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Abstract: The ONKALO rock characterisation facility is located in the Olkiluoto area in the west coast of Finland. It aids in collecting the further data needed for the application of the construction license for the repository of spent nuclear fuel that will be submitted in 2012. It provides an opportunity to develop excavation techniques and final disposal techniques in realistic in situ conditions. The goal of the facility is to provide information for the design of the planned nuclear repository. The ONKALO design method can be considered as a prediction and observation method. Typical rock conditions can be handled using the Observational Method (Peck 1969) approach, and more complex cases (e.g. stress-induced damage, extensively cracked areas, crossings, heat-affected zones, etc.) are handled with numerical and analytical predictions. The design method can be divided into five phases: description of information on existing geology, site investigation and interpretation, obtaining rock mass parameters, calculations, and design. The method has undergone continuous improvement during the different excavation stages and as new rock mechanical challenges have been detected. Examples of Eurocode compatible rock reinforcement design are shown. Finally, the suitability of the current design method for the design of the spent nuclear fuel repository is discussed.

Theme: Design Methods

Keywords: ONKALO, repository, Observational Method, reinforcement, Eurocode
1 INTRODUCTION

Rock engineering design is a challenging and multi-disciplinary task, which ranges from optimisation of the layout, excavation direction and tunnel shape and design of water proofing and grouting to design of rock reinforcement. In typical urban rock engineering, the main problems lie in water proofing and cost-minimisation while maintaining a sufficient level of quality. In ONKALO, the main issue is to meet the high safety and technical requirements while maintaining an acceptable excavation speed and cost. Additional problems arise from imposed material restrictions and from exceptional environmental conditions (e.g. stress-induced damage, thermal loading, high salinity, and long serviceability life) of ONKALO.

ONKALO aids in collecting the further data needed for the application of the construction licence that will be submitted in 2012. ONKALO also provides an opportunity to develop excavation techniques and final disposal techniques in realistic conditions (Posiva 2011a). The goal is to provide information about the planned nuclear repository area. This acquired knowledge consists mainly of geological information, such as rock types and their quality as well as the presence of weakness zones and that of water. The parameters obtained influence the design of the underground facility, and the excavation allows of continuous improvement of the process.

The Eurocodes are a set of European design principles, rules, and guidance intended for the design of load-carrying structures. The codes have been compiled by the CEN Technical Committee 250. The intent of the Eurocodes is to unify the design methodology. In Finland (and in Sweden and Norway), there is no formal procedure on how to design rock spaces. The design is based on a designer’s expertise, experience, views, and specific procedures. The Eurocodes do not explicitly state how to design rock spaces, but they define the minimum requirements on how to design structures. For a more thorough introduction of the use of the Eurocodes in hard rock engineering, please refer to Uotinen et al. 2011.

The Eurocode 7 (Geotechnical design) allows the Observational Method (OM) to be used as a part of the design process, given that certain criteria are met (see next chapter). The OM requires determining actions beforehand and then choosing the corresponding action based on in situ measurements. It was formulated by Terzaghi and published by Peck in 1969. In his paper, Peck states that the most serious blunder is the failure to select appropriate courses for all foreseeable deviations of conditions.

The rock engineering design used in the previously completed contracts (TU1 through TU5) has been documented by Syrjänen et al. (2006, 2007, 2008), Tikkanen et al. (2009), and Nuijten et al. (2010a, 2010b). In 2009, a description of rock reinforcement design methods in use in ONKALO at that time was made (Uotinen et al. 2009), audited, revised, and finally approved for use in the TU4 and TU5 contracts. These documents are available (mostly in Finnish) from the document bank used by Posiva for authorised users. There is no previously published material on the rock engineering design process in ONKALO. However, all the initial data and supplementary work have been published in the Olkiluoto Site Descriptions (Posiva 2004, 2006, 2008, 2011b).

In this paper, we describe the current rock engineering design process in ONKALO. The method has undergone continuous improvement as new rock engineering challenges have been met. Examples of rock engineering design are shown. The authors’ opinion on applying the method to the design of the repository is presented.

The paper is divided into four chapters. The upcoming chapter two describes the methods and materials used. The chapter three describes results, which in this context are improvements of the design process. Finally, chapter four discusses the usability of the design process for the design of the spent nuclear fuel repository.
2 METHODS AND MATERIALS

2.1 Observational Method (OM)
Until the mid-20th century, rock engineering was carried out either by adopting an excessive factor of safety or by making generalised assumptions. Terzaghi noted this and applied what he referred to as the “third method” from soil mechanics. Later Peck published this method (1969) in a slightly modified form. The following quote is a brief summary of the method by Peck:

