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Functional Requirements for Permanent Diaphragm Walls

Master of Science Thesis in the Master's Programme Structural Engineering and Building Technology

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Abstract

There is growing experience of constructing diaphragm walls in Sweden. The experience is still scarce and somewhat limited to few projects. One of the concerns regarding the walls is the ability to assure the quality of them as permanent structures. Due to these uncertainties and limited experience clients such as Trafikverket are reluctant to use diaphragm walls as permanent structures. Trafikverket wants to be able to describe and require the desired performance of diaphragm walls. This can be achieved with the aid of functional requirements, where desired functions of the permanent diaphragm walls are formulated as requirements. This has not yet been performed for diaphragm walls and remains an unanswered question. The use of functional requirements gives more freedom to design, which can lead to new technical solutions and materials in such structures. This is important in order not to prevent development and innovative solutions. The aim of this study was to investigate and to identify the necessary needs and restrictions concerning diaphragm walls as permanent structures and propose relevant functional requirements. Requirements were then identified and structured in levels, from general ones to detailed functional criteria with reference to corresponding methods for verification.

Keywords: Permanent diaphragm walls, diaphragm walls, functional requirements, performance-based design

Preface

The project was carried out between January and June 2014 at the Department of Civil and Environmental Engineering, Division of Structural Engineering at Chalmers University of Technology, Gothenburg, Sweden. The thesis work was performed for NCC AB as part of bigger project carried out for the Swedish Road Administration (Trafikverket).
We would like to thank our supervisors Alexandre Mathern at NCC and Björn Engström at Chalmers for their support and guidance throughout the thesis work. Björn Engström was also the examiner. We would also like to thank the employees at NCC, especially Christina Claeson-Jonsson, Staffan Swedenborg and Tara Wood for their time spent in discussion on the matter. Furthermore, we would like to thank our opponents Arnór Gudmunsson and Freyr Gudmundsson for their collaboration during this semester.

Gothenburg Sweden, June 2014

Gudjón Ólafur Gudjónsson
Jón Grétar Höskuldssson

Contents

1 Introduction

1.1 Background

Diaphragm walls are used as retaining structures in excavation of soil. They prevent the surrounding soil from collapsing into the excavated part, Mahesar and Masiuddin (2004). Diaphragm walls can be used for underground structures, such as infrastructural tunnels or foundations.

Alternative methods for retaining structures are steel sheet piles and secant piles, Alén et al. (2006). The sheet piles are dominant in the Swedish market today especially in the marine environment. During installation the sheet piles are driven down with force, which processes high noise and vibrations. Secant piles are concrete piles cast underground. They are flexible and often without effective reinforcement.

Diaphragm walls are considered stiff and watertight structures that can extend great distances both horizontally and vertically. The construction of the walls minimises noise and vibration compared to construction of sheet pile walls.

There are two main types of constructing diaphragm walls. The difference lies in their usage as temporary or permanent structures. Temporary diaphragm walls are used only as retaining walls during construction of other permanent structures. The permanent diaphragm wall on the other hand serve both as a retaining wall and as a part of a permanent load bearing structure. Temporary diaphragm walls often require more space on the construction site than the permanent ones. This is because the final structure needs to be built on the inside of the temporary walls, usually few meters from the walls on each side. It can therefore be more advantageous to combine the retaining wall and the final structure with a permanent diaphragm wall, especially in urban areas, Alén et al. (2006). Example of diaphragm walls in an urban area can be seen on Figure 1.1.

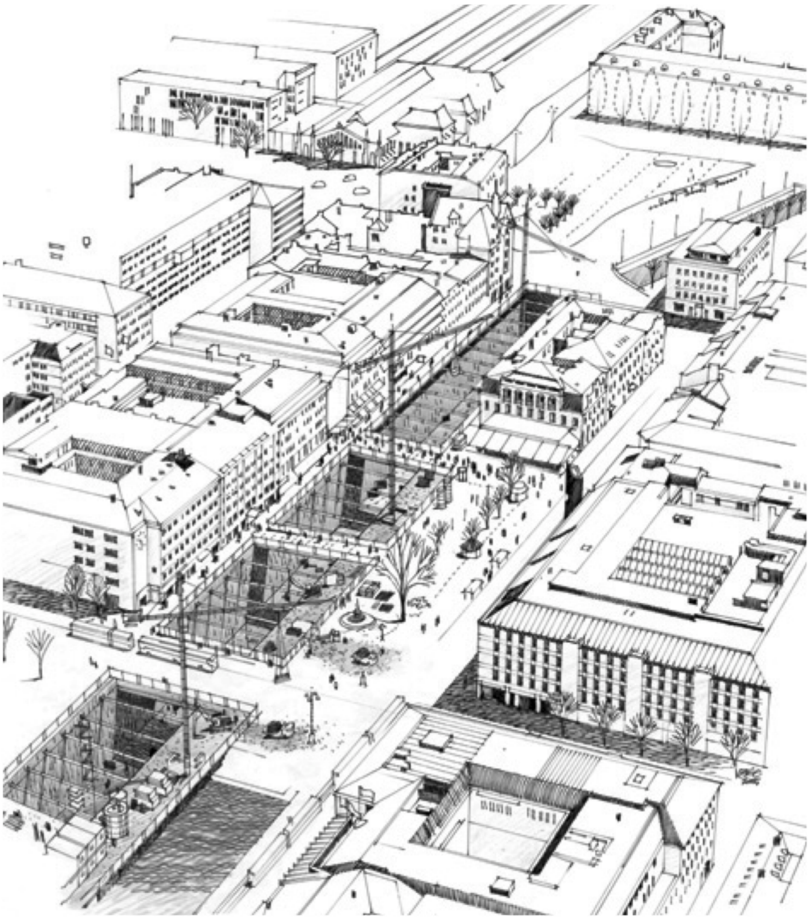

Figure 1.1: Västlänken, planned excavation at Brunnsparken, Gothenburg, modified from Banverket (2005)

The procedure of constructing diaphragm walls starts with the excavation of a trench, which will act as a form. Supporting fluid is provided into the trench during excavation to ensure stability of the trench. After the excavation a reinforcement cage is lifted in and concrete is cast from bottom up as an underwater casting, Wood (2006).

This type of structures is widely used around the world both for temporary and permanent structures. In Europe it has especially been used in England and Germany, Jansson and Wikström (2006).

There is a growing experience of constructing diaphragm walls in Sweden. The experience is still scarce and somewhat limited to few projects. The major ones are the tunnel projects, the Götatunnel (2006) in Gothenburg and the Citytunnel (2008) in Malmö, where diaphragm walls were used as temporary retaining walls, Alén et al. (2006). Most recent projects include a permanent diaphragm walls in housing project in Malmö (2011) and a temporary diaphragm walls in industry project in Helsingborg (2013). Both projects used diaphragm walls in foundations, NCC Construction (2010a), NCC Construction (2010b).

1.2 Problem description

In 2004 the Swedish Road Administration (at the time Vägverket) and the Swedish Rail Administration (Banverket) with the financial support of the Development Fund of the Swedish Construction Industry conducted a development project on permanent diaphragm walls. The purpose of the project was to clarify whether diaphragm walls could be accepted as permanent structures and if so identify necessary requirements and restrictions. The project work was finished with the report "Diaphragm walls as permanent structures" in June 2006, Alén et al. (2006), where it was stated that diaphragm walls can be accepted as permanent structures, but certain issues remained in order to ensure the quality of the walls.

Diaphragm walls are of interest to the Swedish Road Administration (Trafikverket) for future projects since they have been accepted as permanent structures. According to Harryson (2014-03-04), Trafikverket wants to be able to describe the desired performance of diaphragm walls. This can be achieved with the aid of functional requirements, where desired functions of the permanent diaphragm walls are formulated as requirements. This has not yet been performed for diaphragm walls and remains an unanswered question.

The building process today mainly bases the design and construction procedures on law, codes and regulations. This according to Ang and Hendriks (2010) restricts development of new technical solutions and new materials in the construction industry. In order not to limit possible solutions from the beginning a new approach is needed, a performance based approach. The approach is described by Gibson (1982) as

> "the practice of thinking and working in terms of ends rather than means. It is concerned with what a building or building product is required to do, and not with prescribing how it is to be constructed."

It is also stated further by Gibson (1982) that

> "The performance approach permits new developments to be exploited, while safeguarding and assuring a level of quality adequate for the purpose in question. "

For the quality to be ensured the expected performance needs to be described and structured in a way that is applicable to any project.

1.3 Objectives

The objectives of the studies were to analyse typical situations and conditions of permanent diaphragm walls, then to identify desired performance aspects in order to formulate functional requirements, and finally to propose verifying methods to show that the functional requirements are fulfilled. To represent the requirements and the verifying methods in a optimal manner a structure of the requirements in different levels should be developed.

1.4 Method

The project was to be carried out in form of a research study on desired performance aspects of permanent diaphragm wall. The process should include literature study of reports, relevant standards and previous projects in Sweden. Interviews with experienced persons should also be conducted to include first hand experience. The development of the requirements was supposed to include a number of iterations and revision of the requirements in order to represent the desired performance in a clear and proper way. The requirement structure should be based on previous experience in performance-based design.

1.5 Outline

Introduction to the project is presented in Chapter 1 which includes background, problem description, objectives and method. In Chapter 2 a description of permanent diaphragm walls is presented as well as erection methods and previous experience on permanent diaphragm walls. The structure of requirements and previous experience in performance based design are presented in Chapter 3. The identified requirements for permanent diaphragm walls are presented in Chapters 4 to 9, where Chapter 4 includes five overall requirements and the next five chapters (Chapters 5 to 9) include more detailed requirements that fall under the five overall requirements. Chapter 10 presents a discussion and Chapter 11 the conclusion of the thesis work.

2 Diaphragm walls

2.1 Description

Retaining walls are used where risk of failure in soil is present during excavation. The retaining walls can also prevent changes in ground water levels during construction. Diaphragm walls are one of the possible approaches for constructing a retaining wall. The role of diaphragm walls can vary, since they can be designed as permanent structures or temporary supports.

The walls are constructed in panels. The panels can be cast in situ or precast as described in CEN (2010) and DFI (2005). The advantages of using diaphragm walls as permanent structures are many, but there are also some disadvantages as discussed in Alén et al. (2006).

Advantages:

- Rigid structure and dense material
- Small environmental impact
- Economic
- Less space consuming during construction

Disadvantages:

- Uncertainties regarding design
- Uncertainties regarding construction
- Little experience in Sweden
- Risk of leakage through joints between panels

2.2 Erection

When constructing a diaphragm wall the technique used is called "the slurry trench technique", which is originally from USA according to Jansson and Wikström (2006). The erection sequence can be seen in Figure 2.1. The technique mainly consists of:

- Excavation of trench
- Supporting fluid provided for stability
- Reinforcement cage lifted in
- Concrete cast from bottom up

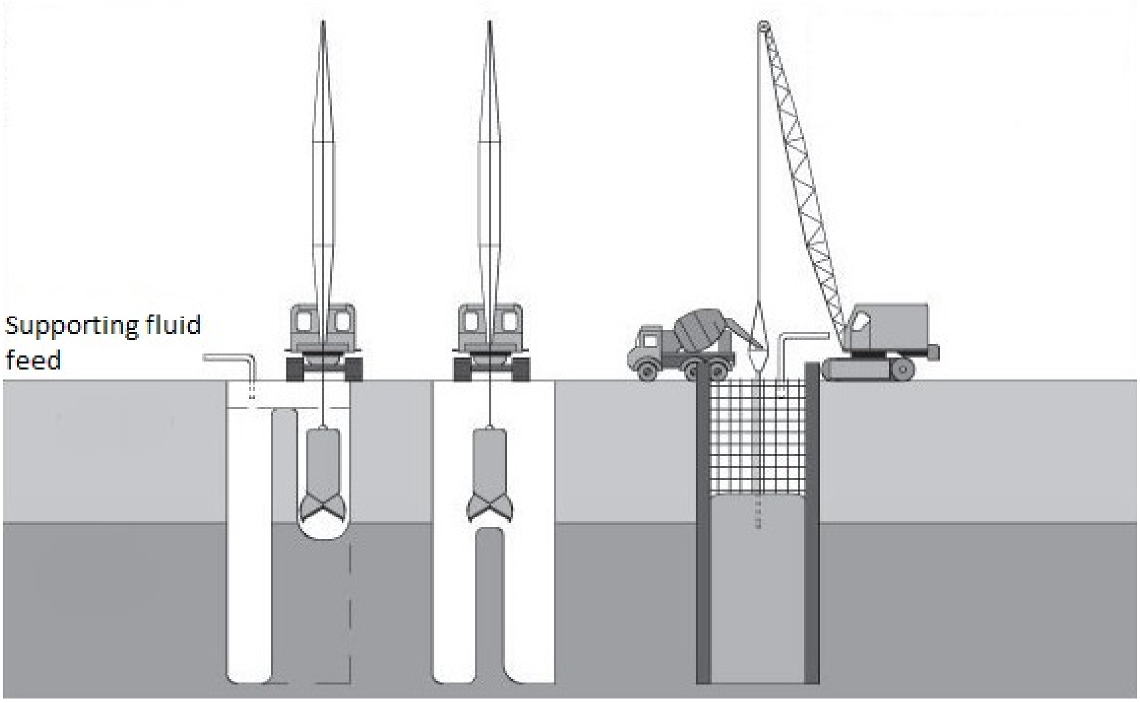

Figure 2.1: Erection sequence of diaphragm walls, modified from Webster (2014)

First a guiding wall is constructed to establish the outline of the diaphragm wall and is refereed to as guide wall, Alén et al. (2006). The guide walls lie parallel to the trench and provide guidance for the excavating equipment. These walls can be made out of precast units or cast in-situ, DFI (2005). The guide walls also prevent collapse of the trench close to surface, CEN (2010).

