condition since the last inspection [EPA, 2011]. Unless stated otherwise, it is recommended that frequent flushing of the reservoir be performed. The flushing of the reservoir will remove any sediment build up as well as regulate the water detention time, which promotes hygiene [EPA, 2011]. Due to the less resource demanding nature of preventative maintenance it is recommended that the WSAs incorporate preventative maintenance in the routine maintenance programme [EPA, 2011].

Preventative maintenance should begin with an inspection and should include the following [EPA, 2011]:

- Site access and security inspection and repair.
- Site maintenance inspection and repair.
- Foundation inspection and repair (where visible).
- Grout, fibreboard inspection and repair.
- Manholes and access hatches inspection and replace.
- Exterior overflow pipes.
- Vents.
- Ladders.

Products used in the maintenance and repair works should be cleared by the WSAs and should be documented in a list of approved products [EPA, 2011]. All activities performed on the reservoirs, should be recorded in a separate log and be stored electronically for future reference [EPA, 2011].

Additional Maintenance Regime Elements

The following elements may also contribute to the management and maintenance of reservoirs within maintenance regimes. These elements include:

- Cleaning - This action includes isolating the reservoir from the network and washing the inside by means of a pressure wash to remove all contaminants that may negatively affect the water quality.
- Disinfection - Various disinfectants and procedures are used to ensure the reservoir is safe to store water in an hygienic manner.
- Disposal - This action includes the removal and disposal of the contaminants and disinfectant from the reservoir after cleaning and disinfection.

Adhere to Standards and Qualification

Before re-entering a reservoir into service it is required by law that it adheres to all the relevant health and safety standards. Inspectors may only enter the facility upon completion of the appropriate training. Appropriate training requirements are available from the Health and Safety Authority (HAS) [EPA, 2011].

All personnel, including maintenance staff and external contractors, should have been fully trained in the hygienic practices. Where necessary, training should be provided to include procedures required if a personnel member has an illness that may pose a contamination risk [EPA, 2011]. If a personnel member is multifunctional, works on water supply and sewage, extra care should be taken to avoid cross contamination. The UK provides hygienic water training through the hygienic training scheme, which upon completion certifies the participant with a "National Water Hygiene Card" [EPA, 2011]. This certification represents the individual's competency with regard to hygienic maintenance and operation practices.

3.3.2 Lessons Learned from International Regimes

International norm dictates an all-encompassing approach to maintenance of infrastructure. This approach is systematic and initiates with the inspection of the facility and concludes with a quality control check, whereby the facility is checked to ensure all regulations and standards are adhered to prior to re-entry into the service network.

The inspection process has various levels of detail. This is evident by starting the inspection with a perimeter inspection and concluding with a detailed internal inspection together with a performance test.

International maintenance regimes' main identifying trait is the implementation of preventative maintenance. This allows action to be taken prior to component or facility failure.

3.3.3 National Regimes

With very little documentation available on the maintenance regimes in place at various municipalities throughout South Africa, focus is placed on the regulatory environment related to municipal governance, thus municipal infrastructure management and maintenance. Current statues that affect municipalities with regard to governance are the Local Government White Paper, Municipal Demarcation Act, Municipal Structures Act, Municipal Systems Act and the Municipal Finance Management Act [COGTA, 2009].

All these statues provide the frameworks needed to develop and implement management and maintenance regimes for municipal infrastructure and more specifically concrete water reservoirs. With the necessary frameworks in place, many municipalities still do not have the appropriate procedures and policies for the management and maintenance of concrete reservoirs [CSIR, 2007]. This is confirmed by the general lack of maintenance documentation and records [Boshoff, 2009].

Inspection

With focus placed on the regulatory environment, the inspection of dams is conducted to the dam safety regulations, sections 117 to 123 of chapter 12 "Safety of Dams" of the National Water Act 1998 [DBSA, 2004]. These regulations stipulate all the necessary safety regulations and detail the requirements for dam operation and maintenance. Although this does not include concrete reservoirs, many of the procedures and recommendations may be beneficial to reservoirs.

The inspection programme sets out the nature and frequency of the inspections [DBSA, 2004]. These inspections may be conducted on a daily, weekly, monthly, annual or 5 yearly basis depending on the circumstances [DBSA, 2004].

The National Water Act (NWA) and regulation set up a generalised classification system for different dams according to the height of the dam and the hazard potential namely, classification I, II and III [NWA, 2012]. The regulation requires the owner to have the dam inspected regularly by an approved professional person (APP) (engineer in old nomenclature) and have a operation and maintenance plan/manual be drawn up [NWA, 2012].

This method of inspecting and drafting an operation and maintenance plan may prove beneficial if applied in a similar manner for concrete reservoirs.

Maintenance

Funding requirements for asset maintenance is a function of the asset needs, however traditional South African practices earmark 10% of the operation cost for maintenance, [Boshoff, 2009].

There is inadequate planned preventative maintenance thus, maintenance may not be appropriately planned for or prioritized, it may be based on immediate consequence of a certain component that has failed and the maintenance requirements thereof [CIDB, 2007]. Applying the approach of inspecting the facility and developing a method of prioritizing maintenance may provide sufficient information to help in identifying scheduling preventative maintenance.

3.4 Infrastructure Asset Management

The International Infrastructure Management Manual is a document that details the principles of asset management. This manual has been compiled by collaboration between various international institutions and individuals that specialize in asset management. Similarly to the IIMM, the PAS 55 highlights the key requirements of asset management systems [Jenkins, 2014]. The ISO 55001, which superseded the PAS 55 in February 2014, places stronger emphasis on stakeholder involvement [Jenkins, 2014]. Furthermore, a key initiative of the IOS 55001 is the alignment of the engineering practices with the financial and accounting practices [Jenkins, 2014].

Asset management is the term used to define the practice of managing assets in order to maintain a required level of service, in the most cost effective manner [IIMM, 2011]. The key elements of asset management are outlined in figure 3.3:

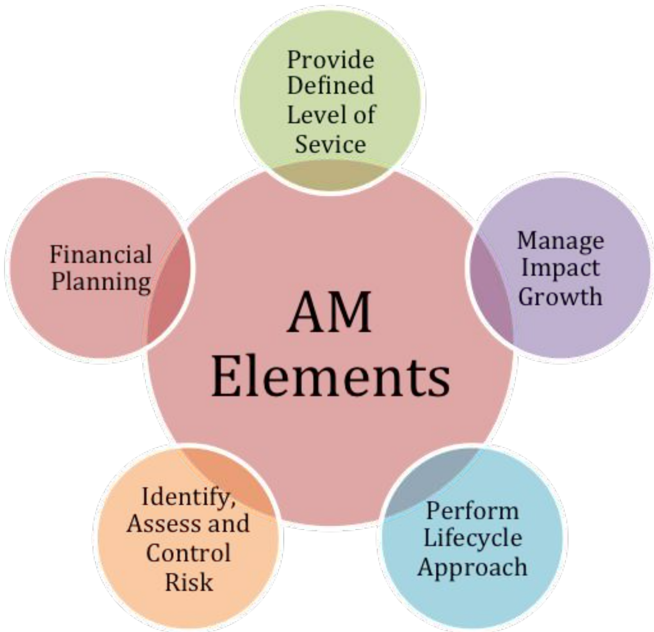


FIGURE 3.3: Key Elements of Asset Management [IIMM, 2011].

In this research, focus will be placed on the lifecycle approach. The lifecycle of an asset is defined as the time interval between commencement and decommissioning of the asset [IIMM, 2011]. During this time interval, the activities performed are referred to as lifecycle activities. The specifics of the activities may vary between different assets, however all activities are present among all assets. The ISO 55001 defines the scope of asset management by developing a strategic-asset management plan (SAMP), which mostly includes the key elements described above [Jenkins, 2014]. By comparison between the IOS 55001 and the IIMM, the most appropriate asset management principles will be highlighted.

3.4.1 Lifecycle Asset Management

The main objective of lifecycle asset management is to achieve the lowest long terms cost, rather than short term saving, when making decisions [IIMM, 2011]. Various lifecycle activities aid in achieving this objective. Figure 3.4 illustrates the main activities that comprise the lifecycle approach to asset management. As defined in the scope, focus shall only be placed on the operation & maintenance and asset monitoring activities. As seen in figure 3.4, operation & maintenance and asset monitoring are key activities in the lifecycle approach that contribute to the functional operation of an asset.

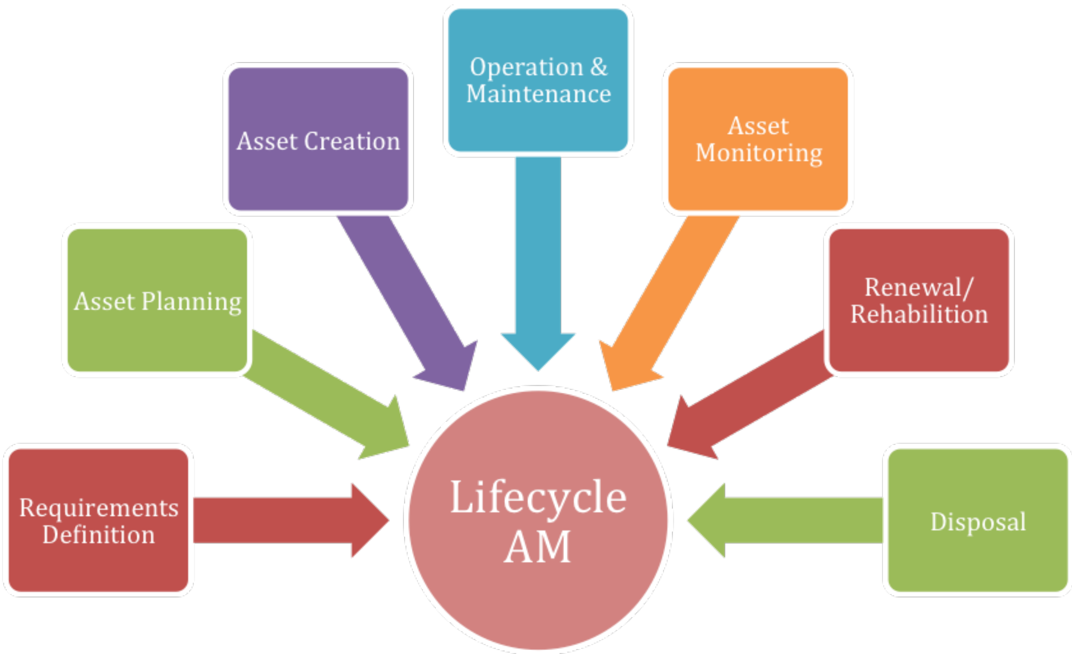


Figure 3.4: Asset Lifecycle Activities [IIMM, 2011].

An important part of the lifecycle asset management approach is gaining asset knowledge. Sub dividing an asset into components allow for increased detail with regard to condition assessment and monitoring [Jenkins, 2014]. However, the component breakdown of an asset is dependent on the type of asset as well as the processes associated with the asset. The component breakdown of an asset follows a hierarchy structure that aids the development of an asset register.

According to the IIMM [2011], there are two different types of asset hierarchy structures. The first is the asset type structure and the second is the asset function structure. Figure 3.5 illustrates the asset type structure that is most suitable to a concrete reservoir as no chemical and mechanical processes are involved.

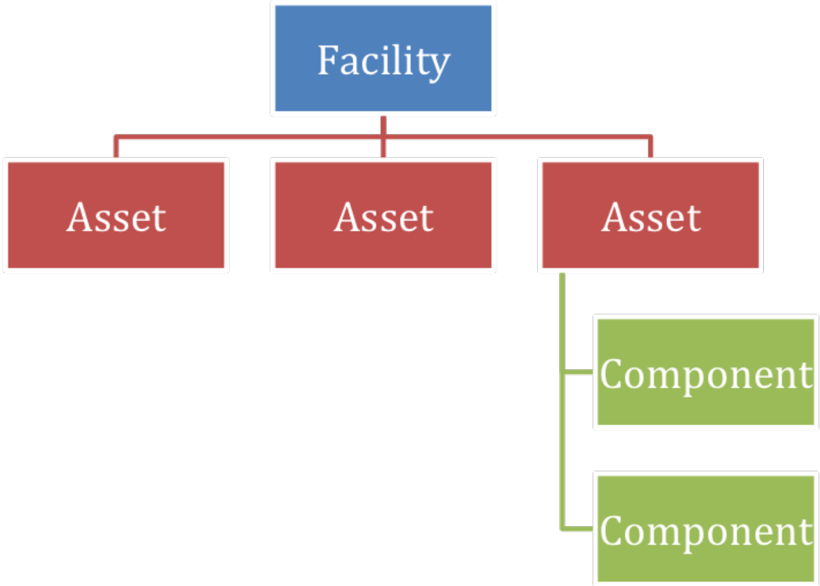


FIGURE 3.5: Asset Register Structure: Asset Type Hierarchy [IIMM, 2011].

The complexity of the hierarchy relates to the degree that the asset has been broken down into [IIMM, 2011]. This level of detail is dependent of the asset in question, however the following should be kept in mind when considering the hierarchy [IIMM, 2011]:

- Different types of assets.
- Information required to manage the assets at different levels.
- Component level required for asset valuation.
- Component level at which maintenance activities and cost are to be assigned.

Asset Monitoring and Condition Assessment

The increase in service outages (asset performance) can be indicative of asset deterioration. Thus asset condition and performance are often linked. The main reason for assessing the current condition of an asset is to acquire the necessary information to enable informed actions regarding the asset. These actions include the mitigation of business risk, avoiding of unplanned outages, to provide accurate predictions of future financial requirements, refine the maintenance strategies and enhance the sustainability of the asset [IIMM, 2011].

Condition assessment is a continuously improving process that needs to align with the institutional objectives [Jenkins, 2014]. Figure 3.7 illustrates the actions that constitute the process of developing an asset condition assessment programme. These items are discussed under the following paragraph.

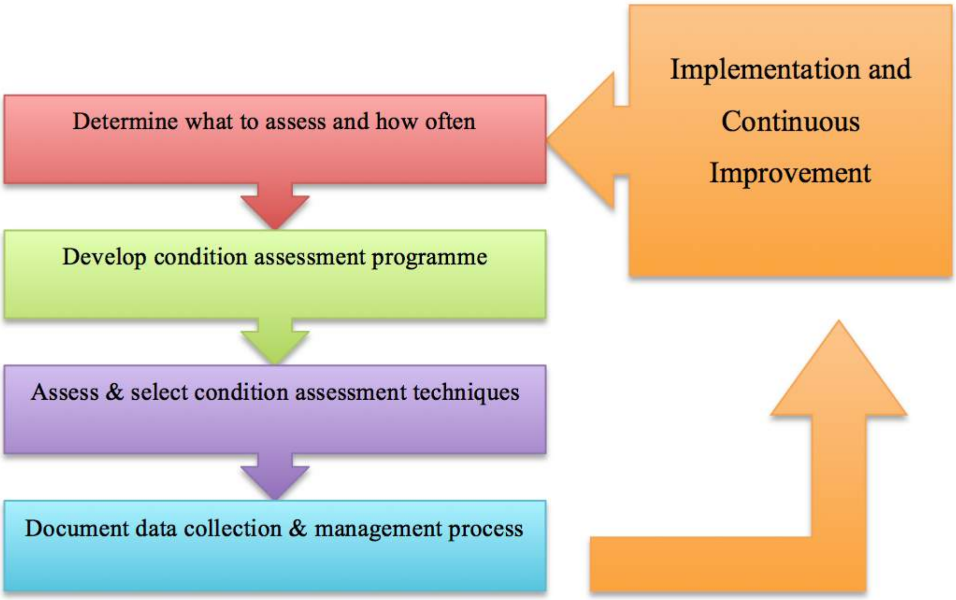


FIGURE 3.6: Process for the development of a condition assessment programme [IIMM, 2011].

Determine what to Assess

Determining which assets or components to assess is generally dependent on the criticality of the component or asset. The older the asset the more likely it is to fail thus usually warranting more frequent condition assessment [IIMM, 2011]. Similarly, the higher the consequence of failure related to an asset or component, the more critical it is and the more frequent assessment it may require [IIMM, 2011].

In situations where financial resources are limited, a risk-based approach can be used for the prioritization of inspection, thus higher risk assets are targeted for inspection [IIMM, 2011]. As well as including the age and risks associated with assets, typical questions can aid in determining which assets to inspect and may include [IIMM, 2011]:

- What is the asset's effective life and estimated remaining useful life until replacement?
- What are the environmental conditions that may accelerate the deterioration?
- Is the asset technically or commercially obsolete?
- Could planned maintenance prevent asset's failure and/or extend useful life?

Condition Assessment Programme

The condition assessment programme focuses on the organizational and business factors related to such programmes. The development of such a programme consists of three main sections namely:

- Status Assessment.
- Options Development.
- Programme Implementation.

The first section consists of assessing the existing condition monitoring practices. The asset, environment, policies and past history data factors contribute to the assessment of these existing practices. The business impacts of these existing practices are also considered.

The second section deals with options development, should the existing monitoring practices be insufficient to meet the assets needs. The options development consists of considering all the related factors in choosing a new condition monitoring system. This includes investigating new assessment options, objectives, resource requirements, frequency of investigation and sample size required. Finally a cost vs benefit analysis is conducted on the adoption of a new system. Once the new system is approved the final section of the programme is initiated.

Programme implementation consists of setting forward a business plan for the new assess monitoring system. The condition monitoring is implemented and is continuously improved.

Condition Assessment Techniques

The most appropriate condition assessment technique may be dependent on the type of asset in question, the sample size, the cost implications and the accuracy required by the specified technique. These techniques can range from simple visual inspections to detailed experimental testing [IIMM, 2011].

When considering various assessment techniques, the economic justification as well as other benefits and limitations need to be considered [IIMM, 2011]. These benefits and limitations may include [IIMM, 2011]:

- Using industry standard methodologies to maximize the use of industry guidance.
- The applicability of the technique to identify the likely failure mode of asset or material in question.
- The level and availability of the skills required in executing assessment techniques.
- The economic implication of the assessment technique, this includes both time and cost.
- Whether the cost and disruption of the more destructive techniques outweigh the possible benefits.
- How does the technique assign the condition rating?

Condition Grading Techniques

The results of the condition assessment will provide qualitative descriptions or quantitative grading that represent the condition of the asset [IIMM, 2011]. The condition assessment of assets is a top-down process, thus higher-level components are assessed and graded before advancing to more detailed components.

There are three levels of detail with regard to condition grading namely:

- The core approach.
- The intermediary approach.
- The advanced approach.

The core approach is geared towards large number of passive assets, such as pipe networks and distribution assets [IIMM, 2011]. Table 3.1 below illustrates a simple core condition-rating model.

TABLE 3.1: Core Condition Rating Model [IIMM, 2011].

Rank	Description of Condition
1	**Very Good Condition** - Only normal maintenance required
2	**Minor Defect Only** - Minor maintenance required (5%)
3	**Maintenance Required to Return to Acceptable Level of Service** - Significant maintenance required (10 - 20%)
4	**Requires Renewal** - Significant maintenance required (20 - 40%)
5	**Asset Unserviceable** - Over 50% of asset requires replacement

Asset Maintenance

The ISO 55001 defines a concept known as ”Resource Support” that includes the maintenance activities to ensure an asset performs to its desired level [Jenkins, 2014]. Maintenance activities however do not increase the asset condition and service potential, rather it slows the asset deterioration [IIMM, 2011]. Figure 2.8 illustrates a maintenance pyramid that represents the key factors to consider when developing a maintenance programme.

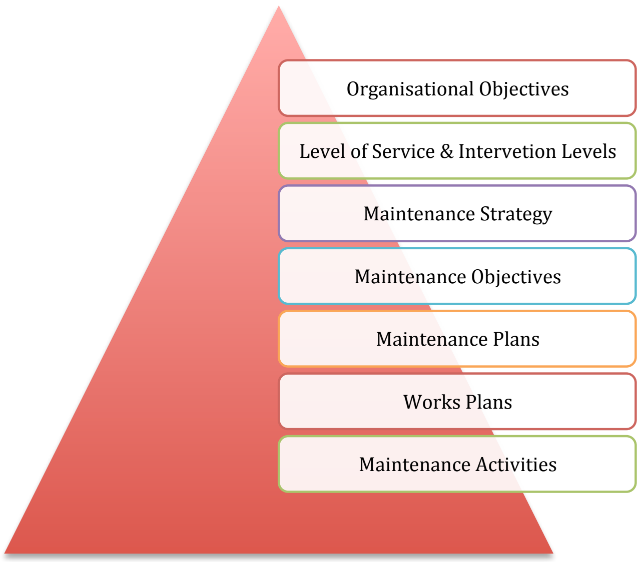


FIGURE 3.7: Maintenance Pyramid [IIMM, 2011].

For each of the factors highlighted above, a brief description will be provided. This description will bring forth the necessary information needed for the development of a maintenance programme. The factors are subsequently discussed.

Organisational Objectives

The organisational objectives may be represented by the vision and mission statement of the authority responsible for the delivery of the maintenance. The organisational objectives drive the asset management plan [IIMM, 2011]. Understanding these objectives will ensure the maintenance plans conforms to the organisational framework, policies, financial and legislative requirements.

Level of Service & Intervention Level

Levels of service are defined by the organisational objectives. These are measurable parameters by which the objectives are interpreted. These parameters often drive the frequency of maintenance [IIMM, 2011].

Maintenance Strategy

A maintenance strategy identifies the tools that will be used to implement the maintenance plan [IIMM, 2011]. Additionally it also defines the roles and responsibilities regarding the maintenance of the asset.

Maintenance Objectives

Maintenance objectives act as a middle (tactical level) level performance measures demonstrating achievement against the levels of service [IIMM, 2011]. Mainte nance objectives ensure commercial and private owners [IIMM, 2011]:

- Remain competitive in the marketplace.
- Increase efficiency and optimize cost.
- Increase profitability of quality products.

Maintenance Objectives

There are two types of asset maintenance activities, those that are planned and those that are not planned. Unplanned maintenance, often referred to as corrective/reactive maintenance, is the activities that are performed on assets that have failed [IIMM, 2011]. The activities' aim is to reinstate the failed asset to active working condition.

Planned maintenance, often referred to as preventative maintenance, is the activities that are preformed prior to asset failure [IIMM, 2011]. These activities aim to correct faults before they lead to asset failure.

Reactive maintenance requires no pre-planning and is thus less resource intensive over the long run, however can have significant short term financial implications. Preventative maintenance requires constant monitoring and scheduling and is resource intensive over the long run, however may result in less significant financial implications. The optimal zone of maintenance is where a balance between preventative and reactive maintenance cost are the lowest. Figure 3.8 illustrates the schematic balancing of maintenance cost to identify the optimal zone.

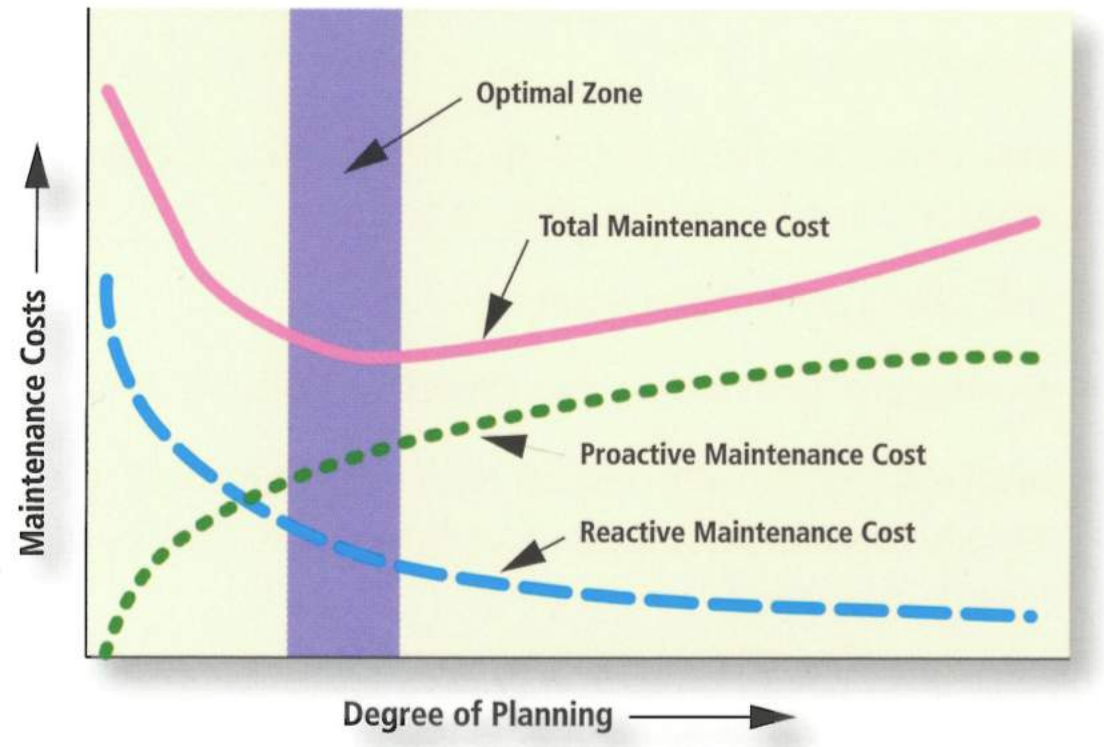


FIGURE 3.8: Schematic Balancing Unplanned and Planned Maintenance Cost [IIMM, 2011].

Work Plans

The work plans depend on the type of maintenance, thus for either unplanned or planned maintenance. Although unplanned maintenance cannot be scheduled, the method of dealing with unplanned maintenance can be planned. The methodology of attending to unplanned maintenance consists of the following [IIMM, 2011]:

- Fault notification and location.
- Mobilization and attendance.
- Restoration of service.

The fault notification can be as a result of service failures that meet the response criteria or the impact of failure on related assets. The location of the fault is recorded and determines the mobilizations actions.

Logistical support is dependent on the location of the fault. The fault information will aid the selection of the response methods as well as the approval of the appropriate work plan. The first task of restoration is restoring service by the quickest and safest means. Repairs may be conducted independently from restoration of service [IIMM, 2011].

In order to develop a planned maintenance plan, the necessary preventative maintenance tasks need to be identified. These tasks can be identified by:

- Experience and industry best practices.
- Manufacturer recommendations.
- Historical activities.
- Risk-based maintenance processes.

Tasks are identified and are then assembled into practical work packages [IIMM, 2011]. Planned maintenance tasks can be used to level resource requirements, thus reducing personnel overheads.

Maintenance Activities

The maintenance activities are dependent on the asset or component that requires the maintenance. Industry best practices and manufacturer recommendations dictate what these activities should be.

3.5 Chapter Summary

A general lack of knowledge and resources are the main causes of inadequate maintenance. Although much has been done to improve the provision of basic water services throughout South Africa, many municipalities are still providing substandard management and maintenance to facilities. The sustained political preference towards new infrastructure creation rather than maintaining existing infrastructure exacerbates this condition.

In an attempt to rectify this problem many initiatives have been proposed and put into practice, however poor adoption rates still threaten the water service industry infrastructure.

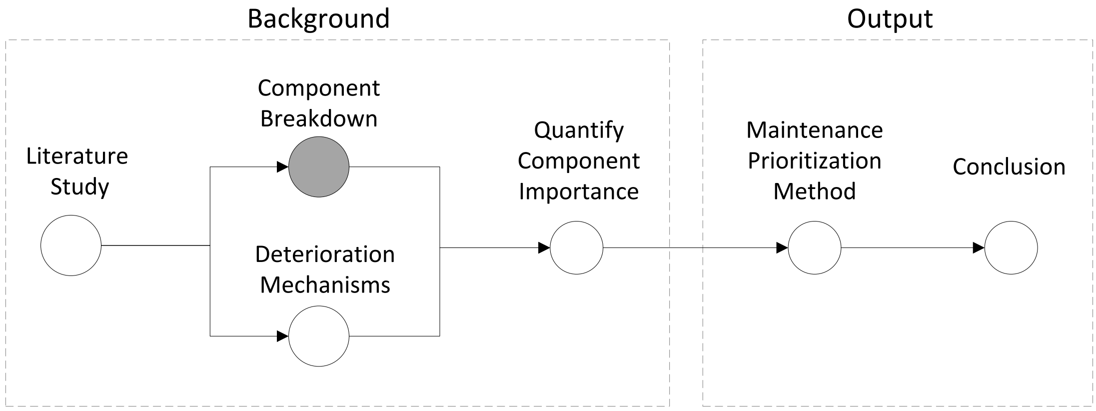
Substandard maintenance alone is not the only cause of current infrastructure condition, however addressing this problem may have many positive spin-offs. A dearth in maintenance policies and practices have been identified.