(a) Exploration sufficient to establish at least the general nature, pattern, and properties of the deposits, but not necessary in detail.
(b) Assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions. In this assessment geology often plays a major role.
(c) Establishment of the design based on a working hypothesis of behaviour anticipated under the most probable conditions.
(d) Selection of quantities to be observed as construction proceeds and calculation of their anticipated values on the basis of the working hypothesis.
(e) Calculation of values of the same quantities under the most unfavourable conditions comparable with the available data concerning the subsurface conditions.
(f) Selection in advance of a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis.
(g) Measurement of quantities to be observed and calculation of actual conditions.
(h) Modification of design to suit actual conditions.
(Peck 1969)

EN 1997-1 (the Eurocode 7: Geotechnical design - Part 1: General rules) states the design requirements, which are also followed in the ONKALO work. Explicitly, the EC7 mentions the Observational Method as a tool to be used as a part of the design process. The limit state based design is required for each geotechnical design situation, and the OM is one of the four allowed approaches. The following quote is from the EC7 concerning the use of the OM:

(1) When prediction of geotechnical behaviour is difficult, it can be appropriate to apply the approach known as "the observational method", in which the design is reviewed during construction.
(2) The following requirements shall be met before construction is started:
— acceptable limits of behaviour shall be established;
— the range of possible behaviour shall be assessed and it shall be shown that there is an acceptable probability that the actual behaviour will be within the acceptable limits;
— a plan of monitoring shall be devised, which will reveal whether the actual behaviour lies within the acceptable limits. The monitoring shall make this clear at a sufficiently early stage, and with sufficiently short intervals to allow contingency actions to be undertaken successfully;
— the response time of the instruments and the procedures for analysing the results shall be sufficiently rapid in relation to the possible evolution of the system;
— a plan of contingency actions shall be devised, which may be adopted if the monitoring reveals behaviour outside acceptable limits.
(3) During construction, the monitoring shall be carried out as planned.
The results of the monitoring shall be assessed at appropriate stages and the planned contingency actions shall be put into operation if the limits of behaviour are exceeded.

Monitoring equipment shall either be replaced or extended if it fails to supply reliable data of appropriate type or in sufficient quantity.

(EN 1997-1 s. 2.7)

The sections marked with the letter P are principles for which there is no alternative, unless specifically stated. In other words, the sections 2.7(2)P through 2.7(5)P are mandatory in Eurocode based use of the Observational Method.

Posiva has published WR 2002-48 (The Observational Method applied to engineering and construction of the access to the ONKALO facility), which describes Posiva’s design strategy to apply the OM to the engineering and construction of the access to the ONKALO facility. The facility is simultaneously considered to be a learning exercise to develop the methodology for the implementation of the repository. The report concludes that the concept of the Observational Method has been misunderstood in certain instances with the perception that design issues are not sorted out in advance, which can lead to sloppy engineering. However, the proper use of the Observational Method is exactly the opposite.

The most important conclusions of WR 2002-48 are:
- the method is applicable to the geotechnical part of the design
- decide-as-you-go (not design-as-you-go or learn-as-you-go)
- total design should be done before realisation
- only a tool to adapt to changing geological conditions.

The learning process, including aspects like safety, logistics, traffic, ventilation, electricity, and main layout strategy, are to be finished before realisation – not during realisation. (Modified from Posiva 2011b.)

2.2 ONKALO Design Method (ODM)

The ONKALO design method can be considered as a prediction and observation (outcome) method. The method repeats cyclically as more information becomes available. The outcome depends on the initial data of the process. The four repeating steps are the core of the method (Fig. 1):

**Site description:** Olkiluoto Site Descriptions (Posiva 2004, 2006, 2008, and 2011a) collect and present all the material produced during investigations and analysis. This step represents the accumulated data from the surrounding rock mass.

**Site investigation:** Every in situ investigation is processed in order to accumulate information and to document the initial data used in the design. The interpretation process is documented to provide full traceability of the parameters.

**Data processing:** The data from site investigations is used to compose the initial data for rock engineering purposes. To obtain the best possible result, it is essential to have a strong co-operation especially between the geologist (GEOL) and the rock engineer (KAT).

**Calculation:** The initial data, functional boundary conditions, and the geometry of the facility are taken into account as the rock engineering calculations are made. The calculation method and the governing regulations (e.g. the Eurocode) that influence the design process are stated. The documents produced in this stage include reinforcement and grouting calculations.
The process repeats as new information becomes available. This is essential for a prediction (based on latest data) and observation (using continued monitoring) method. New information becomes available at the following stages:

**Deep boreholes**: As of 2011, a total of 52 long holes (up to 1 km deep) have been drilled. The drilling investigations can be utilised for establishing the location and properties of particular bedrock structures. In addition to holes drilled from the surface, drilling also takes place underground. Long characterisation holes will also be drilled from ONKALO to the location of the repository. (Posiva 2011c) This data is presented in the Rock Mechanics Model (RMM) and in other borehole analyses.