Then the excavation of the trench starts. Special equipment is used, which can vary both in size and type. The type of equipment used is determined from the conditions and characteristics of the soil. The surrounding soil is used as form and therefore the size of the equipment decides the thickness of the wall. For example a different equipment is needed when excavating through soils with a lot of boulders, Alén et al. (2006).

During excavation the trench is kept full of a supporting fluid and more fluid is added continuously as the trench gets deeper. The fluid condition has to be monitored to ensure that the characteristics are within specified limits. The role of the supporting fluid is to establish stability of the trench. As the surrounding soil varies the mixture of the supporting fluid has to be mixed accordingly. The supporting fluid should also form a layer on each side of the trench to prevent leakage of water from the surrounding soil and vice versa, Wood (2014-02-26). The supporting fluid "is usually a bentonite suspension, a polymer solution or hardening slurry", according to CEN (2010).

When the excavation of the trench is finished, special fabricated stop ends are put in place between panels. The next step is to lift in the reinforcement cage. This phase varies as the panels have different purposes, for example if they are primary or secondary. The reinforcement cage can be equipped with spacers to ensure adequate concrete cover, Swedenborg (2014-02-21) . Example of end stops can be seen in Figure 2.2.

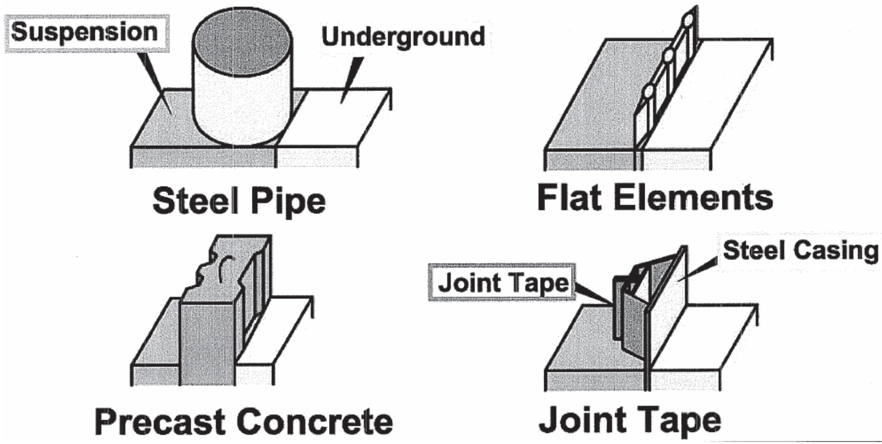

Figure 2.2: Example of vertical joint details for diaphragm walls, modified from Alén et al. (2006)

Before casting the characteristics of the supporting fluid should be verified and when needed, replaced by a new one, CEN (2010). This is performed to minimise the risk of having contaminated supporting fluid. Concrete is then cast from bottom up. The concrete is poured down to the bottom through so called "tremie pipes". The pipes are then lifted during casting but should always be kept submerged in the concrete. The casting speed should fulfill recommendations and be kept at constant rate. The reason is to reduce the risk of having the concrete contaminated with supporting fluid and ensure homogeneous distribution over panels, Alén et al. (2006).

2.3 Previous experience

2.3.1 The Götatunnel project

In the year 2006 an 1.6 km long traffic tunnel was opened in the city centre of Gothenburg. The tunnel consists of an 1 km long rock tunnel and 590 m long parts constructed with the cut and cover method. The cut and cover method was used on both ends of the tunnel. Sheet pile walls were used as temporary support on the west end (Järntorget) of the tunnel. Diaphragm walls and sheet pile walls were then used as temporary supports on the east side (Lilla Bommen). The depth of the diaphragm walls varied from 13 to 30 meters below ground. In total 100 m of longitudinal walls were constructed with 4.5 m long panels and 1.2 m wide. Transverse walls were then constructed between the longitudinal walls with panels 4.5 m long and 0.8 m wide.

Series of tests and inspections were carried out on the diaphragm walls, which were evaluated by Mahesar and Masiuddin (2004) . The following possible problems were identified, which are relevant with regard to performance criteria.

- Water leakage through joints
- Uneven concrete cover
- Cracks at panels surface
- Mixing of bentonite with concrete
- Reduced bond strength
- Crack width problems

2.3.2 The Citytunnel in Malmö

The Citytunnel in Malmö was opened in 2010. The project consisted of constructing railways, a railway tunnel and railway stations. Diaphragm walls and sheet pile walls were used as temporary supports around part of the tunnel and stations, Nordberg (2008). In relation to this project a special reference panel was cast and a temporary diaphragm panel was selected for detailed inspections. The reference panel was cast using normal formwork and without any supporting fluid. Both panels were then equipped with special vertical reinforcement bars for pull out tests, Magnusson and Mathern (2013).

A report based on the test results from the Citytunnel project was published in the report by Magnusson and Mathern (2013). In the report the effect of casting technique on the bond strength and concrete strength was evaluated. Part of the conclusions from the report are:

- According to the tests carried out at the Citytunnel project, the concrete diaphragm wall panels reached the same strength as the concrete cast in the reference panel. Therefore it was concluded that casting under bentonite slurry and with earth as form did not seem to have negative effect on the concrete strength.
- The bond strength of the bars in the diaphragm wall panels at the Citytunnel project was found to be at least 40% lower in average than the one of the bars in the reference panel. These results indicate that casting under bentonite can significantly reduce the bond strength.
- However, the bond strength values obtained for the bars in the diaphragm wall panels at the Citytunnel project were found to be consistent with other experimental results from the literature and with code predictions. It seems rather that the values from the reference panel were specially high.

- In light of the contradictory results further research is needed to investigate the influence of casting in bentonite on the bond between reinforcement bars and concrete.

2.3.3 Development of diaphragm walls for more economic design

A project concerning more economic design of diaphragm walls was carried out by Skanska Sweden AB. The results from the project were published by Hedlund and Wiberg (2013). The aim of the project was to develop frost resistant concrete, placed below water level, that would fulfill the requirements for exposure classes in road tunnels. The effect of the supporting fluid on the bond strength between the concrete and reinforcement was also studied. The supporting fluid used was bentonite slurry.

Part of the conclusions from the report are:

- Underwater frost resistant concrete was developed. The concrete is self compacting and fulfils the exposure classes for road tunnels. Testing were conducted both in the factory and on the finished structure. The results of freezing tests of drilled cylinders showed very good frost resistance in all walls that were cast.
- Studies of the drilled cylinders showed in many cases a thin coating of bentonite slurry around the reinforcement. This happened more frequently on the reinforcement bars nearest to the form where the concrete can not move freely and between two closely adjacent reinforcing bars.
- The testing of the bond strength showed that the strength was much lower when casting in a bentonite supporting fluid rather than casting without a supporting fluid. From the literature study similar results were observed. An assessment of the study shows that the bond strength can be about 30-40 % lower when cast with a supporting fluid.

2.3.4 Diaphragm walls as permanent structures

An industry wide development project was initiated to investigate if diaphragm walls could be accepted as permanent structures, Alén et al. (2006). The project was financed by the Swedish Road Administration, Swedish Rail Administration and the Development Fund of the Swedish Construction Industry (Vägverket, Banverket and SBUF).

The project team was appointed to represent expertise in various areas relevant to diaphragm walls. An interdisciplinary group representing the government, contractors, consultants and universities met two times during the project work. Individual persons in the interdisciplinary group were also interviewed for their special knowledge and experience.

After the initial work, which included literature studies and seminars, Vägverket and Banverket chose to concentrate the work on the following areas:

- Resistance of diaphragm wall, especially issues concerning requirements for materials and execution, constructive solutions and crack width limits.
- Geotechnical issues specifically related to the diaphragm wall tightness, quality and durability.
- Influence of the supporting fluid on diaphragm wall characteristics.
- International experience - Clients and contractors were interviewed about experiences in the construction phase and during the service life.

The work was then based on literature studies, surveys among clients and contractors, interviews with experts and authorities about their experience of diaphragm walls. For the investigation about supporting fluid's impact on diaphragm walls field tests from the Citytunnel in Malmö were used.

The conclusion of the project work was that with current knowledge diaphragm walls can be used as permanent structures with certain conditions, Alén et al. (2006):

- The water cement ratio shall not exceed 0.5.
- In structures with exposure classes corresponding to road environment or dry indoor environment, an inner concrete wall shall be constructed.
- The characteristic crack width in other exposure classes than above should not exceed 0.4 mm in the construction stage and 0.3 mm in the permanent stage. The tightness requirements also need to be fulfilled.
- The anchorage and splice lengths of reinforcement bars should be increased by 10%.

The project group also identified some issues that should be investigated further:

- Magnitude of loads from the soil on the diaphragm walls.
- The impact of diaphragm walls tightness on the surrounding area.
- A more efficent way to formulate the crack width limit to manage problems related to the tightness, durability and environmental impact, both in construction and permanent stages.
- The impact on the concrete properties such as: compressive strength, bond strength and the density of supporting fluid, admixtures and workmanship.

Key factors in achieving good quality of permanent diaphragm walls were identified as:

- Good workmanship and experience of diaphragm walls are crucial for good quality.

- Collaboration between the designer, contractor and the client is essential to achieve good results.
- Reinforcement design and detail solutions for joints should be given special care. Too densely reinforced structures can be unfavourable.
- Supporting fluid characteristics based on monitoring has a crucial impact on the quality of the end product.

3 Introduction to requirements

The early steps of building design begin with identifying the client's/owner's needs for a structure. This structure will have a certain purpose for the client and therefore needs to be built. The most important step is the one that follows, which is called conceptual design. In that process the purpose is studied further and other needs are identified. This may go back and forth during the conceptual design, but eventually leads to a finalised idea of a structural concept based on the identified performance criteria. From there the detailed design can begin, Engström (2013).

In large projects the owner often prefers to leave the detailed design to the contractor. This is established in the form of design-built contracts. There the contractor develops and produces the technical solutions, which fulfil the requirements given by the client. This approach creates possibilities of solutions, which the client did not forsee, and can be more economical. Furthermore, the project can start before the design and drawings are finalised, Mathern (2013).

To satisfy the specified needs the conceptual design has to be performed thoroughly, since poorly developed performance criteria can lead to poor solutions. In the following sections the formulation of requirements and how they can be structured in different levels are described further.

3.1 Previous experience in performance-based design

The building process today mainly bases the design and construction procedures on law, codes and regulations. The use of functional requirements is meant to give greater freedom to that design. This can then lead to development of new technical solutions, new materials in construction and other combinations of materials that are more economical, Ang and Hendriks (2010).

There is a growing interest around the world concerning the adoption of design-build tenders on the basis of functional requirements. This is also the case in Sweden, where the Swedish Transport Administration has decided to adopt this more often into their future contracts. There is a great deal of knowledge on performance-based design within Europe. The problem is that this knowledge needs to be spread wider and used more commonly, Mathern (2013). There is also no general format available for performance-based design. When this becomes the case, the implementation of functional requirements into law, codes and regulations becomes much easier.

A number of reports have been published on the matter and the most influencing ones to this thesis work were, Gibson (1982) and Vägverket (2000).A brief description of those reports is presented in Sections 3.1.1 and 3.1.2 respectively.

3.1.1 Working with the performance approach in building

The performance approach is described in Gibson (1982). The summary of the report states:

> "This report provides a state-of-the-art review by CIB/W60 of the performance approach in building practice, against the background provided by building science. Main chapters deal with setting performance requirements, testing potential solutions against criteria, the evaluation of solutions in relation to requirements and techniques for application."

The performance approach is according to the report:

> "The performance approach is, first and foremost, the practice of thinking in terms of ends rather than means. It is concerned with what a building or building product is required to do, and not with prescribing how it is to be constructed."

