Monitoring of Ageing of Concrete Containments Based on Conditions Assessment by Means of Non-Destructive Testing Methods and Finite Element Analysis

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ABSTRACT

This paper presents the results of the European 5-th Framework Project with Acronym "CONMOD" [1], which aim was to find a practical means to determine the condition of a containment structure, as well as how this can be expected to change with time. That involves combining advanced finite element analysis (FEA) and the latest non-destructive techniques (NDT), with the aim of establishing the condition of reinforced concrete structures, as well as their present and future behaviour under various loading conditions including the effects of ageing.

The quality of the concrete structure is strongly affected by workmanship and construction methods. For any given large structure, the methods of construction will vary, and subsequently so will the quality throughout the structure. Compliance, quality and ageing are related to each other. The ageing factors will vary globally and with depth from the concrete surface depending on the local construction methods, materials and environment.

NDT provides combined information about the condition, compliance and ageing of concrete, which is necessary in order to make a realistic evaluation of the significance of these factors in the long term. NDT provides information about the condition of the concrete in an undisturbed state, which means that small changes in the material properties with time can be reliably detected. The results of this work show that a new approach combining non-destructive testing with finite element analysis is a very useful tool for accurate determination and prediction of concrete containment conditions in nuclear power structures [2].

Key words: Concrete containment, Non-Destructive Testing, NDT, Finite Element Analyses, Ageing, Degradation, Conformity, Defects, Ageing Management, Material Testing, MASW, Nuclear Power Plant

INTRODUCTION

The European Commission and a consortium consisting of four parties, Barsebäck Kraft (Sweden), EDF (France), FORCE Technology (Denmark) and Scanscot Technology (Sweden) agreed upon a project named CONMOD "Concrete Containment Modelling and management". The project was started January 1st 2002 with an extent of a three year period. CONMOD was financed by the European Commission and the partners, as well as the Swedish Nuclear Power Inspectorate (SKI), Oskarshamn (OKG) and Ringhals (NPP) all from Sweden.

The objective of the project was to create a diagnostic method for evaluation of ageing and degradation of concrete containments. This includes obtaining relevant knowledge about the current state and behaviour of materials and structures, to locate, diagnose and manage critical areas or damaged zones, to optimize the maintenance and repair and to estimate the remaining safe lifetime of the containment.

To achieve the goal of the project it was necessary to be able to detect critical damage and deterioration processes as early as possible and therefore it was vital to apply suitable inspection strategies and methods. Suitable inspection routines should be designed to detect and diagnose these but only visual accessible parts of the containment can be examined. Two important tools for this are non-destructive testing and structural analyses using the finite element method.

Because of the size of the reactor containment it was almost not possible to detect all kinds of disorders and not practical to examine minutely each element of the structure, instead non-destructive testing has to be focused on the most important areas, the so called critical areas.

The project benefited from the fact that the decommissioned Barsebäck unit 1 reactor (situated on the Swedish west coast) was accessible throughout the term. The containment provided both generic and specific information in terms of long-term behaviour, effects of construction methods and NDT applications. Construction of Barsebäck unit 1 was initiated in 1970 and the plant was in commercial service in 1975. The containment consists of a single-wall with slip-formed pre-stressed concrete structures with embedded steel liners. Barsebäck unit 1 was decommissioned in 1999 in accordance with a government decision.

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The NDT-methods and FEA-techniques were tested and evaluated at the containment. Included in the project were also destructive material testing of drilled concrete cores from the containment wall, and examinations made directly at site. This material testing project provided important complementary input to the non-destructive testing methods and an opportunity to validate the testing results as well as provide valuable general knowledge about effects of concrete ageing after almost 30 years in service.

FACTORS AFFECTING THE CONDITION AND AGEING

The actual as-built details may and often differ significantly from the design. In addition, this lack of compliance is usually un-documented and may remain unknown throughout the life of the structure. Compliance, quality and ageing are related to each other. There is no universal ageing factor for a large containment structure. The ageing factors will vary globally and with depth from the concrete surface depending on the local construction methods, materials and environment.

