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2012:30

Initial review of physical properties and processes of the buffer and backfill. THM and other physical processes

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SSM perspektiv

Bakgrund

Strålsäkerhetsmyndigheten (SSM) granskar Svensk Kärnbränslehantering AB:s (SKB) ansökningar enligt lagen (1984:3) om kärnteknisk verksamhet om uppförande, innehav och drift av ett slutförvar för använt kärnbränsle och av en inkapslingsanläggning. Som en del i granskningen ger SSM konsulter uppdrag för att inhämta information i avgränsade frågor. I SSM:s Technical note-serie rapporteras resultaten från dessa konsultuppdrag.

Projektets syfte

Denna rapport består av en ”Technical Note” inom SSM:s inledande granskning av SKB:s säkerhetsredovisning SR-Site. Syftet med denna inledande granskning av frågorna kring THM (termisk, hydrologisk samt mekanisk) och andra fysikaliska processer i buffert och återfyllnad i slutförvarsanläggningen är att få en bred granskning och belysning av SR-Site och underreferenser samt att identifiera eventuella behov av kompletterande information eller förtydliganden som SKB bör tillfoga ansökansunderlaget.

Författarens sammanfattning

Behov av kompletterande information eller förtydliganden har identifierats inom flera specifika ämnen (Appendix 2). Några specifika granskningsfrågor har också rekommenderats till fördjupade granskning i huvudgranskningsfasen (Appendix 3).

Projektinformation

Kontaktperson på SSM: Jinsong Liu
Diarienummer ramavtal: SSM2010-4230
Diarienummer avrop: SSM2011-4207
Aktivitetsnummer: 3030007-4008

SSM perspective

Background

The Swedish Radiation Safety Authority (SSM) reviews the Swedish Nuclear Fuel Company's (SKB) applications under the Act on Nuclear Activities (SFS 1984:3) for the construction and operation of a repository for spent nuclear fuel and for an encapsulation facility. As part of the review, SSM commissions consultants to carry out work in order to obtain information on specific issues. The results from the consultants' tasks are reported in SSM's Technical Note series.

Objectives of the project

This report consists of a Technical Note in SSM's initial review phase of SKB's safety analysis SR-Site. The aim of the initial review of issues concerning THM (thermal, hydrological and mechanical) and other physical processes in buffer and backfill in a final repository is to make a broad illustration and review of SR-Site together with its subordinate references, as well as to identify potential needs for complementary information or clarification which SKB should supplement to its license applications.

Summary by the author

Several specific topics for which complementary information and clarifications should be requested from SKB were identified (Appendix 2). Specific review topics for consideration during the Main Review Phase are recommended in Appendix 3.

Project information

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Technical Note 11

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Contents

1. Background, scope and limitations

1.1. Background

For the long term function of the repository one important barrier is the bentonite around the canister and the bentonite backfill in the tunnels. The properties of the bentonite related to thermo-, hydro- and mechanical behaviour of the material is crucial for the barrier functions. This review scrutinizes research results published by SKB regarding the properties of the bentonite under different thermal, hydraulic and mechanical conditions.

1.2. Scope and limitations

The preview is a preliminary review and comprises the results published in relevant SKB reports. Where information is missing or incomplete this is pointed out, and for these cases it cannot be concluded whether the barrier will fulfil requirements or not.

1.3. Organisation of the technical note

This technical note is organized in the following manner. First, in Chapter 2, the basic behaviour of the bentonite is investigated, with focus on how relevant the constitutive modelling is done, or to what extent the FE models capture the different aspects of the material behaviour. An attempt is made to evaluate the quality of the modelling. First it is made on an element scale and then on a more complex scale, where several different actions or properties interact.

In Chapter 3 different internal phenomena, such as sinking or heave of the canister, are investigated. Also the effect of irregularities and missing material is included in this chapter.

Then, in Chapter 4, external actions, such as shear and liquefaction, due to an earthquake are dealt with. Also here the problem of possible freezing of the bentonite is dealt with.

Erosion/piping is briefly treated in a separate chapter, Chapter 5.

Finally, in Chapter 6 the process of production, starting all the way from mining of the bentonite and all the different handling procedures to final placing is also briefly discussed.

In Chapter 7 the review findings are summarized and in Chapter 8 recommendations to SSM are given.

2. Basic behaviour of bentonite

2.1. Background

The purpose of testing and modelling is ultimately to be able to predict with confidence what will happen for different scenarios that the repository might be exposed to during the entire design period. In order to do that, material behaviour must be modelled using a number of different constitutive models. Ideally a material model should include all aspects of the material behaviour, but it would then be very complicated. Instead engineering design usually implies using a number of simpler models, each focusing one main part of the material behaviour. Each constitutive model is usually defined by an equation incorporating one or more parameters. The values of the parameters should be chosen so that the model as accurately as possible predicts the material behaviour.