The report states a number of steps and factors that are important in the formulation and use of performance requirements, those include:

Fields of application:
The performance approach can be used for different fields of application according to Gibson (1982), such as:

- design of single project,
- design of continuing program,
- products,
- design guidance,
- control of design and construction quality

Purpose served:
The formulation of requirements depends on the purpose intended according to Gibson (1982), they may be:

- specific building projects,
- design data and guidance,
- product development and marketing,
- quality control

Type of participant:
The required building performance of a structure depends on the type of participants, since different sets of participants have different types of interest in the structure. Although they can overlap to some extent, they can be split up in 7 categories according to Gibson (1982):

- The community
- Building users
- Clients
- Designers
- Builders
- Manufacturers
- Insurers

Types of documents:
Documents can be arranged for any of the participants mentioned above; the content may range from general to particular and may originate form different organisations. This is why they need to be established carefully to ensure that their technical contents are complementary, consistent and up-to-date. According to Gibson (1982) the document should include:

- Check lists
- General lists of performance requirements
- Design data and aids
- Performance specifications
- Building regulations
- Standards
- Product literature
- Agreement certificates

Document structure:
The documents should have a clear and visible structure; the order however may vary according to circumstances. According to Gibson (1982) the heading of principal clauses are:

- Purpose and context of use
  - Role
  - Relevant agents
- Performance requirements
  - Definition of performance
  - Methods of assessment or verification
  - Performance values

  - Commentary

The Necessary knowledge base:
According to Gibson (1982) effective use of the performance approach depends on knowledge of:

- Users needs
- Context
- Behaviour in use
- Predictive methods

Selecting criteria:
A criterion is a way to measure the performance attributes. According to the report it is very important to be able to measure fulfilment of the requirements, or as it is stated in Gibson (1982):

> "It is of little use defining requirements unless they can be satisfactorily tested."

The selection process is therefore very important and the requirements should be selected with care according to circumstances, or as it is stated in Gibson (1982):

> "Performance requirements may need to be selected by designers when specifying products to be used in building, ... , The importance of particular requirements varies according to circumstances, but often it will be both possible and desirable to concentrate on relatively few 'prime' attributes which decide the character and acceptability of a solution".

Methods of selecting criteria:
According to Gibson (1982) there are five methods of selecting criteria, see below. They are not mutually exclusive. For example the first one is always used in combination with one or more of the others.

- Subjective selection
  - by an individual expert
  - by a group
- Selection based on the availability of test methods
- Selection based on functional analysis
- Selection based on feedback from products in use
  - complaints and records of failures
  - surveys of products in use
- Selection based on the study of user requirements

Comments:
The report is very general and could be applicable to a wide range of performance-based requirements. Because how general the report is on the matter, it can not be used to directly establish requirements for specific structures. It is rather an important tool when it comes to formulation of requirements, what aspects that need to be considered, how they are presented and which are to be included.

3.1.2 Verifying methods for the procurement of bridge properties

A project on functional requirements in design of bridges was carried out by the Swedish Road Administration, Vägverket (2000). The purpose of the study was to develop and describe the terms for functional requirements for bridges and to clarify the problems with the verifying methods.

The project suggested that during formulation of requirements, functional requirements should be independent of each other and as few as possible. Even if this is not possible to the fullest, it should be kept in mind in the formulation process. To ensure that the functional requirements are fulfilled, the project proposed that every requirement needs to be verifiable, quantitatively or qualitatively. This is performed by structuring the requirements in different levels. The levels that the project suggested are, from the highest to the lowest, objectives, functional requirements, functional criteria and acceptable solutions. An example from the report on how the requirements are structured can be seen in Figure 3.1. Each level is described further in the following sections in this chapter.

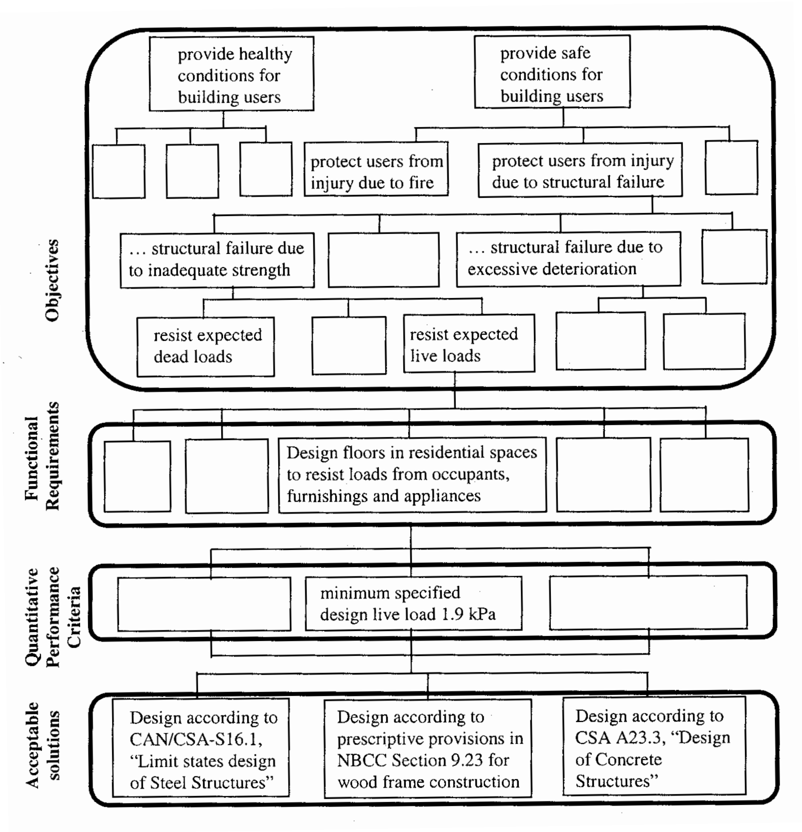

Figure 3.1: Example of how functional requirements can be structured, modified from Vägverket (2000)

Objectives:
Objectives are to identify overall goals for road transport systems like traffic safety, environmental concerns, availability, etc. These goals are then broken down into events that affect the objectives of the project. When the objectives have been broken down to specific events, the objectives are said to be identified. After this has been established the functional requirements can be defined. The project suggested that objectives for bridges might be the following:

- Availability / Accessibility
- Durability
- Road safety
- Environment
- Aesthetics
- Cost-effectiveness
- Optimum service life

- Flexibility
- Robustness

Functional requirements:
Functional requirements are defined as requirements set on different type functions to ensure that the objectives are fulfilled. First there are wide functional requirements, which are set for the whole structure. These are then broken down to specific parts of the bridge. When it is hard to establish functional requirements, a requirements on properties can be used instead. Another possibility, when the objectives are inconclusive in identifying functional requirements on structures or structural parts, is to structure the functional requirements at a higher level. This is performed with respect to various stakeholders that require a bridge. Stakeholders can be broken into:

- Parliament / Government
- Road manager
- Users
- Third parties

Functional criteria:
When the functional requirements have been broken down to a level where they can be quantified, they are called functional criteria. Functional criteria need to be relatively easy to measure and evaluate. There is thou a limit on how detailed they can be defined, since they should not reduce the freedom in design, the possibility to come up with new solutions.

Acceptable solutions:
The acceptable solutions can be for example verifying methods, technical solutions or products that ensure that the functional criteria are fulfilled. The possibility of using other types of methods is allowed, if it can be shown that the functional criteria are fulfilled. Verifying methods can be based on:

- Measurements
- Tests
- Forecasting models
- Calculations

Comments:
The project reported by Vägverket (2000) establishes a good structure of the requirements for bridge construction and describes each level thoroughly. The structure can be used in a similar form for other types of structures. The project implies, however, that within each requirement there can exist many sub-requirements. This can cause misunderstandings and misinterpretation of the requirements. As the project suggested the requirements should be independent of each other and as few as possible.

3.2 Proposed levels of requirements

The requirements are structured in three levels, from general ones that describe the overall performance (general requirements), to detailed performance of the structure (functional requirements), down to specific functions of the structure that can be measured in some way (functional criteria).

Each level does not have any sub-levels, meaning that when a requirement needs to be described in a more detailed way a new level is formed. This also means that requirements in the same level are independent of each other. The requirements do not include any possible solutions, but they only describe the desired performance of the structure in different levels.

There are relatively few prime attributes in the highest level (general requirements). They are meant to describe and set the character for more detailed performance requirements (functional requirements). The functional requirements describe the desired function of the structure in a more detailed way. In order to measure the functional requirements there are specific performance requirements (functional criteria), which are verifiable in some way. The functional criteria should be given in specific values or over a certain range. Such values are however not proposed in this report, since this may vary for each project. The users of the functional requirements are meant to assign their own values that suit their needs, i.e. what they require in order for a solution to be regarded as fulfilled. It is thou recommended not to assign too specific values unless in absolute necessity.

General requirements: Overall performance of the structure
Functional requirements: Detailed performance of the structure
Functional criteria: Specific performance of the structure that is verifiable.

Functional requirements become fulfilled when their functional criteria are fulfilled. When all the functional requirements are fulfilled, the general requirements become fulfilled and the solution can be regarded as acceptable.

For more detailed description of each level, see the following sections.

Example of use: (for clients to set requirements that the contractor has to fulfill) The client desire serviceability of the structure to be fulfilled. This is why the client requires certain tightness (among other functions) of the structure. The client sets specified limits on the functional criteria that are given for tightness, e.g. in the form of certain limited flow through the material. When the contractor has shown that all the criteria under tightness are fulfilled then the tightness requirement is fulfilled. When the contractor has shown that all the functional requirements (all other requirements in the same level as tightness) are fulfilled, the client can be certain of that the serviceability of the structure is ensured.

3.2.1 General requirements

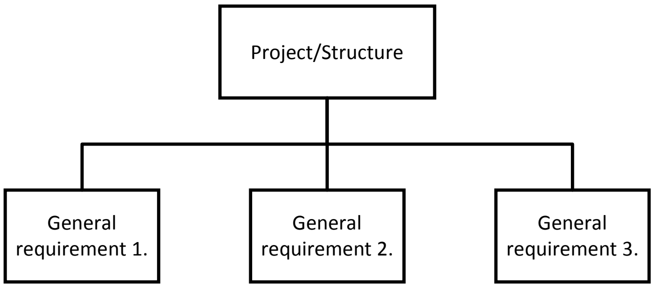

Figure 3.2: General requirements

The general requirements are overall requirements which underline the scope of the project, see Figure 3.2. They classify the requirements and serve as a fundamental basis for other more detailed requirements. The general requirements are not limited to one type of structure/projects, but are more general.

Example of general requirement, *Serviceability*:

> "All aspects of the serviceability of the structure should be fulfilled", for further description see Section 4.2

3.2.2 Functional requirements

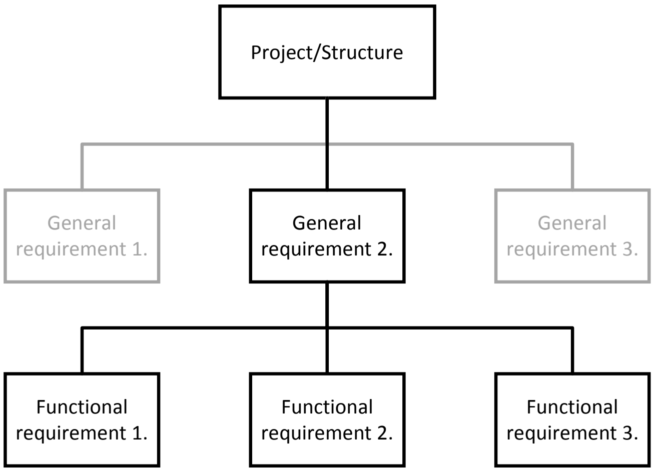

Figure 3.3: Path from general requirements to functional requirements

Functional requirements describe certain aspects of the desired performance of the structure. Each functional requirement defines an important factor to the general requirement it is categorised under, see Figure 3.3. Carefully developed functional requirements are necessary to ensure the quality of the structure. They should therefore cover all necessary aspects of the structure in order to fulfill the clients needs. A structure reaches its full potential, when the functional requirements are considered throughout each stage of the project, from early design to the owner's operation, Vägverket (2000).

Example of functional requirement, *Limited deformation,* (falls under Serviceability):

> "The serviceability of a structure should not be endangered by deformations". For further description see Section 6.3

3.2.3 Functional criteria

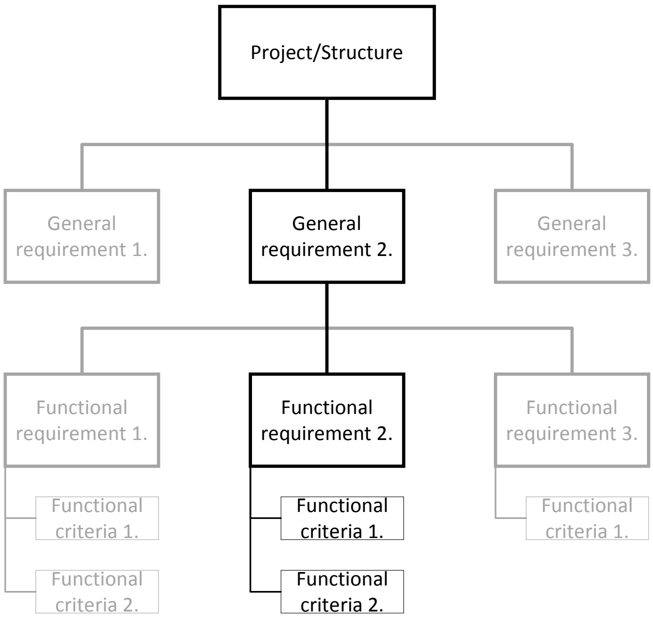

Figure 3.4: Path from general requirements to functional criteria

When the functional requirements have been broken down to the level where they can be measured, they are called functional criteria. This is the lowest level of the requirements, see Figure 3.4. The functional criteria are expressed in specific limit values. It is therefore important to establish verifying methods for each criterion. They should be case specific and easy to measure and evaluate. They should however not be too specific in order not to limit possible solutions. They should be established on known principles or other forecasting methods,Vägverket (2000).