Investigating international management and maintenance policies and practices will identify key concepts that can aid in addressing South Africa's infrastructure maintenance problem. By comparison, South Africa's general lack of maintenance documentation and traditional practice of earmarking 10% of the operational cost towards maintenance are key differences between international and local maintenance practices.

To address the problem of water infrastructure condition in South Africa, application of good asset management principles, such as acquiring asset information, planning maintenance activities, monitoring of facilities and routine documentation, is needed.

Chapter 4

Reinforced Concrete Reservoirs Component Breakdown



4.1 Defining Reinforced Concrete Reservoirs

In order to identify the key distresses faced by these structures, it is important to understand the structure and its related parts. Following the asset management principles discussed in Chapter 3, the Component Breakdown of a reservoir is performed in this chapter. An asset hierarchy will be developed to provide a framework in which data is collected, reported and decisions are based upon. The asset hierarchy will be based on asset and type.

From inspection of Euro, British and SANS design codes and the collaboration with previously designed and constructed reservoirs design drawings, the following key categories have been identified [SANS 10100:3, 2014]:

- Structure (Walls, Columns, Joints, Sealants, Bearings etc.).
- Components (Manholes, ladders, ventilators etc.).
- Drainage (Agricultural drainage, subsurface drainage).
- Pipe Work (feeder pipe, scour pipes and valves, outlet pipe).
- Roof (Structural component however separate from structure).

Specific reference will be made to the draft SANS 10100 Part 3: Design of concrete liquid retaining structures. This code is however still a draft and is to date not published.

4.1.1 Structure

Structure refers to the sections of the reservoir that consists of reinforced concrete and constitutes the bulk of the reservoir. The main parts of the structure are the following:

- Floors.
- Columns.
- Walls.

Floors

The floor is generally constructed by casting a concrete slab, either in one piece or in several smaller pieces. Different classes of concrete can be specified, with common specifications being 35/19 [du Toit, 2014]. The first digits indicates the concrete strength after 28 days and the second the maximum aggregate size. The thickness of the slab may vary depending on the size of the reservoir, geotechnical conditions on site and drainage requirements. General thickness's range from 150 mm to 300 mm [Perduh, 2014].

Once the slab is cast and has reached a certain level of curing it receives a power floated finish [Kruger, 2014]. The slab is constructed with construction/expansion joints, which are in place to reduce the risk of cracking. The reinforcement in the slabs is continuous through the joint [Kruger, 2014]. Waterproofing the joint is essential to minimizing the losses due to seepage. The designer specifies the waterproofing technique based on the requirements of the structure and soil conditions [Perduh, 2014].

Floor Waterproofing

Typical waterproofing on a floor joint consists of waterproof fabric placed over the joint. Either polysulphide sealant or multiple layers of bituminous paint may accompany this fabric [Kruger, 2014]. This type of waterproofing is applied after the structure is constructed. Additional waterproofing is placed at designated joints prior to casting if required. This additional waterproofing consists of a PVC rearguard waterstop and polyethylene sheets [Kruger, 2014]. These sheets are placed underneath the slab and are perforated to allow water to drain away. In order to drain the reservoir for inspection or maintenance, the floor is sloped with the drainage system at the lowest point.

Columns

The presence of columns is dependent on the roof design and size. If the roof has a dome shape design, columns may not be necessary [du Toit, 2014]. If a flat slab roof design is chosen, columns will be required and are subject to structural design requirements.

The internal columns are generally comprised of a base or footing and the upright column [van Dalsen, 2014]. These columns are submerged and have expansion joints installed to allow movement. Due to water penetration, additional concrete cover may be required.

Walls

The walls of the reservoirs are constructed using two different techniques. The first technique is employed in smaller sized reservoirs, whereby the floor and wall is cast as one monolithic structure [SANS 10100:3, 2014].

The walls are reinforced with steel reinforcing to the specification of the structural designer. The moments and shear effect of the hydrostatic pressure forces acting on the monolithic structures requires specific detailing to minimize the risk of opening at the corner. The appropriate design could incorporate a strut and tie system [SANS 10100:3, 2014].

The second technique views the wall as a thin walled vessel. Thus the wall is cast separate from the floor and can move and expand independently. Movement of the wall is achieved by placing movement bearings at both ends of the wall. Teflon bearings are typically used in these structures [du Toit, 2014]. The Teflon bearing is a two part strip bearing capable of load capacities of up to 36 t/m.

This design allows for greater sizes as the bending moment no longer exists and the only forces acting on the walls are that of hydrostatic tension forces. Due to the design type, additional reinforcing may be required. The additional reinforcing is achieved by the use of post tension reinforcing cables. In order to make use of this technique, anchors for the cables are required. On circular reservoirs these anchors are distributed equally around the structure and are referred to as buttresses [Kruger, 2014]. The buttress is a section of the wall that is thickened and strengthened in order to support the tension forces of the cables. The size of the buttress is dependent on the tension of the cable required [Perduh, 2014]. This design however requires substantial waterproofing at the floor wall joint.

Wall/Floor Joint Waterproofing

Due to the movement of the wall, the waterproofing of the wall floor joint comprises of expansive materials. The vertical joint between the floor and the wall is filled with an expanding material and acts in a similar way as the joints in the floor slab. A specification of 20 mm thick synthetic waterproofing is commonplace [Kruger, 2014].

In order to waterproof the expanding corner joint, it is filled with a triangular fillet. Closed cell polyethylene is a commonly used product for the corner fillet with a specification of 70 x 70 (100 kg/m^3) [Greeff, 2014]. The same waterproof fabric used on the floor joints accompanies the fillet. An overrun of 100 mm on both the horizontal and vertical surfaces along side the fillet is commonplace [van Dalsen, 2014].

4.1.2 Components

The components associated with reinforced concrete reservoirs are generally asset access based. These components do not affect the structural integrity of the reservoir. Serviceability is not severely affected, however ease of maintenance and inspection is compromised with the failure of these components. The category of components include:

- Accessibility components (External ladders, Internal ladders, landings, grids).
- Manholes.
- Ventilators.

Accessibility Components

Access ladders consist of an external and internal ladder. The internal and external ladders are subject to varying environmental conditions, thus require different specifications. Platforms are usually beneath the access hatch and are thus subject to the same environmental conditions as the internal ladders. All access components should be in accordance with the Occupational Health and Safety Act, National Building Standards and SANS requirements.

External Ladder

The external ladder is fitted to the outer wall of the reservoir structure and provides access to the roof, where access to the inside of the reservoirs can be gained. Structural steel is used in the construction of the ladder [Kruger, 2014]. Hot-dipped galvanization of the steel is commonly specified to protect the steel from corrosion.

In order to restrict the access to top of the reservoir, the ladder is encased with a circular hoop with a door at the top or bottom [van Dalsen, 2014]. Restricting access to the top of the structure prevents tampering with the structure and its contents, as well as deterring vandalism. Vandalism damage on the access ladder is illustrated in figure 4.1.

FIGURE 4.1: External Access Ladder with vandalism damage to ladder door, Botmaskop reservoir October 2014.

Internal Ladder

The internal ladder is fabricated in the same manner as the external ladder, minus the hoop and security door [Kruger, 2014]. Depending on the size of the reservoir, the ladder may be fixed to an additional support structure. In the case where the ladder is connected to a support structure, a landing is provided at the top [Kruger, 2014].

Platform/Landing

It is preferable to provide a landing beneath the access hatch. Banded hot dipped galvanized grating is commonly specified [Kruger, 2014]. Hand railings generally accompany the landing. The dimension of the landing is dependent on the requirements of the structure and is specified by the designer.

Manhole

The manholes are steel covers over access holes to the service parts of the structure. The manhole covers are standard and are fabricated from cast iron. To ensure the safety of the stored content and the inspectors, it is a requirement that the manholes can be lock in both open and closed positions. The size of the manhole may vary, however sufficient size to enable an inspector wearing breathing apparatus to enter is required. Figure 4.2 illustrates a typical manhole with a lockable system.

FIGURE 4.2: Manhole with lock system in place, Botmaskop reservoir October 2014.

900∅ mm cast iron manhole with a cover key & lock system is a common specification [Kruger, 2014]. The frame of the manhole is secured to the concrete with the use of fishtail lugs that are welded to the corners.

Ventilators

The ventilator on a reservoir acts in a similar manner as an air valve on a pipe network. It allows entrapped air to be expelled from the reservoir during filling and air to be drawn in during drainage. A reservoir is not subject to the same forces as a pipe network, however fill/drainage rates should be considered.

Ventilators are constructed from galvanized steel in order to protect them against corrosion [Kruger, 2014]. Smaller reservoirs require smaller ventilators. A small ventilator may be fabricated from 150∅ 4 mm thick galvanized steel pipe. This pipe is fabricated with a two consecutive 90^o bends as illustrated in figure 4.3. The two consecutive bends cause the orifice opening to face downwards, thus preventing contaminants from entering the reservoir. A mesh is used to cover the orifice opening [van Dalsen, 2014].

FIGURE 4.3: Reservoir Ventilator consisting of two 90^o bends with mesh, Botmaskop reservoir October 2014.

4.1.3 Drainage

Drainage can be categorized into two main categories, namely subsoil drainage (agricultural drainage) and wall drainage.

Floor Drainage

The installation of floor drainage is for the detection of leakage beneath the floor slab. The designer my omit the need for subsoil drainage if, [SANS 10100:3, 2014]:

a. The footprint of the WRS is relatively small.

b. The floor slab is cast in one operation, i.e. without the use of joints.

c. The type of foundation material permits. Foundations on problem soils such as dolomite and dispersive soils may require drainage systems.

The SANS 10100:3 [2014] specifies a perforated slipsheet to be placed beneath the floor slab. This sheet is generally 250 micron polyethylene perforated @ 500 c/c with a 20∅ steel pipe. 110∅ uPVC CORDRAIN is commonly used to drain the water that seeps through to the drainage sump [SANS 10100:3, 2014]. These pipes are encased in no-fines concrete as per the specification in the SANS design code.

The outside perimeter of the reservoir has an apron slab with a specific fall away from the structure [van Dalsen, 2014]. This leads any water that may accumulate on the outside away from the structure. The apron slab connects to an open channel around the perimeter that allows the water to flow towards drainage pipes. The drainpipes, with a fall away from the reservoir, connect to the drainage sump.

The drainage sump is an additional structure situated close to the reservoir, where all the drainage system pipes lead. These pipes include the floor drainage pipes, overflow and scour pipe [Kruger, 2014]. From the drainage sump the water is transported away from the reservoir through a concrete drainage pipe. The destination of the water is dependent on the designer, usually storm water drainage systems. Figure 4.4 shows the drainage sump.

FIGURE 4.4: Drainage sump situated nearby to reservoir, Botmaskop reservoir October 2014.

Wall Drainage

Drainage behind the external wall is provided to limit the horizontal water pressure onto the wall. The perforated wall drainage pipes must be placed with rows of openings to the bottom. These pipes are encased in a stone trench and are wrapped in a geotextile filter cloth [Kruger, 2014]. The cloth provides protection against the ingress of fines.

4.1.4 Pipework

The pipework of the reservoir provides it the functionality of allowing water to enter and be stored, as well as the drain out the water for use. The main pipes in a reservoir are the following:

- Inlet Pipe & Valve.
- Outlet Pipe & Valve.
- Scour Pipe & Valve.
- Overflow Pipe.

Each of the above mentioned pipes serve a specific function and should any of these functionalities be compromised, the serviceability of the structure is compromised. The specifications of the pipes used are based on the hydraulic requirements of the facility [Greeff, 2014]. These requirements are based on the average annual daily demand (AADD). Thus the sizing of the pipe diameter is based on the required fill - and drainage rates of the reservoir. With reference to the continuity equation 4.1 show below, the diameter of the pipes can be calculated.

$$Q = V * A \tag{4.1}$$

With;

$$A = \frac{\pi D^2}{4} \tag{4.2}$$

Inlet Pipe & Valve

The inlet pipe can be cast into the floor or fixed to the external wall depending on the size of the reservoir and required flow rate. In a smaller reservoir, the inlet pipe may simply be fixed to the external wall. In this case the pipe is secured to the wall with holderbats [van Dalsen, 2014]. Larger reservoirs may require that the inlet pipe be cast into the floor. A puddle flange is connected to the pipe to minimize leakage [Kruger, 2014].

Generally the valves that control the flow into the reservoir are situated at the water treatment works or pumping station. However, should additional valves be placed at the reservoir, a vosa type float valve is most common [van Dalsen, 2014]. This valve works on the basis that a lever arm with a float is connected to the valve. If the water level drops enough, the float sinks and opens the valve, thus allowing water to fill the reservoir. Once the water level reaches a specific level, the float rises and closes the valve. This valve automatically controls the amount of water in the reservoir.

Outlet Pipe & Valve

The outlet pipe is positioned at ground level. The size of the outlet pipe is dependent on the drainage flow rate requirements. The outlet pipe is cast into the floor, with a bellmouth attachment [Kruger, 2014]. The edge of the bellmouth is flush with the floor.

A puddle flange is secured to the pipe, along with a form of waterproofing [Kruger, 2014]. The pipe extends downwards into the foundation and bends 90^o to shifts the flow horizontally towards the desired destination. A flange gate valve closes the reservoir from the network during routine maintenance. This valve remains open during service.

Scour Pipe & Valve

On smaller reservoirs, the scour pipe may be connected in a similar manner as the outlet pipe. In these cases, there is no bellmouth connection. In larger reservoirs, a sump may be constructed with a banded hot-dipped galvanized grid over it, with the scour pipe installed at the lowest point. The scour pipe leads to a flange gate valve or equivalent valve situated in the drainage sump [Kruger, 2014].

Overflow Pipe

The overflow pipe is used to drain the structure and prevent damage due to over loading, as a result of excessive filling. The ultimate limit state condition of the structure is taken at the top of the wall, assuming that the outlets are blocked, [SANS 10100:3, 2014]. To prevent damage to the structure, the overflow pipe is positioned just below the top of the wall as illustrated in figure 4.5, thus reducing the water level to below the wall tops.

FIGURE 4.5: Reservoir Overflow pipe, Botmaskop reservoir October 2014.

Dependant on the reservoir size, the overflow pipe may be fastened to the walls or a similar support structure or may be cast into concrete. Regardless of the size of the pipe or reservoir, the intake of the overflow has bellmouth inlet [Kruger, 2014]. A puddle flange is installed beneath the floor of the reservoir. This flange acts as a leak control flange beneath the surface of the concrete floor.

4.1.5 Roof

The roof is part of the structure, however is considered a separate component. The roof has two main designs, the one being flat slab design and the other being a dome design.

Flat Slab Roof

The flat slab of the reservoir is constructed in a similar manner to traditional slabs. If needed, post-tensioning cables may be specified to provide additional structural support. The flat slab design is wood floated finished and is giving the necessary fall to allow water drainage.

A moveable connection between the wall and the roof is specified. A Teflon ton/m bearing is commonly used to allow for movement [du Toit, 2014]. With the flat slab design it may be necessary to provide internal columns to reduce the sagging of the slab.

Dome Roof

The dome design eliminates the need for internal columns, however may be more difficult to construct. The geometry of the dome structure makes it stronger, thus it can be made thinner and lighter. A 100 mm dome roof is a common specification [Kruger, 2014]. Like the flat slab design, the roof can move independently from the walls. To allow this movement a similar bearing system used in flat slab designs may be specified.

4.2 Chapter Summary

The goal of this chapter is to identify the main components and sub-components in a reinforced concrete reservoir. The identification of these components will aid in identifying the maintenance activities related to each. Each component and sub-component has an importance related to the provision of service of the structure, which will form the basis of the prioritization method.

Figure 4.6 shows a summarised component breakdown for a reinforced concrete reservoir, which outlines the components as well as the subcomponents related to the facility.

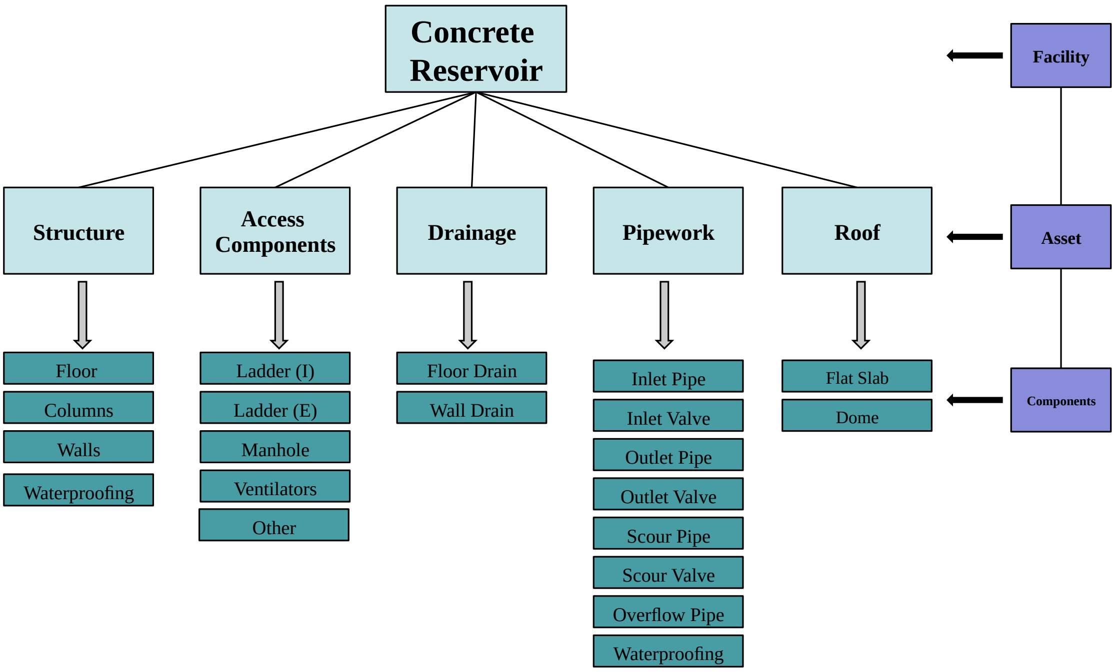
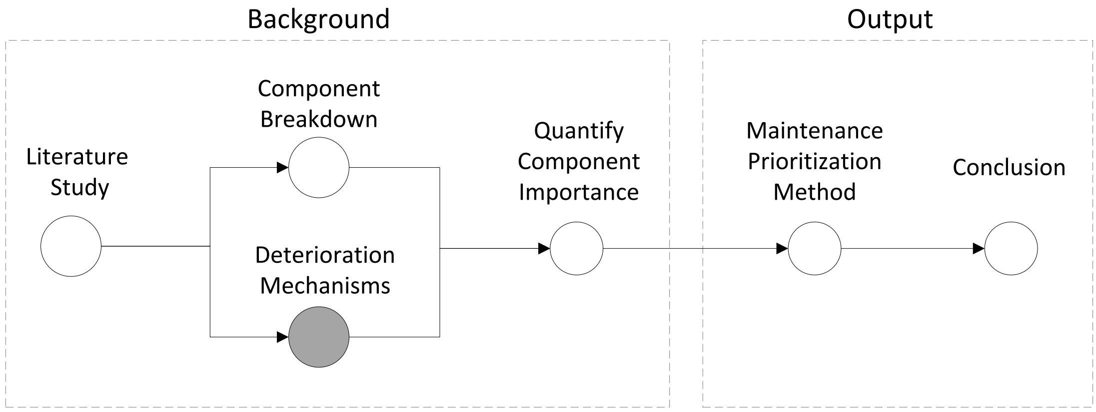


FIGURE 4.6: Reinforced Concrete Reservoir Component Breakdown

Throughout the component breakdown reference is made to the components and the materials that they are constructed from. It is clear that the structure and roof are constructed predominantly from concrete. The access components along with the pipework are constructed mainly from steel, while the drainage and waterproofing comprise a variety of materials which may include PVC, geotextile cloth, polyethylene, and other similar synthetics. From this observation three main materials (concrete, steel and synthetics) have been identified that will form the basis of the deterioration mechanism identification.

Chapter 5

Deterioration Mechanisms



5.1 Introduction

As described in Chapter 4, a reservoir can be subdivided into 5 main categories of components. These components and related sub-components are often constructed from similar materials. Figure 5.1 illustrates the breakdown of these materials.

Each material type is subject to varying deterioration mechanisms. This chapter will identify and provide a brief description of each mechanism along with the appropriate identification methodologies thereof. This chapter forms the building blocks for the development of the prioritization method and provides reference information to the user in order to apply the method. These mechanisms can be physical, chemical or mechanical and can affect each component in the structure differently. For a detailed description of these mechanisms refer to Appendix D.

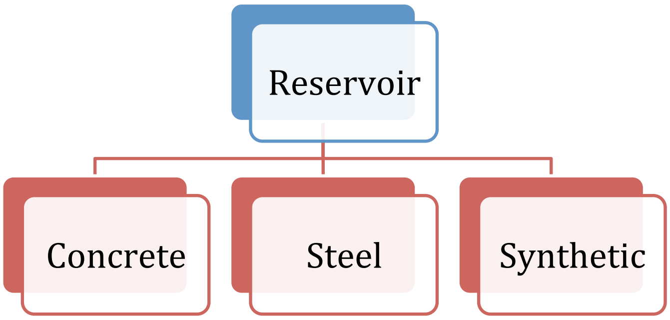


FIGURE 5.1: Reservoir Material Breakdown

In the research focus will be placed on the deterioration mechanisms and their identification methodologies, thus remedial actions falls outside the scope of this study and will not be discussed.

5.2 Concrete Component Deterioration

The structure comprises predominantly concrete with reinforcing steel. The deterioration of concrete leads to structural deterioration and can be attributed to a number of factors. The following are the most common types of concrete degradation [Roux, 2013].

- Delamination & Spalling.
- Carbonation.
- Leaching.
- Sulphate Attack.
- Chloride Penetration & Corrosion.
- Alkali-aggregate Reaction.
- Freeze & Thaw.
- Hardness of water affects.

Each of the deterioration factors will be discussed in the following paragraphs. These factors will aid in the identification of the risk associated with these structures as well as on site identification of deterioration mechanisms.

5.2.1 Delamination and Spalling

When concrete separates form the main portion of concrete, usually at the surface of corroded reinforcing, it is referred to as delamination. The concrete delaminates when corrosion induced cracks propagate to neighboring cracks and form fracture planes [Li et al., 2007]. The fracture plane forms parallel to the rebar and concrete surface. With sufficient corrosion, the concrete cover will fall off from the substrate concrete at the fracture plane [Li et al., 2007].

Detecting delaminations is easier after the concrete has set and dried [NRMCA, 2004]. Delamination and spalling can be identified by means of a visual inspection if the concrete is already separated from the substrate. If delamination has not yet separated from substrate it can be identified by means of acoustics. Delaminated areas are characterized by the emission of a hollow sound when tapped with a hammer or any heavy solid object [NRMCA, 2004].

A procedure known as ”Chain Drag” is used to perform the inspection on concrete road surfaces, however can be adapted for structures [ASTM, 1997]. The procedure involves dragging a chain across the concrete surface and noting the tonal deviations [ASTM, 1997]. The chain can be substituted for a hammer or steel rod. Tapping against an area that is not affected by delamination's will provide a reference tone, usually higher pitched. There are numerous methods used for the identification of delamination in concrete, however different these methods are, most rely on acoustics. The following are a number of identification techniques:

- Electro-Mechanical sounding device.
- Rotary Percussion procedure.
- Impulse-Response method.
- Impact-Echo method.

Each of the above mentioned methods use some form of apparatus to induce an acoustic wave through the suspected concrete area. The wave propagates through the concrete and reflects back when it interacts with objects of varying densities. As delamination's are generally voids in the concrete, their density is less than that of the concrete. The wave reflection is recorded by specialized instruments and recorded using computers and specialized software.

5.2.2 Aggression by Carbon Dioxide (Carbonation & Leaching)

Carbonation of concrete may occur to structures that are exposed to the environment, while a phenomenon known as leaching is present in hydraulic structures [MAPEI, 2011]. Carbonation of concrete is caused by the penetration of CO_2. The phenomenon transforms the lime in concrete that generates hydration of cement into calcium carbonate ($CaCO_3$) [MAPEI, 2011].

In order to verify if the deterioration of concrete is due to carbonation, a colour tests is performed. The area of concrete in question is treated with 1% phenolphthalein solution in ethanol [MAPEI, 2011]. This test works on the basis of chemical indicators. When the solution comes into contact with non-carbonated concrete, it turns red. Thus carbonated concrete does not change colour. Figure 5.2 illustrates the identification of carbonated concrete on a core sample.

FIGURE 5.2: 1% Phenolphthalein in Ethanol solution [MAPEI, 2011].

The only way of containing the spread of carbonation is to remove the area of concrete that is carbonated and replace it.

Visual inspection is the only way to identify the presence of leaching. A detailed inspection of the surface of concrete suspected of being affected by leaching will provide tell tail signs, such as visible aggregates without the cementitious matrix. Figure 5.3 illustrates the effects of leaching on a concrete surface.

FIGURE 5.3: The Effect of Leaching on a Concrete Surface [MAPEI, 2011].

5.2.3 Aggression by Sulphates

The deterioration of concrete due to sulphate attack is caused by three main chemical reactions namely, the formation of gypsum, decalcification of the cementitious phase and the recrystilisation of ettringite [QCL Group, 1999]. Concrete becomes susceptible to sulphate attack at a ground water concentration of about 0,2% [QCL Group, 1999].

The identification of sulphate attack in concrete deterioration is complex and generally requires chemical analysis. Calcium sulphate is present in the production of cement. Normal sulphate content is between 0,4% to 0,6% [MAPEI, 2011]. Thus should chemical analysis indicate higher sulphate content, the presence of sulphate attack may be assumed.

Again the identification of deterioration due to the presence of expansive ettringite is complex and requires specialized knowledge and equipment. An X-Ray diffractogram is used to register the peak values of substances in the concrete, thus indicating the ettringite. Figure 5.4 illustrates the peak values of an X-ray diffractogram analysis of deteriorated concrete.

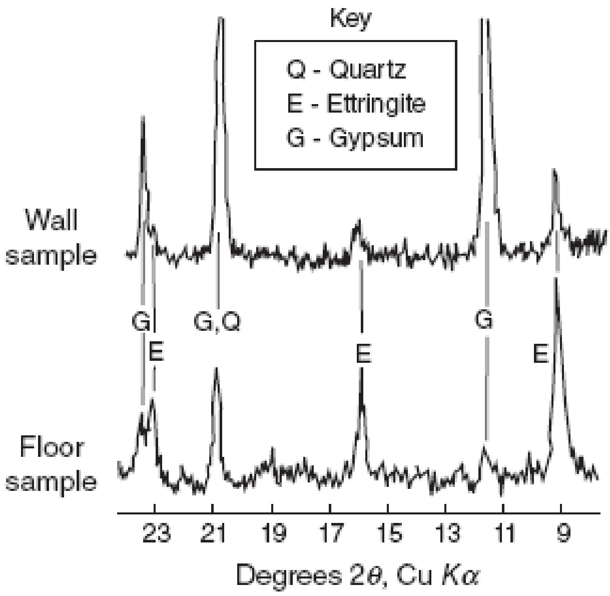


FIGURE 5.4: X-ray diffractogram analysis of deteriorated concrete [Monteiro and Mehta, 2014].

If the results of the diffractogram analysis indicate values that are considerably higher than normal levels (difference of at least 30%), then deterioration of concrete, and secondary corrosion of reinforcement may be attributed to sulphate attack.

Figure 5.5 illustrates the symptomatic representation of concrete deterioration due to sulphuric aggression. The expansion of ettringite may result in the spalls seen in figure 5.5. The inspection of the concrete at these effected areas may provide additional evidence of sulphuric aggression as concrete may be porous due to the presence of thaumasite.

FIGURE 5.5: Deterioration caused by sulphate attack [MAPEI, 2011].

5.2.4 Aggression by Chlorides (Chloride Penetration and Corrosion)

Structures that are exposed to environments with high chloride contents are susceptible to chloride penetration and ultimately corrosion of the reinforcement. The deterioration of concrete due to the aggression by chlorides is a two-stage process. The initial stage involves chloride ion penetration and the initiation of corrosion. The second stage involves the propagation of the corrosion process once the ions reached the steel surface.