**ONKALO experience**: The experience accumulated in ONKALO is extensive: many of the straight tunnel sections have pilot hole data, which has been thoroughly analysed by rock engineers and geologists. The designer has implemented the data generated by Posiva. The designer inspects the tunnel on a regular basis, and the most critical observations can lead to corrective measures or additional reinforcement. To predict areas most prone to stress-induced damage, modelling was carried out from the entire technical area (TU5 and TU5A shown in Fig. 2). Wedge analysis has been performed in areas where the cracks can interact and create blocks. Additionally, the rock engineering design, based on Q classification, has been carried out for areas TU4, TU5 and TU5A. (Nuijten 2011)

**Pilot holes**: From the end of the ONKALO tunnel, a number of 50- to 300-metre-long pilot holes will be drilled at pre-determined locations. The purpose of these pilot holes is to verify the rock quality in the location the tunnel is going to be before any excavation takes place, and in particular to locate any water-conducting fracture zones and other rock characteristics that may be significant for the construction. (Posiva 2011d) This method will be used extensively during the excavation of the repository.

**Round mapping**: A brief inspection of the rock quality is performed immediately after excavation, and if anything out of the ordinary is observed, the designer comes to the site as soon as possible. Otherwise, the site visits follow a predefined schedule. The Q classification has two pitfalls when applied to the ONKALO conditions: the cracking direction in relation to local anisotropy direction and the local stress-driven
behaviour. Using the geometry, crack information, anisotropy, and stress-driven damage analysis, the classification can be adjusted. Systematic mapping produces extensive data which is used as the final control for the reinforcement. It also enables the discovery of blocks that may require additional reinforcement. (Hatakka 2011)

**Monitoring:** The rock reinforcement solutions are optimised to meet the known and predicted conditions at the moment of design. If the design of ONKALO (or the spent fuel repository) is modified, this could cause localised damage in the previously reinforced parts. Additionally, the pre-existing parts have to cope with the altering environmental conditions (e.g. salinity, pH, heat…) as well as the vibration of the blasting work. Vibrations and *in situ* stress changes caused by excavation can break loose small rock pieces or poorly applied shotcrete that has evaded controlling measures. Continuous monitoring of the previously constructed and reinforced parts is vital in order to prevent accidents. Scaling is to be performed on a regular basis on rock surfaces to safely bring down loosened rock.

### 3 RESULTS

Three examples are given. The first one is stress-induced damage prediction based on the ONKALO experience (Fig. 2). The second example is the processing of pilot hole data for usage in rock engineering preliminary design (Fig. 3). The last example describes how round mapping can occasionally require a refined design (Fig. 4).

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*Figure 2.* Conservative prediction of stress-induced damage in the technical area (TU5 and TU5A). Damage is marked by green (light grey in print). Damage depth modelled using Midas GTS 3.0.0(4) (modified from Martinelli 2010)
The first example is stress-induced damage prediction based on published stress data in Posiva 2008 (Fig. 2). The figure shows a part of the technical area of ONKALO. The damage is predicted using the stress-induced damage strength of 57% of uniaxial compressive strength. According to Site Report 2008 (Posiva 2008), the stresses are in the order of $\sigma_H = 32$ MPa, $\sigma_h = 20$ MPa, and $\sigma_z = 12$ MPa ($z = 420$ m). The conservative results show a worst-case damage depth of 300 mm in the south–north-oriented tunnels and 200 mm in the shaft walls with up to 1,150 mm in the bottom parts of shafts. The expected (mean) results (see Martinelli 2010) show no damage in any of the tunnels and 100 mm in the shaft walls with up to 750 mm in the bottom parts of the shafts. Currently (23rd November, 2011), only the exhaust air shaft (the northern-most shaft in Fig. 2) has been raisebored in the technical area. Some damage has been detected, and analysis is on-going.

Figure 3. Example of Pilot Hole 17 (PH17) data of demonstration tunnel DT1 (location shown in Fig. 2) The first image (KUVA 1) shows the dominant rock type, the second image shows the Q classification with subparameters, the third image shows the localized joint orientations and the last image shows the water inflow, joint aperture and salinity. (Tirinen 2011)

The second example shows processed the pilot hole data for rock engineering purposes (Fig. 3). This pilot hole (PH17) was located in the first demonstration tunnel (see Fig. 2), and it was aligned to follow the tunnel orientation in the centre of the profile.
The data shows a water-bearing weakness zone intersecting with the end of the tunnel. It was later decided that this demonstration tunnel be shortened. The fracture information (shown in the second and third panels of Fig. 3) was used in wedge analysis to verify that the preliminary design for the tunnel is adequate.