Each functional requirement has one or more functional criteria that falls under it. Each criterion needs to be verified, before the requirement can be considered fulfilled. In order to give examples of functional criteria all the criteria in this report are related to the required properties of permanent diaphragm walls. It should also be noted that in some cases the same functional criterion can be located under more than one functional requirement. This is the case when the same factors need to be verified for different requirements.

There are many ways to verify the functional criteria. First there are measurements of any sort. Then there are predictive methods which, according to Gibson (1982), are testing (laboratory and full-scale), calculations and known solutions.

Example of functional criterion, *Limited permanent wall deformation,* (falls under Limited deformation - Serviceability):

"The wall should not deform in its transverse direction more than 1:100 of its length due to short term or long term influences". For further description see Section 6.3.1

3.3 Possible solutions

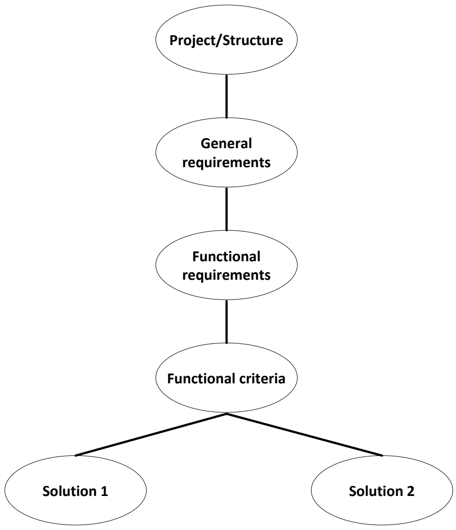

Figure 3.5: Path from requirements to possible solutions

Possible solutions are formulated with regards to the requirements and should fulfill them at all time. They are not directly a part of the requirements but rather a way to fulfill them. Figure 3.5 shows the possibility of having different solutions that all fulfill the requirements. The possible solutions come in the form of technical solutions and products, Vägverket (2000). There are two classes of possible solutions and they are categorised on how detailed they are. First are overall solutions, which are products that fulfill all the requirements. These can be structural systems or whole structures. Then there are detailed solutions, which are technical solutions or detailed products that constitute one structural system. Many detailed solutions can be included in one overall solution and each of them has to fulfill its requirements.

Example of overall solution, *A certain diaphragm wall*:

"A certain diaphragm wall can be accepted as a solution if every aspect of the wall fulfills the requirements given".

Example of detailed solution, *Wall with sufficient stiffness,* (falls under Limited permanent wall deformation - Limited deformation - Serviceability):

"The stiffness of the wall is sufficient enough to show that it does not deform at any time more than 1:100 of its length under all possible loads".

3.4 How to use the requirements

In this section the steps needed to establish functional requirements on desired performance aspects are described. This could be used in the process of developing requirements for client-builder contracts. For visual representation see Figure 3.6

1. Identify desired performance aspects of the structure. These are the aspects that the client/owner believs are needed to ensure the quality of the structure. They are related to the functional requirement of this report.

2. Compare the desired performance aspects to the proposed functional requirements given in this report, see Chapters 5 to 9

3. Evaluate [Yes/No] if all the identified desired performance aspects are covered by the functional requirements in this report. Keep in mind that if the desired performance aspects are very general, they could be represented as general requirements. Description of the general requirements can be found in Chapter 4.

4. If Yes. Evaluate if there are functional requirements in this report that are not related to the desired performance aspects, requirements that would be too conservative/constraining for the project considered. In such cases those requirements are to be removed from the list. Keep in mind that there might be reasons for their existence other than what was considered as desired performance, for example load bearing aspects that need to be established for all structures.

5. If No. Formulate functional requirements related to the desired performance aspects that are not represented in this report. See Sections 3.3 and 3.3.2 for description of functional requirements. When this is finalised go back to step 3.

6. Formulate functional criteria, see Sections 3.3. and 3.3.3. Assign limits to the criteria and suggest verifying methods. Keep in mind to have them as open as possible in order not to limit the solution and that there might exist criteria in this report that are applicable to the actual desired performance aspects.

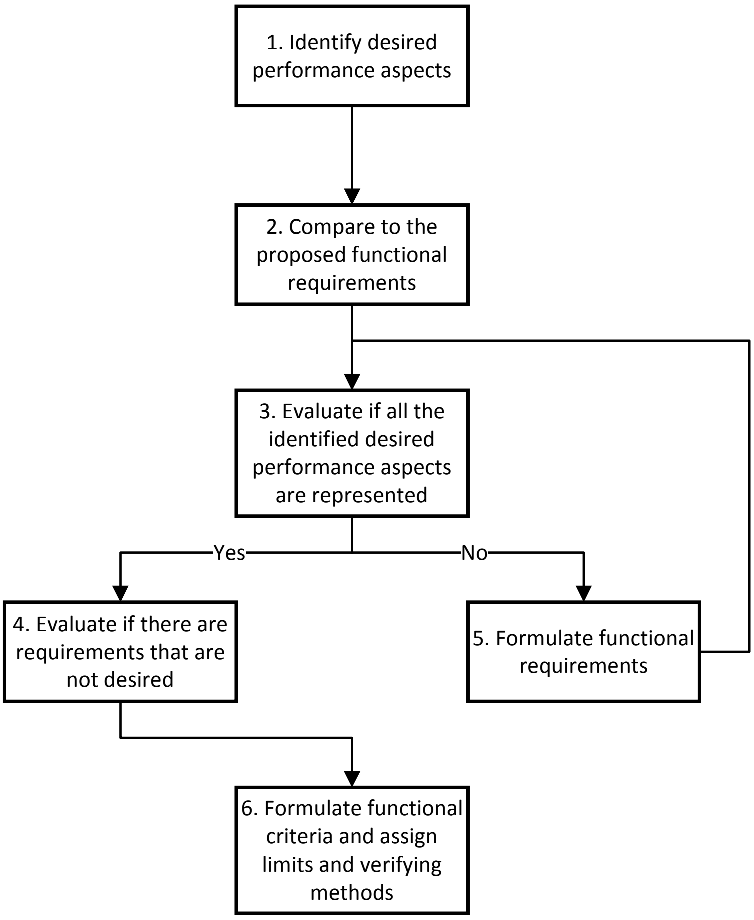

Figure 3.6: Steps needed to establish functional requirements with regards to desired performance aspects

4 General requirements

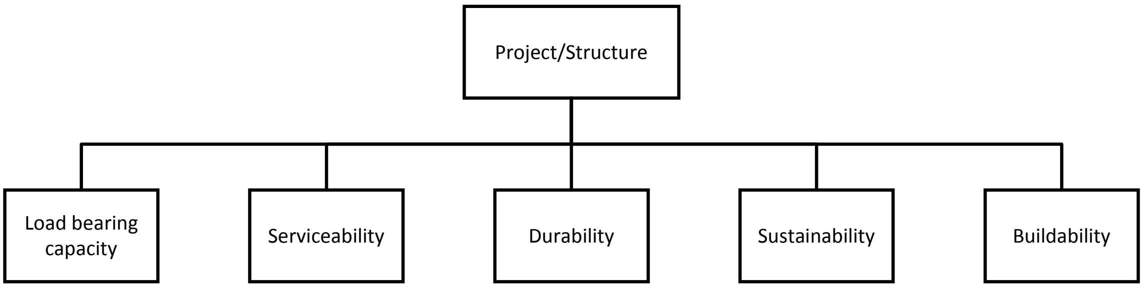

Figure 4.1: General requirements

In this Chapter the five general requirements that were identified in this project are described, see Figure 4.1. In Chapters 5 to 9 functional requirements are proposed and described with their functional criteria, respectively. The requirements, both general and functional, should apply for multiple types of structures. This, however, does not apply to the functional criteria which are related specifically to permanent diaphragm walls.

4.1 Load bearing capacity

Load bearing capacity is a necessary requirement for every man made structure. Load bearing capacity can be defined as the ability of structures and structural systems to safely resist loads. The design should take into account the different environmental conditions during the life cycle of structure. Load bearing capacity is a fundamental requirement that can be found in codes, laws and regulations around the world and is covered in EN-1990 - Basis for structural design, CEN (2002).

4.2 Serviceability

All aspects of serviceability of a structure should be fulfilled. Even though load bearing capacity is ensured, the structure has to remain fit for required service functions, CEN (2002). A verification of serviceability should be established early in projects. Serviceability is a fundamental requirement that can be found in codes, laws and regulations around the world and is covered in EN-1990 - Basis for structural design, CEN (2002).

4.3 Durability

In order for a structure to be durable it should not loose its load bearing capacity and serviceability during its lifetime. In order to achieve durability, effects of the degradation mechanism must be under control and therefore service life design is needed. Structures should therefore be designed and executed for resistance to environmental actions. These requirements can be related to quality control during execution and verification of design, CEN (2002). Durability is a fundamental requirement that can be found in codes, laws and regulations around the world and is covered in EN-1990 - Basis for structural design, CEN (2002).

4.4 Sustainability

Urbanisation where individuals are moving from rural to urban area, is an ever growing trend in the world we live in. The majority of the worlds populations lives in cities today. This tendency will continue to grow in the coming years according to WHO (2014). "By 2030, 6 out of every 10 people will live in a city, and by 2050, this proportion will increase to 7 out of 10 people". The growing cities require large amount of energy for construction, operation, maintenance and decommission of buildings and infrastructure. According to the International Energy Agency, IEA (2014), buildings represent about 40% of the primary energy consumption of today's market. The process also involves substantial use of natural resources and raw materials. It generates emission of greenhouse gases and produces vast amount of solid waste. In order to minimise these effects on the environment the demand for sustainable constructions becomes more vital with every passing year.

Sustainable construction can be said to aim at minimising the environmental impacts, securing economic stability and overall quality during the whole life cycle of the building. In order to clarify the concept better the Holcim foundations, Holcim (2013), definition is appropriate.

> "Sustainable construction aims to meet present day needs for housing, working environments and infrastructure without compromising the ability of the future generations to meet their own needs in time to come"

Many things have to be considered in sustainable construction. Those include design and management, materials performance, construction technologies, monitoring, safety and working conditions, flexibility in usage to name few, Holcim (2013).

Environmental concerns have been increasing lately in modern societies. Sustainability in construction has been proposed as a new approach to apprehend these concerns. According to CEN/TC (2005) and ASCE (2006), many countries are well into the process of making sustainability a part of their codes, laws and regulations. It was therefore considered important to include sustainability in this report as a general requirement.

4.5 Buildability

Buildability governs the ease of construction and is highly related to the project cost. Buildability is of importance for the client-builder aspect. As the term indicates the process is measured on how efficient a building can be constructed. Even so it includes not only that process but also the planning and design of the construction. For the buildability requirement relevant application rules can be found in CEN (2002), both in Section 2.1 "Basic requirements" and in Section 2.2 "Reliability management".

5 Load bearing capacity

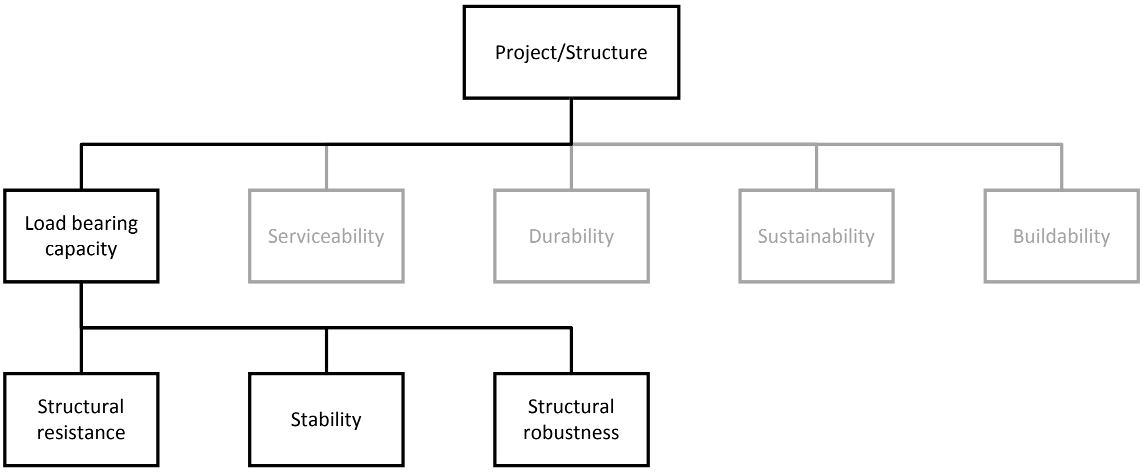

Figure 5.1: Functional requirements for load bearing capacity

Three functional requirements have been identified for load bearing capacity which are structural resistance, stability and structural robustness, see Figure 5.1. They describe the required functions of the structure in relation to load bearing capacity. Detailed description of load bearing capacity as a general requirement can be found in Section 4.1

5.1 Structural resistance - functional requirement

The structure should be able to safely resist all possible loads. Therefore the loads need to be defined correspondingly and take into account different construction stages. During the life cycle of the structure external and internal conditions may change so the capacity of the structure needs to be known. Structural resistance is stated as a principle in EN-1990 - Basis for structural design, CEN (2002). Four functional criteria have been identified for structural resistance which are bending resistance, shear force resistance, tension resistance and buckling resistance, see Figure 5.2.