Special investigations are conducted when responses from the structure are found to deviate from the normal established responses. Deviating responses may occur globally or at a given position on the structure with the passing of time. At this stage both NDT and FEA has been used as separate tools for analysis of the structure. It has been necessary to apply FEA techniques to interpret the NDT responses obtained. Also, as a final stage, FEA has been used to predict the changes in NDT responses that may occur with time.

The Profile of the structure obtained in this way is used to up-date the structural model. The function of the structure (leak-tightness and load-bearing capacity) is then re-evaluated. This must include time-dependant (ageing) parameters that can directly or indirectly (as a consequence of) affect the structure. These changes will affect mechanical wave transmission and they can be modelled using FE-analysis. The key to applying NDT in the ageing management process is in being able to recognise the changes that might occur in the structure with time. These changes may be slow and progressive and may or may not in themselves have any serious effect on the functioning of the structure.

Traditional methods of inspection such as visual surveys combined with core sampling are inadequate and may be misleading for a large structure such as containment wall. Visual surveys give no indication of the concrete condition at depth. Core sampling should be made at sections which are representative for the structure and which reflect the variations in condition that can be expected. This requires some form of non-destructive pre-survey.

Cores should be taken to almost the full concrete section thickness in order to detect the differences in concrete properties that can be expected across thick sections. This is however rarely the case. Local conditions can vary significantly, e.g. due to construction effects (casting joints and slip-form anomalies) and these can affect the condition of the cores. See figure 1. If analyses of cores are used as the basis for ageing of concrete then these anomalies must be excluded. Global variations in the quality of concrete and the condition of cores after drilling make it unlikely that short to medium term ageing processes can be recognised on the basis of cores alone.

Possible casting defects

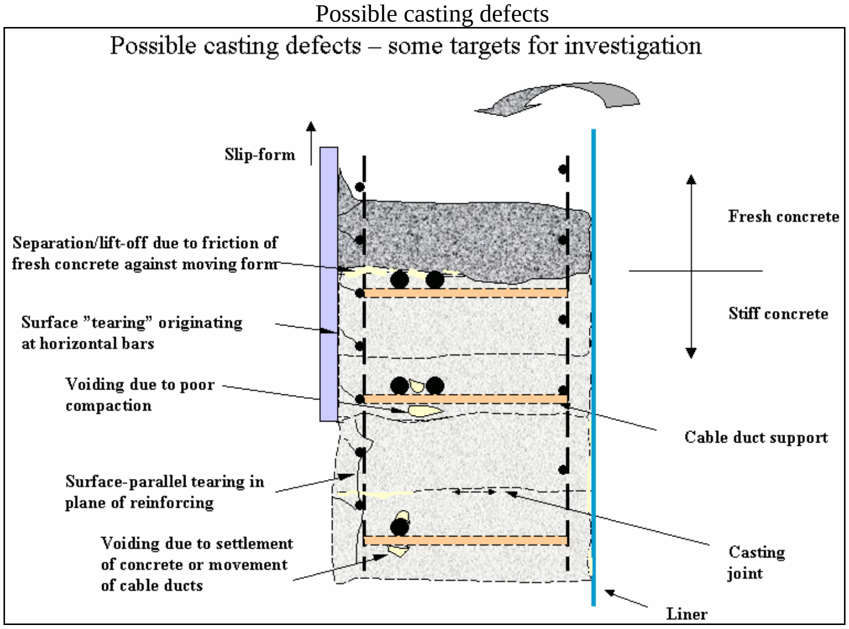

Figure 1

NON-DESTRUCTIVE TESTING

Non-destructive testing provides the means to obtain information about the structure, its components and materials. With e.g. modern radiographic techniques (x-ray) we are able to quite easily penetrate walls up to 1.5 m thick to obtain information about relatively small details; to scan large surface areas using radar to map reinforcing and cable ducts; to use elegant seismic/acoustic techniques to describe the concrete structure and mechanical properties. By combining these techniques we obtain a full and descriptive picture of the internal structure and condition of large volumes of reinforced concrete in its undisturbed state in the structure. Another advantage with the seismic methods used for the CONMOD project is that they all can be used while the reactors are in operation.