The identification of the presence of chlorides in concrete can be conducted by means of chemical analysis. Should the chemical analysis indicated chloride concentrations exceeding the normal levels (0,2% - 0,4%, relative to the weight of the cement) it may be assumed that chloride has infiltrated the concrete and may result in deleterious effects. Additionally, there are two other methods used for the identification of chloride presence in concrete. These are [MAPEI, 2011]:

- Colour test. (Fluorescein and silver nitrate solution, UNI 7928 Standards).
- X-ray diffraction analysis.

Taking a core sample from the suspected deteriorated concrete and spraying it with a solution of fluorescein and silver nitrate allows a chemical reaction to commence [MAPEI, 2011]. This test works on the basis of chemical indicators as the reaction causes the concrete area, which is penetrated by chlorides to turn light pink. The concrete section that is unaffected by the chloride penetration turns dark.

Tests indicate that a 0.1M silver nitrate solution produces the most distinct transformations in colour [Bramforth, Price and Emerson, 1997]. Visual inspection of the concrete surface and suspected areas can aid in the identification of corrosion of reinforcement. A telltale sign of the corrosion of the reinforcement is the brownish florescences (rust stains) that is emitted from the cracks. Figure 5.6 illustrates the red brownish colour associated with corrosion of reinforcing steel in concrete structures.

FIGURE 5.6: Reinforcement corrosion due to chloride ingress with secondary concrete delaminations [MAPEI, 2011].

The second method employs the use of X-ray diffraction analysis. This method shows the products of chloride penetration. The levels of the products can be used to deduce the amount of chloride penetration. There are various additional methods of identifying the presence of chloride that includes, but are not limited to [Bramforth et al., 1997]:

- Petrographic Examination.
- Quantab Method (Chloride indicator strip).
- X-ray Fluorescence.
- Spectrophotometry.
- Scanning Electron Microscopy.

All of the techniques listed above rely on the identification of either the products of chloride or the presence of chloride itself using various equipment and procedures. Each technique has a set of advantages and disadvantages that may make it more appropriate than another. The listed items are less common and are therefore mentioned, however will not be detailed in this document.

5.2.5 Alkali-Aggregate Reaction (AAR)

The Alkali-Aggregate reaction (AAR) appears in two forms - the alkali-silica reaction (ASR) and the alkali-carbonate reaction (ACR). ASR is classed as a heterogeneous solid-liquid reaction [Diamond, 1989]. ASR affects the durability of the concrete in that it forms a gel that expands when in contact with moisture. The absorption of moisture causes the gel to expand, which induces pressure, expansion and the cracking of the aggregate and the surrounding paste. ASR gel only becomes a problem when the gel expands at a rapid rate and exceeds the tensile strength of the concrete [Farny and Kerkhoff, 2007].

There is a difference between the formation of alkali-silica gel and the damage resulting from the reaction. Thus the identification methodology for ASR damage consists of investigating the symptoms of the reaction. There are tree common tests that can be performed to identify the presence of ASR, which include:

- Los Alamos Staining Method (Sodium Cobaltinitrite).
- Petrographic Examination.
- Uranyl-Acetate Treatment Procedure.

The Sodium Cobaltinitrite reacts with the potassium in the alkali-silica gel and acts as a chemical indicator [MAPEI, 2011]. The reaction forms a chemical reaction that causes a coloured precipitate to form. Thus, if the ASR is present the gels colour will change to light greenish yellow as illustrated in figure 5.7 [MAPEI, 2011].

FIGURE 5.7: Los Alamos Staining colour test [MAPEI, 2011].

A petrographic examination of a prepared specimen of the suspected concrete is the most positive method of identification [Farny and Kerkhoff, 2007]. The silica gel may appear as a darkened area within the aggregate or around the perimeter [Farny and Kerkhoff, 2007].

Detecting the presence of the alkali-silica gel by means of the uranyl-acetate treatment procedure involves spraying the solution over a freshly exposed area of concrete and rinsing it with water. Once the area is prepared, it is inspected under ultraviolet light [Farny and Kerkhoff, 2007]. The reactive particles and surrounding gel will appear either bright yellow or green [Farny and Kerkhoff, 2007].

Due to the specialized nature of these tests, it might be more practical to rely on symptomatic identification of ASR. The following section details a variety of symptoms that commonly arise due to the presence of the ASR.

Expansion

Longitudinal cracks, map cracking and in extreme cases spalled (delaminated) concrete surfaces, closed joints and relative displacement of the structure are key indicators of the presence of ASR [Farny and Kerkhoff, 2007]. Figure 5.8 illustrates a severe case of concrete deterioration caused by ASR.

FIGURE 5.8: Severe Deterioration caused by ASR. Visible cracking, joint closing, spalling of concrete, lateral offset of concrete [Farny and Kerkhoff, 2007].

Cracking

A Network of cracks is a good indication of concrete deleteriously affected by ASR. Figure 5.9 demonstrates the characteristic longitudinal cracks associated with ASR. The expansive pressures induced by the gel exceed the tensile strength of the concrete. The longitudinal cracks occur due to the lack of lateral restraint in concrete [Farny and Kerkhoff, 2007].

FIGURE 5.9: Longitudinal Cracks as a result of ASR [Farny and Kerkhoff, 2007].

Surface Deposits (Efflorescence)

ASR gel or calcium carbonate may be present in the cracks. These deposits, sometimes referred to as efflorescence or exudations, can range in colour from dark gray to white [Farny and Kerkhoff, 2007]. Figure 5.10 illustrates the deposits from the ASR.

FIGURE 5.10: White Deposits from ASR [Farny and Kerkhoff, 2007].

Popouts

Popouts are small segments of concrete that fragment from the surface of concrete. Figure 5.11 illustrates the surface of concrete affected by popouts. The inset shows a close-up, thus illustrating the size relative to a pen tip.

FIGURE 5.11: Popouts caused by small sand particles [Farny and Kerkhoff, 2007].

Popouts are caused due to expansion and contraction of porous aggregates. A popout is formed to relive the pressure cause by the formation of gel beneath the surface [Farny and Kerkhoff, 2007]. A good indication of ASR is the presence of gel at the popout location.

Colour Change

Discolouration of the concrete surface is often associated with ASR. The area near a crack my exhibit pinkish, brownish or bleached colourations [Farny and Kerkhoff, 2007].

5.2.6 Freeze-Thaw

Damage due to freeze thaw cycles oocurs when moisture penetrates the concrete and freezes. The freezing causes the water to expand causing internal pressure and may lead to concrete spalling. The damages cause by repeated freeze thaw cycles are generally cracks and in severe cases concrete spalls. The symptoms are also present in other deterioration mechanisms. Thus the structure had to be subjected to freezing temperatures for the deterioration to be attributed to freeze thaw cycles. Figure 5.12 illustrates the deterioration of concrete caused by the repeated freeze and thaw cycles.

FIGURE 5.12: Deterioration caused by Frost Action [MAPEI, 2011].

It should however be noted that the deterioration of concrete caused by freeze thaw cycles is not common in South Africa.

5.2.7 Hardness of Water Affects

Soft water may cause the leaching of calcium hydroxide in the cement paste due to the low ion content [Ballim, 2012]. The hardness of the water, with respect to the corrosion process, is determined by a measure of the bicarbonate ion concentration (HCO_3) [Ballim, 2012]. This varies from the total hardness, which refers to the total summation of the calcium and magnesium cations.

There is no way to visually determine the hardness of water affects. Visual inspection of the facility may reveal symptomatic indicators, however hardness of water affects can only be confirmed by water quality analysis. As the SANS 241 code requires water quality analysis, a water sample can be sent to a laboratory to determine hardness of water. If water is significantly soft, damage due to hardness of water can be expected.

5.3 Steel Components Deterioration

Many of the components that are essential to the serviceability of a service reservoir are constructed using various forms of steel. These steel components may range from cast iron, galvanized steel, structural steel and stainless steel. It is assumed that the corrosion process on the reinforcing steel is similar to that of the steel components within the structure as all components come into contact with concrete. The following are common types of steel deterioration associated with concrete structures [Song and Shayan, 1998]:

- Uniform corrosion.
- Galvanic corrosion.
- Localized corrosion (Pitting, Crevice and Fillform).
- External current imposed corrosion.
- Stress corrosion cracking .
- Hydrogen induced embrittlement.

It should however be noted that there are other forms of corrosion, such as fretting, cavitation, exfoliation, de-alloying etc. that are not associated with concrete structures. For the purpose of this study, these forms of corrosion shall be omitted. A brief description of the mechanisms and identification methodology of each corrosion type will be provided. For a detailed description refer to Appendix D.

5.3.1 Uniform Corrosion

Uniform corrosion presents itself as brownish deposits on the surface of a metal and is most commonly referred to as rust. It is the most common form of corrosion and is found in water tubes, reinforcing steel and hydraulic structures [Schmutz, 2013]. Although this form of corrosion is very frequent, it seldom leads to significant damage, due to the predictability of the process [Schmutz, 2013].

Uniform corrosion can be identified by means of a visual inspection. This is done by investigating the suspected area and looking for characteristic traits that include, the corrosion of the entire exposed surface as well as the appearance of the brownish rust deposits. If uniform corrosion is suspected, the inspection of the depth of the corrosion, can be used to verify. Figure 5.13 illustrates the schematic representation of the uniform corrosion depth of a specimen.

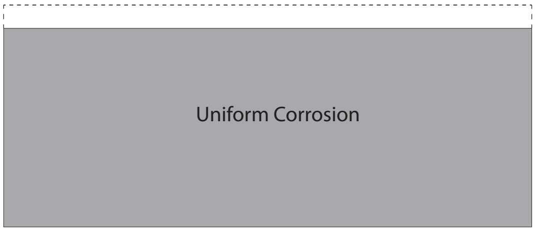


FIGURE 5.13: Uniform Corrosion Depth.

5.3.2 Galvanic Corrosion

Galvanic corrosion, also referred to as bimetallic corrosion, involves the deterioration induced when two dissimilar metals are coupled in a corrosive environment [Stuart, 2013]. Moisture acts as an electrolyte, thus causing the existence of a galvanic cell. A anode and cathode forms due to the potential difference between the two metals and is known as metallic nobility.

Galvanic corrosion can be identified be means of a visual inspection if the required conditions are present, thus the presence of two different metals. If two different metals have been identified, a visual inspection can take place. Figure 5.14 illustrates typical galvanic corrosion, whereby the less noble metal is more corroded than the more noble metal.

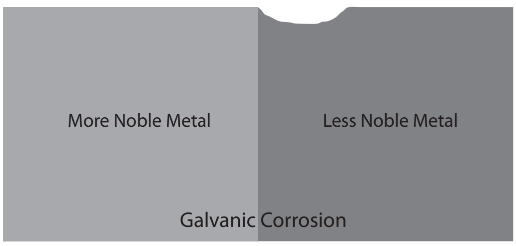


FIGURE 5.14: Galvanic Corrosion.

5.3.3 Localised Corrosion

Localized corrosion targets specific areas of metals and can have severe affects on the metal component. The consequences of localized corrosion is more significant than that of uniform corrosion in that failure occurs without warning and after short exposure periods [Nimmon and Hinds, 2003]. There are various forms of localized corrosion, however for the purpose of this study only the types commonly found or associated with concrete structures will be considered. This includes:

- Pitting Corrosion.
- Crevice corrosion.
- Fillform.

Pitting Corrosion

Pitting corrosion is the result of attack of chloride on the metal surface and is confined to a point or small area [Song and Shayan, 1998]. The corrosion penetrates the passive film and leads to rapid anodic dissolution at the point of penetration [Song and Shayan, 1998].

Pitting can be identified by visual inspection as it is characterized by the formation of small holes or "pits" in the surface of the steel. A clear indication of pitting is if the material adjacent to the pit remains in contact and the pit is corroded. Figure 5.15 illustrates the profile of a surface of metal that is affected by pitting corrosion.

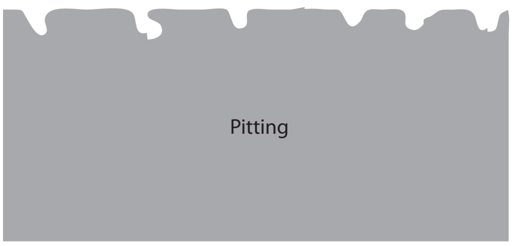


FIGURE 5.15: Pitting Corrosion.

Crevice Corrosion

Crevice corrosion tends to form with a stagnant corrosive solution on the surface of a metal sample [Stuart, 2013]. This corrosion type is characterized by the removal of metal surface area underneath a connection or adjacent metal sample. Visual inspection of the suspected area can be conducted to determine the presence of crevice corrosion. Figure 5.16 illustrates the typical crevice corrosion profile.

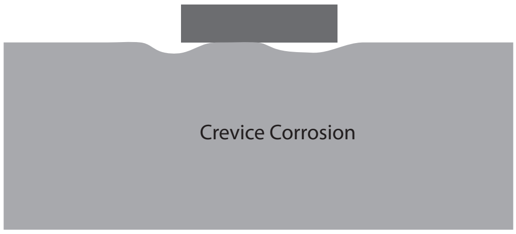


FIGURE 5.16: Pitting Corrosion.

Fillform

Fillform is a type of crevice corrosion that occurs an aggressive solution breaches the protective film and corrodes the metal underneath. Fillform usually starts in a small area where a defect in the protective film is found [Stuart, 2013]

Fillform commonly presents as bubbles forming on the surface of coated metals. A visual inspection of the suspected area can be performed to confirm the presence of fillform corrosion. Figure 5.17 is a schematic representation of the profile of a metal sample that is subjected to fillform corrosion.

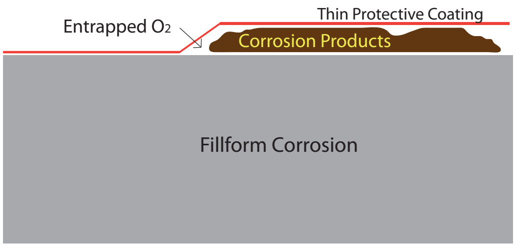


FIGURE 5.17: Fillform Corrosion.

5.3.4 External Current Imposed Corrosion

Current flowing through a metal in a corrosive environment supports the flow of ions which support the corrosion process [Nimmon and Hinds, 2003]. If a sample of metal is suspected of being corroded by means of current imposed corrosion, a multimeter, device used in electrical applications to measure the Volts and Amperes over an electrical circuit, can be used to measure if any current is flowing through sample. If a current is present then current imposed corrosion can be assumed.

5.3.5 Stress Corrosion Cracking

Static tensile stress in combination with corrosion forms stress corrosion cracking that can eventually lead to failure of the component [Nimmon and Hinds, 2003]. Stress corrosion cracking presents as micro cracks on the surface of the metal sample and is undetectable to the naked eye, thus visual inspection on site is not possible. The identification of stress corrosion cracking (SCC) can be done by microscopic examination. Figure 5.18 illustrates the typical profile of a metal sample subject to stress corrosion cracking.

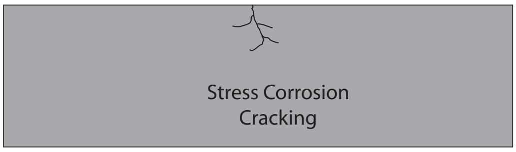


FIGURE 5.18: Stress Corrosion Cracking.

5.3.6 Hydrogen Induced Embrittlement (HIE)

Hydrogen dissolves into all metals to some extent [Stuart, 2013]. The dissolved hydrogen causes the loss of ductility in metals and the deformation of local plastic materials [Song and Shayan, 1998].

Various methods exist that test the susceptibility of a metal to embrittlement due to hydrogen diffusion, however it remains very difficult to detect deterioration due to hydrogen on site. Often there are no visible signs of hydrogen induced embrittlement prior to component failure. Only in extreme circumstance will small hydrogen bubbles form, causing shiny blister at the fracture plane. Thus, in extreme case can visual identification of the symptoms be applied [Woodtli and Kieselbach, 1999].

5.4 Synthetic Components Material Deterioration

This section will focus on any other materials used during the construction of a service reservoir. These materials are generally associated with the waterproofing of the structure. This is usually materials of a polymer nature, such as PVC or polyethylene or synthetics like plastic, rubber, epoxy etc.

5.4.1 Cementitious Protective Coat

In order to increase the durability of the internal surface of the concrete water reservoir, the surface is coated with a cementitious protection layer [Kimbrey, 2014]. Mechanical weathering and poor surface preparation, prior to product application, will be the primary cause of failure of this system [Kimbrey, 2014].

Mechanical damage will be visible on the surface of the top seal if any weathering has occurred [Kimbrey, 2014]. Damage to the surface can be identified by means of visual inspection.

5.4.2 Synthetic Waterproofing (Polyolefin & Epoxy)

All joints (construction, expansion, connection etc.) will generally be sealed with Sikadur Combiflex, a tape like system [Kimbrey, 2014]. Visual inspection can be used to assess the weathering that may occur due to mechanical action. Similar to the cementious top seal, if poor surface preparation was done, de-bonding will occur and product will delaminate.

5.4.3 Synthetic Waterproofing (Polyurethane)

Reservoir construction joints will generally have the SikaSwell 2507 cast in [Kimbrey, 2014]. SikaSwell is a polyurethane composite that expands when in contact with water [SIKA, 2007]. It is used as waterproofing in construction joints and around pipes and steel work that go through concrete [SIKA, 2007].

Visual inspection of construction joints can be conducted to determine if any damage to the waterproofing has occurred.

5.4.4 Synthetic Waterproofing (Polyvinyl chloride)

The wall-floor joint of the water reservoir will generally have a PVC waterbar installed as additional waterproofing [Kimbrey, 2014]. Improper installation or damage due to misalignment of rebar in joint can damage the waterbar.

As the waterbars are cast into the concrete, they are not visible. Water leakage from the wall-floor joint can be an indicator of damage to the waterbars. Thus only symptomatic identification of damage can be identified.

5.5 Chapter Summary

In this chapter, the deterioration mechanisms and identification methodologies associated with the different materials used in the construction of a service reservoir has been investigated. Table 5.1 summarises the various mechanisms associated with concrete as well as indicating the various identification methodologies that can be employed.

TABLE 5.1: Concrete Deterioration Mechanism Identification Methodologies.

Material	**Mechanism**	**Visual Inspection/ NDT**	Laboratory/ Other Experimental Test (Specialized)
Concrete	Delamination/ Spalling	Chain Drag(acoustics), Visual Inspection	Electro-Mechanical Sounding, Rotary Percussion Procedure, Impulse-Response, Impact-Echo
	Carbonation	1% phenolphthalein solution	n/a
	Leaching	Visual Inspection	n/a
	Sulphate Attack	Visual Inspection (Symptomatic)	Chemical Analysis, X-Ray Diffractogram
	Chloride Penetration/ Corrosion	Fluorescein and silver nitrate solution, Visual Inspection (symptomatic)	X-Ray Diffraction Analysis, Petrographic Examination, Quantab, X-Ray Flourescence, Spectrophotometry, Scanning Electron Microscopy
	ASR	Sodium Cobaltinitrite, Visual Inspection (Symptomatic)	Petrographic Examination, Uranyl-Accetate Treatment
	Freeze-Thaw	Visual Inspection (Symptomatic)	n/a
	Hardness of Water	Visual Inspection (Symptomatic) if water quality test has been performed	Water Quality test

As can be seen from table 5.1, all of the mentioned mechanisms can be identified using visual inspection or some form of non-destructive techniques. Some of the mechanisms symptoms can be identified visually, but laboratory tests are required to confirm the deterioration mechanism.

Table 5.2 summarises the deterioration mechanisms and the associated identification methodologies for the metal components.

TABLE 5.2: Metal Deterioration Mechanism Identification Methodologies.

Material	**Mechanism**	**Visual Inspection/ NDT**	**Laboratory/ Other Experimental Test (Specialized)**
Metals	Uniform	Visual Inspection	n/a
	Galvanic	Visual Inspection	n/a
	Pitting	Visual Inspection	n/a
	Crevice	Visual Inspection	n/a
	Fillform	Visual Inspection	n/a
	External Current	Visual Inspection (Multimeter)	n/a
	SCC	Visual Inspection (Microscope)	Micrpscopic Examination
	HIE	Visual Inspection (Symptomatic)	ASTM standards for metal susceptability

Similar to the concrete mechanisms, most of the deterioration mechanisms faced by metal components can be identified by means of a visual inspection, if components are accessible.

Table 5.3 summarises the deterioration mechanisms and the associated identification methodologies for the other components.

TABLE 5.3: Other Deterioration Mechanism Identification Methodologies.

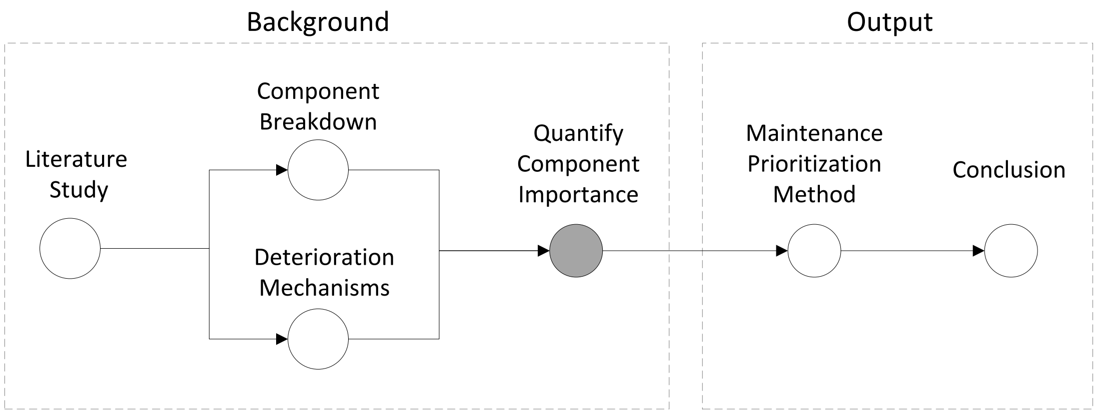
Material	**Mechanism**	**Visual Inspection/ NDT**	**Laboratory/ Other Experimental Test (Specialized)**
Other	Cementitious	Visual Inspection	n/a
	Polyolefin/ Epoxy	Visual Inspection	n/a
	Polyurethane	Visual Inspection	n/a
	PVC	Visual Inspection (Symptomatic)	n/a

The conclusion drawn from the investigation is that each of the mechanisms can be identified, to a certain extent, by means of a visual inspection. This identification often relies on symptomatic identification of the mechanisms. Additionally, various experimental tests can be used to verify the presence of the identified mechanisms.

Visual inspection is thus the chosen method of inspecting reinforced concrete reservoirs for deterioration, as it can apply to all types of materials and components and can cover a large surface are.

Chapter 6

Quantifying Component Importance



6.1 Introduction

In order to obtain the value of importance of each component to its related asset and of each asset to the overall facility, industry professionals were consulted.

This chapter consists of two main sections. The first section of this chapter will discuss the questionnaire and related requirements and the second section will discuss the data that has been obtained. Providing background on the questionnaire will help understand the results from the data.

6.2 Questionnaire

In order to acquire the relevant data, a survey was conducted by means of a questionnaire. An electronic form was distributed to informants, thus streamlining the data collection and analysis process. Refer to Appendix D for the Questionnaire.

6.2.1 Target Audience

Subjective sampling often referred to as judgement sampling, is a method of deliberately deciding on the informants and sample size for the purpose of gathering the most relevant data [Tongca, 2007]. The informants are chosen due to the knowledge or experience that they may possess within a related field. With the study focusing on the prioritization of maintenance activities, the field of expertise relates to that of civil engineering and maintenance.

As this questionnaire follows the subjective sampling method, it is important to define the target audience. The audience is defined by the qualities and experience that they possess. The audience can thus be characterized as civil engineering practitioners with knowledge related to concrete water retaining structures.

The working group responsible for the development of a draft standard for concrete water retaining structure design, are individuals with experience relevant to the design, construction and maintenance of reinforced concrete water reservoirs, among other hydraulic structures. This working group consists of twenty individuals and will be the target audience for this survey.

6.2.2 Questions

The questionnaire consists of 4 sections related to maintenance prioritization, namely:

- Professional Experience.
- Asset Importance.
- Component Importance.

- Inspection Recommendations.

Each of the sections consists of a number of questions, designed to acquire the most accurate data on the various conditions related to the facility.

Section 1: Professional Experience

"Please enter the amount of experience, in years that you have in the civil engineering industry."

As all of the information gathered in the questionnaire is based on the experience of the informants, it is important to assess the sample group's competence level. The purpose of this question is to determine the validity of the data obtained, thus assessing the average amount of experience of the sample group.

Section 2: Asset Importance

"We would like to express the overall condition of the FACILITY as a summation of the condition of the individual assets. How would you rate the contribution of each asset towards the overall condition of the FACILITY?"

In this question, the informants are asked to assign a value to each of the 5 assets, (*structure, access components, drainage, pipework, roof*) based on the contribution they believe each asset should have towards the overall condition of the facility. The purpose of this question is to determine what relevance each asset has on the overall condition value of a concrete water reservoir.

Section 3: Component Importance

In this section, the informants are asked to assign a value to each component, based on the contribution they believe each component should have towards the overall condition of the specific asset to which it relates. The purpose of this question is to determine what relevance each component has on the overall condition value of the different assets. Below is the formulated question for the asset "STRUCTURE".

"We would like to express the overall condition of the asset "STRUCTURE" as a summation of the condition of the individual components. How would you rate the

contribution of each component towards the overall condition of the asset "STRUCTURE"?"

This question is repeated for the assets, Access Components, Drainage, and Pipework. It is however not necessary to apply this question on the Roof asset, as it consists of one monolithic structure with no visibly distinguishable components.

Section 4: Inspection Recommendations

"What would you recommend as the appropriate inspection interval for the asset "STRUCTURE"?"

To determine the frequency of inspection requirements, the informants are asked to select the most appropriate frequency of inspection for each asset based on their experience.

6.3 Data Obtained

Once the electronic survey form had been distributed among the target audience, the data that was obtained needed to be analysed. In order to analyse the data, it must be converted from its raw form to usable information.

6.3.1 Data Conversion

From each question asked in the questionnaire, a number of responses were obtained. The desired end output is to represent each asset and component as a percentage value of the total condition, thus what percentage value does each asset and component contribute to the overall condition. To achieve this conversion, three key steps and equations are required. Step 1: is to calculate the averages for each of the assets and components answered and organize them into a table. To calculate the averages equation 6.1 below was used.

$$\bar{X} = \frac{\sum_{i=1}^{i=n} X_i}{n} \tag{6.1}$$

$\bar{X}$ = Average of selected range.

X_i = Single value in selected range.

n = Number of values in selected range.

$\sum$ = Summation of values.

Step 2: is to sum the total averages in order to calculate the percentage that each asset and component contributes. Using equation 6.2 below calculates the sum of the averages over a given range.

$$\sum_{i=m}^{n} a_i = a_m + a_{m+1} + ... + a_{n-1}a_n \tag{6.2}$$

a_i = Total sum of selected range.

a_m = Single value in selected range.

Step 3: consists of using the average and the summation values to convert the information to percentages. These percentages represent the contribution of each asset or component to the overall value. Equation 6.3 below is used to convert values to percentages.

$$W_i = \left(\frac{\bar{X}}{\sum_{i=m}^{n} a_i} \right) \times 100 \tag{6.3}$$

W_i = Percentage contribution of each asset or component (%).

As a verification step to ensure no calculation errors were made, the percentages are summed using the equations above and verifying that it sums to 100%.

6.3.2 Conversion Results

Twenty individuals received the electronic questionnaire and over a time period of a month, from 1 August 2014 - 29 August 2014, 9 responses were recorded. Dividing the number of responses by the number of questionnaires received yields a response rate of 45%. Using this response rate with a 90% level of confidence yields a 21% margin for error.

Due to the subjective sampling technique applied to the questionnaire, the margin for error is compensated for by the amount of experience of the target audience. From these responses the following results were obtained.

Section 1 Results: Experience

The average experience of the target audience is 32.8 years. The least amount of experience is 10 years and the most is 40 years. However, 8 out the 9 respondents have more than 30 years of experience thus, 10 years is considered to be an outlier.

With the average experience of the target audience being 32.8 years and taking into account the experience is related to hydraulic structure and structural design and construction as defined in chapter 2, it is assumed that this level of experience of the respondents compensates for the large margin of error with respect to the sample size and rate of response.

With this compensation taken into account, the remainder of the results is assumed to be representative of the expert opinion of the majority of the professional population, engineering practitioners.