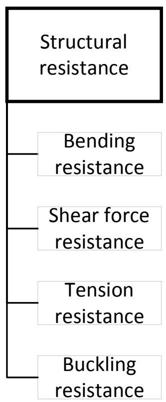

Figure 5.2: Functional criteria for structural resistance

5.1.1 Bending resistance - functional criterion

The structure should be able to safely resist bending moment due to various combinations of possible loads.

- **Method of verification:** Verify bending resistance with calculations assuming loads and load combinations according to codes or adequate testing methods. It can be measured in bending moment.
- **Commentary:**
  - Alén et al. (2006), Section 3.3: The position of props and anchors affects the size and distribution of moment along diaphragm walls.
  - CEN (2010), Section 5.1.1: "The depth and the extent of the geotechnical investigation should be sufficient to identify all ground formations and layers affecting the construction, to determine the relevant properties of the ground and to recognise the ground conditions".
  - CEN (2010), Section 8.2.2.3: "Except where otherwise specified, vertically of the panels (including their ends) shall be 1% of depth in both transverse and longitudinal directions".

5.1.2 Shear force resistance - functional criterion

The structure should be able to safely resist shear force due to various combinations of possible loads.

- **Method of verification:** Verify shear force resistance with calculations assuming loads and load combinations according to codes or adequate testing methods. It can be measured in force.
- **Commentary:**
  - Alén et al. (2006), Section 2.2: Shear force resistance in joint sections between panels is possible with certain types of joints.
  - Alén et al. (2006), Section 3.3: The position of props and anchors affects the size and distribution of shear forces along diaphragm walls.
  - CEN (2010), Section 5.1.1: "The depth and the extent of the geotechnical investigation should be sufficient to identify all ground formations and layers affecting the construction, to determine the relevant properties of the ground and to recognize the ground conditions".

5.1.3 Tension resistance - functional criterion

The structure should be able to safely resist tension force due to various combinations of possible loads. Tension may occur when the structural member is subjected to external load parallel to the longitudinal direction of the member.

- **Method of verification:** Verify tension resistance with calculations assuming loads and load combinations according to codes or adequate testing methods. It can be measured in force.
- **Commentary:**
  - No specific recommendations for tension resistance were identified for diaphragm walls.

5.1.4 Buckling resistance - functional criterion

The structure should be able to safely resist compression force due to various combination of possible loads. Buckling is the sudden global failure of stability in a member under compressive force. At failure the member deflect without control with a displacement perpendicular to the longitudinal direction of the member. The compressive force at buckling may be less than the sectional resistance in compression.

- **Method of verification:** Verify buckling resistance with calculations assuming loads and load combinations according to codes or adequate testing methods. It can be measured in force.
- **Commentary:**
  - No specific recommendations for buckling resistance were identified for diaphragm walls.

5.2 Stability - functional requirement

The structure should be able to safely resist various combinations of possible loads without loosing structural integrity. Overall stability is assured when all forces exerted on the structure are in equilibrium. Stability is stated as a principle in EN-1990 - Basis for structural design, CEN (2002). Three functional criteria have been identified for stability which are soil stability, trench stability and stability of structures, see Figure 5.3.

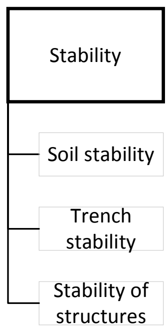

Figure 5.3: Functional criteria for stability

5.2.1 Soil stability - functional criterion

The soil should be able to withstand the loads exerted on it. It is governed by the shear strength of the soil. The stability of soil is influenced by the groundwater and earth pressure. These can vary with time and should be evaluated for any stage of construction.

- **Method of verification:** Verify the stability of the soil according to codes and possible stability risks
- **Commentary:**
  - CEN (2010), Section 7.2.4: "The stability considerations shall take account of the following factors:"
    - Groundwater pressures
    - Earth pressures
    - Shear strength parameters of the soil

5.2.2 Trench stability - functional criterion

Stability of the trench should be ensured during construction in order to be able to erect the diaphragm walls. The stability of the trench in diaphragm wall construction is established by the pressure from the supporting fluid. The fluid is present in the trench during excavation and until the end of casting concrete. The fluid exerts hydraulic pressure on the trench walls causing it to remain stable. The supporting fluid also forms a filter cake on the walls, that inhibits the fluid from flowing out and other liquids of flowing into the trench.

- **Method of verification:** Verify trench stability with the characteristics of the supporting fluid, see CEN (2010) Section 6.2 Tables 1 and 2.
- **Commentary:**
  - Alén et al. (2006), Section 2.2: "Internal shoring and/or backward anchors can be used to ensure stability of the excavation".
  - Alén et al. (2006), Section 3.2.1: The viscosity of the supporting fluid depends on the surrounding soil:
    - Cohesion soil / Clay: Low permeability of soil. In some cases the supporting fluid can consist only of water.
    - Friction soil: High permeability of soil. Supporting fluid must form filter cake to inhibit leakage.
    - Rock: For deep trenches it is not possible to construct diaphragm walls because of too high permeability.
  - DIN (1986), Section 9.1.1: "Pressure of the supporting liquid at any given point should be greater than 1.05 times the groundwater".
  - For detailed instructions on panel stability see CEN (2010), Section 7.2.

5.2.3 Stability of structures - functional criterion

The overall stability of the diaphragm wall should be ensured during construction and during its intended service life. This also concerns the stability of adjacent structures that could be influenced by the erection of the diaphragm walls.

- **Method of verification:** Verify the overall stability of structures for various combinations of possible loads according to codes and verify the stability risks of adjacent structures.
- **Commentary:**
  - Alén et al. (2006), Section 2.2: The panels need to be anchored to the soil because of little connection between panels.
  - CEN (2010), Section 4.2.3: "The survey shall be carried out and be available prior to the commencement of the works and its conclusions shall be used to define threshold values for any movement which may affect adjacent structures by the works area constructions".
  - CEN (2010), Section 7.2.4: One of the factors that shall be taken into account for stability is:
    * Construction details of the adjacent structures.

5.3 Structural robustness - functional requirement

A structure shall be designed and constructed to withstand accidental actions with, depending on the cause, a reasonable limitation of the damage and other consequences. Four functional criteria have been identified for structural robustness which are fire resistance, collision resistance, explosion resistance and earthquake resistance, see Figure 5.4. Robustness is defined in EN 1991-1-7 - Actions on structures, CEN (2006a) as

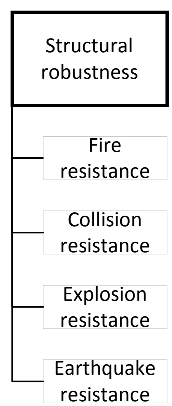

Figure 5.4: Functional criteria for structural robustness

"Robustness is the ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause."

5.3.1 Fire resistance - functional criterion

The structure should be able to withstand actions from fire during a certain period of time. Diaphragm walls are underground and the distance between adjacent exits can be longer than in the average structure. Within that time the evacuation should be possible as well as rescue operations without collapse of the structure.

- **Method of verification:** Verify fire resistance of the structure with calculations assuming loads and load combinations according to codes or adequate testing methods.

- **Commentary:**
    - Alén et al. (2006), Section 2.2: "The inner wall of a two layer wall may be advantageous to function both as a barrier with respect to the external water pressure and water barrier for chlorides and from fire event".

5.3.2 Collision resistance - functional criterion

In case of impact from a collision the diaphragm wall has to be able to keep its function as a retaining structure, even if some damage occur, because if a collapse happens, the consequences can be catastrophic. Since diaphragm walls are retaining walls, a collapse can cause the surrounding soil to move, which can have effects on the surrounding structures as well.

- **Method of verification:** Verify collision resistance of the structure with calculations assuming loads and load combinations according to codes or adequate testing methods.
- **Commentary:**
    - CEN (2006a), EN-1991-1-7 treats accidental actions caused by impact.

5.3.3 Explosion resistance - functional criterion

In case of an explosion the diaphragm wall has to be able to keep it function as retaining structure even if some damage occur because if a collapse happens the consequences can be catastrophic. Since diaphragm walls are retaining walls, a collapse can cause the surrounding soil to move, which can have effects on the surrounding structures as well.

- **Method of verification:** Verify explosion resistance of the structure with calculations assuming loads and load combinations according to codes or adequate testing methods.
- **Commentary:**
    - CEN (2006a), EN-1991-1-7 treats accidental actions caused by explosions.

5.3.4 Earthquake resistance - functional criterion

In case of earthquake the diaphragm wall has to be able to withstand actions generated from the earthquake. Earthquakes generate waves that travel through the soil. The action from earthquake waves need special consideration when designing diaphragm walls. The horizontal movements generated from earthquakes need to be distributed between the panels of diaphragm walls.

- **Method of verification:** Verify earthquake resistance of the structure with calculations assuming loads and load combinations according to codes or adequate testing methods.

- **Commentary:**
  - Alén et al. (2006), Section 4.1.1: "The usual performance for diaphragm walls is upright panels with limited internal collaboration. Continuous reinforcement between these panels are used only in exceptional cases, for example, for a design that will withstand extreme loads such as earthquakes".
  - Alén et al. (2006), Section 4.3.2.3: "Continuous horizontal reinforcement becomes necessary only in cases where the load effect perpendicular to diaphragm walls plan is distributed differently to adjacent panels so that they risk being separated from each other. Earthquake is an example of such a load cases and for earthquake resistant buildings, continuous horizontal reinforcement is required".
  - CEN (2004), EN-1998 treats design of structures for earthquake resistance.

6 Serviceability

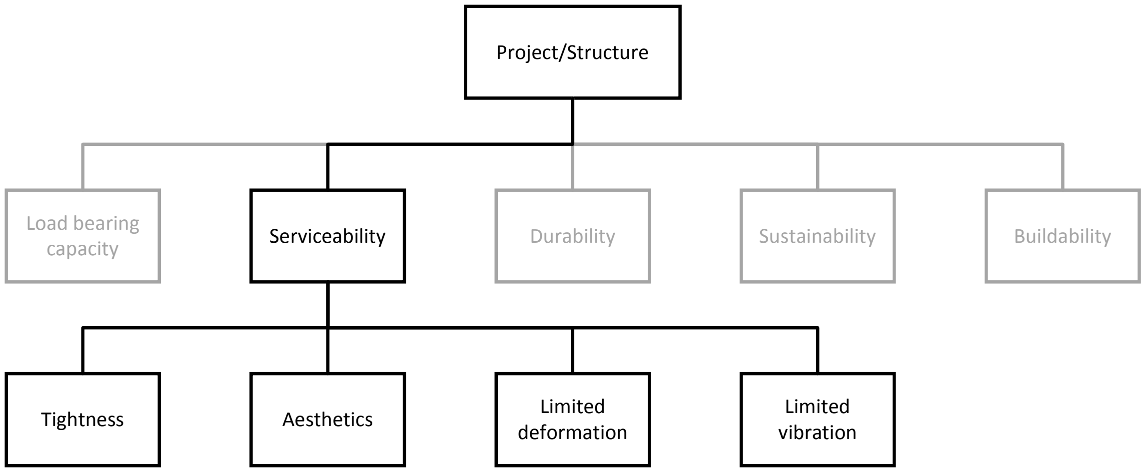

Figure 6.1: Functional requirements for serviceability

Four functional requirements have been identified for serviceability, which are tightness, aesthetics, limited deformations and limited vibration, see Figure 6.1. They describe the required functions of the structure in the service state. Detailed description of serviceability as a general requirement can be found in Section 4.2

6.1 Tightness - functional requirement

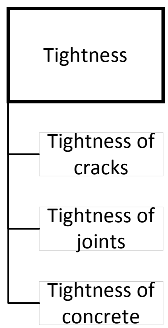

Figure 6.2: Functional criteria for tightness

The permeability of the structure should be limited such that the tightness is kept sufficiently high. It is important to specify how much tightness that is required for each project. The tightness requirement is considered fulfilled, when the tightness is sufficiently high so that the serviceability of the structure is not endangered. The term tightness often implies water tightness but can also includes other types of tightness. Tightness requirements can be found in EN-1992-3 - Design of concrete structures, CEN (2006b). It is also stated as a principle in EN-1997-1 - Geotechnical design, CEN (2005). Three functional criteria have been identified for tightness, which are tightness of cracks, tightness of joints and tightness of concrete, see Figure 6.2.

6.1.1 Tightness of cracks - functional criterion

Crack distribution and crack widths should be controlled by reinforcement or other measures such that the tightness of the wall is kept sufficiently high. The tightness depends on the width and amount of cracks in the wall. Crack width becomes particularly important for walls located under the groundwater table, especially for high pressure. The position of the reinforcement can vary in diaphragm walls because of lack of visibility during installation. Inaccurate position may lead to larger cracks.