The most important rule to follow is that inspections should focus on the site-specific conditions and obtaining this information is not simply achieved by random sampling of the structure. An effective approach to the problem, bearing in minds that the whole process of investigating and analysing containment involves a number of disciplines and their interaction, is to make inspections in stages:

1. Preliminary investigation to obtain a first impression and evaluate the performance of techniques and practical issues
2. Main investigation according to specific plans customised for the structure in question and including a basic survey without pre-conditions and a customised plan according to the particular needs at that site
3. Special investigations at critical points or dealing with issues that have been identified as being critical

The simplest form of NDT and use of this information is to check conformity, e.g. reinforcement size and position or wall thickness etc. The techniques available today, including processing software, are quite sophisticated allowing us to create three-dimensional diagrams showing the as-built structure and to compare with design. Even in these relatively simple cases we are unwise to rely on only one technique.

RESULTS FROM SITE INVESTIGATIONS

The investigations of the Barsebäck 1 containment have taken three years and have included 4 stages of site investigations, material sampling and a study of background material such as reports from earlier investigations and data from the construction stage. A very large amount of test data has been accumulated, which in retrospect may be seen as partly superfluous. However, at the end of the day it has been possible to identify the issues relevant to assessing the condition of this type of structure and therewith an effective and robust inspection program that will make this possible.

In Table 1 below a list is given of the NDT methods thought to be sufficient and suitable. Except for the HECR the other NDT-techniques can be used with the reactor still in operation as access is only required to one side of the containment wall.

Overview of the NDT methods and their capabilities for investigation of concrete containments

Method	**Objective**	**Result**	**Comment**
Radar	Rebar and cable duct position and depth	Good	Max depth approx 400 mm
HECR (High Energy Computed Radiography)	Rebar and cable duct position, size and condition	Good.	Max 350 mm from image plate
HECR	Other details of concrete internal (high resolution)	Good	Small and large voids easily detected.
HECR	Void detection and detection of alien materials in concrete	Good.	Small and large voids easily detected.
HECR	Concrete thickness (2-sided access)	Good.	Max thickness 1400 mm
MASW	Concrete thickness and thickness of layers	Good. High potential.	**General:** Seismic response should be modelled for comparison. Robust method not sensitive to local anomalies. Provides information on various wave modes in wall including surface and standing waves.
MASW	Concrete mechanical properties and quality	Good. High potential.	
MASW	Quality of bond between concrete and embedded steel liner	Good. High potential.	

Table 1:

When carrying out finite element analyses (FEA) of the reactor containment, a library of FE models has to be established, this can be used during initial and up-dated analyses of the structure. These models can also be used to assist in planning NDT and other inspection methods. The FE models range from global and local models for evaluation of the leak-tightness and load-bearing capacity of the structure, to “digital mock-ups” of important areas that simulate seismic responses that can be used to predict and interpret the NDT response on site.

This library of FE models must be site-specific, and must cover the issues of relevance. If a complete study is at hand, a fully 360-degree global model of the containment is recommended, complemented with local models at critical areas (singularities) such as the major penetrations. In some situations, so-called wedge models, or even axi-symmetrical models are sufficient. At Barsebäck Unit 1 a combination of an axi-symmetrical model, a horizontal plane strain model, and a detailed 3D-model of a pipe entry (Figure 2) was used. This was used in order to study the global behaviour of the structure in an undisturbed region, as well as the response of a typical wall section with pre-stressing buttresses, and a detailed study of a pipe entry.

Having access to a diagnostic tool that can describe the condition and geometry of the containment wall it is possible:

1. To determine a global trends (normal responses) and deviations from these
2. To determine changes that may occur to the material and structure with time

The change that concrete or concrete/steel bond might undergo may be a slow process, such as drying of the concrete or long-term strength gain. It may on the other hand be a relatively sudden change such as cracking or corrosion to the liner. Whatever the case, the consequence of an ageing process can be modelled as can the effect this will have on, for example, the seismic response. An example is given in Figure 2. In this case a loss of bond between liner and concrete occurs at a given time.

The figure represents a concrete wall with embedded reflector. The impact at the surface causes wave reflection which has been modelled in this example. The seismic events could be registered with an array of transducers placed on the concrete surface. At the present a single transducer is used.