Section 2 Results: Overall Condition

Using the conversion equations discussed in section 6.3.1, the following table has been generated. Table 6.1 below summarizes the different average values assigned between 1 and 5. The averages are summed and converted to percentages. These percentages represent the contribution of each asset to the overall condition of the facility.

TABLE 6.1: Overall Facility Condition with percentage distributions.

Facility			
Asset	**Std Deviation**	**Average Output**	**% Weight**
Structure	0.00	5	25%
Access Component	0.96	2.44	12%
Drainage	0.57	4.11	21%
Pipework	0.79	3.78	19%
Roof	0.50	4.56	23%
$\sum$		**19.89**	**100%**

The standard deviations indicated in table 6.1 are a measure of the amount of variation from the averages. Structure having a *"0.00"* deviation means all the values were equal. With all the deviations being less than 1, thus within one standard deviation from the mean, it is considered that the data is sufficiently uniform to compensate for the low response rate. The standard deviations are presented in each of the remaining sections. The information displayed in table 6.1 is graphically presented in figure 6.1. Form figure 6.1 it can be seen that the structure and the roof contribute the most to the overall condition of the facility.

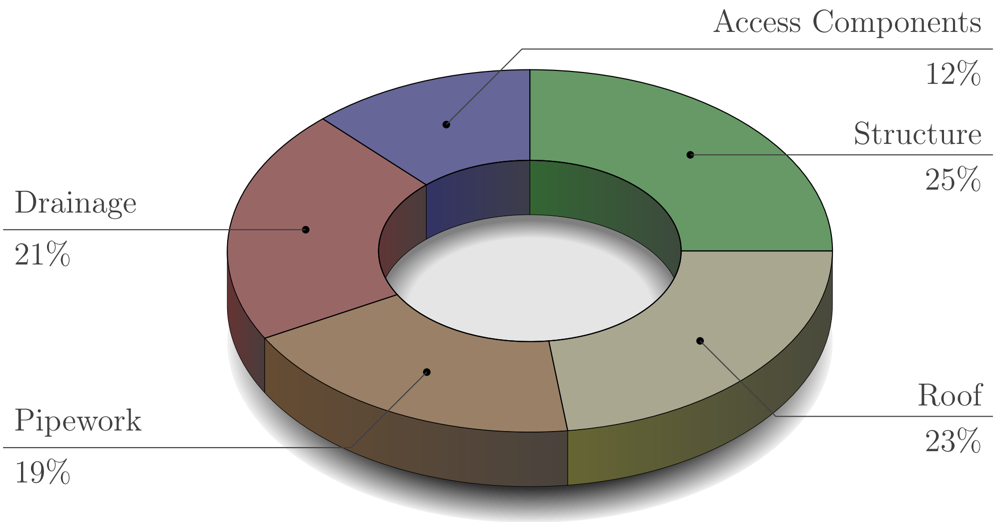


FIGURE 6.1: Percentage Contributions of Each Asset towards the Overall Condition of the Facility.

The access components contribute the least to the overall condition of the facility, while the drainage and the pipework contribute an average amount. The access components are thus able to deteriorate significantly without having a severe affect on the overall condition of the facility.

Section 3 Results: Asset Condition

Structure

Table 6.2 summarises the the different average values assigned to each component of the asset "Structure". These averages are converted to percentages that represent the contribution of each component to the overall condition of the asset "Structure".

TABLE 6.2: Structure Averages with Percentage Distributions.

Structure			
Asset	**Std Deviation**	**Average Output**	**% Weight**
Floors	0.68	4.44	25%
Columns	0.94	4.33	25%
Walls	0.47	4.67	26%
Waterproofing	0.79	4.22	24%
$\sum$		**17.67**	**100%**

The information displayed in table 6.2 is graphically presented in figure 6.2. From figure 6.2 it can be seen that the contributions of each component are fairly equally distributed, however the walls are considered to be slightly more important.

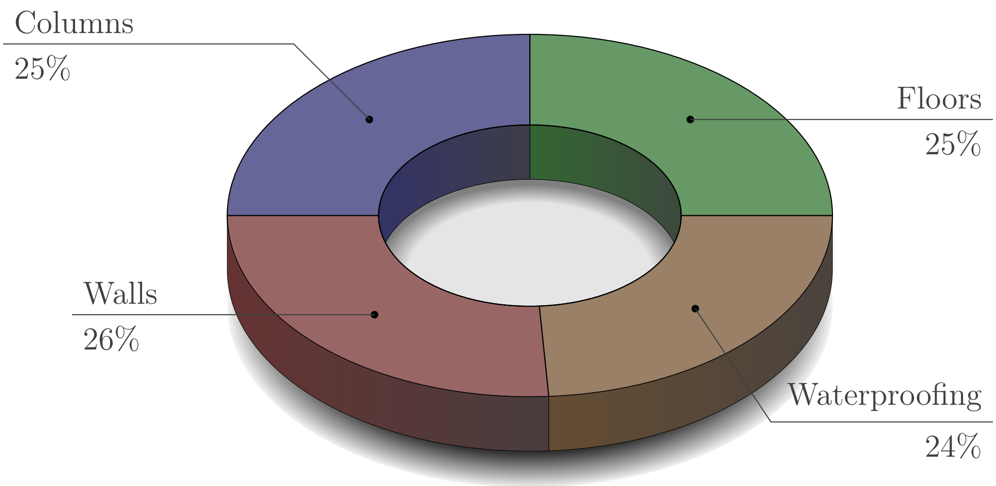


FIGURE 6.2: Component Contributions for Structure Asset.

The contribution of the walls to the overall condition of the asset "Structure" is more significantly experienced in dome shaped reservoirs where columns may not be present. The results from the questionnaire for each asset will be presented in a similar manner as that of the asset "Structure" above.

Access Components

Table 6.3 summarises the the different average values assigned to each component of the asset "Access Components". These averages are converted to percentages that represent the contribution of each component to the overall condition of the asset "Access Components".

TABLE 6.3: Access Components Average with Percentage Distributions.

Access Components			
Asset	**Std Deviation**	**Average Output**	**% Weight**
Internal Ladder	0.67	4.00	23%
External Ladder	0.67	3.67	21%
Manhole	0.63	3.22	19%
Ventilators	0.96	3.56	21%
Other	0.79	2.78	16%
$\sum$		**17.22**	**100%**

The information displayed in table 6.3 is graphically presented in figure 6.3. It can be seen that both internal/external ladders and the ventilators contribute the most to the overall condition of the asset "Access Components", although only marginally more.

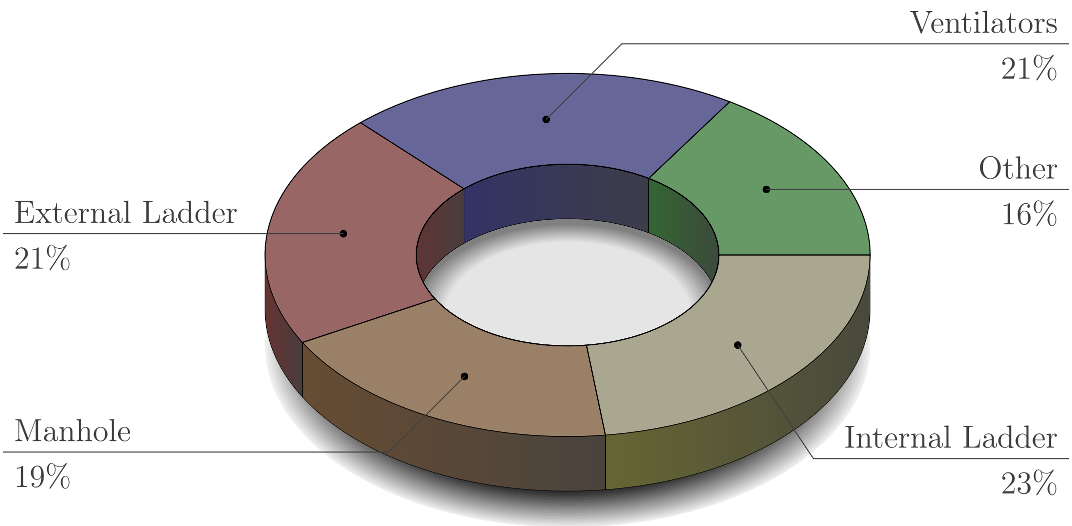


FIGURE 6.3: Component Contributions for Access Components Asset.

"Other 16%" as seen in figure 6.3 refers to external fixtures that are fitted to the structure such as radio towers, weather instrumentation etc.

Drainage

Table 6.4 summarises the the different average values assigned to each component of the asset "Drainage". These averages are converted to percentages that represent the contribution of each component to the overall condition of the asset "Drainage".

Table 6.4: Drainage Averages with Percentage Distributions.

Drainage			
Asset	**Std Deviation**	**Average Output**	**% Weight**
Floor Drain	0.79	4.22	53%
Wall Drain	0.63	3.78	47%
$\sum$		**8**	**100%**

The information displayed in table 6.4 is graphically presented in figure 6.4. From figure 6.4 is can be seen that the contribution of each component is fairly equally distributed, however the floor drains are slightly more important with a 53% contribution.

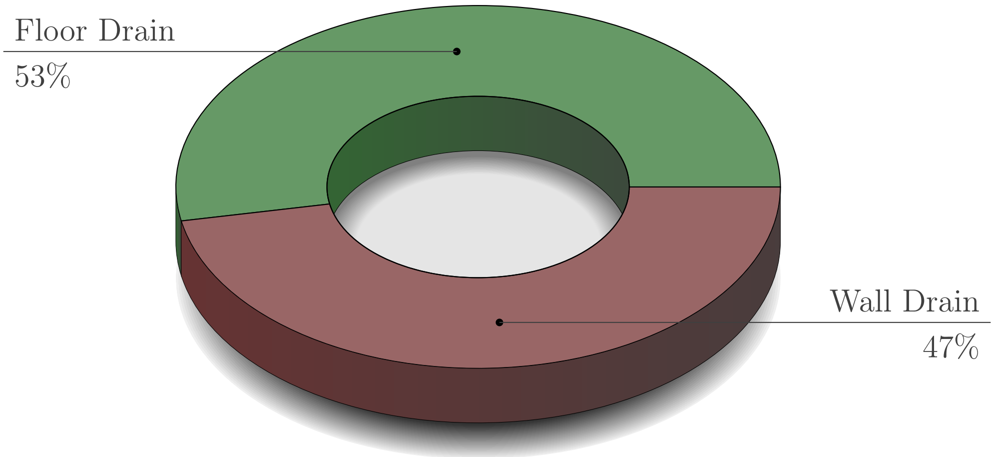


Figure 6.4: Component Contributions for Drainage Asset.

The wall drains, with a contribution of 47% are equally important as the floor drains, however the floor drains aren't easily inspected, as they are cast into or under the floor, thus they contribute a larger portion.

Pipework

Table 6.5 summarises the the different average values assigned to each component of the asset "Pipework". These averages are converted to percentages that represent the contribution of each component to the overall condition of the asset "Pipework".

TABLE 6.5: Pipework Averages with Percentage Distributions.

Pipework			
Asset	**Std Deviation**	**Average Output**	**% Weight**
Inlet Pipe	0.63	3.78	12%
Inlet Valve	0.67	4.00	13%
Outlet Pipe	0.87	3.89	13%
Outlet Valve	0.99	4.11	13%
Scour Pipe	0.94	3.33	11%
Scour Valve	0.83	3.44	11%
Overflow Pipe	0.99	4.11	13%
Waterproofing	0.94	4.33	14%
$\sum$		**31.00**	**100%**

The information displayed in table 6.5 is graphically presented in figure 6.5. From figure 6.5 is can be seen that the contribution of each component is fairly equally distributed. With the asset "Pipework", the waterproofing is considered to be the most important factor with a 14% contribution.

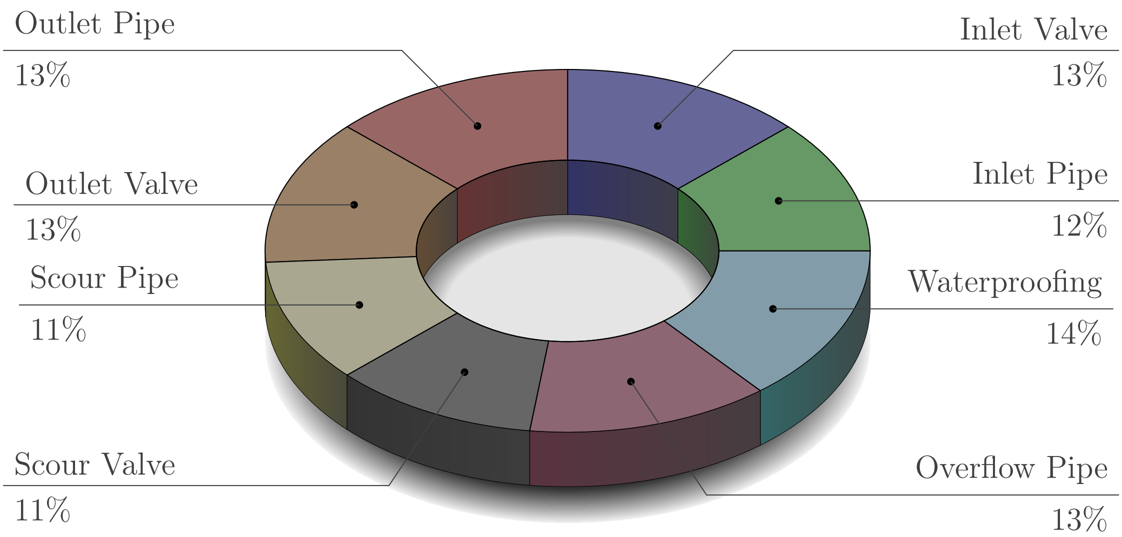


FIGURE 6.5: Component Contributions for Access Components Asset.

Roof

As there are only two roof designs being considered in this study and each design views the roof as a single structure, there are no components related to the roof, thus it was not necessary to include this component into the questionnaire.

Redistribution of Percentages

If a reservoir is inspected and found to be absent of a particular subcomponent, the subcomponent importance percentages need to be redistributed in order to allow the prioritization method to function.

Taking the "Structure" component as an example, the subcomponents related to it may be dependant on the roof design. Thus if a dome roof is used, there may be an absence of internal columns. It is therefore proposed that a standard redistribution of percentages method be implemented in such a case.

The "Structure" subcomponents are, floor, walls, columns and waterproofing. Each subcomponent has an importance percentage assigned to it and sums up to 100% as detailed in the previous sections. Should one of the above mentioned subcomponents not be present, its percentage should be subtracted from the total, in this case 100%. The remainder of the components will then sum to 100% minus the missing component percentage. This allows the remainder of the subcomponents to retain their respective importance ratios relative to each other.

This method of percentage redistribution may be implemented on other components, should any of the subcomponents not be present.

Section 4 Results : Inspection Recommendations

The final section of the questionnaire asks the respondents for the inspection interval that is most appropriate to each component. Figure 6.6 shows a bar diagram of the average inspection interval for each of the components along with the standard deviations of each.

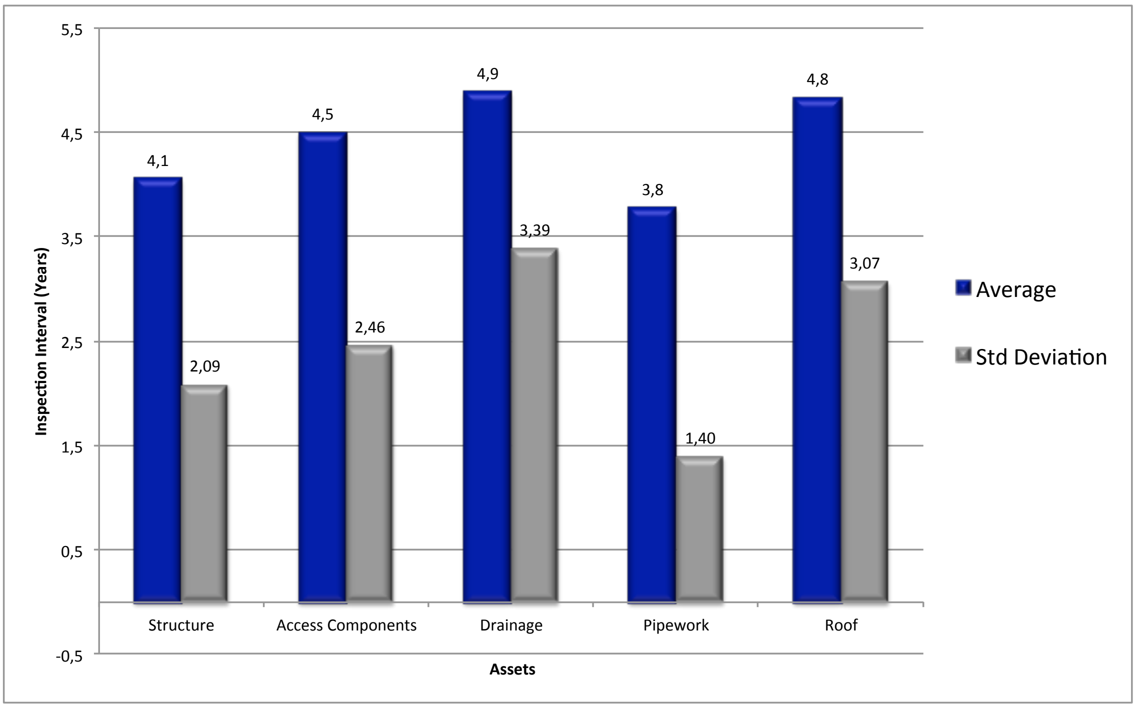


FIGURE 6.6: Inspection Intervals for each Asset.

From figure 6.6 it can be seen that each component requires inspection of at least once every 4 years, except for pipework. The average inspection interval across the different components is 4.4 years. Pipework is a component that requires the most frequent inspection of once every 3.8 years.

In order to avoid inspecting the facility's components individually, the inspection interval for the entire facility will be that of the asset "Pipework". Thus all the other components will be inspected more frequently than required, however this reduces the number of inspections as a whole.

6.4 Chapter Summary

With all of the results converted to percentages and the contribution of each component and sub-component discussed individually, the values can be applied to a concrete reservoir as a whole. Applying these percentages to the facility breakdown, figure 4.6 in chapter 4 yields the following result.

Figure 6.7 illustrates the percentage contribution breakdown of each sub-component to its respective component and each component to the overall facility.

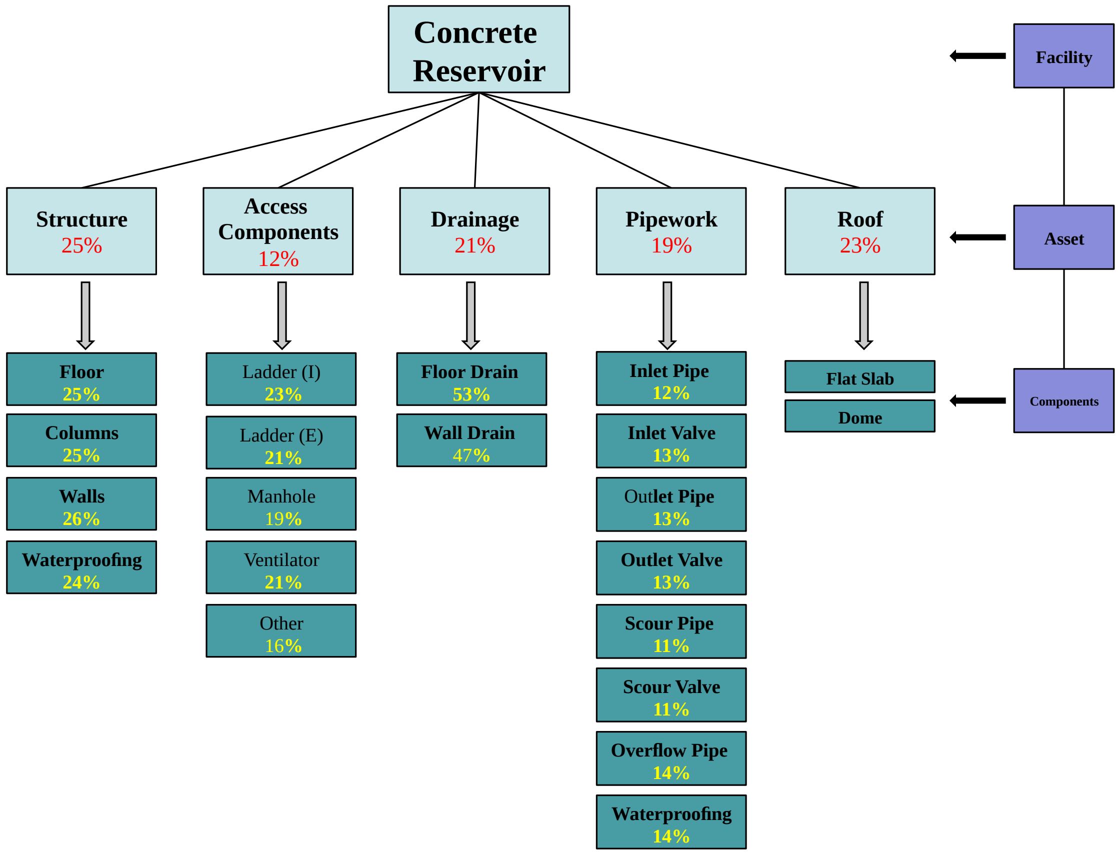


FIGURE 6.7: Overall Facility breakdown - Percentage Contributions.

The percentages indicated in red are the contributions from each component towards the overall condition of the facility. The percentages indicated in yellow are the contributions of each sub-component towards the overall condition of the component to which it relates.

The percentage values as indicated in figure 6.7 are the results from the survey, however the application of these values in the field may not be practical. Taking the low response rate and relative high margin of error into account, it may be more practical to modify the values to more rounded numbers. It is therefore proposed that the values be rounded to the nearest five.

In order to round the numbers, a consistent technique needs to be applied. This technique will round values from 8% to 12% to 10%, from 13% to 17% to 15%, from 18% to 22% to 20% and 23% to 27% to 25%. The application of this technique however cannot be applied to the pipework's subcomponents as it will no longer sum to a 100%. For this reason it is decided to apply this technique to only the structure, access and drainage components.

Figure 6.8 illustrates the proposed rounded values to be applied to the prioritization method.

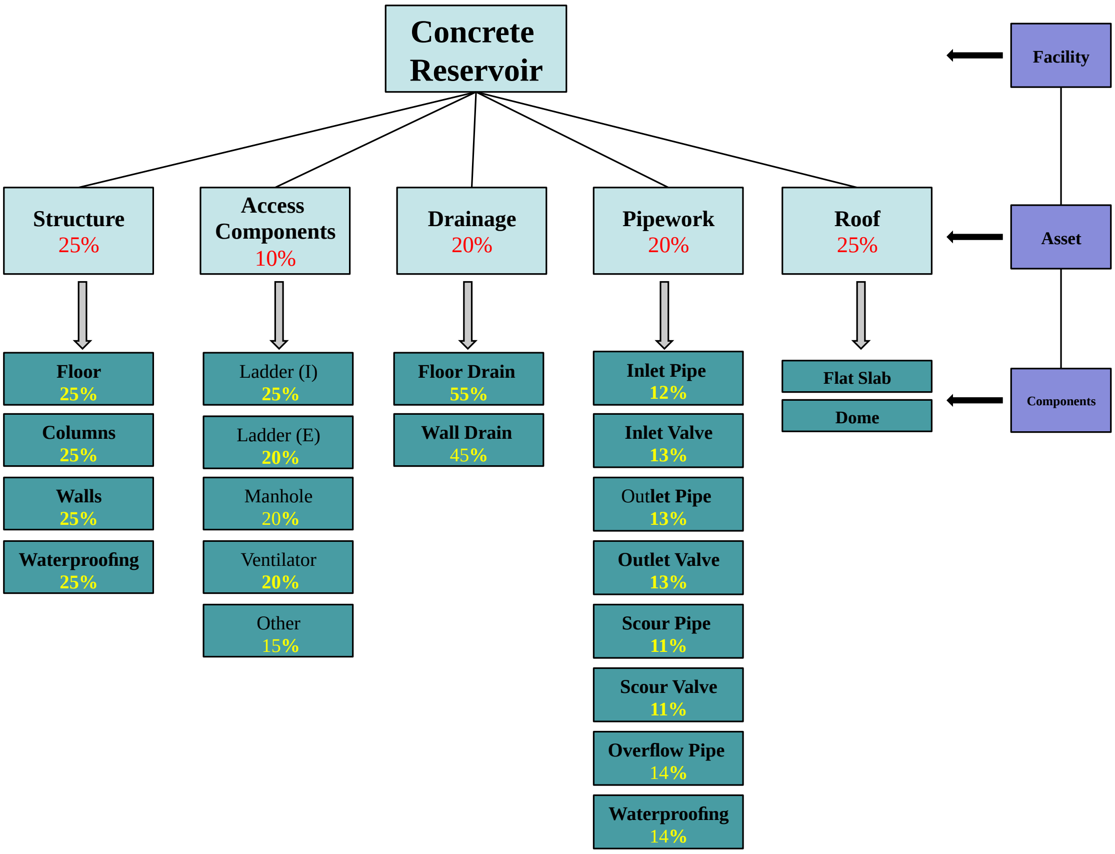


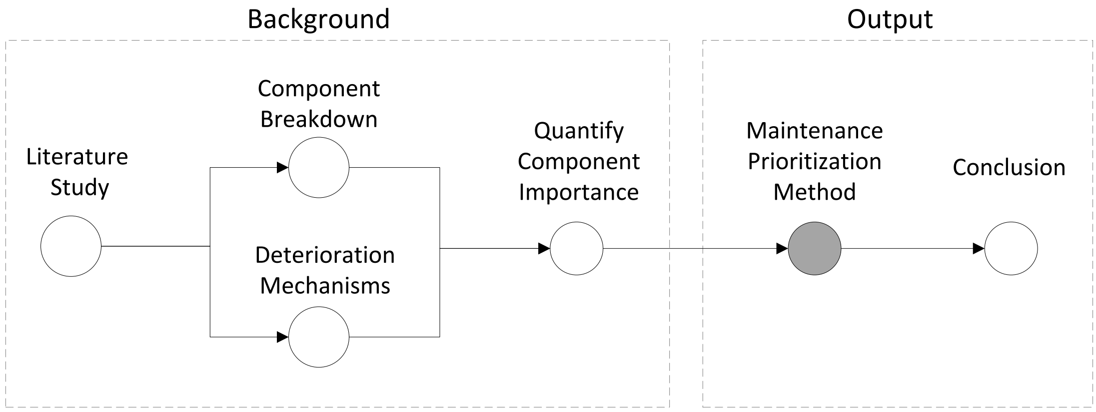
FIGURE 6.8: Proposed Percentage Contributions.

The pipework is the most inspection intensive asset of the reservoir structure and with a contribution of 20%, it is important to ensure that the pipework components remain functional. Inspecting the standard deviations in figure 6.6, it can be seen that the asset "Pipework" has a standard deviation of 1.40. Thus most of the values are within one standard deviation from the mean (i.e in a range of 2.4 - 5.2 years).

With this in mind it can be assumed that the inspection intervals can be rounded off to the nearest whole number, similar to the contribution percentages. It is therefore concluded that the pipework needs to be inspected every 4 years, and to avoid scheduling multiple inspections the remaining component should also be inspected at the same interval.

Chapter 7

Prioritization Method



7.1 Introduction

This chapter details the maintenance prioritization method for reinforced concrete water reservoirs. Throughout this document, various factors were researched and discussed that form the building blocks for the development of this prioritization method. The aim of this chapter is to combine the identified factors and concepts into a structured method that can be used to inspect a concrete water reservoir, assess the condition and finally provide recommendations for the prioritization of maintenance activities.

7.2 Prioritization Method

7.2.1 General Information

This method provides procedures and techniques for the condition assessment of reinforced concrete water reservoirs for the purpose of scheduling and prioritization of maintenance activities. The condition assessment data of reinforced concrete water reservoirs can be used to determine:

- The condition indices of the structures.
- The maintenance requirements.
- The prioritization at water network level.

This method is intended for persons undertaking the condition assessment of reinforced concrete water reservoirs. Additionally, municipalities can adopt this method to standardize the way condition data is captured for reinforced concrete water reservoirs, thus facilitating the development of a comprehensive nation wide asset register.