- **Method of verification:** Verify tightness of cracks with calculations predicting crack spacing's and crack widths under the quasi-permanent load combination. Crack spacings and crack widths can be measured after construction on the visible parts of the wall. Crack spacings and widths can be measured in length.
- **Commentary:**
  - There are no specific requirements given in CEN (2010) or DIN (1986) on crack widths.
  - Crack width requirement depends on exposure class of the concrete.
  - Additional crack width requirements for corrosion protection of reinforcements in road and railway tunnels in Sweden can be seen in Section 7.1.2.

6.1.2 Tightness of joints - functional criterion

Joints should be designed, detailed and executed properly such that the tightness of the wall is kept sufficiently high. Diaphragm walls are constructed in panels. Each panel is cast separately causing limited bond between panels. If the joints are not executed properly, they can become the crucial factor concerning water tightness of diaphragm walls, Alén et al. (2006).

- **Method of verification:** Verify tightness of joints with adequate testing methods.
- **Commentary:**
  - CEN (2010), Section 7.1.10: "Design shall consider that diaphragm walls cannot be expected to be completely watertight, since leakage can occur at joints, at recesses or through the wall material".
  - Alén et al. (2006), Section 2.2: The joints in permanent diaphragm walls should be fitted with a joint tape for enhanced sealing between panels.
  - Alén et al. (2006), Section 4.3.2.3: Different types of connection methods at vertical joints between diaphragm wall panels, see Figure 2.2:
    * Steel pipe
    * Flat elements
    * Precast concrete
    * Steel casing, with joint tape

6.1.3 Tightness of concrete - functional criterion

The permeability of concrete should be limited such that the tightness of the wall is kept sufficiently high. Permeability is the property that governs the rate of water or other liquids passing through concrete under a pressure gradient. Factors that effect the permeability according to Ramachandran and Beaudion (2000) are cement content, CO_2 concentration in the atmosphere, relative humidity and concrete density. Other factors include aggregates and water cement ratio, Alén et al. (2006).

- **Method of verification:** Verify tightness of concrete with calculations predicting the permeability or with adequate testing methods on in-situ or on drilled samples after construction.

- **Commentary:**

  - CEN (2010), Section 6.3.4: "The water/cement ratio shall not exceed 0.6".
  - CEN (2010), Section 6.3.2.2: "The maximum size of aggregates shall not exceed 32 mm".
  - CEN (2010), Section 6.3.3: "The minimum cement content shall be related to the maximum aggregate size", see Table 6.1.

Table 6.1: Maximum grain size with respect to minimum cement content, CEN (2010)

Maximum grain size mm	**Minimum cement content** kg/m^3
32	350
25	370
20	385
16	400

6.2 Aesthetics - functional requirement

The visible parts of the structure should communicate safety, reliability and be without disturbing defects to the observer. Therefore the aesthetics requirement needs to be fulfilled to meet the serviceability requirements. Aesthetics is a philosophical term that governs how we see art, culture or even nature. Verification of serviceability can be based on aesthetics requirements according to EN-1990 - Basis for structural design, CEN (2002). Two functional criteria have been identified for aesthetics, which are limited crack widths and appropriate concrete surface, see Figure 6.3.

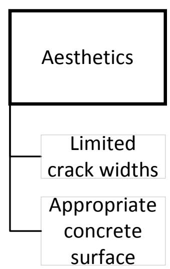

Figure 6.3: Functional criteria for aesthetics

6.2.1 Limited crack widths - functional criterion

For aesthetic reasons crack widths should be limited such that they are not disturbing to the observer. One side of the diaphragm wall is visible. Therefore the cracks and crack width have to be controlled by reinforcement or other measures on that side to fulfill the aesthetics requirement.

- **Method of verification:** Verify limited crack widths with calculations predicting crack widths under the quasi-permanent load combination. They can be measured after construction on the visible parts of the wall. Crack widths related to aesthetic demands are measured on their visibility, e.g. how visible they are to the observer.
- **Commentary:**
  - No specific recommendations for crack widths related to aesthetic demands were identified. However, it should be noted that recommendations for crack width limits are relevant for other functional criteria, see Section 6.1.1 and 7.1.2.

6.2.2 Appropriate concrete surface - functional criterion

For aesthetic reasons the concrete surface should be satisfactory and not disturbing to the observer. Insufficient concrete cover where reinforcement or other cast-in parts are visible, is not acceptable with regard to aesthetic demands. During construction of diaphragm walls it can be difficult to monitor the concrete cover due to the lack of visibility caused by the supporting fluid.

- **Method of verification:** Verify appropriate concrete surfaces by inspections on the visible part of the wall. In some cases it is even beneficial to include additional concrete cover to take possible deviations into account. Sufficient concrete surface is measured by visible defects on the surface of the wall.
- **Commentary:**
  - No specific recommendations for appropriate concrete surface with regards to aesthetic demands were identified.

6.3 Limited deformation - functional requirement

The functions of the structure should not be disturbed by deformations. The term deformation describes the change in size and shape of objects. It is caused by loading or deformations such as shrinkage or thermal strain. The requirement is considered fulfilled, when the serviceability of the structure is not disturbed by deformations. The requirement governs therefore the deformations that may occur under short term and long term loading. Verification of serviceability can be based on deformation requirements according to EN-1990 - Basis for structural design, CEN (2002). Three functional criteria have been identified for limited deformation, which are limited permanent wall deformation, limited temporary wall deformation and limited soil deformation, see Figure 6.4.

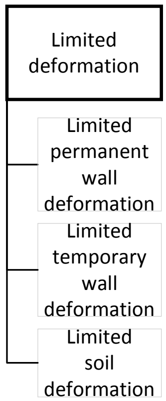

Figure 6.4: Functional criteria for limited deformation

6.3.1 Limited permanent wall deformation - functional criterion

The functions of the structure should not be disturbed by permanent deformations under the quasi-permanent load combination. Permanent wall deformation is the permanent change in size or shape of a structure or structural parts. Diaphragm walls are under sustained loading from the surrounding soil. It is therefore important to predict the permanent deformation in order to verify the deformation requirement in the service state.

- **Method of verification:** Verify limited permanent deformations with calculations assuming quasi-permanent load combination. The development of permanent wall deformation can be measured with land surveying.
- **Commentary:**
  - CEN (2010), Section 8.2.2.3: "Except where otherwise specified, verticality of the panels (including their ends) shall be 1% of depth in both transverse and longitudinal directions".
  - DFI (2005), Section 12.1: "Panel joints should be within 6 inches of the correct position and within 1% of vertical if not specified otherwise".
  - Alén et al. (2006), Section 3.2.1: Measured deformation values from Götatunnel and Citytunnel projects:
    - Götatunnel: Horizontal displacements in soft clay were less than 10 mm.
    - Citytunnel: Deformations in clay were less than 5 mm.

6.3.2 Limited temporary wall deformation - functional criterion

The functions of the structure should not be disturbed by temporary deformations with regard to variations in short term load combination. Temporary wall deformation is the reversible displacement of a structure or structural parts due to variations in short term loading. During deformation the serviceability of the structure can be jeopardized even if the deformation is reversible. It is therefore important to limit the temporary deformation in order to fulfill the deformation requirement in the service state.

- **Method of verification:** Verify limited temporary deformation with calculations with regards to possible short term variation of loading. Temporary wall deformations can be measured with land surveying instruments.
- **Commentary:**
  - No specific recommendations for limitation of temporary wall deformation with regards to limited deformation requirement were identified for diaphragm walls.

6.3.3 Limited soil deformation - functional criterion

The functions of the structure should not be disturbed by soil deformations under the quasi-permanent load combination. Soil deformation, or soil settlement, is when soil decreases in volume because of applied stress. The process is time dependent and should be considered in the design. If the settlements are large and propagate over the predicted values, they become a problem. Uneven settlement may cause major problems to the structure and should be avoided.

- **Method of verification:** Verify limited soil deformations with calculations assuming quasi-permanent load combinations. Soil deformation can be measured with land surveying instruments.
- **Commentary:**
  - CEN (2010), Section 8.5.2: "When a diaphragm wall acts as a vertical bearing structure, special care should be taken for the cleaning of the bottom of the excavation".

6.4 Limited vibration - functional requirement

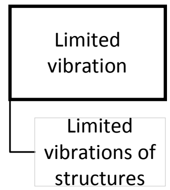

Figure 6.5: Functional criterion for limited vibration

Vibrations during construction work must be limited with regard to the serviceability and stability of adjacent structures, especially unstable ones. Oscillations of objects might cause them to vibrate or move out of their original position. Such movements can effect the objects properties function and their stability. Verification of serviceability can be based on vibration requirements according to EN-1990 - Basis for structural design, CEN (2002). One functional criterion has been identified for limited vibration, which are limited vibration of structures, see Figure 6.5.

6.4.1 Limited vibrations of structures - functional criteria

Vibrations should have limited effects on structures, both surrounding structures and on the construction site. Because of the specific construction technique used for diaphragm walls the vibrations are minimized. Vibrations from the execution of diaphragm walls may effect the surrounding panels or adjacent structures. The main causes of vibrations come from the excavation of the trench in case of rough soil.

- **Method of verification:** Verify limited vibrations of structures with measurements. Vibrations can be measured with special vibration sensors. The sensors can be put on nearby structures or in the soil.
- **Commentary:**
  - The limit for vibration is often determined for each project, Swedenborg (2014-02-21).
  - CEN (2010), Section 8.4.2.3: "The use of chisels, other tools, or blasting, which affect the nearby panels already filled with concrete or hardening slurry shall not be made before the material in panels has sufficient strength to resist the stresses developed during these construction operations".

7 Durability

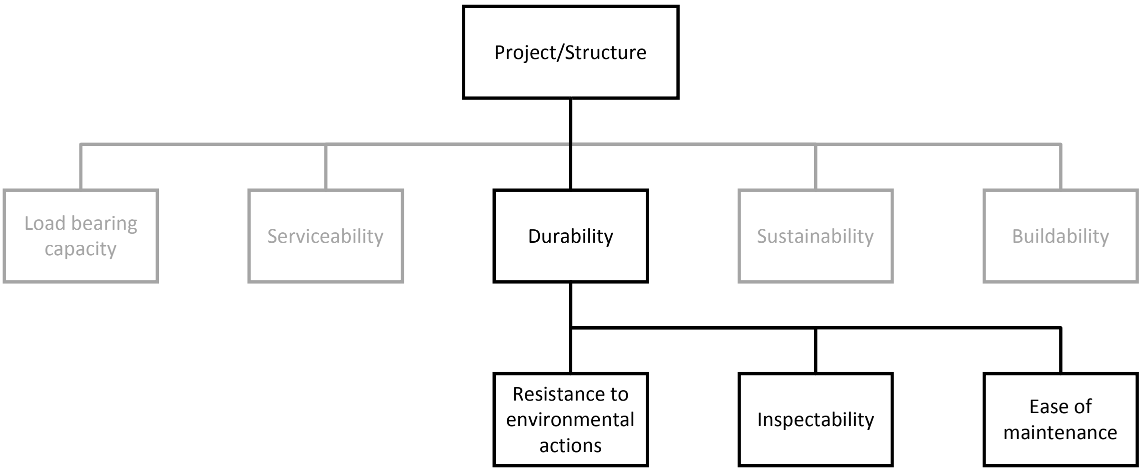

Figure 7.1: Functional requirements for durability

Three functional requirements have been identified for durability which are resistance to environmental actions, inspectability and ease of maintenance, see Figure 7.1. They describe the required functions of the structure in order to achieve durability. Detailed description of durability as a general requirement can be found in Section 4.3

7.1 Resistance to environmental actions - functional requirement

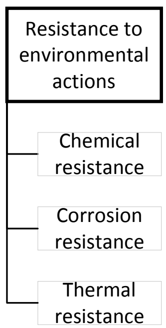

Figure 7.2: Functional criteria for resistance to environmental actions

The structure should safely withstand environmental actions during the design service life. Degradation processes cause material to loose its performance under environmental actions. Degradation processes usually originate from chemical attacks, corrosion or thermal changes, Alén et al. (2006). Identification of environmental conditions is stated as a principle in EN-1990 - Basis of structural design, CEN (2002) and an application rule for the estimation of deterioration. Three functional criteria have been identified for resistance to environmental actions, which are chemical resistance, corrosion resistance and thermal resistance, see Figure 7.2.

7.1.1 Chemical resistance - functional criterion

The concrete of permanent diaphragm walls has to be able to withstand chemical actions during the design service life. In order to achieve this it is important to identify environmental conditions and possible chemical actions. Chemical actions can be for example: salt attack, sulfate attack and leaching of calcium, Alén et al. (2006).

- **Method of verification:**

  Verify chemical resistance by investigating conditions, mechanisms and then model and calculate to predict the chemical actions. Experience from previous projects can also be utilised.

- **Commentary:**

  - CEN (2010), Section 7.7.1: "The minimum cover in relation to environmental condition and to adhesion shall comply with EN 1992 (all parts)".

7.1.2 Corrosion resistance - functional criterion

Reinforcement and other embedded steel details in permanent diaphragm walls should not start to corrode during the design service life. Reinforcement corrosion can be initiated by several reasons, for example: carbonation and chloride ingress, Alén et al. (2006).