Figure 4. Example of post-excavation wedge analysis (location shown in Fig. 2) using UnWedge 3.0.18 (Matikainen 2010)

The third example shows a post-excavation based on tunnel observations from systematic mapping stage (Fig. 4). Based on fracture mapping, three long fractures were interacting in an area where there was low fracture density and high fracture persistence. This enabled the formation of a fairly large wedge, shown at the top of Fig. 4. The standard bolting solution was not enough to hold the block (factor of safety 0.582), but it was found stable if shotcrete was taken into account (FOS 3.498). The design approach in ONKALO is to support wedges with bolts and to support small wedges between bolts with shotcrete. Therefore, additional longer bolting pattern was applied to the area to support the potential wedge by bolts alone (FOS 1.314). This produced a fairly dense bolting grid, as shown in Fig. 4.

The ONKALO design method has undergone continuous improvement during use. A selection of major improvements in chronological order:
- implementation of shotcrete standards EN 14487, EN 14488, and EN 14889
- determination of sufficient bolt length
- determination of bolt anchorage length
- determination of initial parameters for modelling and limit state analysis
- use of SRF and ESR parameters of Q system (NGI system) in ONKALO
- added new bolt types (cold drawn bolts, new expansion anchor bolt type)
- design of mesh plate reinforcement
- latest in situ stress measurements from levels -400 … -500
4 DISCUSSION

The results indicate that the ONKALO design method can also be applied to the design of the spent nuclear fuel repository. However, the learning part is now over, and the design solutions to each foreseeable problem are to be established beforehand. It is expected that something out of the ordinary may occur. In these cases, the solution is to be described as a process (e.g. “Design process in case of unexpected rock conditions”), and the design methodology can be described, as has been the case in ONKALO. However, the end repository is not a practice ground, and continuous improvement can only be done in a limited scale in predetermined fashion.

It is suggested to describe the most probable rock types (RT) using variable criteria and then design the matching excavation shapes, reinforcement types, and grouting fans. For example, good quality mica gneiss rock could be designated as MGN10, where MGN stands for Mica Gneiss and 10 designates the Q classification corresponding to good quality. The Rock Types should be chosen so that they cover approximately 90% of the design cases. Too many reduce the usability of the system and too few cannot take into account the most common deviations. The rest 10% of the design cases are designed using the limit state calculations (e.g. numerical modeling, wedge analysis, stochastic analysis, etc.) according to declared methodology.

There are two major changes compared with the design methodology of ONKALO. The first one is that the durability and coupled physical issues of the reinforcements were chosen to be studied in detail more carefully and that a temporary service length time of 30 years was chosen for the rock reinforcement. In the design of the repository, easily monitored and maintenance parts may have a lower service life, but all other reinforcement must be designed to last the entire design life time of ONKALO (120 years). The design life for 120 years and severe conditions have already been carried out in the rock engineering of the ONKALO shafts and shaft rock reinforcement, since these facilities cannot be upgraded easily later on.

The second major change is the desire to minimise the amount of high pH products (e.g. shotcrete, concrete, and grout), which could be harmful for the bentonite buffer. Reduction of shotcrete has been tested in the POSE (Posiva ONKALO Spalling Experiment) niche, exploratory niche 5, and in the demonstration tunnels DT1 and DT2. Shotcrete can be replaced by using steel mesh with suitably small grid spacing. Grouted rock bolts can be replaced by ungrouted mechanically anchored bolts (expansion anchors) with secondary metal pipe encasing for corrosion protection. Secondary rock anchors (e.g. mesh anchors) can also be replaced by threaded bars with expansion anchors. For secondary rock anchors, the corrosion protection can be achieved by using sacrificial dimensioning or a secondary metal pipe encasing. For all steel components the primary corrosion protection is the correct choice of steel material type.

Slotted wedge anchors (aka. Kiruna bolts) are not recommended, because they can become loose during the planned service life.

On a larger scale, there are many things to be considered in the rock engineering design. One such thing is the safety during construction and operation (e.g. double exit policy). There are significant material flows related to excavation and transportation of dangerous materials (e.g. explosives and fuel). There are multiple moving vehicles during construction and during use and the traffic planning will affect the layout. Ventilation and other infrastructure will affect tunnel cross section size and require auxiliary space. The electricity supply will require auxiliary space and secondary routes and fire protection measures. The excavation equipment requires certain amount of space, loading and turning areas, maintenance area and storage area. Given the desire to minimize space, it should be thought out how to store the canisters, rock, explosives, maintenance equipment, work equipment (e.g. bolts, wire mesh, concrete, grout...), fuels and gases and safety containers.
In all likelihood the ONKALO design method can be applied to the design of the spent nuclear fuel repository. The methodology should now be finalized and modified for use in the repository area. It may also be adapted to be used in other similar high reliability facilities (e.g. other repositories or research laboratories deep underground). For conventional rock engineering projects, the Observational Method as described in the Eurocode is sufficient and the benefit from the added systematisation of the ONKALO design method may be less than the introduced expense.

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