7.2.2 Training Requirements

The training requirements for the implementation of the prioritization method is dependent on the level of detail of the inspection. The overview inspection (preliminary screening ,see section 7.2.7) requires basic training, as it is self explanatory, whereas the detailed inspection requires extensive training.

7.2.3 Types of Distress Identification

There are three main material groups used in the construction of concrete reservoirs. These material groups are, concrete, steel and other (usually synthetics such as plastics PVC and epoxy). Each of these material groups face different distresses that can be identified using different methods.

Table 7.1 summarizes the different distresses that each material may face and highlights the identification techniques associated with each. The table also shows the different identification methods. Visual identification and other non technical methods are the most suitable way to identify distresses as they require minimal technical knowledge and training. Additionally, these methods can cover vast areas in a short periods.

TABLE 7.1: Types of distress Identification methods.

		Overview	**Detailed**
	Mechanism	**Visual/ NDT**	**Laboratory**
Concrete	Delamination/ Spalling	X	X
	Carbonation	X	
	Leaching	X	
	Sulphate Attack	X	X
	Chloride Penetration/ Corrosion	X	X
	ASR	X	X
	Freeze-Thaw	X	
	Hardness of Water	X	X
Metals	Uniform	X	
	Galvanic	X	
	Pitting	X	
	Crevice	X	
	Fillform	X	
	External Current	X	
	SCC	X	X
	HIE	X	X
Other	Cementitious	X	
	Polyolefin/ Epoxy	X	
	Polyurethane	X	
	PVC	X	

Most of the visual related identification methodologies work on the basis of symptomatic identification. A key drawback of employing visual inspection methods is the inaccuracies and disparities that can arise, due to their subjective nature. It is for this reason that the detailed method is to be used in collaboration with the visual inspection methods. Refer to section 7.2.7 for a description of the application of the identification methodologies.

7.2.4 Reservoir Selection

The owner of the reservoir (WSP, WSA, or municipality) can suggest a service reservoir for inspection, however the most appropriate selection criteria is to look at the historical records of a reservoir if any are available. These records can provide information that will help decide which reservoir to inspect, such as reservoir condition, previous inspection and cleaning dates.

If a group of reservoirs have previously been inspected, the overall condition data that this method may provide can be used to determine which reservoir to schedule for inspection.

7.2.5 Inspection Procedure

The inspection procedure consists of performing three vital checks of the facility. These checks are performed in a systematic and ordered way. These checks include the inspection of the perimeter in order to check for possible contamination points, an exterior check to identify any possible structural defects and weaknesses and finally an interior inspection to check for structural defects not visible externally as well as signs of deterioration that may lead to contamination.

Perimeter Inspection

The inspector should initiate the reservoir inspection by performing a perimeter inspection. The aim of the perimeter inspection is to determine if the reservoir can be contaminated from external sources. This includes a detailed inspection of any and all external fixtures to the reservoir. Among the fixtures are ventilators manholes and overflows.

The inspector should mark a beginning point and proceed to inspect the reservoir surroundings in a clockwise or anticlockwise fashion, denoting anything that may be cause for concern. Once a full revolution of the reservoir has been conducted, the inspector may proceed to the next step of the inspection process.

Exterior Inspection

Following the perimeter inspection, a detail external surface inspection is required. The aim of this inspection is to assess the structural integrity of the reservoir. This inspection includes the identification of any possible cracks, holes, deterioration of paint/exterior coating and any other signs of wear.

It is recommended that the inspector starts the inspection from the external access ladder and inspects the surface of the reservoir in a clockwise or anticlockwise manner. The inspector should progress slowly in the chosen direction looking up and down to cover the entire external surface area and denoting anything that may be of concern. Once the inspector has completed a full revolution and returned to the external access ladder, he/she can make their way onto the roof. The inspector should inspect the access to the roof. This inspection should include the door and lock system to ensure it is in working condition. Once this is complete, the inspection may proceed to the next step.

Interior Inspection

After the exterior inspection, the internal surface of the reservoir can be inspected. In order to perform this inspection, the inspector needs to determine the most appropriate manner of internal inspection, as the reservoir may be filled with water. Depending on the constraints facing the reservoir, there are three common methods of inspecting the interior of a reservoir. These methods include fully draining the reservoir, the use of a certified SCUBA diver or the use of a remotely operated vehicle to perform the inspection.

The internal surface should be inspected for any signs of deterioration. This may include, corrosion, cracks, holes, pitting etc. Additionally the inspector should perform a roof flood test to check the condition of the roof. Specific attention should be given when inspecting the joints and the waterproofing of the joints.

The interior inspection must include a valve and any other moveable mechanical part performance test to check for deterioration. Apart from deterioration, the inspection of these items are to ensure that their correct operational functionality remains intact.

Additional Inspection Items

Apart from inspecting the surfaces of the structure and components, additional characteristics of the reservoir can be inspected to determine the performance of the facility as a whole. The additional inspection items include inspecting the appropriateness of reservoir volume detention times, the filling/draining regime (does the reservoir run dry), a water quality analysis, the performance of cathodic protection if applicable and an assessment of the reservoir's adherence to regulatory and statutory requirements. These activities do not necessarily relate to the prioritization of maintenance activities, however do promote good management practice, which in turn relates to future inspections.

7.2.6 Condition Allocation

Degree of Deterioration

The degree of distress relates to the measure of its deterioration severity. Table 7.2 describes the possible deterioration severity that relates to each of the degree numbers. These consequences are based on the potential urgency of maintenance or rehabilitation required.

TABLE 7.2: Degree Classification System. *Adapted from* [TMH 12, 2000]

Degree	Severity	Description
0	-	No distress visible.
1	Slight	Distress difficult to discern. Only the first signs of distress are visible.
2	Slight to warning	More than slight but less than warning.
3	Warning	Start of secondary defects. (Distress notable with respect to possible consequences).
4	Warning to Severe	More than warning but less than severe.
5	Severe	Secondary defects are well developed (high degree of secondary defects) and/or extreme severity of primary defect.

In order to correctly and as accurately as possible assign the degree value, the flow diagram illustrated in figure 7.1 should be used. The flow diagram details the logic behind the allocation of degree values.

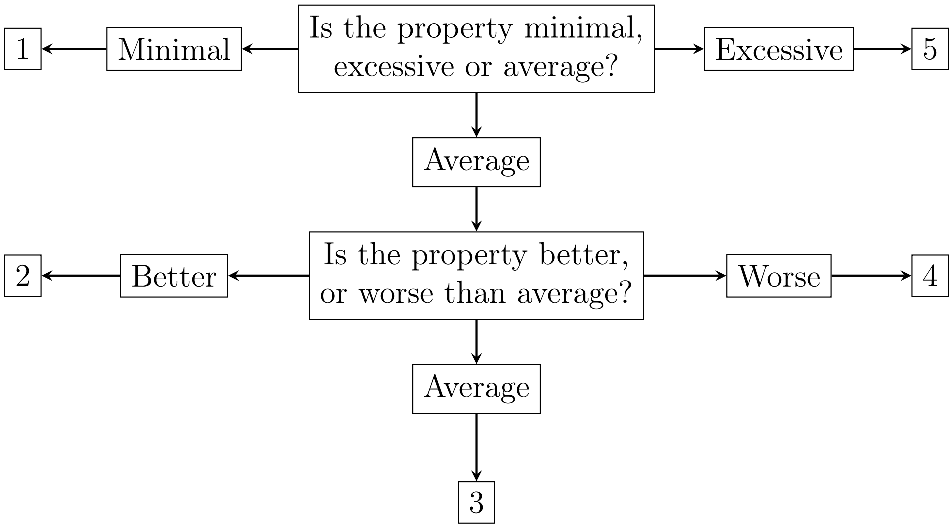


FIGURE 7.1: Five Point Classification Flow Diagram: Degree. *Adapted from* [TMH 12, 2000]

Extent of Deterioration

The extent of distress is a measure of how widespread the distress is over the area of a reservoir. Table 7.3 provides a description for each of the extent ratings.

TABLE 7.3: Extent Classification System. *Adapted from* [TMH 12, 2000]

Extent	Estimation (%)	Description
1	< 5	Isolated occurrence. Does not represent the entire area of reservoir. Is usually associated with a change in material properties.
2	5 - 20	More than isolated but less than intermittent occurrences.
3	20 - 60	Intermittent occurrence, over large areas of the reservoir or extensive occurrence over limited area. Usually associated with material quality or maintenance procedures.
4	60 - 80	More than intermittent but less than extensive occurrences.
5	80 - 100	Extensive occurrence. This is usually a result of poor material quality or inadequate maintenance.

Similar to the degree of distress, a flow diagram is supplied to accurately classify the extent of distress. Figure 7.2 illustrates the logic behind the allocation of extent.

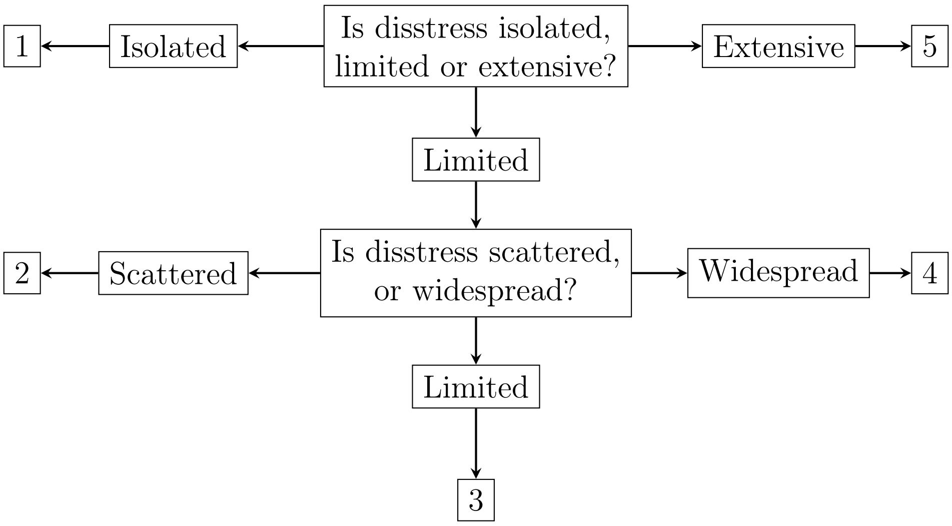


FIGURE 7.2: Five Point Classification Flow Diagram: Extent. *Adapted from* [TMH 12, 2000]

7.2.7 Condition Assessment: Facility Screening

The identifying of the distresses will be conducted in two levels of details, by means of a preliminary and secondary screening of the facility. The first level employs the overview identification methodologies, thus allowing greater areas to be covered. The second more detailed level identification methodologies are used when the results from the overview assessment are inconclusive or if the condition value obtained exceeds a predefined condition value limit. The inspector or the owners, depending on the level of confidence required, specifies this condition value limit. The facility has a condition index between 0 - 25 (see section 7.3 for further details). A recommended condition value limit for the implementation of the detailed identification methodology is a value of ≥ 20. This means that at least one of the condition parameters, degree or extent, has a value of 5, which is the upper limit.

Preliminary Screening

In order to conduct the preliminary screening, the facility will be inspected according to the guidelines set out in section 7.2.5. Following these guidelines, the use of the visual and non-technical identification methodologies are required.

Inspect the facility using the overview techniques and determine the appropriate condition value accordingly.

Secondary Screening

Should a condition value limit be exceeded during the preliminary screening, a secondary screening should be performed. The secondary screening only focuses on the distress which condition index exceeded the condition value limit. Thus if the distress has a more detailed identification methodology and the initial condition value exceeds the predefined condition value limit, a secondary screening of that distress is performed. If no detailed identification methodology exists, then no secondary screening is required. Additionally, if a secondary screening is performed and the condition value differs from the preliminary screening, the secondary screening value should be used.

7.2.8 Condition Calculations

Once the screening of the facility is complete, the overall condition of the facility can be calculated. This value represents the overall condition of the reservoir, based on the conditions of the different distresses identified and the contribution percentages of each component and asset. To calculate this overall value is a process of three steps. These steps are the following:

- Step 1: Calculate Component condition value.
- Step 2: Calculate Asset Condition Value based on component contributions.
- Step 3: Calculate Facility Condition based on asset contributions.

Step 1: Calculating the component condition consists of multiplying the degree and extent together to produce a condition index. With extent and degree being values between 0 - 5, yields a condition index range of 0 - 25. Equation 7.1 calculates the condition index for each identified distress.

$$Condition\,Index_{DE} = Degree \times Extent \tag{7.1}$$

To calculate the condition value of the component in question, the condition indices for each distress are summed together. Equation 7.2 calculates the sum of the condition indices. Equation 7.3 calculates the total possible condition index value.

$$Sum_{DE} = \sum_{DE} Condition\, Index_{DE} \tag{7.2}$$

$$Total_{DE} = (number\, of\, Distresses\, \times\, 25) \tag{7.3}$$

Equation 7.4 describes the conversion of the total component condition index value to a condition percentage. The percentage is subtracted from 1 to indicate the condition, thus poor conditions will have a low percentage value and good conditions will have a high percentage value.

$$\%\, Component_{condition} = \left(1 - \frac{Sum_{DE}}{Total_{DE}}\right) \times 100 \tag{7.4}$$

Step 2: Calculating the asset condition values consists of multiplying each component's condition percentage with each component's contribution value respectively. These values are then summed together to represent the condition of the specific asset. Equation 7.5 below calculates the overall condition of the specific asset.

$$\%\, Asset_{condition} = \sum C_c\, \times\, C_r \tag{7.5}$$

C_c = Component condition value as calculated in equation 7.4.

C_r = Relevance value of component as calculated in Chapter 5.

This process is repeated for each asset thus yielding condition values for each asset respectively.

Step 3: Calculating the overall condition of the facility consists of summing the asset condition values multiplied by each asset contribution value respectively as identified in figure 6.7. Equation 7.6 is used to calculate the overall facility condition.

$$\%\, Facility_{condition} = \sum A_c\, \times\, A_r \tag{7.6}$$

A_c = Asset condition value as calculated in equation 7.5.

A_r = Relevance value of asset as calculated in Chapter 5.

Equation 7.7 is equation 7.6 written out as it applies to the reservoir assets.

$$\%\,Facility_{condition} = S_c\,(S_r) + AC_c\,(AC_r) + D_c\,(D_r) + P_c\,(P_r) + R_c\,(R_r) \qquad (7.7)$$

S_c = Asset "Structure" condition value.

S_r = Asset "Structure" overall relevance value.

AC_c = Asset "Access Components" condition value.

AC_r = Asset "Access Components" overall relevance value.

D_c = Asset "Drainage" condition value.

D_r = Asset "Drainage" overall relevance value.

P_c = Asset "Pipework" condition value.

P_r = Asset "Pipework" overall relevance value.

R_c = Asset "Roof" condition value.

R_r = Asset "Roof" overall relevance value.

The condition of the overall facility is expressed as a percentage, with a facility in good condition represented by a high percentage value and a poor condition facility represented by a low percentage value.

7.2.9 Example Scenario Calculations

For the purpose of clarifying the calculation process, the following fictitious scenario is devised and all the calculations of the asset "Structure" along with all related components will be conducted. All the degree and extent values are fictitious and are only for explanation purposes. All contribution values used in this example are actual values obtained from the questionnaire.

Figure 7.3 illustrates the reservoir breakdown as discussed in Chapter 3. From figure 7.3 can be seen the asset "Structure" and related components that will be used in this example.

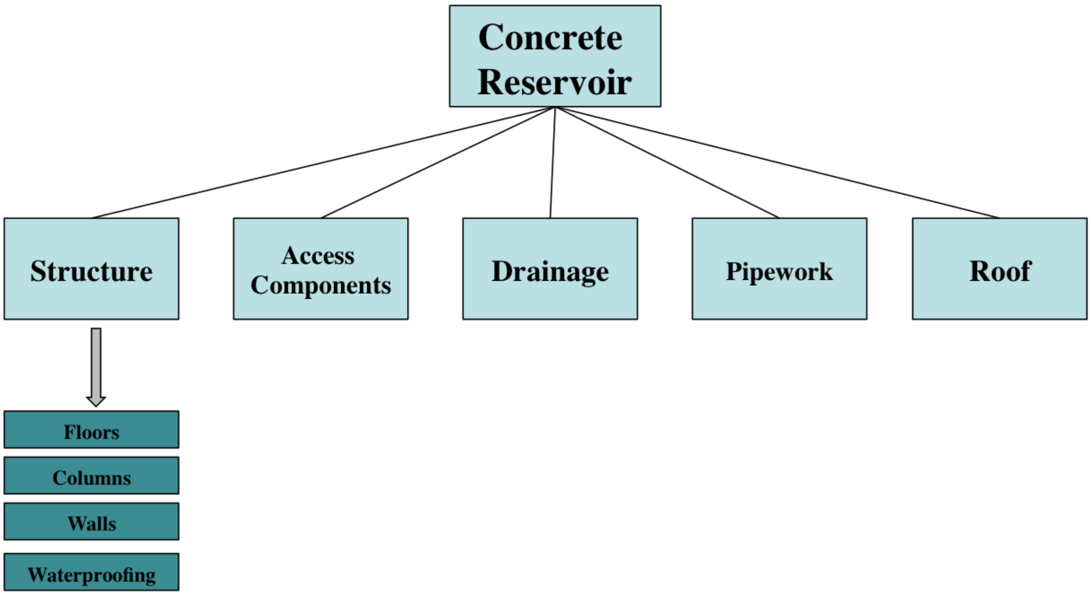


FIGURE 7.3: Reservoir Breakdown - Structure and Components.

For each of the components under the asset Structure, a table is used to calculate the condition value. Table 7.4 provides reference to where in the document the relevant information can be found.

TABLE 7.4: Additional Information Reference Table

Additional Information	
Item	**Reference**
Floors	Chapter 5 - Table 5.1
Columns	Chapter 5 - Table 5.1
Walls	Chapter 5 - Table 5.1
Waterproofing	Chapter 5 - Table 5.3
Subcomponent Relevance %	Chapter 6 - Figure 6.8
Component Relevance %	Chapter 6 - Figure 6.8

The condition assessment tables used in the calculation process have been created by combining the deterioration mechanisms summarised in tables 5.1, 5.2 and 5.3 together with the degree and extent tables 7.2 and 7.3.

Table 7.5 illustrates the typical condition values that are acquired from the inspection process for the floors. The calculation of the condition value is also shown.

TABLE 7.5: Condition Assessment Of Floors

Structure																
	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**						**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**			
Floor	Delamination & Spalling				x				x						**3**	**82.5**
	Carbonation			x						x					**4**	
	Leaching	x							x						**0**	
	Sulphate Attack			x							x				**6**	
	Chloride Penetration & Corrosion		x									x			**4**	
	Alkali Silika Reaction (ASR)			x						x					**4**	
	Freeze Thaw		x							x					**2**	
	Hardness of Water					x					x				**12**	
	Additional Comments & Recommendations													**T**	**35**	
														M	**200**	
	T = Total	Total condition index as calculated														
	M = Max	Maximum possible condition index														

Table 7.6 illustrates the condition values and calculations for the columns of a reservoir. The process followed is the same as for the floor of the reservoir however is applied to the columns.

TABLE 7.6: Condition Assessment Of Columns

Structure																
	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**						**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**			
Columns	Delamination & Spalling				x				x						**3**	**77.5**
	Carbonation				x					x					**6**	
	Leaching			x					x						**2**	
	Sulphate Attack			x							x				**6**	
	Chloride Penetration & Corrosion			x								x			**8**	
	Alkali Silika Reaction (ASR)					x				x					**8**	
	Freeze Thaw				x					x					**6**	
	Hardness of Water			x							x				**6**	
	Additional Comments & Recommendations													**T**	**45**	
														M	**200**	
	T = Total	Total condition index as calculated														
	M = Max	Maximum possible condition index														

Table 7.7 illustrates the condition values and calculations for the walls of a reservoir. Similar to the floor and the columns, the condition assessment is applied to the walls of the reservoir.

TABLE 7.7: Condition Assessment of Walls

Structure																
	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**						**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**			
Walls	Delamination & Spalling				x					x					**6**	
	Carbonation					x					x				**12**	
	Leaching				x						x				**9**	
	Sulphate Attack			x								x			**8**	
	Chloride Penetration & Corrosion				x							x			**12**	
	Alkali Silika Reaction (ASR)				x						x				**9**	**63**
	Freeze Thaw			x							x				**6**	
	Hardness of Water					x					x				**12**	
	Additional Comments & Recommendations													**T**	**74**	
														M	**200**	
	T = Total	Total condition index as calculated														
	M = Max	Maximum possible condition index														

Table 7.8 illustrates the condition values and calculations for the waterproofing of a reservoir. The condition assessment that is applied to the waterproofing has a different table (see table 7.4 for more information) as the mechanisms that affect the waterproofing differ from the mechanisms that affect the concrete. A different table will also be used if any metal components are to be assessed.

TABLE 7.8: Condition Assessment of Waterproofing

Structure																
	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**						**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**			
Waterproofing	Cementitious				x				x						**3**	
	Polyolefin/Epoxy			x						x					**4**	
	Polyurethane					x					x				**12**	
	PVC			x							x				**6**	**75**
	Additional Comments & Recommendations													**T**	**25**	
														M	**100**	
	T = Total	Total condition index as calculated														
	M = Max	Maximum possible condition index														

With all the components of the asset "Structure" conditions calculated and tabulated, the condition of the asset structure can be calculated. Table 7.9 illustrates the calculation of the overall asset "Structure" condition value. The relevance values used are the proposed values as discussed in section 6.4 in figure 6.8.

Table 7.9: Calculation of Asset "Structure" Condition Value

Structure			
Component	**Condition Value**	**Relevance %**	**CxW**
Floors	82.50	25%	**21**
Columns	77.50	25%	**19**
Walls	63.00	25%	**16**
Waterproofing	75.00	25%	**19**
	Total %		**75**

Repeating this process for each asset and related component will yield the condition values for each asset. For the purpose of this example assume this process was repeated and the following values were obtained. These condition values together with the contribution values can be used to calculate the overall condition value for the facility. Table 7.10 illustrates the overall condition value of a reinforced concrete water reservoir.

Table 7.10: Overall Facility Condition Value.

Facility - Concrete Reservoir			
Asset	**Condition Value**	**Relevance %**	**CxW**
Structure	75	25%	19
Access Component	43	10%	4
Drainage	87	20%	17
Pipework	75	20%	15
Roof	55	25%	14
	Total %		**69**

The full prioritization guideline tables can be found in Appendix E.

In this scenario, the overall condition of the facility is 69%. The different component condition values range from 43% to 87%. This means that some of the component condition values lie below 50% and may require attention but the component importance value may indicate that the component only contributes a small percentage to the overall condition.

This information is presented in such a way that maintenance activities can be prioritised among individual components of a single reservoir as well as between multiple reservoirs at network level. The percentage values provide the user (facility manager) with additional information that can be used to prioritise maintenance activities at both component and network level.

7.2.10 Validation of Prioritization Method

In order to validate the prioritization of maintenance method, it needs to be applied to a reservoir over its life cycle. This should be compared to a similar reservoir to which the method is not applied, which can be used as a control. If the reservoir on which the method has been applied outperforms the control with regard to condition, the method may be assumed to be beneficial. The results from this comparison may serve as a validation of the method.

This method of validation is however not possible as it will require extended industry application and monitoring that fall beyond the scope of this study. Additionally, it will also be very difficult to ensure that no external factors skew the results over such a long time period.

The validation of the component importance is not practical because it is based on opinion. This opinion is from professional industry practitioners, however a level of subjectivity may be present. All the standard deviations are less than one, thus within one standard deviation from the mean, which indicates a relatively small data scatter given the low response rate. The validation of the approach is therefore based on rational reasoning.

The approach used for the development of the maintenance prioritization method is the same as used in the TRH/TMH manuals and bridge management systems. This approach consists of defining the infrastructure, inspecting and identifying potential deterioration factors, assessing the infrastructure condition and the performing maintenance based on the information. The validity of this approach is proven, as these manuals and systems have been implemented across South Africa for many years and the economic benefits of using a systems approach has been proven as stated in section 1.2.

The validity of the approach thus serves as validation of the maintenance prioritization method.

7.3 Chapter Summary

The output of this research is the development of a method for the prioritization of maintenance activities for reinforced concrete reservoirs. The aim of this chapter is to combine all the identified and investigated building blocks necessary for the creation of such a method. This chapter provides a method to facilitate the obtaining of a priority index for concrete water retaining structures (i.e concrete reservoir).

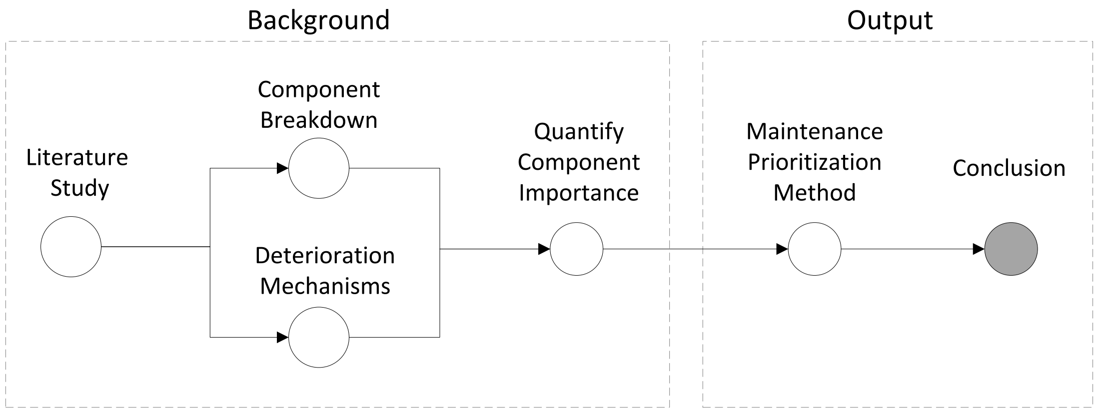
The development of the maintenance prioritization method provides the inspector/owner with a systematic approach to inspect reinforced concrete reservoirs and it allows credible data to be acquired. The approach followed by the prioritization method is similar to the TRH/TMH manuals and Bridge Management Systems. Thus, due to the familiarity of these manuals and systems and the simplicity of the prioritization method the application of this method requires very little training.

The method follows a logical format and the inclusion of an example calculation provides the reader with the necessary information to implement the method.

The method used to represent the condition of the reservoir promotes uniformity amongst all components and subcomponents and if applied to numerous facilities, may promote the development of a comprehensive asset register.

Chapter 8

Findings, Conclusions and Recommendations



8.1 Introduction

This chapter draws conclusions from the findings of each chapter throughout this document and places it in context with regard to the research objectives. Recommendations will be made based on the conclusions drawn. The key research shortcomings of the study are highlighted. The chapter concludes by suggesting possible future research in the area of study.

8.2 Problem Statement and Research Objectives

In Chapter 1 it was stated that the condition assessment and management of road and road structural infrastructure in South Africa is conducted according to guidelines set out in the TRH/TMH manuals and bridge management systems respectively. It further states that the condition of the DWAF infrastructure has declined from 2006 to 2011 and that no similar document exists for water retaining structures (more specifically reinforced concrete water reservoirs) and that the absence of such a document leads to disparities of condition data and lack of uniformity with respect to inspection and maintenance of these structures. It attributes the absence of such a document to the lack of knowledge related to the behaviour of concrete reservoirs and its components, deterioration patterns faced by these structures and the risks associated with these deterioration patterns/mechanisms.

To address this problem it was proposed to investigate the necessary factors needed to develop a method that can be used to assess the condition of concrete reservoirs and to provide recommendations for the maintenance and management thereof. The approach used for this method is the same as that of the TRH/TMH and BMS systems. These investigated factors will then form the building blocks of this method. The primary objectives of the study were thus as follows:

- Define the components of concrete reservoirs.
- Identify the distresses faced by these components.
- Identify the common identification methodologies of these distresses.
- Quantify the contribution of each component to the overall condition of the reservoir.
- Develop a maintenance prioritization method.

Throughout this document each objective was addresses and solved. The following section discusses the findings of the research.

8.3 Findings

From literature reviewed in Chapter 3 is was found that the South African water infrastructure industry is currently facing rapid deterioration and that new infrastructure is being provided, often at the expense of maintaining existing infrastructure. Furthermore it was found that South Africa's maintenance regimes that are in place might not be on the same standard as international norms. This is due to the general lack of documentation and to South Africa's tendencies to earmark 10% of the operational cost towards the maintenance, rather than investigate the maintenance requirements of the reservoirs and budget accordingly. Literature further indicated that although South Africa is familiar with asset management principles, many municipalities are unable to implement these principles, due to a lack of knowledge and resources.