- **Method of verification:**

  Verify corrosion resistance by investigating conditions, mechanisms and then model and calculate to predict the corrosion. Experience from previous projects can also be utilised.

- **Commentary:**

  - Alén et al. (2006), Section 4.3.4: Crack width requirements for corrosion protection of reinforcing steel:
    - Swedish road tunnels: $w_k = 0.15 - 0.3$ mm.
    - Swedish railway tunnels: $w_k = 0.3$ mm.
  - CEN (2010), Section 7.7.1: "The minimum cover in relation to environmental condition and to adhesion shall comply with EN 1992 (all parts)".
  - Alén et al. (2006), Section 2.2: "The inner wall of a two layer wall may be advantageous to function both as a barrier with respect to the external water pressure and water barrier for chlorides and from fire event".

7.1.3 Thermal resistance - functional criterion

The permanent diaphragm wall has to be able to withstand thermal attacks during the design service life. Thermal damage can be for example: frost damage and fire damage.

- **Method of verification:** Verify thermal resistance by investigating conditions, mechanisms and then model and calculate to predict the thermal actions. Experience from previous projects can also be utilised.
- **Commentary:**
  - Alén et al. (2006), Section 2.2: "The inner wall of a two layer wall may be advantageous to function both as a barrier with respect to the external water pressure and water barrier for chlorides and from fire event".
  - Alén et al. (2006), Section 4.2.2: "Air content in the fresh concrete should be least 2.5% and max 5.0%".
  - Hedlund and Wiberg (2013): "Results of freezing tests of the drilled cylinders show very good frost resistance in all of the sample walls".
  - CEN (2010), Section 7.7.1: "The minimum cover in relation to environmental condition and to adhesion shall comply with EN 1992 (all parts)".

7.2 Inspectability - functional requirement

The structure should be designed and arranged such that it is easy to check and identify unforeseen needs for repair. Careful inspection should take place during construction and throughout the service life to ensure structural performance and durability of the structure. Components and details that are not executed properly in one stage of the construction, may affect the performance in another stage or during the service life of the structure. It is therefore important that the inspection process is well organized and as easy to perform as possible. According to EN-1990 - Basis for structural design, CEN (2002), verification of reliability management can be based on adequate inspection. One functional criterion has been identified for inspectability, which is ease of inspections, see Figure 7.3.

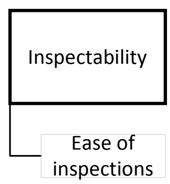

Figure 7.3: Functional criterion for inspectability

7.2.1 Ease of inspections - functional criterion

The structure should be easily inspected, tested or monitored during its design service life. Diaphragm walls require careful inspection and monitoring. It is important that this is performed before and during construction to reach the required quality of the walls. According to Alén et al. (2006) inspections and testing have to be performed for permanent diaphragm walls in the excavation phase (supporting fluid and workmanship) and casting phase (materials and workmanship). The criterion governs the effort needed to measure the properties of the diaphragm walls before, during and after construction.

- **Method of verification:** Verify ease of inspections by evaluating how much effort has to be undertaken to visually inspect, test and monitor the structure.
- **Commentary:**
  - CEN (2010), Chapter 9: Includes detailed requirements of supervision, testing and monitoring for the execution of diaphragm walls.
  - CEN (2010), Section 9.3: "The following items shall be supervised and controlled during the various phases of construction:"
    - Preliminary work prior to the excavation:
      - Location of the wall
      - Materials
      - Reinforcement cages and other elements to be inserted
    - Wall construction:
      - Excavation method
      - Where appropriate verticality and alignment
      - Cleaning the excavation
      - Forming the joints
      - Placing reinforcement
      - Concrete placing record
  - Alén et al. (2006), Section 5.1.4: Non-destructive tests:
    - Seismic/acoustic methods (UPE, IE, SASW)
    - Electromagnetic methods
    - Radiographic methods
  - CEN (2010), Annex B: Control schedules during execution for diaphragm walls.

7.3 Ease of maintenance - functional requirement

The structure should be designed and arranged such that it can easily be maintained during its design service life. All structures have to be more or less maintained during its service life. It is important that this is taken into consideration during design and construction of the structure. Proper accessibility to details that may need maintenance or replacements are very important. Details that can be maintained without or with limited traffic disruptions are preferable. Verification of durability can be achieved with intended maintenance according to CEN (2002) - Basis for structural design. One functional criterion has been identified for ease of maintenance, which is accessibility to details, see Figure 7.4.

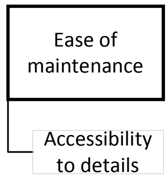

Figure 7.4: Functional criterion for ease of maintenance

7.3.1 Accessibility to details - functional criterion

Structure details should be easily accessible to ensure proper maintenance of the structure or structural parts during the design service life. It is important that details or sections of the diaphragm walls that may need maintenance are as accessible as possible. For each project the expected exposure has to be well identified and analysed to be able to predict the maintenance needed during the design service life. Special care has to be taken during design in order to ensure accessibility to important details.

- **Method of verification:** Verify accessibility to details with a plan for maintenance based on service life design principles.
- **Commentary:**
  - Alén et al. (2006), Section 4.4.6: "When the durability (and lifespan) are not quantitatively determined, i.e. the degradation process is not known. This makes it difficult to plan for future maintenance and repairs, unless relatively frequent inspections are undertaken by the construction. However, if the durability (and lifespan) are quantitatively known, it is possible to better plan for future maintenance procedures, as the degradation process is also known".

8 Sustainability

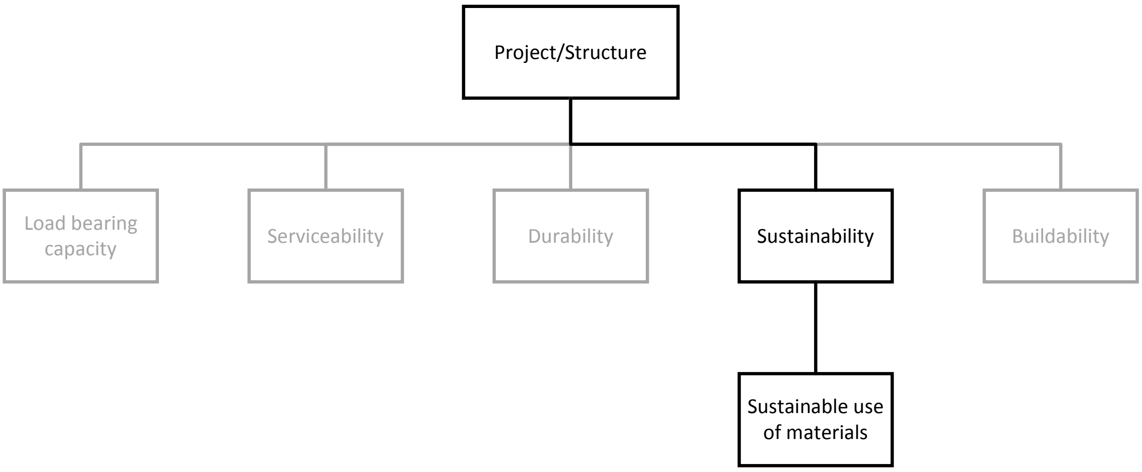

Figure 8.1: Functional requirement for sustainability

One functional requirement has been identified for sustainability, which is sustainable use of materials, see Figure 8.1. It describes the required function of the structure concerning sustainability. Detailed description of sustainability as a general requirement can be found in Section 4.4.

8.1 Sustainable use of materials - functional requirement

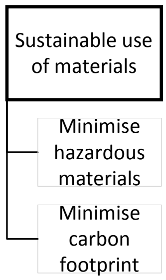

Figure 8.2: Functional criteria for sustainable use of materials

Materials used in the construction of diaphragm walls shall be as sustainable as possible and minimise the environmental effects. Every product causes some environmental impact in its manufacturing process, during use or in the end of its usage. It is therefore important to recognise the environmental impact of products during their life cycles in order to get a sustainable use of materials, European-Commission (2014b). Hazardous and polluting materials shall be avoided unless in absolute necessity. In those cases the impact on the environment shall be studied to the fullest and all precautions shall be taken to minimise the environmental effects. This includes all relevant phases of the construction and the design service life of the structure. The transportation of the materials shall be considered. Materials that can be acquired in the surrounding area of construction are usually considered more environmental friendly than others that need long transportation to the construction site.

A number of environmental legislations are available within the European union, European-Commission (2014a). It is the decision of each country to choose, if they are implemented or not. This will not be discussed here, but rather that there is a policy called the Integrated product policy which governs sustainable use of materials within Europe, European-Commission (2014b). Similar policies can be found world wide, e.g. U.S. equivalent Sustainable Material Management, EPA (2013). Even thou this has not yet been implemented into the design procedure within the European union it is well on its way, CEN/TC (2005). It can be added that there exists a basic requirement in CEN (2002) that states that suitable choice of materials should be made. Two functional criteria have been identified for sustainable use of materials, which are minimise hazardous materials and minimise carbon footprint, see Figure 8.2.

8.1.1 Minimise hazardous materials - functional criterion

The use of hazardous materials shall be minimised in construction of diaphragm walls. Diaphragm walls are placed under ground and the materials will come in contact with the surrounding soil. Therefore it is of great importance that the materials are not hazardous to the soil and the groundwater.

- **Method of verification:** Verify toxicity levels of materials in order to minimise the usage of hazardous materials, for example with the BASTA-system, BASTA (2014).
- **Commentary:**
  - CEN (2010), Section 4.2.1: "special features shall cover, where relevant, presence of polluted ground".
  - The BASTA-system is a Swedish database for toxicity levels in construction materials. It governs the productions sequence of materials and evaluates the hazard to the environment, BASTA (2014).
  - CEN (2010), Section 11.4: "Nuisance and/or environmental damage that can be caused by the diaphragm wall work shall be kept to a minimum".
  - CEN (2010), Section 11.5: "Such nuisance and/or environmental damage can be caused by", among others:
    - Ground pollution
    - Surface water pollution
    - Groundwater pollution
    - Air pollution

8.1.2 Minimise carbon footprint - functional criterion

The construction of diaphragm wall shall aim to minimise the carbon footprint. The origin and every step of the material production should be put into a perspective when it comes to carbon footprint. For example from the aggregate and cement production to the final product i.e. concrete. A definition of carbon footprint was suggested in the report: A Definition of 'Carbon Footprint', Wiedmann and Minx (2007):

> "The carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product."

- **Method of verification:** Verify the emission of green house gasses for products in order to minimise the carbon footprint, for example with, Climate Declaration, a database which describes the emissions of green house gasses for product's life cycle and falls under the Environmental Product Declaration, EPD (2014). It is expressed as carbon dioxide equivalent (CO_2e).
- **Commentary:**
  - No specific recommendations for carbon footprint were identified for diaphragm walls.

9 Buildability

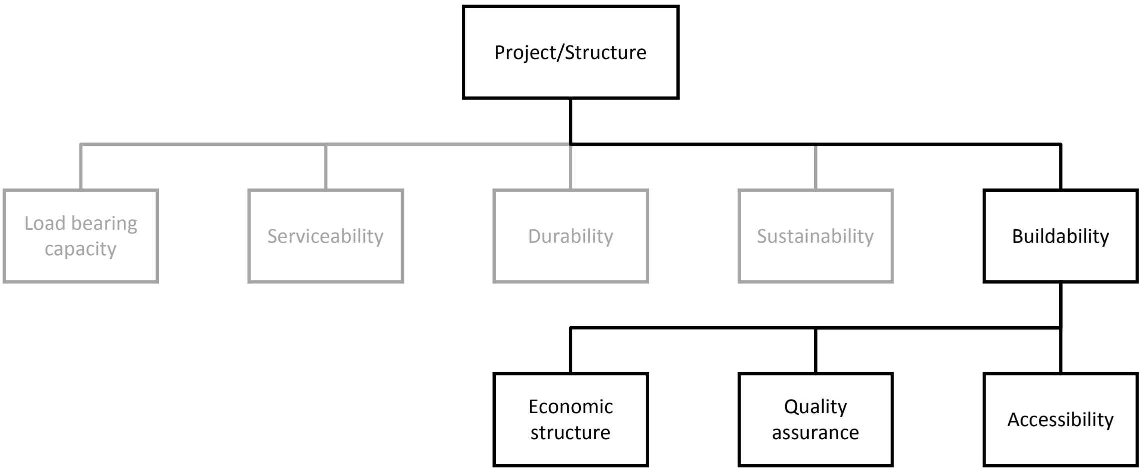

Figure 9.1: Functional requirements for buildability

Three functional requirements have been identified for buildability which are economic structure, quality assurance and accessibility, see Figure 9.1. They describe the required functions of the structure concerning buildability. Detailed description of buildability as a general requirement can be found in Section 4.5.