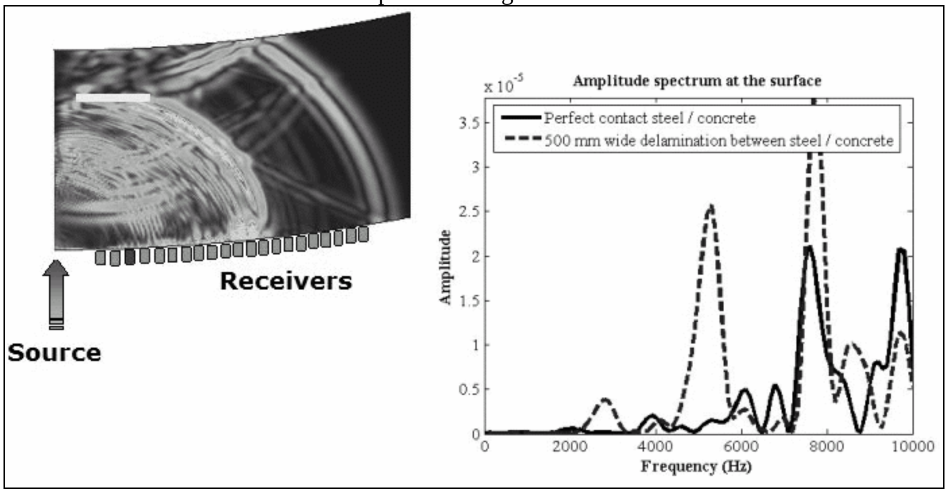

Figure 2

Figure 3 and 4 show a section through the containment and the positions chosen for NDT and material sampling. Note that NDT has in some cases been made at several positions around the containment circumference at any given level.

The positions were chosen in order to include both slip-formed (LCW) and fixed formed concrete. A deciding factor has also been the appearance of the concrete as well as the existence or not of cracks. The tests have been concentrated on the outer pre-stressed containment wall.

Containment and position of test level 4 (+112 m), position 2 – Pipe entry and surrounding wall. The method of seismic data collection is shown to the right.

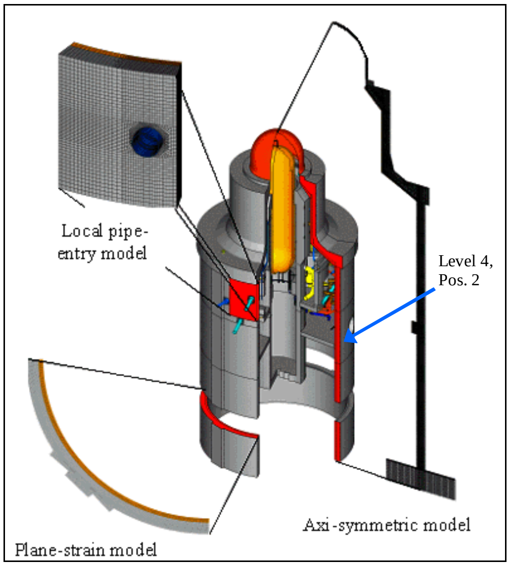

Figure 3

The figure shows a section through the containment and the positions chosen for NDT and material sampling. From bottom: Base slab, lower cylindrical wall, conical roof and upper cylindrical wall.

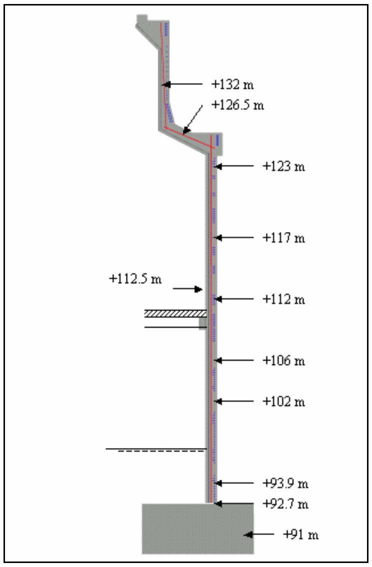

Figure 4

Multi-channel Analysis of Surface Waves (MASW)

One of the new seismic methods used in CONMOD is the MASW [3] [4]. This method involves collecting seismic wave data through a sensor placed on the concrete surface and multi-shot impulses (hammer strikes) at increasing distance from the sensor. The information is transformed from the offset-time (x-t) domain into the frequency-phase velocity (f-VPH) domain. The method makes no assumptions about the nature of the seismic event in relation to the phase velocity, and the construction of the frequency-phase velocity image is performed through an objective pattern-recognition technique. The MASW method enables a record of the total wave field of both surface (R-wave) and compression wave (P-wave) events.