Many different types of reservoirs are present in South Africa, however from interviews conducted with design professionals, it became clear that reinforced concrete reservoirs are the most common. Investigation into the components of reinforced concrete reservoirs defined a reservoir as 5 main assets comprising of three main materials groups, namely concrete, steel and synthetics. With the main materials identified, further investigation into each material type was conducted.

From literature it was identified that each material type faces different deterioration mechanisms and that each mechanisms presents its own set of challenges, with respects to identification and assessment. Additionally it was found that the most appropriate way to identify mechanisms that cause deterioration of each material type is by using visual assessment techniques. It furthermore found that this may however lead to inaccuracies due to the subjective nature of visual assessments and suggests the inclusion of a more detailed identification methodology. Chapter 6 aimed to investigate the contribution of each component to the overall condition of the facility. The identification of each components contribution to the overall facility aids the prioritization of maintenance, as it quantifies the importance of each component and inadvertently quantifies the risk that each component poses to the overall facility.

The data obtained throughout this research is combined to develop the prioritization method posed in chapter 7. The research proposes a method that includes the detailing of a systematic inspection process, the identification methodologies required and the appropriate condition allocation procedures.

A key component of this method is its similarity to the widely used TRH/TMH manuals and bridge management systems. With the condition assessment and allocations techniques similar to these pre-existing maintenance methods, adoption of this method is made easy.

Applying this method will provide comprehensive condition information that can be used to schedule maintenance activities. This condition information will aid in identifying the maintenance requirements and can drive future maintenance programmes. The scheduling of these activities will allow resources (financial and others) to be made available for when they are needed. Additionally, this information can supplement the budget calculations and aid in financial planning. The economic benefits of this approach is proven as discussed in section 1.2. Thus applying this method on reinforced concrete reservoirs will have similar economic benefits.

8.4 Shortcomings

The following shortcomings with regard to the research study have been identified:

- The general lack of documentation and information related to the condition of municipal infrastructure is a major shortcoming in this study. A severe disparity in the available data causes uncertainty and a lack of confidence in the accuracy of the data. This leads to assumptions being made on the condition of concrete reservoirs, based on the condition of the water industry as a whole. With a lack of documentation, the distresses and maintenance requirements are also unknown. This necessitated a distress and maintenance requirement identification based on material properties, rather than environmental conditions, which may represent a more accurate view of the deterioration of these facilities.

- The sample size of the questionnaire is limited. Due to the limited number of individuals who have the relevant experience and the low response rate, uncertainty regarding the validity of the data arose. It is recommended that if further research into this topic were to be done, the questionnaire be distributed to individuals with relevant engineering experience however, not in the draft design code working group. This will increase the sample size and provide more information, which can be used to substantiate the data obtained in this document.

8.5 Recommendations

The following recommendations are made regarding this research study based on the findings and shortcomings previously identified:

- It is recommended that this study forms the basis of future research into water infrastructure maintenance prioritization. Thus should further research be conducted into maintenance aspects related to concrete water reservoirs, the information in the study should be used as a basis.
- Furthermore it is recommended that future study in this area of research expands this concept of maintenance prioritization to different types of concrete water retaining structures. This would include water treatment plants and waste water treatment plants. It is recommended that should this concept be expanded, special focus be placed on the chemical composition of the water and the effects thereof on the facility.
- It is recommended that future studies should perform similar component contribution analysis; however ensure the inclusion of a larger sample size. The inclusion of a larger sample size will yield more significant results and will represent the engineering population more accurately.

8.6 Areas of Further Research

This study can be expanded to various forms of water infrastructure. Further research on this study may include the following:

- Cost-benefit analysis of the improvement of financial planning and overall maintenance of reservoirs based on the additional condition information from the prioritization method.
- Applicability of using prioritization data for the estimation of municipal budgets.

- Research the applicability of prioritization guideline on other forms of water infrastructure.

- Development of a mobile application, preferably tablet based, which simulates the prioritization guideline. The app would collect the condition data and the information would be stored to a cloud server. This server would act as an comprehensive asset register.

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Appendix A: Industry Interviews

Interviewee Details

Name: - Kevin Kimbrey
Company:- SIKA
Job Title: - Head Target Market - Sealing and Bonding, Regional Manager - Western Cape and Orange Free State

Questions

What products are commonly used for the waterproofing of drinking service reservoirs? (This may include the waterproofing of the expansion joints, construction joints, floor-wall interface etc.)

To renovate or to help increase durability if the concrete is substandard , we would apply the Sika Topseal 107 cementitious protective coating , All joints (expansion,construction and wallfloor joints) would be sealed with the Sikadur Combiflex system . Reservoir construction joints will generally have the Sikaswell 2507 cast in as well anf the expansion and wall floor joints will have a PVC waterbar as well . Reason for the back up is 2 fold – water is precious and to help eliminate construction defects like the cast in waterbar twisting and becoming un-affective.

What types of deterioration do these products normally encounter? *Mechanical damage is what will affect the systems and Bad surface preparation when applying the products which would show de-bonding failure.*

Is it possible to visually identify the deterioration of these products, if so the how? What do you look for? *Machinable damage will be visible and so would delamination of the product.*

What remedial actions need to be taken? *Both systems can be repaired fairly easily . The Sika Topseal 107 will have a surface clean up and just a re-coat in the affected area . The Sikadur Combiflex can be repaired by removing and re-welding a new piece in its place*

Life expectancy of products is very difficult to determine , but we have case studies of reservoirs well over 20 years and still in good condition and not needing any maintenance.

Name: - Mercia Greeff
Company: - WEC Consult *Consulting Engineers & Project Managers*
Job Title: - Structural Engineer (Associate) Stellenbosch, Western Cape

Questions

What, in your opinion, are the main components that need to be designed for with a reinforced concrete reservoir(water reservoir)? Please list all the components, both civil and other that main form part of the structure.

Strip foundation, wall, layer works, subsoil drainage, surface bed, bases, columns, roof slab, joints, inlet (including inlet valve box), outlet (including outlet valve box), scour (including scour valve box), ventilators, access ladders and manholes, surface water drainage, requirements for telemetry (access, valves, pipework)

From the list above, what is considered the most important component with respects to structural integrity?

Wall

From question above, what is considered the most important component with respects to the provision of service?

Inlet and outlet

According to what standard are these structures designed to?

BS 8007, EN 1992-3

With respects to waterproofing, what are the common products that you would specify in the technical drawings?

Sikaswell S2, Sika Combiflex

What factors influence the sizing of the inlet and outlet pipes/structures?

The sizing of the pipes is dependent on hydraulic factors, including the required flow and relative height and position of the reservoir. The sizing of the valve boxes is dependent on the size of the pipes, which may need reducers before and after valves and flow meters, required inlet and outlet runs before and after the flow meter, minimum distances between the walls of the structure and pipe flanges, relative levels between pipes and the ground level, work space.

Have you heard of, or have had contact with the SANS 10100 - Part 3: Design of concrete liquid retaining structures code?

I have heard of the code, but have not had contact with it.

Name: - Milos Perduh
Company: - AECOM *Waterside Place, South Gate, Tyger Waterfront, Carl Cronje Drive, Bellville, 7530*
Job Title: - Structural Engineer, Bellville, Western Cape

Questions

What is the most common concrete specification for the use in the floor slab? For example sub class 30/19, or 35/19: Both classes may be used. It also depends on the type of structure. 35/19 are normally used for lager post tensioned reservoirs.

Depends on the design, size of the structure and soil conditions. It starts from 150 and goes up to sometimes 700-800 mm.

What factors determine which waterproofing products/techniques to use on reinforced concrete reservoirs?

Aggressiveness of the water and the soil.

Are any movement bearings specified for reservoirs and if so what are the most frequently specified type?

Only if one has a sliding wall. Teflon sliding bearings.

If post tensioning is used on circular reservoirs, what determines the size of the buttress that anchors the cables?

Depends on the forces. Practical considerations also play a roll.

6. What is the most common reinforced concrete design found in SA?

(SANS 10100 and BS 8007)

Questions

Name: - Lisa du Toit
Company: - Element Consulting Engineers
Job Title: - Structural Engineer, Western Cape

What is the most common concrete specification for the use in the floor slab? For example sub class 30/19, or 35/19:

35/19

What thicknesses of the floor slab are generally specified?

200mm

3. What factors determine which waterproofing products/techniques to use on reinforced concrete reservoirs?

Shape of reservoir; construction method

If post tensioning is required, how is the size of the buttress determined?

Design; practical considerations

Are any movement bearings specified for reservoirs and if so what are the most frequently specified type?

Sliding joint at wall / roof interface; movement waterstops at expansion joints

Does a dome roof eliminate the need for internal columns? If yes, when would a dome design be considered over a flat slab roof design?

Dependent on design, size and loading. Usually considered either when columns are not possible or if span is too large or for aesthetic purposes

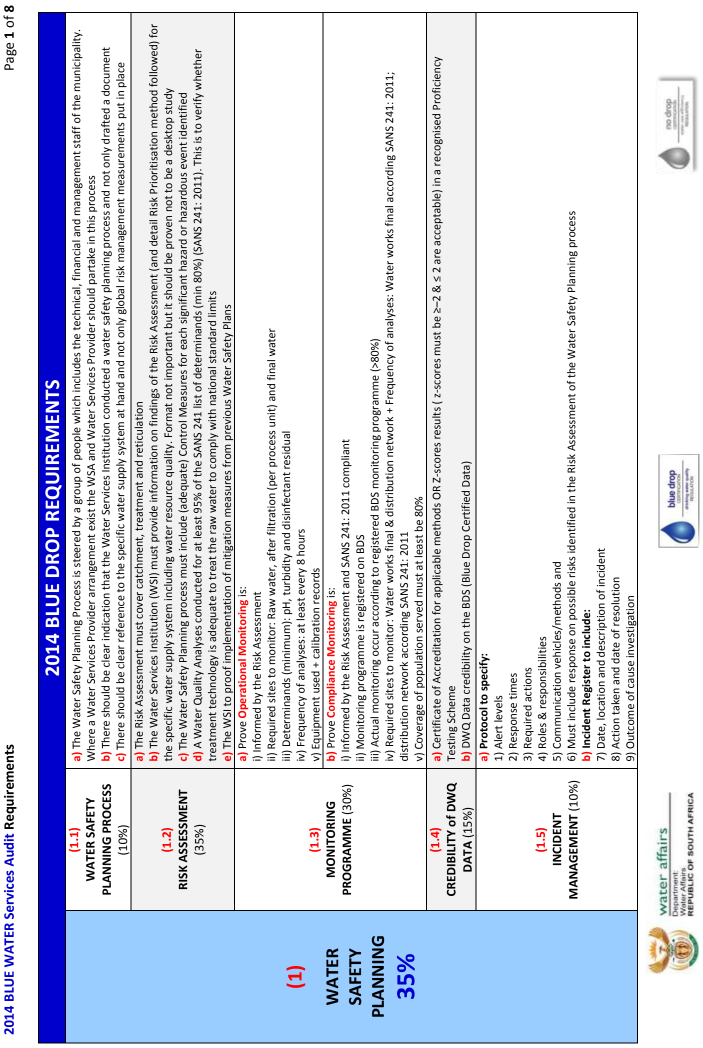
What is the main cause for a reservoir to have service failures? (Service failure being defined as unable to provide water to reticulation network)

This should not happen! Could be due to maintenance, or the need for repair due to cracking or leaking

What is the most common reinforced concrete reservoir design found in SA? Square, round, sunken etc?

Circular; partially sunken or backfilled.

Appendix B: Blue Drop Score Sheet



2014 BLUE WATER Services Audit Requirements — Page 1 of 8

2014 BLUE DROP REQUIREMENTS		
(1) WATER SAFETY PLANNING 35%	(1.1) WATER SAFETY PLANNING PROCESS (10%)	a) The Water Safety Planning Process is steered by a group of people which includes the technical, financial and management staff of the municipality. Where a Water Services Provider arrangement exist the WSA and Water Services Provider should partake in this process b) There should be clear indication that the Water Services Institution conducted a water safety planning process and not only drafted a document c) There should be clear reference to the specific water supply system at hand and not only global risk management measurements put in place
	(1.2) RISK ASSESSMENT (35%)	a) The Risk Assessment must cover catchment, treatment and reticulation b) The Water Services Institution (WSI) must provide information on findings of the Risk Assessment (and detail Risk Prioritisation method followed) for the specific water supply system including water resource quality. Format not important but it should be proven not to be a desktop study c) The Water Safety Planning process must include (adequate) Control Measures for each significant hazard or hazardous event identified d) A Water Quality Analyses conducted for at least 95% of the SANS 241 list of determinands (min 80%) (SANS 241: 2011). This is to verify whether treatment technology is adequate to treat the raw water to comply with national standard limits e) The WSI to proof implementation of mitigation measures from previous Water Safety Plans
	(1.3) MONITORING PROGRAMME (30%)	a) Prove Operational Monitoring is: i) Informed by the Risk Assessment ii) Required sites to monitor: Raw water, after filtration (per process unit) and final water iii) Determinands (minimum): pH, turbidity and disinfectant residual iv) Frequency of analyses: at least every 8 hours v) Equipment used + calibration records
		b) Prove Compliance Monitoring is: i) Informed by the Risk Assessment and SANS 241: 2011 compliant ii) Monitoring programme is registered on BDS iii) Actual monitoring occur according to registered BDS monitoring programme (>80%) iv) Required sites to monitor: Water works final & distribution network + Frequency of analyses: Water works final according SANS 241: 2011; distribution network according SANS 241: 2011 v) Coverage of population served must at least be 80%
	(1.4) CREDIBILITY of DWQ DATA (15%)	a) Certificate of Accreditation for applicable methods OR Z-scores results (z-scores must be ≥–2 & ≤ 2 are acceptable) in a recognised Proficiency Testing Scheme b) DWQ Data credibility on the BDS (Blue Drop Certified Data)
	(1.5) INCIDENT MANAGEMENT (10%)	a) Protocol to specify: 1) Alert levels 2) Response times 3) Required actions 4) Roles & responsibilities 5) Communication vehicles/methods and 6) Must include response on possible risks identified in the Risk Assessment of the Water Safety Planning process b) Incident Register to include: 7) Date, location and description of incident 8) Action taken and date of resolution 9) Outcome of cause investigation

FIGURE B-1: Blue Water Service Audit Requirements [DWAF, 2014].

2014 BLUE WATER Services Audit Requirements Page **2** of **8**

	BONUS (1): **Sampler's Training**	**To be eligible for this bonus, WSI's must provide proof of training of samplers or Sampling Quality Control measures (Name the Sampling Training Course, Duration, Service Provider, and detail of Attendees)** **1) Evidence of relevant sampling training that will ensure credibility of the sampling process; or** **2) Evidence of control measures to ensure sampling credibility**
	BONUS (2): **Incident Management Protocol Communication**	**Communication on the Incident Management Protocol process with all relevant staff within the Municipality**
(2) **DWQ PROCESS MANAGE-MENT & CONTROL** **8%**	**(2.1)** **WORKS CLASSIFICATION COMPLIANCE** (15%)	Treatment works classified according the requirements of Regulation 2834- ONLY the classification as it appears on BDS will be used. Supporting evidence to allow the correct classification to be loaded on BDS, Water Services Institutions remains accountable for correctness of information / classification Certificate to be displayed at treatment works (*confirmed during on-site assessments*)
	(2.2) **PROCESS CONTROL REGISTRATION COMPLIANCE** (50%)	a) Process Control Staff must be Registered according to Regulation 2834 with the Department of Water Affairs. Water Services Institutions to prove per treatment works that Process Control Staff complies with the legislative requirements of: i) Number of Process Controllers' ii) Complying with the required Classification levels b) The Supervisor must comply with legislative requirements Information as it appears on BDS will be used ONLY, WSI's to ensure correct classification of all staff per treatment plant
	(2.3) **WATER TREATMENT WORKS' LOGBOOK** (35%)	a) A logbook is in place to record all incidents and observations at the water treatment works b) Evidence is presented that the logbook process is (i.e. communication medium between process controllers and shifts) being implemented (It is NOT required to be implemented for the entire assessment period)
	BONUS (1): **Process Control Training**	**Proof of Process Control staff being subjected to relevant training the past 12 months to allow Process Controllers to meet the education requirements towards higher level draft Regulation 17 Registration (Year 2013)**
	BONUS (2): **Process Control Excellence**	**a) Process Control Staff classified according the requirements of draft Regulation 17 on the Blue Drop System** **b) Process Control Staff and Supervisor compliance confirmed against draft Regulation 17 (must comply at least 75% in each of the shifts)- WSI must indicate shift patterns and Supervisor on BDS. WSI to explain measures in place when a shift does not comply with regulatory process control requirements** **c) WSI must indicate process controllers and/or supervisors that are 'shared' across different plants/sites**
Water Quality Data Period – 1 January 2013 – 31 December 2013		
(3) **DRINKING WATER QUALITY VERIFICATION**	**(3.1.1)** **MICROBIOLOGICAL DWQ COMPLIANCE** (50%)	The Microbiological Quality of the water supply must comply with the South African National Standard (specifically, the 2014 Blue Drop Limits which have been derived from SANS241: 2006 and 2011) as per the Excellent Requirements set by the Blue Drop Programme (*E coli*) - Excellent Compliance (97% for <100 000 population) & (99% for >100 000 population)
	(3.1.2) **CHEMICAL DWQ COMPLIANCE** (45%)	The Chemical Quality of the water supply must comply with the Excellent Requirements set by the Blue Drop Programme for all chemical-health determinands listed in the South African National Standard (the 2014 Blue Drop Limits, derived from SANS241: 2006 and 2011) Chemical – Health (Acute and Chronic): - Excellent Compliance (95% for <100 000 population) & (97% for >100 000 population) - Good Compliance (93% for <100 000 population) & (95% for >100 000 population)

water affairs
Department:
Water Affairs
REPUBLIC OF SOUTH AFRICA

FIGURE B-2: Blue Water Service Audit Requirements [DWAF, 2014].

2014 BLUE WATER Services Audit Requirements

30%	(3.1.3) **OPERATIONAL COMPLIANCE** (5%)	The compliance of operational determinands must comply with the 2014 Blue Drop Excellent Limits set by the Blue Drop Programme - Excellent Compliance (93% for <100 000 population & 95% for >100 000 population) - Good Compliance (90% for <100 000 population & 93% for >100 000 population)
	BONUS (1): **Aesthetic DWQ Compliance**	The Aesthetic Quality of the water supply must comply with the Excellent Requirements set by the Blue Drop Programme for all aesthetic determinands listed in the 2014 Blue Drop Limits - Excellent Compliance (93% for <100 000 population & 95% for >100 000 population) - Good Compliance (90% for <100 000 population & 93% for >100 000 population)
	PENALTY (1): **Data Difference**	**Should there be a difference between data available on BDS and that which is presented in hardcopy for verification the penalty will apply**
	PENALTY (2): **<11 Months' Data**	**Less than 11 months data available to assess Microbiological and Chemical compliance**
	PENALTY (3): **Notification of Failure**	**If there is any significant (sustained) failure with no evidence of a Water Quality Alert Notice (Boil Water Notice) being issued, this penalty will apply. NB! This may have an implication on qualification for certification**
(4) MANAGE-MENT, ACCOUNTA-BILITY, & LOCAL REGULATION 10%	(4.1) **MANAGEMENT COMMITMENT** (30%)	Management's commitment to effective Drinking Water Quality Operations & Management should be portrayed by Proof of signature approval of the: a) Water Safety Plan b) DWQ Monitoring Programme c) Water Treatment Plant Logbook d) Operations and Maintenance Budget e) Water Services Development Plan
	(4.2) **PUBLICATION OF PERFORMANCE** (25%)	Evidence should be provided on the various means of drinking water quality information made public to the constituencies supplied with drinking water from this specific water supply system Forms of Publication: >Newspaper publication >Municipal Billing >Community Radio >Annual Report >Posters & Pamphlets >Population and Promotion of "My Water" >Electronic Webpage Water Services Institutions must provide evidence of adequate marketing of Existing Blue Drop Certified water supply systems
	(4.3) **SERVICE LEVEL AGREEMENT/ PERFORMANCE AGREEMENT** (15%)	Should there be an institutional arrangement between the Water Services Authority and the Water Services Provider, then it is essential that the legislatively required contract (Section 19 of the Water Services Act) stipulate the Service Level Agreements between the two entities. A copy of this document is required, **OR** Should the Water Services Authority fulfil the function of Water Services Provider as per Section 78 arrangements, then it is required that the responsible manager (official) have a Performance Agreement (Workplan) in place which stipulates Drinking Water Quality Management Responsibilities
	(4.4) **SUBMISSION OF DWQ DATA** (30%)	a) 12 months of data had been submitted on the Blue Drop System (BDS) (DWA will only consider data available on the BDS) b) **All** compliance monitoring test results are required to be submitted c) As per a requirement of the Water Services Act, compliance data submission occurred monthly (Section 62 of the Water Services Act, Section 9

Figure B-3: Blue Water Service Audit Requirements [DWAF, 2014].

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		Regulations) (measured as BDS submission compliance)
	BONUS (1): **Publication of Performance**	**Availing information on Drinking Water to relevant public in 3 or more forms listed**
	BONUS (2): **Performance Agreement**	**Workplans of Process Controllers aligned to Operations and Maintenance Manual**
	BONUS (3): **Procurement processes**	**Proof that systems are in place to not run short of Chemicals & Consumables required for treatment**
	PENALTY: Submission of DWQ Data	Penalty will apply should the Department find proof during / post assessment that the WSI are guilty of an offence as per Section 82 of the Water Services Act, by only submitting partial information in order to present a false impression of DWQ Performance and/or compliance
(5) ASSET MANAGE-MENT 14%	**(5.1) ANNUAL PROCESS AUDIT** (20%)	Process Audit Report on technical inspection/assessment of treatment facility and evidence of implementation of findings This process assessment should've been done within the 12-month assessment period
	(5.2) ASSET REGISTER (15%)	The Institution must present a complete Asset Register. The asset register must: a) Detail relevant equipment and infrastructure b) Indicate asset description c) Location d) Condition (remaining life) e) Replacement value
	(5.3) AVAILABILITY & COMPETENCE of MAINTENANCE TEAM (15%)	a) The Institution must present evidence of a competent Maintenance Team (in form of Organogram; Contract or Invoice). Logbook with maintenance entries will serve as adequate evidence (for Mechanical, Electrical, Instrumentation and Civil work) b) Additional prove required on team competency (e.g. Qualification & Experience & Trade-test)
	(5.4) OPERATIONS & MAINTENANCE MANUAL (15%)	O&M manual to contain: a) Civil, mechanical, electrical detail / drawings of plant b) Design capacity of plant c) Operational schedules, maintenance schedules d) Process detail and control e) Mechanical and electrical equipment specification f) Fault finding g) Monitoring

water affairs Department: Water Affairs REPUBLIC OF SOUTH AFRICA — blue drop — no drop

Figure B-4: Blue Water Service Audit Requirements [DWAF, 2014].

2014 BLUE WATER Services Audit Requirements

	(5.5) OPERATIONS & MAINTENANCE BUDGET and EXPENDITURE (20%)	The Institution must present credible evidence of: **a)** Maintenance Budget (as part of Operations Budget) **b)** Maintenance Expenditure (as part of the Operations Expenditure) **c)** Maintenance Expenditure should be more than 5% of the Operations Expenditure in Total for the preceding Financial Year Financial expenditure to apply as per Municipal Budget Year: Jul 2012 to Jun 2013
	(5.6) DESIGN CAPACITY vs. OPERATIONAL CAPACITY (15%)	Proof to be submitted of the documented design capacity and documented daily operating capacity over the past 12 months Groundwater dependant systems must have an acceptable plan which stipulates abstraction patterns that will prevent aquifer damage Flow meters must be calibrated at least annually
Blue Drop Requirements= TOTAL 97%		

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blue drop

no drop

FIGURE B-5: Blue Water Service Audit Requirements [DWAF, 2014].

2014 BLUE WATER Services Audit Requirements

2014 NO DROP REQUIREMENTS (Water use efficiency)

(6) **WATER USE EFFICIENCY & WATER LOSS MANAGE-MENT** **3%**	**(6.1)** **WATER BALANCE** (30%)	Provide MONTHLY and ANNUAL composite IWA water balance diagrams and supporting documents for the complete system as part of the water audit (as a component in the WSDP) as per Regulation 509 of 2001 Clause 10 of the Water Supply Regulations. Balance diagram to specify as a minimum the main components of the IWA balance including Water Losses broken down into: **a)** System input volumes **b)** Billed metered and unmetered usage **c)** Unbilled Authorised Consumption **d)** Water losses broken down into Real and Apparent Losses **e)** Free Basic Water, and **f)** Non Revenue Water and to be supported by a schematic showing bulk meters, zones and main infrastructure components *Note: WSI's to ensure that units are clearly indicated against numeric values in water balance (e.g. 100 kl/annum, 50 m^3/day, etc)*
	(6.2) **WDM STRATEGY and BUSINESS PLAN and IMPLEMENTATION** (30%)	**a)** Evidence must be provided of a Council approved WDM strategy and business plan consisting of at least the following: - Background and Context - Situation Assessment including a Needs Statement - Key Issues and Challenges - Focus Areas of Intervention - List of Proposed Interventions - Set targets for demand, NRW, commercial and real losses - Budget and Multi-year Implementation Timeline **b)** Provide evidence of implementation against the above Plan in terms of: - List of Interventions (Projects) - Movement against targets for demand, NRW, commercial and real losses - Budget and Multi-year Implementation Timeline *(Reg 509 of 2001 Clause 10)*
	(6.3) **COMPLIANCE and PERFORMANCE** (40%)	**a)** Provide historic data in order to calculate the following: - Physical (real) water loss trend - Commercial water loss trend - Water use efficiency trend **b)** Provide the following data (grey cells only) with supporting documentation, in order to calculate the WSI baseline profile for: - Physical (real) water loss status - Commercial water loss status - Water use efficiency status

Population number served:		**SIV (System Input Volume) (kl/annum):**		**Average system pressure (m):**	
Households served:		**Authorised, Billed and Metered (kl/annum):**		**Usage (l/cap/day):**	
Total connections:		**Authorised, Billed and Unmetered (kl/annum):**		**Non-revenue (l/cap/day):**	

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no drop

FIGURE B-6: Blue Water Service Audit Requirements [DWAF, 2014].

2014 BLUE WATER Services Audit Requirements

		Metered connections:		Authorised and Unbilled (kl/annum):		Real losses (l/cap/day):	
		Unmetered connections:		Authorised Consumption (kl/annum):		% Metering	
		Households with deemed of flat rate billing:		Revenue water (kl/annum):		Efficiency =	
		Number of metered connections billed:		Non-revenue water (kl/annum):			
		Proven Industrial use (kl/annum):		Water losses (kl/annum):			
		Length of mains installed :		Apparent or Commercial losses (kl/annum):		Water loss =	
		Assumed commercial losses :		Real or Physical water losses (kl/annum):			
	PENALTY: Inclusion in the IDP	Components listed under Criteria 1.2 were not included in the IDP					
	BONUS (1): Training in WDM	a) The Institution must present evidence of a competent Water Loss Management Team (in form of an Organogram) with <20% vacancy ratio in accordance with Clause 66 (Staff matters) of the Municipal Systems Act 32 of 2000 b) Proof required on team manager competency (Qualification & Experience) with the following additional requirement: Manager to have suitable tertiary qualification with suitable experience c) The Institution must present evidence of a competent structured Maintenance Team (in form of Organogram with well-defined positions and job descriptions; Contract or Invoice). Logbook with maintenance entries will serve as adequate evidence d) Additional proof required on team competency for the team presented under (c) above (e.g. Qualification & Experience & Trade-test) e) Indicate number of suitably qualified plumbers per 1000 connections					
No Drop Requirements= TOTAL 3%							

2014 BLUE DROP Score (%) = 97% Blue Drop score (DWQ Management) + 3% No Drop Score (Water use efficiency)

BLUE DROP REQUIREMENTS WILL ACCOUNT FOR 97% OF THE 100% BLUE DROP SCORE

NO DROP REQUIREMENTS WILL ACCOUNT FOR 3% OF THE 100% BLUE DROP SCORE

Figure B-7: Blue Water Service Audit Requirements [DWAF, 2014].