9.1 Economic structure - functional requirement

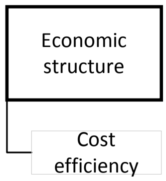

Figure 9.2: Functional criterion for economic structure

The structure should be designed and produced such that the cost of the structure is as low as possible without loosing the required quality. The cost of influencing the project grows as it proceeds. It is essential to have well organised planning from the beginning. Sometimes project designers favour certain solutions from the start. This may lead to disregards of the project cost. In such a case the project cost becomes very important and needs to be estimated with precision. Margins for unforeseen effects and events shall be included to avoid under- or overestimation. In EN-1990 - Basis for structural design, CEN (2002), it is stated as a principle that structures shall be designed and executed in an economical way. One functional criterion has been identified for economic structure which is cost efficiency, see Figure 9.2.

9.1.1 Cost Efficiency - functional criterion

The cost of the structure should be kept as low as possible without loosing the required quality. By estimating the total cost, cost efficiency of structures can be evaluated. The total cost estimations of the project should be finalised before construction begins. The total cost should include the capital cost for the construction and also the operation and maintenance cost.

- **Method of verification:** Verify the cost for all phases of the structure and estimate the total cost.

- **Commentary:**

  – Alén et al. (2006), Section 7.1.1: "From a geotechnical point of view, it will be economically feasible and profitable to perform a relatively extensive probing in the form of field and laboratory testing".

  – Alén et al. (2006), Chapter 8: "The permanent diaphragm wall is an economically desirable solution compared to the temporary and concrete structures formed in a conventional manner".

  – DFI (2005), Section 16.1: "Payment is usually made on a unit price basis, as measured by square feet of vertical wall face".

9.2 Quality assurance - functional requirement

In order to minimise the probability of errors and defects the requirement for quality assurance has to be fulfilled. Quality assurance plays an important role in buildable design. The term goes for all parts of the project, the construction in whole down to single details. Quality assurance should also help to verify the intended quality. Application rules for quality management can be found in EN-1990 - Basis for structural design, CEN (2002). Two functional criteria have been identified for quality assurance which are design quality and execution quality, see Figure 9.3.

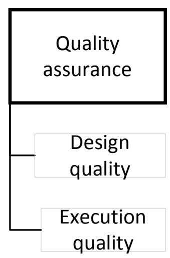

Figure 9.3: Functional criteria for quality assurance

9.2.1 Design quality - functional criterion

Design quality of the structure should be assured in order to fulfil the desired properties. The design quality relies on careful planning and thorough investigations on site in order to reach the intended quality of the structure. It can be considered advantageous to base the design procedures on established solutions. With established solutions the uncertainties of the end product are minimised.

- **Method of verification:** Verify the design quality of the structure with investigations, experience from earlier projects and calculations.

- **Commentary:**
  - CEN (2010), Section 4.2.1: "Special features shall cover, where available, previous experience with diaphragm walls or underground works on or adjacent to the site".
  - CEN (2010), Section 7.1.1: "The basic European Standards for the design of diaphragm walls are EN 1990, EN 1991 (all parts), EN 1992 (all parts), EN 1997 (all parts) and EN 1998 (all parts)".

9.2.2 Execution quality - functional criterion

Execution quality of the structure should be assured in order to fulfil the desired properties. The execution phase governs the actual work needed to build any structure. This has to be performed with precision in order to reach the highest quality.

- **Method of verification:** Verify the execution quality of the structure with previous experience, effective workmanship, established solutions and on-site testing.
- **Commentary:**
  - CEN (2010), Section 8.8.3.13: Minimum casting speed of 3 m/h to ensure concrete integrity.
  - Alén et al. (2006), Section 3.2.2: Maximum casting speed of 10 m/h, it is thou recommended to not go over 5 m/h to avoid separation of the concrete.
  - CEN (2010), Section 6.3.6.1: "Concrete used for diaphragm walls shall:"
    * Have a high resistance against segregation
    * Be of high plasticity and good cohesiveness
    * Flow well
    * Be adequately self-compacting
    * Be sufficiently workable for the duration of the placement procedure
  - CEN (2010), Section 8.8.3: Concreting under a supporting fluid:
    * Horizontal travel distance of concrete should be less than 3.0 m.
    * Concrete and supporting fluid shall be kept apart in the tremie pipe.
    * To start, the tremie pipe shall be lowered to the bottom of the trench, then raised approximately 0.1 m.
    * The tremie pipe shall always be immersed in fresh concrete.
  - Alén et al. (2006), Section 4.3.4: Strict requirements on crack widths may lead to reduced workability of the concrete.
  - CEN (2010), See table 1 and 2 for required properties of the supporting fluid.

– Alén et al. (2006), Section 4.2.1: "Normally there is 4-6% bentonite in the supporting fluid".
– CEN (2010), Section 8.8.1.7: "Vibration of the concrete shall not be used." to avoid segregation and mixing with the supporting fluid.

9.3 Accessibility - functional requirement

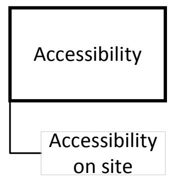

Figure 9.4: Functional criterion for accessibility

The construction site, executed parts of the structure and complete structure should be accessible during the construction such that all relevant project tasks can be carried out satisfactory. Accessibility is the quality of being available when needed. It governs how easily an object can be used, how it influences other factors and the required effort for alterations. It is an important factor in construction, both during and after construction. Accessibility is a major factor in urban areas, both concerning the construction site as well as the surrounding traffic. Accessibility requirements can be found in Eurocodes under execution standards, for diaphragm walls in CEN (2010). One functional criterion has been identified for accessibility which is accessibility on site, see Figure 9.4.

9.3.1 Accessibility on site - functional criterion

The construction site should be accessible such that all relevant project tasks on the construction site can be carried out satisfactory. Accessibility on the construction site is important for the construction of diaphragm walls. It governs how accessible the site is to undertake the procedures needed to construct the walls. It also governs the possibility to manage undesirable events.

- **Method of verification:** Verify accessibility on site with planning and documentation.
- **Commentary:**
  – CEN (2010), Section 8.3.1.1: "The working platforms shall be stable, above the water table, horizontal and be suitable for traffic of heavy equipment and lorries".
  – CEN (2010), Section 8.3.1.2: "The working platform and the access ramps shall be stable under adverse conditions".
  – CEN (2010), Section 8.4.3.3: "In situations where significant loss of support fluid can occur, an additional volume of supporting fluid, and possibly sealing materials or suitable fill, shall be stored in a readily accessible area".

10 Discussion

10.1 Performance-based approach

The structure of the requirements is very important to the users of the requirements. It is important that the structure is visible and that each level is described clearly and thoroughly. Clear distinctions should be made between different levels of requirements. It should also be kept in mind that the requirements should not include or favor any type of solution, in order not to limit possible solutions beforehand.

It is important to have few prime requirements expressed at the highest level. They should be structured as widely as possible and be used to describe and set character to the lower more detailed requirements. The formulation of the desired performance should be based on previous experience in the field and the user's needs. The process should include constant iterations and evaluations of the functional requirements and their verification in order to represent the desired performance in the best way possible. The lowest level of the requirements should include criteria that can be verified in a reliable way. Otherwise it is impossible to ensure that the requirements can be fulfilled.

Key factors in formulation of requirements:

- Visible structure of the requirements
- Complete descriptions of each level of requirements
- Clear difference between levels of requirements
- Requirements should not include or favor any certain solutions
- Relatively few prime requirements
- Identify performance aspects
- Constant iterations and evaluation of functional requirements
- Verifying methods for performance factors

After the formulation of principles is finished, the client, the one that desires the performance, sets limits on the criteria, preferably as widely as possible in order not to disregards possible solutions. This is however not performed in this report, since each limit may need to be unique to specific projects. The structure in this report should rather act as a tool to be used in performance based design of any kind. Alterations may be needed of the structure of requirements, since it was formulated around the desired performance of permanent diaphragm walls. This should mainly concern the functional criteria, which are case specific to permanent diaphragm walls. The higher levels (general and functional requirements) should be applicable to a number of different structures.

Limitations:
The current European legislation is often considered to be an inhibiting factor in the development of performance based design within Europe, Mathern (2013).

It can be hard to establish the right set of requirements to cover all aspects of the desired performance of the structure. It can take several attempts and number of iterations and when it is finalised, it is a possibility that it only suits one type of structures. This causes further development to be more expensive and time-consuming than if it was more open.

It is a possibility that only larger contractors are able to participate in functional based bidding, since large amount of work has to be put in the process of developing this type of work ethics, Mathern (2013).

From the present study it was clear that it is next to impossible to categorise important factors without a proper structure and description for different levels of requirements. Otherwise they become hard to fulfill and miss the attention needed to secure the required performance of the structure.

10.2 Formulation of functional requirements for diaphragm walls

The proposed requirements were identified on the basis of a thorough investigation of the performance of permanent diaphragm walls. This was performed with the help of literature studies, technical reports and by conducting interviews with experienced persons. The identified performance required to ensure quality of the wall was then represented in the form of functional requirements. This process included a number of iterations and evaluation of the requirements against the desired performance, which eventually led to the establishment of functional criteria, factors that should be verified in some way.

The requirements should however not be considered to be a comprehensive list, but rather a working platform or a tool to base further formulation of performance-based requirements on. One way of developing and formulating appropriate requirements can be established by applying the proposed requirements to a specific project, (for example as suggested in Section 3.5.) This might then lead to the identification of more functional requirements or even general requirements and in some cases reduce the number of requirements given in this report. There are still some requirements that are considered to need further studies or that overlap each other in some way. Those include:

- Concerns related to fire events comes in the form of two criteria in the reports. This is because they are used to evaluate two different parameters concerning fire events. Distinctions should be made between them on the basis that one describes structural failure due to fire (Fire resistance, Section 5.3.1) and the other describes reduced durability in the case of fire (Thermal resistance, Section 7.1.3).

- Safety of persons especially safety at the construction site has been increasingly important as a requirement in modern societies. Safety was however not implemented directly as a requirement in this thesis. This was mainly because safety of persons can not be regarded as a desired performance of structures. You much rather should require certain performance of the structure that increases the safety of persons. This can be for example structural safety, represented in the load bearing capacity requirement especially during construction. A number of effects of safety can also be argued for all the other general requirements. It was concluded that adequate safety should be ensured through fulfillment of the other requirements.

- Only one functional requirement is proposed for sustainability. This might suggest that there should only be this one. On the contrary, there most definitely exist additional requirements. During the thesis project a number of requirements were identified, but the work led to inconclusive expansion of those requirements. This was due to lack in depth on the matter and partly due to the time frame given for the thesis work. Three pillars of sustainability are according to EPA (2011), economy, society and environment. The economy aspects are covered in some way under the buildability requirement. Society was not included because of difficulties to determine verifying methods for the society aspects. The environmental aspect is thought to be covered in comprehensive depth under the efficient use of materials requirement in sustainability.

- For the execution phase there are a number of factors that influence the quality of the final structure. According to Alén et al. (2006) one of the major factors that influences the quality of diaphragm walls is effective workmanship. It is even recommended as a pre-qualification requirement by Alén et al. (2006) in the bidding process of diaphragm wall projects. It effects the structure in number of ways and could be established under several of requirements. It was therefore hard to establish it under one specific general requirement. For example under:

  - Load bearing capacity, since poor workmanship can lead to structural failure
  - Serviceability, since insufficient workmanship can lead to lack of serviceability
  - Durability, since errors and defects caused by insufficient workmanship can decrease the durability

  The conclusion was that it suited best under the buildability requirement, since that requirement governs the ease of construction, which affects a number of aspects, including load bearing capacity, serviceability and durability. There it governs the quality assurance and verifies that the execution is fulfilled.

11 Conclusion

Diaphragm walls have been accepted as permanent structures by Trafikverket since 2007. However, Trafikverket has not yet used diaphragm walls as permanent structures, because of little experience in Sweden and uncertainties regarding verification of the quality, Trafikverket signed a research contract with NCC on the matter. Part of this research was this thesis work. In this study the desired performance of permanent diaphragm walls was identified and they were expressed in the form of functional requirements. The conclusion of this work includes:

- For the desired performance to be represented in the best way a complete structure of requirements needs to be established beforehand.
- The structure of requirements has to be established in levels, from wide requirements to specific detailed ones.
- Verifying methods are needed to show that the desired performance is fulfilled.
- The representation of different levels of requirements is proposed as:
  - General requirements: Overall performance of the structure.
  - Functional requirements: Detailed performance of the structure.
  - Functional criteria: Specific performance of the structure that is verifiable.
- Proposal of requirements at different levels:
  - Five general requirements were proposed, which should be applicable to various types of structures.
  - Functional requirements were identified under each general requirement. The functional requirements should be applicable to various types of structures.
  - Functional criteria were identified under each functional requirement. The functional criteria were identified specifically for diaphragm walls.

11.1 Further studies

The structure of the requirements was formulated to be applicable for various types of projects/structures. Since this thesis focused mainly on the permanent diaphragm walls, it could be interesting to see how it works with other types of projects/structures. The functional requirements can also be developed further especially under the sustainability requirement. For permanent diaphragm walls the functional criteria could be developed further and limitations be identified.

Summation of relevant factors for further studies:

- Apply the proposed structure of requirements to other projects/structures.
- Develop functional requirements further, especially with regard to sustainability.
- Develop specific limits for the functional criteria on permanent diaphragm walls.

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