In the figures 5-6 data are shown for Level 4, position 2, which is the wall surrounding pipe entry.

MASW test from inside of containment suggesting the inner wall thickness is 330 mm.

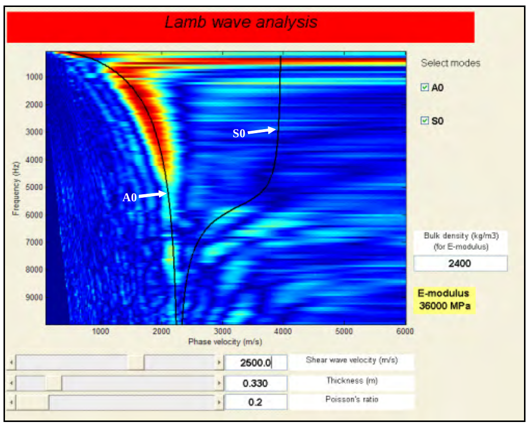

Figure 5

Position 2, MASW from outside. The result suggests a full wall thickness of 1.15 m.

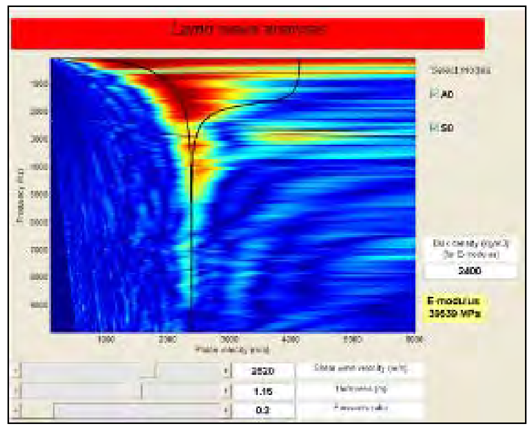

Figure 6

There is reason to suspect that the contact between the inner wall and steel liner is not so good based on the Lamb wave analysis above. The low phase velocities measured for wavelengths greater than 330 mm follow the AO curve for a free plate with thickness 330 mm. In other words the low velocities are due to the fact that the inner wall resonates independently.

The advantage of the MASW is that much more signals and data are collected. That makes it possible to analyse all types of waves and phenomena from the same raw data. By sampling a larger amount of data from various distances of the accelerometer the wave speeds (V_P/compression and V_R/surface) can be estimated more accurate than from just two points as is the case for SASW (Spectral Analysis of Surface Waves). In SASW the slope of a curve (phase velocity) is determined from two testing points (accelerometers) at two different distances from the instrumented hammer. With MASW the slope of the curve is determined from many test points at many different distances from the accelerometer. That makes the MASW a more robust and accurate with regards to the phase velocity (dispersion curves).

High Energy Computed Radiography (HECR) – void detection.

The Pipe entries were included in the investigations for obvious reasons, NDT being carried-out as part of CONMOD and intrusive investigations made as part of this project. One of them was Position 2, Pipe entry no. 4. The risk of voids occurring in the box-out was considered to be dependant on whether or not the drainage pipe at the top of the box-out had been cut off even with the concrete surface. It was thought that this had been done in the case of B1. Radiographs and later fibre-optic inspection showed however that this was not the case. (Figure 7)

The pipe-entry construction was special. The lower slip-formed wall was cast with special box-outs as shown in figure 7 (d). The box-outs were made of wood, with foam polystyrene being used for the inner part placed against the liner plate. Having cast the slip-formed wall the box-outs were removed leaving a hole in the wall. Pipe ducts were placed inside the hole and the connections made with the liner plate. The duct was cast into the slip-formed wall by pouring concrete around, having first placed formwork on the outside faces. The duct and surrounding octagonal concrete in the box-out thus formed a ”plug” in the slip-formed wall.