Appendix C: Technical Design Drawings

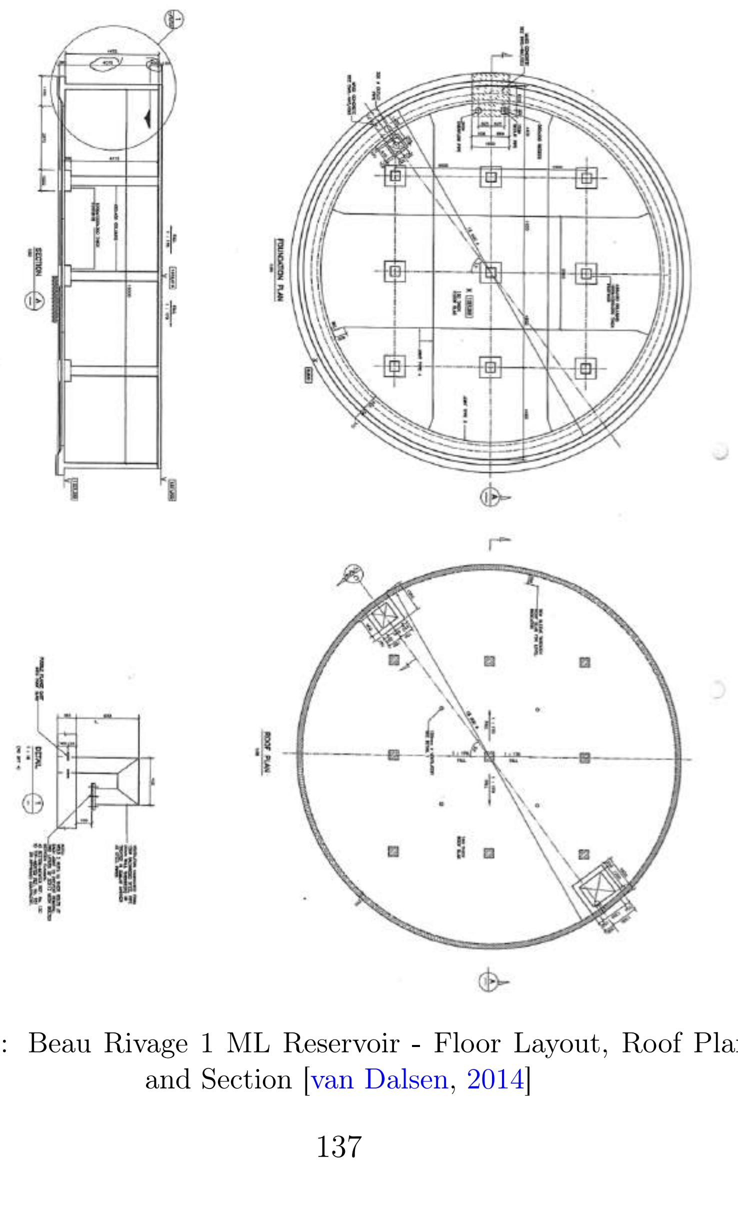


Figure C-1: Beau Rivage 1 ML Reservoir - Floor Layout, Roof Plan Detail and Section [van Dalsen, 2014]

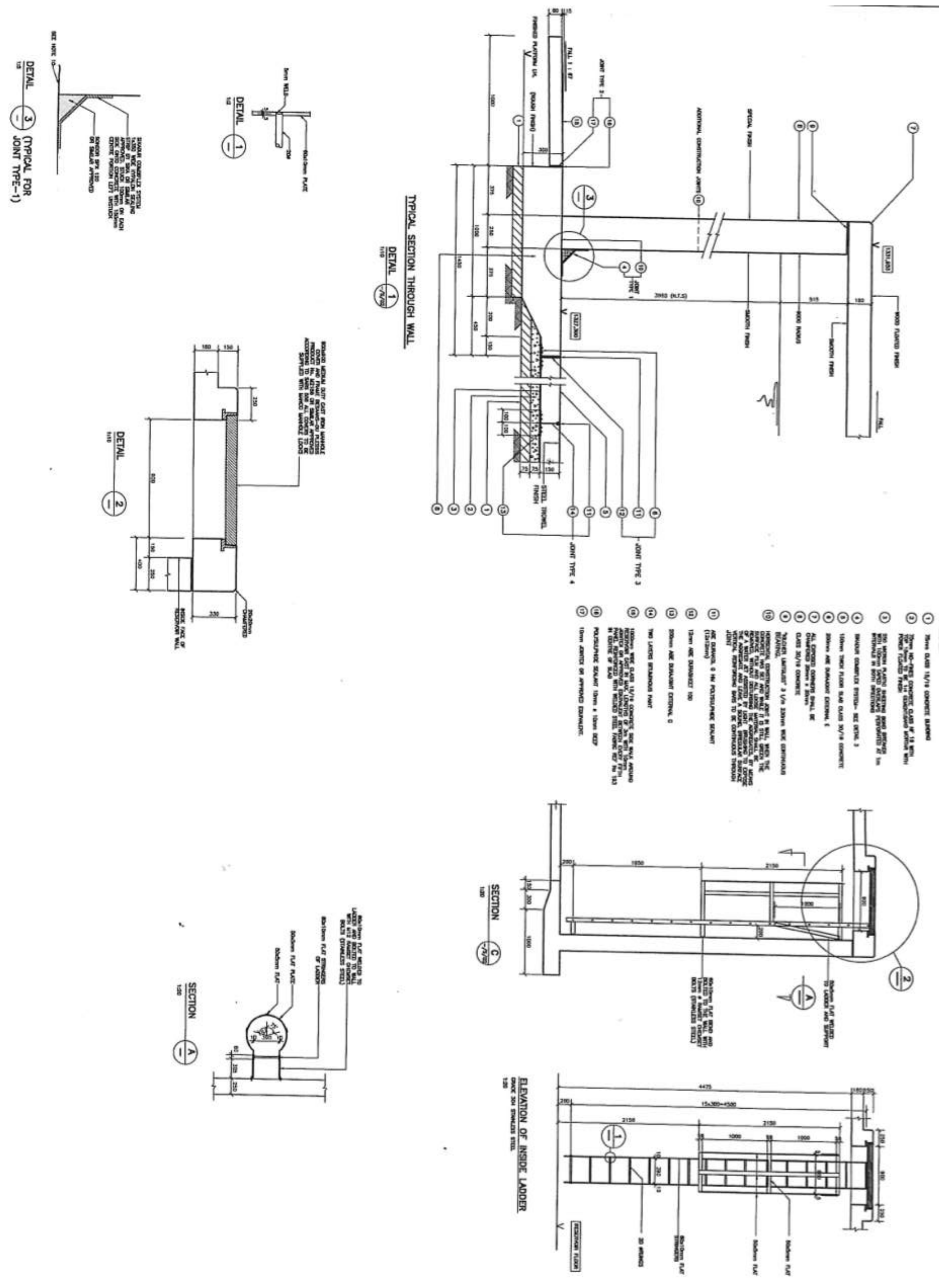


FIGURE C-2: Beau Rivage 1 ML Reservoir - Wall Joints and Ladder Details [van Dalsen, 2014]

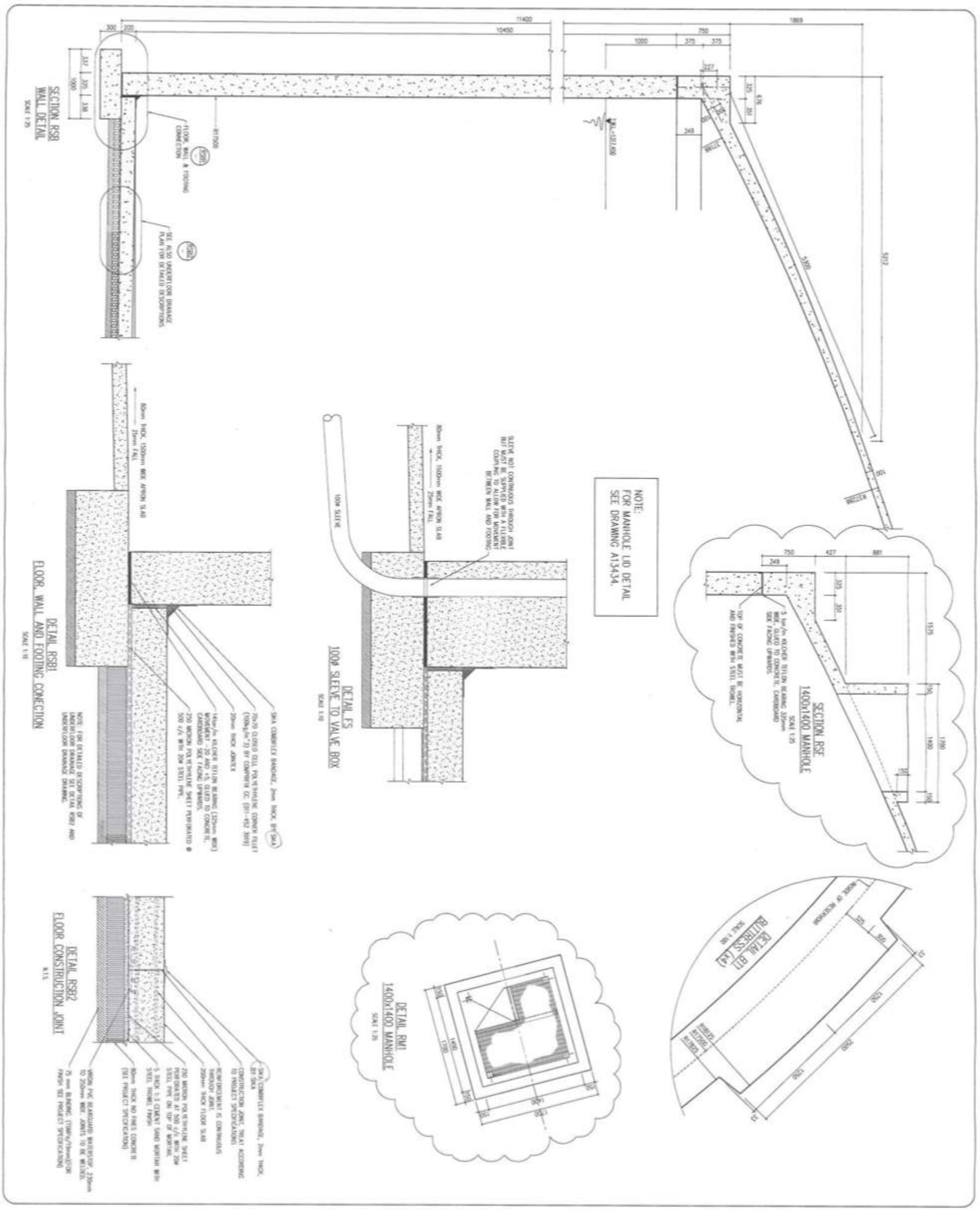


FIGURE C-3: 9Ml - Dome Roof Reservoir Concrete Sections and Details [Kruger, 2014]

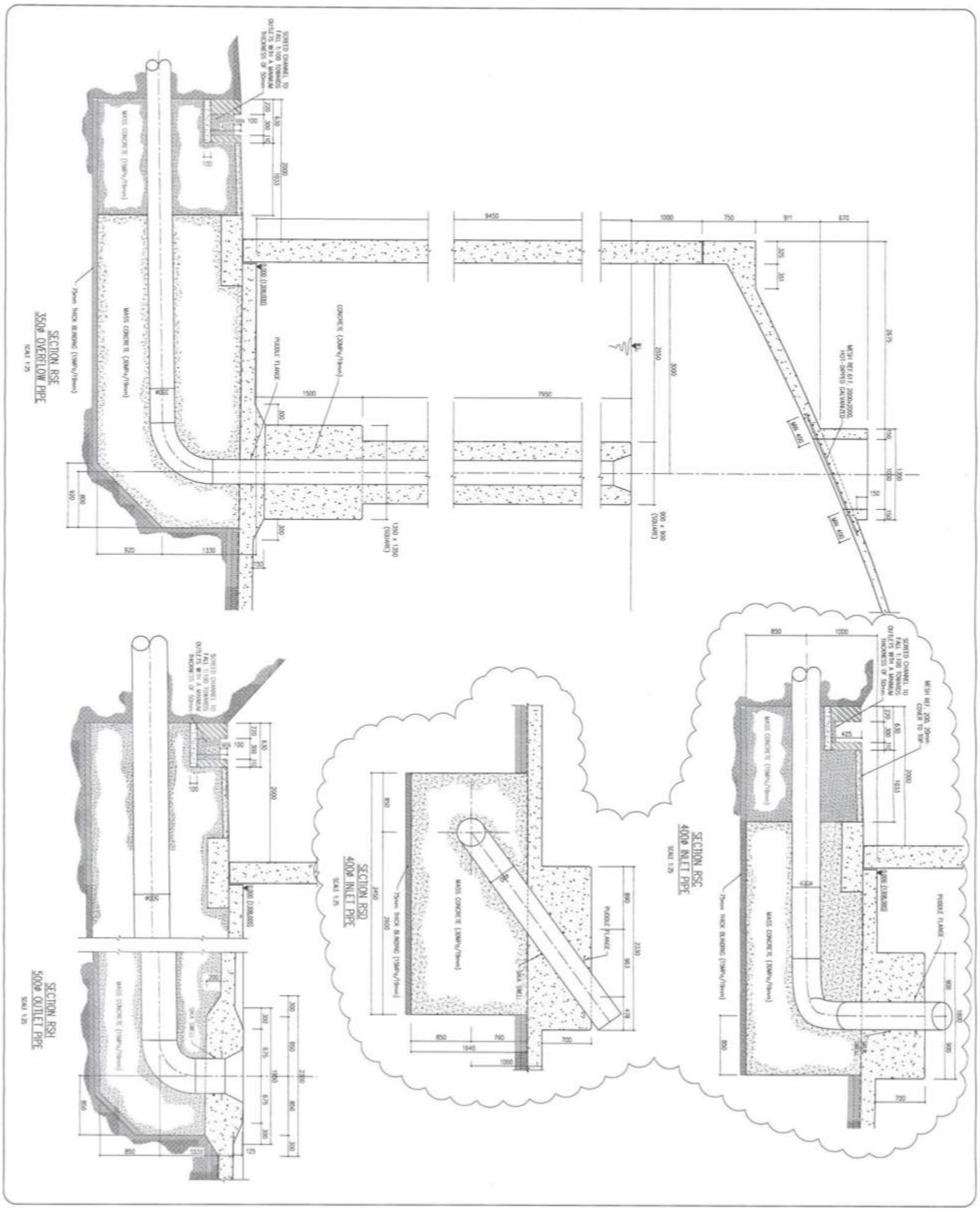


FIGURE C-4: 9Ml - Dome Roof Reservoir Pipe Detail Sections [Kruger, 2014]

Appendix D: Detailed Description of Deterioration Mechanisms

D-1 Concrete Deterioration Mechanisms

D-1.1 Delamination and Spalling

Delamination and spalling occur due to a number of factors and environmental conditions. Two main instances under which delamination and spalling occur are concrete surfaces that are troweled (or float finished) and the corrosion of reinforcing steel near the concrete surface. Due to conventional construction techniques employed in South Africa, it is assumed that the floor of the reservoir is troweled, or has some form of power floated finish, and the walls and related structures are cast in formwork. This means that delamination in the floor slab is primarily due to finishing (troweling) and delamination in the walls is primarily due to corrosion of reinforcing steel. It should be noted that delamination in the floor slab may also be attributed to corrosion of the reinforcement.

Delamination in concrete floor slabs affects the top 3 - 6 mm and is primarily caused by premature and improper finishing [NRMCA, 2004]. A thin layer of air or water separates the delaminated concrete layer from the remaining slab [NRMCA, 2004]. Cracking and discolouration may be visible due to rapid drying of surface during curing. Disturbances of the delaminated surface may cause fragments to break away leaving blister like patches on the concrete surface [NRMCA, 2004].

Delamination of concrete can also be caused by the corrosion of reinforcing steel near the concrete surface [NRMCA, 2004]. This causes in most cases a loss of structural serviceability, illustrated by cracking and delamination of the concrete.

The delamination of concrete affects the aesthetics of the structure as well as the serviceability [Li et al., 2007]. Li et al. [2007] suggest that concrete structures are more susceptible to reinforcement corrosion once delamination of concrete has occurred.

Reduced concrete cover and more permeable concrete allow chlorides to penetrate to the steel. The rusting of the upper layer of reinforcing steel severs the bond between the surrounding concrete and the steel. This severed bond causes corrosion related delamination [NRMCA, 2004]. Figure D-1 illustrates the delamination of concrete.

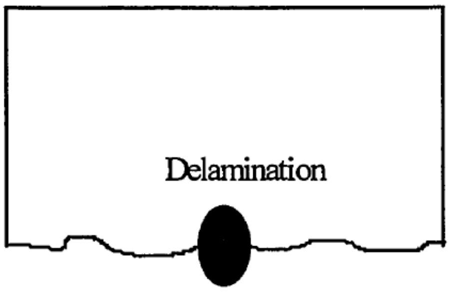


FIGURE D-1: Delamination of Concrete [Stanish, 1997].

D-1.2 Aggression by Carbon Dioxide (Carbonation & Leaching)

The deterioration of concrete due to the aggression of CO_2, may manifest in various ways depending on the surrounding environment. The degree of carbonation depends on environmental factors such as, the amount of chemicals and pollutants in the surroundings. The carbonation of concrete involves the following chemical reaction [Ballim, 2012]:

$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O \tag{1}$$

Prior to the aggression of CO_2, normal concrete has a pH of approximately 13. This pH level causes a passive iron oxide film to form around the reinforcement steel. This film insulates the steel from the environment, thus preventing corrosion [MAPEI, 2011]. Carbonation reduces the pH to ± 8.5, thus neutralizing the film and exposing the reinforcement steel rods to the aggression of oxygen and humidity in the environment. Carbonation propagates through the concrete as a "front" [Ballim, 2012]. Figure D-2 illustrates the advancement of the carbonation "front".

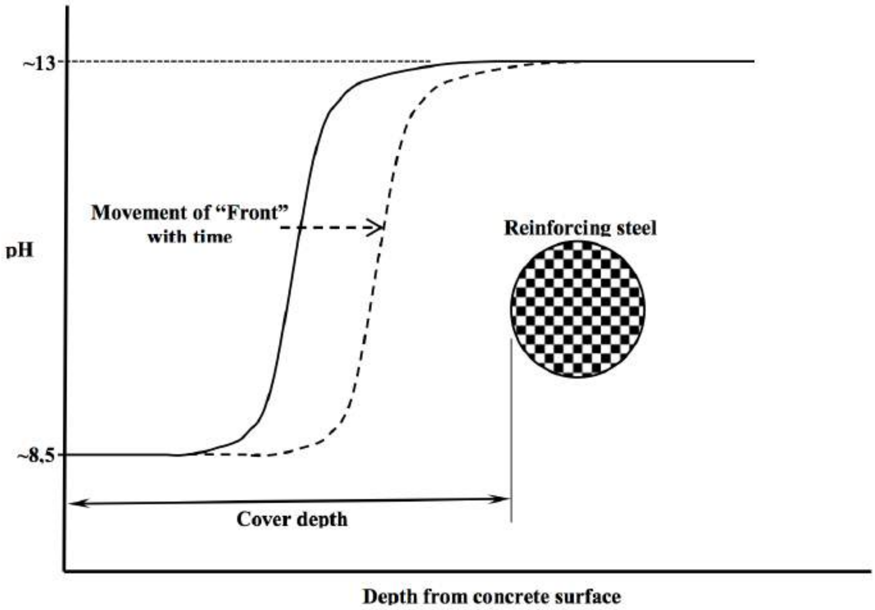


FIGURE D-2: Advancement of Carbonation "front" [Ballim, 2012].

The corrosion process is initiated by these conditions and causes the steel rods to expand up to 6 times their original volume [MAPEI, 2011]. The expansion of the rods causes internal pressure that leads to tensile splitting stress and may separate the cover concrete from the remainder of the structure.

Leaching is the removal action, of the cementitious matrix, which water exerts on the surface of the concrete [MAPEI, 2011]. Leaching is aggravated by the acidity of the water due to the presence of aggressive carbon dioxide [MAPEI, 2011].

D-1.3 Aggression by Sulphates

The deterioration of concrete due to sulphate attack is caused by three main chemical reactions. The formation of gypsum, decalcification of the cementitious phase and the recrystilisation of ettringite are the three main reactions [QCL Group, 1999]. Concrete becomes susceptible to sulphate attack at a ground water concentration of about 0,2% [QCL Group, 1999].

Sulphate ions are transported through the cementitious matrix by water and react with calcium hydroxide to from gypsum [MAPEI, 2011]. The formation of gypsum may cause expansion however is generally linked to loss of strength and mass [QCL Group, 1999].

Sulphate ions that are in contact with the cement paste causes alumina containing hydrates to be converted to a high sulphate form of ettringite [QCL Group, 1999]. This formation of is known as secondary ettringite [MAPEI, 2011]. The mechanisms that cause these ettringite crystals to expand are still subject of uncertainty among researchers, however consensus regarding the deleterious effects of the crystals on concrete have been reached.

Decalcification is important where sulphates solutions are lower in pH, thus the environment is more acidic. This reaction leads to greater amounts of gypsum formation, which may lead to loss of stiffness and expansion [QCL Group, 1999]. At temperatures below 100^{o}C and relative humidity of 95% with the presence of calcium carbonated, thaumasite may form [MAPEI, 2011]. Thaumasite provokes decalcification and may reduce concrete to a pulp.

D-1.4 Aggression by Chlorides (Chloride Penetration and Corrosion)

Structures that are exposed to environments with high chloride contents are susceptible to chloride penetration and ultimately corrosion of the reinforcement. Diffusion and absorption are the main mechanisms that cause chloride penetration in structures that are exposed to wet/dry cycles [Bioubakhsh, 2011]. Corrosion of metals is a thermodynamically spontaneous and unavoidable reaction [Song and Shayan, 1998]. This reaction is detrimental to the metallurgical properties of the reinforcing and the rate of corrosion depends on the environmental medium and metal characteristics.

The deterioration of concrete due to the aggression by chlorides is a two-stage process. The initial stage involves the concrete being subjected to high chloride environments, thus inducing chloride ion penetration through the concrete cover to the outermost layer of steel. Once the ions reach the reinforcing, they de-passivate the surrounding area. In the presence of air and water corrosion will commence [QCL Group, 1999].

The second stage involves the propagation of the corrosion process once the ions reached the steel surface. During this stage, active corrosion takes place. Figure D-3 illustrates the most commonly referred to service life model of concrete structures that are subjected to corrosion as proposed by Tuutti [1982].

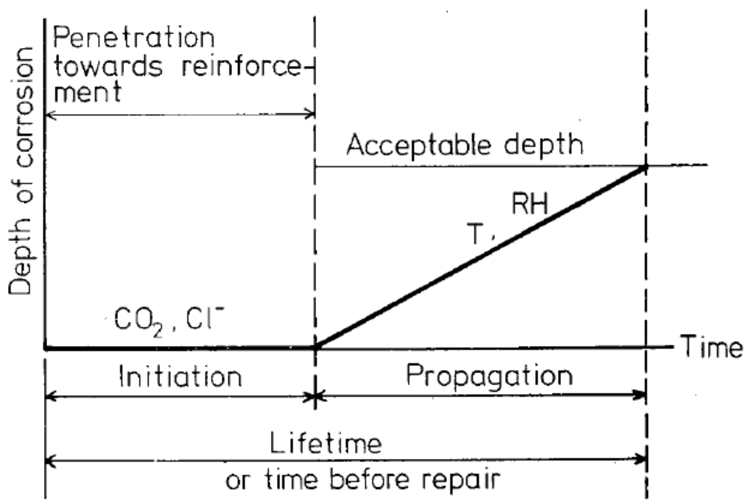


FIGURE D-3: Service life model of structures subjected to chloride corrosion [Tuutti, 1982].

The service life model illustrates the initial penetration of the chloride ions to the surface of the reinforcement. Furthermore it illustrates the rate of corrosion once corrosion has been initiated. This model details the corrosion process over the lifetime of the structure. The products of the steel corrosion expand in volume, up to 600%, causing internal tension forces, which results in lateral spalling [QCL Group, 1999].

D-1.5 Alkali-Aggregate Reaction (AAR)

The Alkali-Aggregate reaction (AAR) appears in two forms - the alkali-silica reaction (ASR) and the alkali-carbonate reaction (ACR). The alkali-carbonate reaction is sometimes referred to as the alkali-carbonate rock reaction (ACRR) [Farny and Kerkhoff, 2007]. Both reactions contribute to the deterioration of the durability of concrete however the ASR is more common. The specific composition of aggregates that form the ACR is not very common. Due to the high occurrence of aggregates containing reactive silica minerals, focus will be placed on the alkali-silica reaction.

ASR is classed as a heterogeneous solid-liquid reaction [Diamond, 1989]. ASR affects the durability of the concrete in that it forms a gel that expands when in contact with moisture. The absorption of moisture causes the gel to expand, which induces pressure, expansion and the cracking of the aggregate and the surrounding paste. The mechanism of ASR is twofold as described below:

$$Alkali + Reactive\ Silica \rightarrow Alkali\text{-}Silica\ Gel \tag{2}$$

$$Alkali\text{-}Silica\ Gel + \text{Moisture} \rightarrow expansion \tag{3}$$

The formation of alkali-silica gel does not necessarily indicate a destructive ASR. ASR gel only becomes a problem when the gel expands at a rapid rate and exceeds the tensile strength of the concrete [Farny and Kerkhoff, 2007].

D-1.6 Freeze-Thaw

Cold temperatures only affect the durability of concrete if moisture is present inside the concrete. "Critical Saturation" is the determined level of humidity within concrete that will cause damage if the moisture freezes [MAPEI, 2011]. When water transforms to ice it expands in volume by approximately 9% [Monteiro and Mehta, 2014]. This volumetric expansion causes hydraulic pressure that exceeds the tensile strength of concrete and leads cracks and possible concrete spalls.

D-1.7 Hardness of Water Affects

Soft water can be aggressive towards concrete due to the low dissolved ion content of the water. Due to the low ion content, the water can leach out the calcium hydroxide in the cement paste as it tries to establish an ion balance [Ballim, 2012]. The rate of ion transfer, the balancing of ions to equilibrium, is dependent on the concentration gradient. This concentration gradient is the difference between the water and concrete calcium compounds [Ballim, 2012].

The hardness of the water, with respect to the corrosion process, is determined by a measure of the bicarbonate ion concentration (HCO_3) [Ballim, 2012]. This varies from the total hardness, which refers to the total summation of the calcium and magnesium cations.

D-2 Steel Deterioration Mechanisms

The mechanisms that contribute to the corrosion of metal, in any environment consist of the following [Song and Shayan, 1998]:

- **Depolarization** - The depolarization reagent is transported through the surrounding medium to the surface of the metal. Oxygen is the reagent and is commonly dissolved in the medium or exists naturally in an aqueous liquid.
- **Electrochemical Reactions** - The reaction between the metal and surrounding medium occurs at the interface between them, due to the oxidation of the metals and the reduction of O_2 or H^+.
- **Reaction Products** - The corrosion products accumulate on the surface of the metals and are then transported away, leaving room for new reaction products to form. These products may be the passive film, iron oxide or hydrogen gas.

Should any of the processes be absent or cease, the progression of the corrosion will also end. Figure D-4 illustrates the diffusion of O_2 through concrete to the surface of the metal, thereby initiating the corrosion processes.

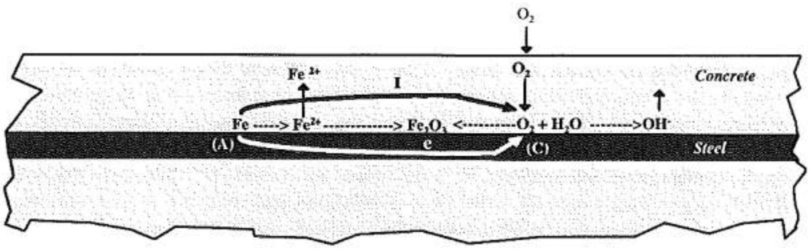


FIGURE D-4: Metal Corrosion Process within concrete [Song and Shayan, 1998].

Figure D-4 also illustrates the anodic and cathodic elements, denoted by A and C respectively, present in the electrochemical reaction process.