Realising the difficulties in casting the filler concrete and effectively joining with the upper surfaces of the octagonal box-out, a special void was formed in the upper part as shown (in yellow) in figure 7 (d). This was to accommodate any air that might be trapped inside and against the upper surface. The void occupied the upper section of the octagon and stretched to the sloping back surface The void was formed using foam polystyrene. It was intended to fill the void after having cast the filler concrete. This was to be done with the help of a pipe that entered the void from below and to which access was possible from the outside of the pre-stressed wall. Another pipe – the drainage pipe – was cast in the upper part of the void and likewise accessible from the outside of the wall.

In actual case the lower filler pipe and upper drainage pipes were placed too high and too low respectively in the void. This resulted in the grout being mixed with the water inside the void and improper drainage. It was not possible to properly check if the voids had actually been filled.

Graphic presentation of radiographic beam from Betatron at pipe entry

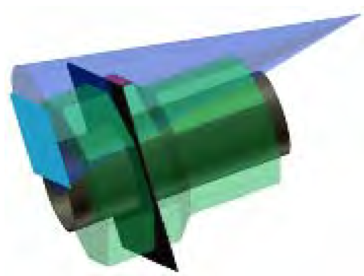

Figure 7(a)

Radiographic image of wall above pipe entry showing void as dark areas.

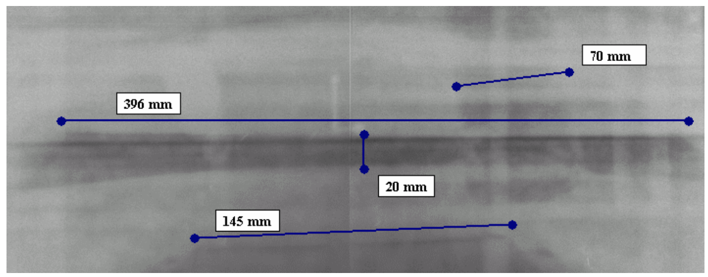

Figure 7(b)

Void as seen from fibre-optic (left); liner plate in void (centre) with thin covering of material; injection (black) and drainage (light) pipes inside void (right).

Figure 7(c)

X-section of wall at pipe entry showing void and fibre-optic inspection point (arrow, Left).
Right: The large box-outs are for pipe entries. The innermost part is formed with foam polystyrene. The shutter appears to be held in place with a central rod, which presumably is fixed to the liner.

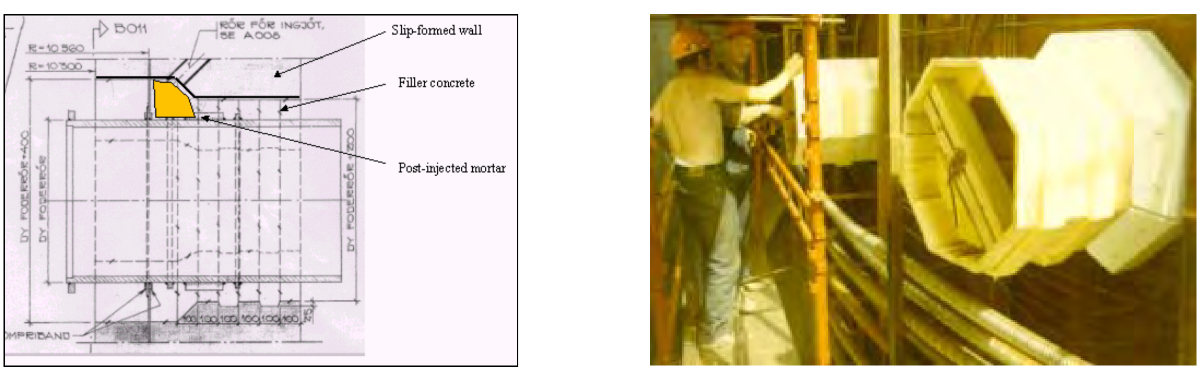

Figure 7(d)

The use of HECR confirmed the suspicion that there could be voids in the injection grout above the pipe entry due to the construction method and this was confirmed. However, there was no apparent corrosion to the liner plate, which was the major concern. The wall thickness was found to be considerably greater than design. The moisture level inside the void was (RH) 82%, which was as expected.

If there is access to both sides of the structure then the best method of detecting voids in concrete and cable ducts cast in thick concrete is radiography. Voids as small as 20 mm diameters were detected in a 1200 mm thick concrete wall. HECR was used extensively in CONMOD with approximately 10 m^2 of concrete being covered.

CONCLUSION

The problem of concrete ageing is one that is described by mechanical changes to the concrete, be it slow and progressive or sudden. The changes apply both to the concrete as well as the steel embedded in the concrete and how the concrete and steel interact. These conditions and changes can be described by seismic testing methods, if they are backed up by advanced scientific modelling techniques. The potential of these techniques in characterising concrete changes needs to be further investigated and procedures developed that adapt the technology to specific types, i.e. patterns of concrete change, such as natural changes or deterioration. A bridge between ageing prediction using FEA modelling techniques and prediction of seismic response to these changes using similar FEA techniques is required. There is potential in examining wave velocity profiles, reflection patterns and frequency-dependant attenuation in recognising and characterising crack growth. The ageing mechanisms need however to be defined more clearly and modified to include the effects of original quality and compliance. The initial or passive state of the structures should be modelled to determine the long-term effects of initial state-induced stresses. This would include cracks that have previously been formed and other factors relating to original condition and geometry.

The seismic response of the containment wall has been modelled using a Finite Element technique, in which the in-going parameters have been determined using NDT and other investigation methods on site. The solution to this model is not unique and it is therefore necessary to construct the model with the help of complementary techniques, which in this case includes NDT and material sampling. A match between predicted and actual seismic responses has been achieved. This reflects the agreement between the assumed (according to initial NDT investigations and not theoretical) and actual condition and geometry of the containment wall.

The geometry of the wall, i.e. the thickness, the depth to liner and cable ducts etc. can be determined by combining NDT techniques [5]. Some global variation in these parameters can be expected. In an ageing management scheme, reference sections should be established in which these parameters have been established along with a corresponding seismic model. Any changes in the seismic response with time can then be analysed with respect to changes in the condition of the concrete alone. The effects of variations in internal geometry, e.g. reinforcing and cable duct depth and liner/concrete bond, should be evaluated in a sensitivity analysis of seismic response.

The use of seismic techniques for crack characterisation has not been fully demonstrated in this project due to lack of time and suitable objects. The technique finally adopted, MASW, has shown itself to be a robust method with great repeatability. Also, the method provides a spectrum of different data, e.g. both surface and standing wave patterns. In terms of crack growth monitoring then there is potential in exploring the possibilities of using this combined information with frequency-dependant attenuation of surface and compression waves.

A clearer definition is required of the term ”ageing” of concrete. The different kinds of ageing should be clarified, e.g. long-term and progressive changes such as strength gain and drying or crack initiation and growth due to periodic load testing. These need to be defined more clearly in their context in order for a management methodology to be defined for each case. The ageing problem should also be recognised as being very much dependant on original quality and compliance.

The greatest challenge lies ahead as we are not only faced with the problem of structural condition at this time, but also how this will change with time. The project is unique and interesting and has an element of credibility perhaps not found in many “similar” studies, as we were dealing with and had at our disposal a real containment structure which has existed under real conditions for almost an entire design lifetime.

REFERENCE

[1] Shaw P., Force Technology report – CONMOD – Main Report, European 5-th Framework Project (2005)
[2] Shaw P., Rasmussen J., Pedersen T.K., Force Technology report – A Practical Guide to Non Destructive Examination of Concrete, Nordic Innovation (2004)
[3] Rydén N., Lund Institute of Technology, Doctoral Thesis – Surface Wave Testing of Pavements (2004)
[4] Rydén N., Lund Institute of Technology, Licentiate Thesis – A Novel Concept for Seismic Pavement Testing (2002)
[5] Shaw P., Force Technology, A Study of NDE Performance in the Condition Assessment of Concrete Structures – Rilem proceedings PRO 16 Life prediction and Ageing Management of Concrete structures (2001)