D-2.1 Uniform Corrosion

Uniform corrosion presents itself as brownish deposits on the surface of a metal and is most commonly referred to as rust. If the entire metal surface is subjected to the corrosive environment, uniform corrosion will result. The exposed metal surface is converted to its oxide form [Stuart, 2013]. Uniform corrosion presents when the anodic and cathodic areas are too close to one another to be separated. An electron is transferred from the metallic surface and is consumed by the cathodic reduction [Schmutz, 2013]. The processes forms uniformly on the surface of the steel and may be randomly distributed along the steel surface [Song and Shayan, 1998].

Uniform corrosion is the most common form of corrosion and is found in water tubes, reinforcing steel and hydraulic structures [Schmutz, 2013]. Although this form of corrosion is very frequent, it seldom leads to significant damage, due to the predictability of the process [Schmutz, 2013]. The uniform thinning of the entire surface of the metal, generally without any localized attack, is the general characterized with uniform corrosion. Figure D-5 illustrates the thinning of the metal with the deposits of the corrosion products.

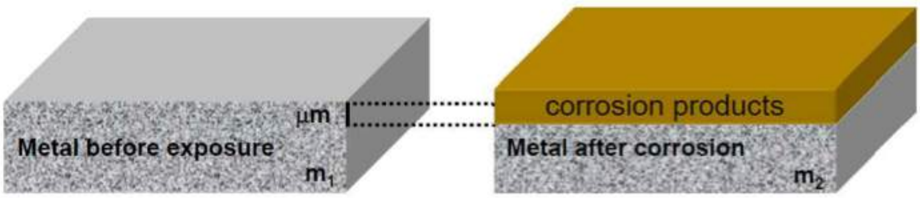


FIGURE D-5: Schematic description of Uniform Corrosion [Schmutz, 2013].

D-2.2 Galvanic Corrosion

Galvanic corrosion, also referred to as bimetallic corrosion, involves the deterioration induced when two dissimilar metals are coupled in a corrosive environment [Stuart, 2013]. Moisture acts as an electrolyte, thus causing the existence of a galvanic cell. A galvanic couple forms between the various metals causing one metals to act as the anode and the other to act as the cathode. Figure D-6 illustrates the corrosion due to a galvanic coupled that formed between to different metals.

The formation of and anode and a cathode is due to the potential difference between the different metals [Stuart, 2013]. This potential difference is referred to as the metallic nobility. The less noble metal will form the anode while the more noble metal will form the cathode. Due to the potential difference when

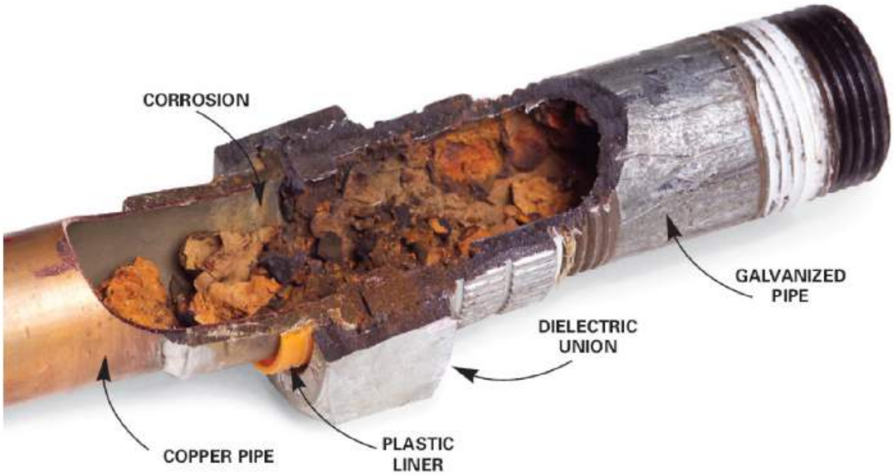


FIGURE D-6: Galvanic Corrosion of Water Pipes [Stuart, 2013].

submerged in the electrolyte, the current will flow from the anode to the cathode, which increases the rate of corrosion on the anode [Francis, 2000].

D-2.3 Localized Corrosion

D-2.3.1 Pitting Corrosion

Pitting corrosion is the result of attack of chloride on the metal surface and is confined to a point or small area [Song and Shayan, 1998]. The corrosion penetrates the passive film and leads to rapid anodic dissolution at the point of penetration [Song and Shayan, 1998]. Pitting is considered one of the more dangerous corrosion processes, as it is difficult to predict and design against and it leads to the failure of steel components [Stuart, 2013]. Figure D-7 shows the manifestation of pitting on a section of steel piping.

FIGURE D-7: Pitting of Piping section [Schmutz, 2013].

D-2.3.2 Crevice Corrosion

Crevice corrosion tends to form with a stagnant corrosive solution on the surface of a metal sample [Stuart, 2013]. This stagnation of the solution usually occurs due to the geometry of the metal sample in question along with the capillary forces of water. This stagnation results in the build-up of chlorides and leads to the formation of a differential aeration cell [Nimmon and Hinds, 2003]. This aeration cell has a lower oxygen content and forms an anode thus facilitating the corrosion process. Thus crevice corrosion generally occurs under washers, fastener heads, threads and clamps [Stuart, 2013].

D-2.3.3 Fillform

Fillform is a type of crevice corrosion. It occurs when the aggressive solution breaches the protective film (insulation) and corrodes the metal underneath. Fillform usually starts in a small area where a defect in the protective film is found [Stuart, 2013]. If the corrosion process starts, it causes the ingress of more moisture thus causing more corrosion. This form of corrosion is commonly associated with painted metals or metals coated with an epoxy layer such as the internal components of hydraulic structures [Stuart, 2013].

D-2.4 External Current Imposed Corrosion

When a stray current flows through the reinforcement of a hydraulic structure, the flow of electrons supports the corrosion process [Nimmon and Hinds, 2003]. This type of corrosion can be present in soils and flowing or stationary fluids. In terms of reservoirs, water quality monitoring equipment that is not properly insulated may cause the stray of electrical current and result in this type of corrosion.

D-2.5 Stress Corrosion Cracking

Static tensile stress in combination with corrosion forms stress corrosion cracking that can eventually lead to failure of the component [Nimmon and Hinds, 2003]. The initiation of this corrosion process is imperceptible, thus leading the sudden and unexpected failure [Song and Shayan, 1998]. Post tension reinforcing in hydraulic structures are particularly susceptible to this form of corrosion due to the high tensile stresses and the presence of water [Song and Shayan, 1998].

D-2.6 Hydrogen Induced Embrittlement (HIE)

Hydrogen dissolves into all metals to some extent [Stuart, 2013]. The dissolved hydrogen causes the loss of ductility in metals and the deformation of local plastic materials [Song and Shayan, 1998]. Prestressed tendons that are cathodically overprotected are of greatest concern in reinforced concrete structures. Hydrogen embrittlement is not permanent, if the environmental conditions are changed prior to the formation of cracks, the hydrogen can diffuse itself from the metal surface, thus restoring ductility [Stuart, 2013].

D-3 Synthetic Deterioration Mechanisms

D-3.1 Cementitious Protective Coat

In order to increase the durability of the internal surface of the concrete water reservoir, the surface is coated with a cementitious protection layer [Kimbrey, 2014]. SikaTop Seal -107 ZA is commonly used [Kimbrey, 2014]. This top seal is two part polymer modified cementitious waterproofing slurry. It can be used as a protective layer against freeze-thaw attack, de-icing salts and chloride ingress [SIKA, 2011]. Mechanical weathering and poor surface preparation, prior to product application, will be the primary cause of failure of this system [Kimbrey, 2014].

D-3.2 Synthetic Waterproofing (Polyolefin & Epoxy)

All joints (construction, expansion, connection etc.) will generally be sealed with Sikadur Combiflex systems [Kimbrey, 2014]. This system consists of a modified flexible polyolefin (FPO) waterproofing tape with different epoxy adhesives. This product is most commonly used on water retaining structures and drinking water reservoirs [SIKA, 2013]. Figure D-8 below illustrates the application of the waterproofing tape.

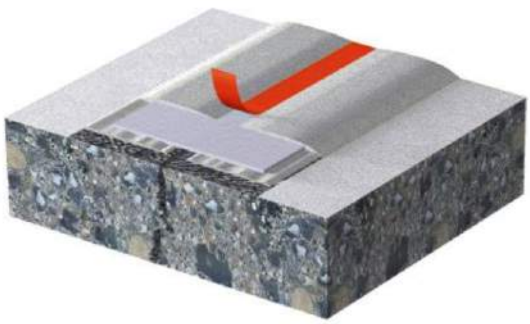


FIGURE D-8: Application of Waterproofing Tape [SIKA, 2013].

D-3.3 Synthetic Waterproofing (Polyurethane)

Reservoir construction joints will generally have the SikaSwell 2507 cast in [Kimbrey, 2014]. SikaSwell is a polyurethane composite that expands when in contact with water [SIKA, 2007]. It is used as waterproofing in construction joints and around pipes and steel work that go through concrete [SIKA, 2007]. Figure D-9 illustrates the profile of the SikaSwell 2507 along with the pressure relief chambers.

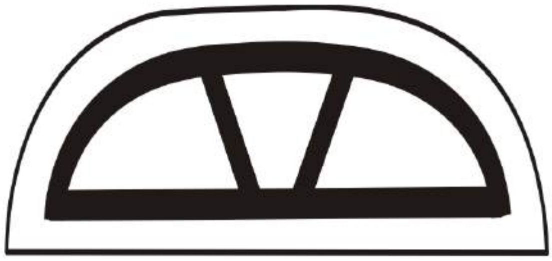


FIGURE D-9: SikaSwell 2507 Profile with Pressure Relief Chambers [SIKA, 2007].

D-3.3 Synthetic Waterproofing (Polyvinyl chloride)

Figure D-10 illustrates different waterbar designs for the use of waterproofing of joints in water retaining structures.

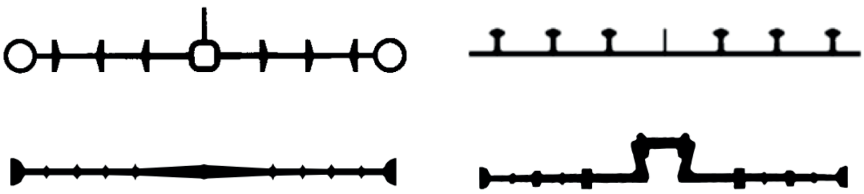


FIGURE D-10: PVC Waterbar Designs for Water Retaining Structures [SIKA, 2014].

Appendix E: Prioritization Method Tables

TABLE E-1: Condition Assessment Of Floors

Structure																
	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**						**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**			
Floor	Delamination & Spalling															
	Carbonation															
	Leaching															
	Sulphate Attack															
	Chloride Penetration & Corrosion															
	Alkali Silika Reaction (ASR)															
	Freeze Thaw															
	Hardness of Water															
	Additional Comments & Recommendations													**T**		
														M		
	T = Total	Total condition index as calculated														
	M = Max	Maximum possible condition index														

TABLE E-2: Condition Assessment Of Columns

Structure															
	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**					**Total (D*E)**	%
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**		
Columns	Delamination & Spalling														
	Carbonation														
	Leaching														
	Sulphate Attack														
	Chloride Penetration & Corrosion														
	Alkali Silika Reaction (ASR)														
	Freeze Thaw														
	Hardness of Water														
	Additional Comments & Recommendations													**T**	
														M	
	T = Total	Total condition index as calculated													
	M = Max	Maximum possible condition index													

TABLE E-3: Condition Assessment Of Walls

Structure															
	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**					**Total (D*E)**	%
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**		
Walls	Delamination & Spalling														
	Carbonation														
	Leaching														
	Sulphate Attack														
	Chloride Penetration & Corrosion														
	Alkali Silika Reaction (ASR)														
	Freeze Thaw														
	Hardness of Water														
	Additional Comments & Recommendations													**T**	
														M	
	T = Total	Total condition index as calculated													
	M = Max	Maximum possible condition index													

TABLE E-4: Condition Assessment of Waterproofing

Structure															
	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**					**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**		
Waterproofing	Cementitious														
	Polyolefin/Epoxy														
	Polyurethane														
	PVC														
	Additional Comments & Recommendations												**T**		
													M		
	T = Total	Total condition index as calculated													
	M = Max	Maximum possible condition index													

TABLE E-5: Condition Assessment Of Internal Ladders

Access Components															
	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**					**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**		
Internal Ladder	Uniform Corrosion														
	Galvanic Corrosion														
	Pitting Corrosion														
	Fillform Corrosion														
	External Current Corrosion														
	SCC Corrosion														
	HIE Corrosion														
	Additional Comments & Recommendations												**T**		
													M		
	T = Total	Total condition index as calculated													
	M = Max	Maximum possible condition index													

TABLE E-6: Condition Assessment Of External Ladders

Access Components															
	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**					**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**		
External Ladder	Uniform Corrosion														
	Galvanic Corrosion														
	Pitting Corrosion														
	Fillform Corrosion														
	External Current Corrosion														
	SCC Corrosion														
	HIE Corrosion														
	Additional Comments & Recommendations												**T**		
													M		
	T = Total	Total condition index as calculated													
	M = Max	Maximum possible condition index													

Table E-7: Condition Assessment Of Manholes

Access Components																
	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**						**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**			
Manhole	Uniform Corrosion															
	Galvanic Corrosion															
	Pitting Corrosion															
	Fillform Corrosion															
	External Current Corrosion															
	SCC Corrosion															
	HIE Corrosion															
	Additional Comments & Recommendations													**T**		
														M		
	T = Total	Total condition index as calculated														
	M = Max	Maximum possible condition index														

Table E-8: Condition Assessment Of Ventilators

Access Components																
	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**						**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**			
Ventilator	Uniform Corrosion															
	Galvanic Corrosion															
	Pitting Corrosion															
	Fillform Corrosion															
	External Current Corrosion															
	SCC Corrosion															
	HIE Corrosion															
	Additional Comments & Recommendations													**T**		
														M		
	T = Total	Total condition index as calculated														
	M = Max	Maximum possible condition index														

Table E-9: Condition Assessment Of Other Fixtures

Access Components																
	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**						**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**			
Other Fixtures	Uniform Corrosion															
	Galvanic Corrosion															
	Pitting Corrosion															
	Fillform Corrosion															
	External Current Corrosion															
	SCC Corrosion															
	HIE Corrosion															
	Additional Comments & Recommendations													**T**		
														M		
	T = Total	Total condition index as calculated														
	M = Max	Maximum possible condition index														

TABLE E-10: Condition Assessment of Floor Drain

Drainage

	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**						**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**			
Floor Drain	Cementitious															
	Polyolefin/Epoxy															
	Polyurethane															
	PVC															
	Additional Comments & Recommendations													**T**		
														M		
	T = Total	Total condition index as calculated														
	M = Max	Maximum possible condition index														

TABLE E-11: Condition Assessment of Wall Drain

Drainage

	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**						**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**			
Wall Drain	Cementitious															
	Polyolefin/Epoxy															
	Polyurethane															
	PVC															
	Additional Comments & Recommendations													**T**		
														M		
	T = Total	Total condition index as calculated														
	M = Max	Maximum possible condition index														

TABLE E-12: Condition Assessment Of Inlet Pipe

Pipework

	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**						**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**			
Inlet Pipe	Uniform Corrosion															
	Galvanic Corrosion															
	Pitting Corrosion															
	Fillform Corrosion															
	External Current Corrosion															
	SCC Corrosion															
	HIE Corrosion															
	Additional Comments & Recommendations													**T**		
														M		
	T = Total	Total condition index as calculated														
	M = Max	Maximum possible condition index														

TABLE E-13: Condition Assessment Of Inlet Valve

Pipework																
	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**						**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**			
Inlet Valve	Uniform Corrosion															
	Galvanic Corrosion															
	Pitting Corrosion															
	Fillform Corrosion															
	External Current Corrosion															
	SCC Corrosion															
	HIE Corrosion															
	Additional Comments & Recommendations													**T**		
														M		
	T = Total	Total condition index as calculated														
	M = Max	Maximum possible condition index														

TABLE E-14: Condition Assessment Of Outlet Pipe

Pipework																
	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**						**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**			
Outlet Pipe	Uniform Corrosion															
	Galvanic Corrosion															
	Pitting Corrosion															
	Fillform Corrosion															
	External Current Corrosion															
	SCC Corrosion															
	HIE Corrosion															
	Additional Comments & Recommendations													**T**		
														M		
	T = Total	Total condition index as calculated														
	M = Max	Maximum possible condition index														

TABLE E-15: Condition Assessment Of Outlet Valve

Pipework																
	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**						**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**			
Outlet Valve	Uniform Corrosion															
	Galvanic Corrosion															
	Pitting Corrosion															
	Fillform Corrosion															
	External Current Corrosion															
	SCC Corrosion															
	HIE Corrosion															
	Additional Comments & Recommendations													**T**		
														M		
	T = Total	Total condition index as calculated														
	M = Max	Maximum possible condition index														

TABLE E-16: Condition Assessment Of Scour Pipe

Pipework

	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**						**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**			
Scour Pipe	Uniform Corrosion															
	Galvanic Corrosion															
	Pitting Corrosion															
	Fillform Corrosion															
	External Current Corrosion															
	SCC Corrosion															
	HIE Corrosion															
	Additional Comments & Recommendations													**T**		
														M		

T = Total Total condition index as calculated
M = Max Maximum possible condition index

TABLE E-17: Condition Assessment Of Scour Valve

Pipework

	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**						**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**			
Scour Valve	Uniform Corrosion															
	Galvanic Corrosion															
	Pitting Corrosion															
	Fillform Corrosion															
	External Current Corrosion															
	SCC Corrosion															
	HIE Corrosion															
	Additional Comments & Recommendations													**T**		
														M		

T = Total Total condition index as calculated
M = Max Maximum possible condition index

TABLE E-18: Condition Assessment Of Overflow Pipe

Pipework

	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**						**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**			
Overflow Pipe	Uniform Corrosion															
	Galvanic Corrosion															
	Pitting Corrosion															
	Fillform Corrosion															
	External Current Corrosion															
	SCC Corrosion															
	HIE Corrosion															
	Additional Comments & Recommendations													**T**		
														M		

T = Total Total condition index as calculated
M = Max Maximum possible condition index

TABLE E-19: Condition Assessment of Waterproofing

Pipework																
Waterproofing	**Deterioration Mechanisms**	**Degee (D)**							**Extent (E)**						**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**			
	Cementitious															
	Polyolefin/Epoxy															
	Polyurethane															
	PVC															
	Additional Comments & Recommendations													**T**		
														M		
	T = Total	Total condition index as calculated														
	M = Max	Maximum possible condition index														

TABLE E-20: Condition Assessment Of the Flat Slab

Roof															
	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**					**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**		
Flat Slab	Delamination & Spalling														
	Carbonation														
	Leaching														
	Sulphate Attack														
	Chloride Penetration & Corrosion														
	Alkali Silika Reaction (ASR)														
	Freeze Thaw														
	Hardness of Water														
	Additional Comments & Recommendations												**T**		
													M		
	T = Total	Total condition index as calculated													
	M = Max	Maximum possible condition index													

TABLE E-21: Condition Assessment Of the Dome

Roof															
	Deterioration Mechanisms	**Degee (D)**							**Extent (E)**					**Total (D*E)**	**%**
		0	**1**	**2**	**3**	**4**	**5**		**1**	**2**	**3**	**4**	**5**		
Dome	Delamination & Spalling														
	Carbonation														
	Leaching														
	Sulphate Attack														
	Chloride Penetration & Corrosion														
	Alkali Silika Reaction (ASR)														
	Freeze Thaw														
	Hardness of Water														
	Additional Comments & Recommendations												**T**		
													M		
	T = Total	Total condition index as calculated													
	M = Max	Maximum possible condition index													

Appendix F: Questionnaire

Research Input Form - Development of a Guideline for the Prioritisation of Maintenance for Reinforced Concrete Water Reservoirs

SANS 10100 – 3 WORKING GROUP INVITATION TO PARTICIPATE

Dear Participants

I am performing research at the University of Stellenbosch under the guidance of Prof JA Wium. The research focuses on the prioritization of maintenance activities associated with water retaining structures (i.e. reinforced concrete reservoirs). This information ties into the SANS 10100 Part 3 – Design of concrete water retaining structures, as detailed knowledge regarding WRS deterioration and maintenance plans will help with future structural design.

For the purpose of my study I will research the following:

- Identification of the assets and components of concrete water reservoir structures
- The risks associated with the identified assets and components
- Quantification of the weights of importance for each asset and components

I would like to invite you to participate in this study and would appreciate your feedback on a questionnaire. The questionnaire consists of 4 sections and will take no longer than 10 min.

Participation in this study is voluntary. Information will only by used for statistical and academic purposes. All participants will remain anonymous and information will not be distributed.

Your input will provide insight into the most critical aspects related to concrete water retaining structures and prioritisation of the maintenance thereof.

For further information, please feel free to contact Prof JA Wium at the University of Stellenbosch.

- janw@sun.ac.za
- +27 21 808 4348.

I sincerely thank you for your cooperation.

Kind Regards

Paul Duvenage

The survey consists of four sections:
Section 1 - Professional Experience
Section 2 - Asset Importance
Section 3 - Component Importance
Section 4 - Inspection Recommendations

* Required

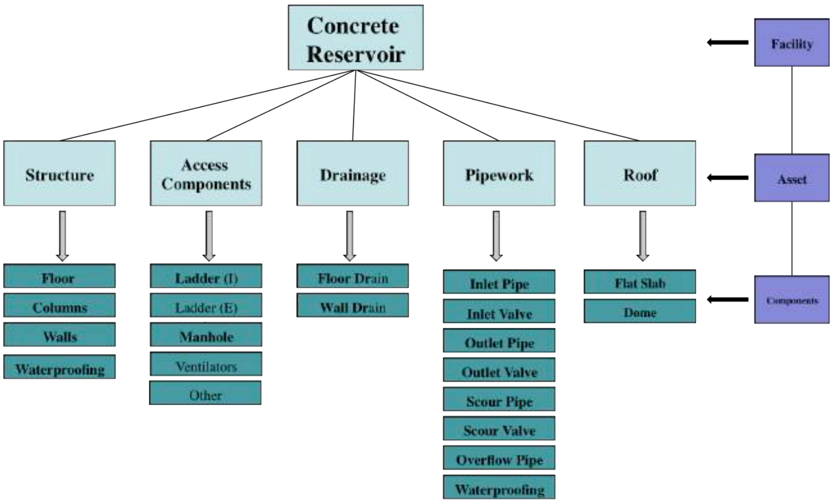
Section 1 - Professional Experience

The following section aims to identify the relevant experience of the participants. This will be used as a measure of the average experience of the participants. This average experience will justify the accuracy and validity of the data received.

1. **(Q1) - Please enter the amount of experience, in years, that you have in the civil engineering industry.** *
This may be design, construction, materials, management, etc. experience. (e.g. 15)

Section 2 - Concrete Water Reservoir Asset Importance

The figure below illustrates the components of a reinforced concrete water reservoir. There are two levels of detail, assets and components. This breakdown of assets and components was conducted by consulting previously designed detailed drawings and references to the SANS 10100:3 design code. The following section will focus on the assets.



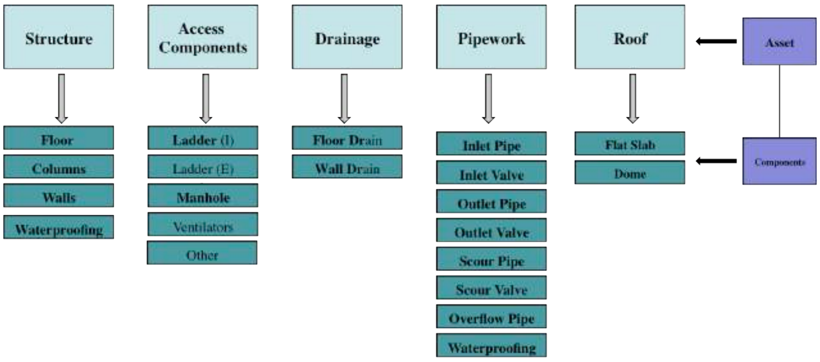
Overall Facility Condition

2. **(Q1) - We would like the express the overall condition of the FACILITY as a summation of the condition of the individual assets. How would you rate the contribution of each asset towards the overall condition of the FACILITY?** *
Express your answer as a rating out of 5. With 5 being the most important, thus having the greatest contribution and 1 being least important, thus having the lowest contribution. You can assign more than one of the same value.
Mark only one oval per row.

	1	2	3	4	5
Structure					
Access Components					
Drainage					
Pipework					
Roof					

Section 3 - Concrete Water Reservoir Component Importance

The following section will focus on the components of the assets.



Overall Asset Condition

3. **(Q1) - We would like the express the overall condition of the asset "STRUCTURE" as a summation of the condition of the individual components. How would you rate the contribution of each component towards the overall condition of the asset "STRUCTURE"? ***
Express your answer as a rating out of 5. With 5 being the most important, thus having the greatest contribution and 1 being least important, thus having the lowest contribution. You can assign more than one of the same value.
Mark only one oval per row.

	1	2	3	4	5
Floors					
Columns					
Walls					
Waterproofing					

4. **(Q2) - We would like the express the overall condition of the asset "ACCESS COMPONENTS" as a summation of the condition of the individual components. How would you rate the contribution of each component towards the overall condition of the asset "ACCESS COMPONENTS"? ***
Express your answer as a rating out of 5. With 5 being the most important, thus having the greatest contribution and 1 being least important, thus having the lowest contribution. You can assign more than one of the same value.
Mark only one oval per row.

	1	2	3	4	5
Internal Ladder					
External Ladder					
Manhole					
Ventilator					
Other Fixtures					

5. **(Q3) - We would like the express the overall condition of the asset "DRAINAGE" as a summation of the condition of the individual components. How would you rate the contribution of each component towards the overall condition of the asset "DRAINAGE"? ***

   Express your answer as a rating out of 5. With 5 being the most important, thus having the greatest contribution and 1 being least important, thus having the lowest contribution. You can assign more than one of the same value.

   Mark only one oval per row.

	1	2	3	4	5
Floor Drainage	◯	◯	◯	◯	◯
Wall Drainage	◯	◯	◯	◯	◯

6. **(Q4) - We would like the express the overall condition of the asset "PIPEWORK" as a summation of the condition of the individual components. How would you rate the contribution of each component towards the overall condition of the asset "PIPEWORK"? ***

   Express your answer as a rating out of 5. With 5 being the most important, thus having the greatest contribution and 1 being least important, thus having the lowest contribution. You can assign more than one of the same value.

   Mark only one oval per row.

	1	2	3	4	5
Inlet Pipe	◯	◯	◯	◯	◯
Inlet Valve	◯	◯	◯	◯	◯
Outlet Pipe	◯	◯	◯	◯	◯
Outlet Valve	◯	◯	◯	◯	◯
Scour Pipe	◯	◯	◯	◯	◯
Scour Valve	◯	◯	◯	◯	◯
Overflow Pipe	◯	◯	◯	◯	◯
Waterproofing	◯	◯	◯	◯	◯

Section 4 - Inspection Recommendations

This section aims to acquire feedback in terms of the best practices with regards to these structures.

7. **(Q1) - What would you recommend as the appropriate inspection interval for the asset "STRUCTURE"? ***

   Choose most appropriate from drop down list.

   Mark only one oval.

   ◯ 1 year
   ◯ 2 years
   ◯ 3 year
   ◯ 4 year
   ◯ 5 years
   ◯ > 5 years
   ◯ >10 years

8. **(Q2) - What would you recommend as the appropriate inspection interval for the asset "ACCESS COMPONENTS"? ***
Choose most appropriate from drop down list.
Mark only one oval.

- 1 year
- 2 years
- 3 year
- 4 year
- 5 years
- > 5 years
- >10 years

9. **(Q3) - What would you recommend as the appropriate inspection interval for the asset "DRAINAGE"? ***
Choose most appropriate from drop down list.
Mark only one oval.

- 1 year
- 2 years
- 3 year
- 4 year
- 5 years
- > 5 years
- >10 years

10. **(Q4) - What would you recommend as the appropriate inspection interval for the asset "PIPEWORK"? ***
Choose most appropriate from drop down list.
Mark only one oval.

- 1 year
- 2 years
- 3 year
- 4 year
- 5 years
- > 5 years
- >10 years

11. **(Q5) - What would you recommend as the appropriate inspection interval for the asset "ROOF"? ***

Choose most appropriate from drop down list.

Mark only one oval.

- 1 year
- 2 years
- 3 year
- 4 year
- 5 years
- > 5 years
- >10 years

Thank You for Your Participation

Thank you very much for your participation in this survey, your time and effort is most appreciated.

Your input is invaluable to this research.