Usually some well-defined laboratory tests on samples of the material are performed to determine these parameters. Other tests are then performed and the ability of the constitutive model to predict the material behaviour for different boundary conditions and testing conditions can then be checked and the laws assumed to be valid, can be verified.

Once the basic behaviour is understood and the constitutive models are chosen and verified, more complex models, usually finite element models, can be used for predictions of more complex problems, regarding initial and boundary conditions as well as other internal and external actions.

Finally some full scale or large model scale tests are performed in order to monitor performance for a limited number of scenarios and the ability of the advanced modelling to predict real behaviour can be evaluated. Once this is done and found satisfactory, more complex scenarios, which perhaps cannot be easily modelled in the laboratory can be modelled and predicted.

All test results will incorporate some scatter due to natural variations in the tested material, small variations in testing performance, accuracy in monitoring etc. It is therefore important to make an estimate of the expected scatter of each parameter, ideally in terms of standard deviations and possibly what type of statistical distribution best describes the scatter. As this often requires comprehensive testing and which might not be possible to accomplish, a reasonable variation width should be estimated and used, giving a range for expected or possible behaviour which will not be exceeded.

2.2. Constitutive model/element model

As pointed out earlier, it is desirable with one constitutive model, which incorporates most of the aspects of material behaviour. Such models are not readily available or even developed and therefore simpler models are often used, which satisfactorily can model certain aspects of the material behaviour.

Below the fundamental properties are briefly discussed and commonly used models indicated.

2.2.1. Deformation properties

Swelling pressure

The swelling pressure is given as a function of void ratio at full saturation and the constitutive model is thus very simple. It is entirely empirical as it is based on a function for a curve fitted to experimental test results. (e.g. TR-10-44, pp 57-58)

Deformation Modulus

In most cases theory of elasticity is used and a modulus of elasticity is defined for the bentonite. In geotechnical engineering the modulus is often assumed to be linear with the logarithm of stress, as is done here.

2.2.2. Strength properties

Strength of material is indeed very complicated and today numerous advanced constitutive models have been formulated and advocated by different researchers. However, within the discipline of soil mechanics the by far most widely accepted model is Mohr/Coulomb failure criterion. It only requires two parameters, cohesion, c', and internal friction angle, φ'.

2.2.3. Hydraulic properties

Darcy’s law is assumed to be valid and all hydraulic conductivities are given as average values.

2.2.4. Thermal properties

Apart for the classical thermal properties as heat conductivity and heat capacity, other properties of the bentonite as strength and deformation properties and hydraulic properties are affected by temperature and must be determined.

2.3. Laboratory testing

2.3.1. Deformation properties

Swelling pressure

The swelling pressure has been tested for a number of bentonites in a cylindrical laboratory device usually referred to as an oedometer. The results are easy to reproduce and the scatter is rather limited. A hysteresis effect has been documented, implying that the stress history has a certain bearing on the swelling pressure at a given void ratio.

Deformation Modulus

A number of oedometer tests have been performed and the modulus for loading and unloading has been determined.

2.3.2. Hydraulic properties

The hydraulic conductivity has been determined for many different void ratios, temperature and chemical composition of the pore fluid.

2.3.3. Thermal properties

The thermal properties of the bentonite at different densities and degrees of saturation are fairly well known and understood.

2.4. Numerical modelling of complex problems

Numerical modelling using the finite element method has been made using primarily two different FEM programs, namely Code Bright and Abaqus.

Predictions have been made for a number of important scenarios and the thus obtained predictions are to a limited extent compared with some full or model scale performance in the next section. Thereby a preliminary evaluation is obtained as verification of the accuracy of the ability of the program to actually predict complex behaviour.

2.4.1. Key references

SKB TR-10-44. Åkesson M, Börgesson L, Kristensson O, SR-Site Data Report – THM modeling of buffer, backfill and other system components.

SKB TR-95-20. Börgesson L, Johannesson L-E, Sandén T, Hernelind J, Modeling of the physical behaviour of water saturated clay barriers.

SKB TR-10-11. Åkesson M, Kristensson O, Börgesson L, Duek A,
THM modelling of buffer, backfill and other system components.

2.5. Full scale testing

Limited full scale testing has been done. The best documented is the Canister Retrieval Test, CRT and the Prototype Repository TBT.

2.6. What have and have SKB not demonstrated. What needs further explanations and research and which unanswered questions remain?

Necessary additional verification/information:
For many of the problems which must be analyzed, it is necessary to use a model which encapsules most aspects and features of the material behaviour. Such a constitutive model requires that a number of parameters are evaluated and with these parameters given the model should be able to predict what will happen when the canister and its surrounding barriers are subjected to different external or internal actions.

The model will reveal answers and predict the behaviour. But with what certainty? How reliable are the results? The only way to verify the models predicting capability is to compare predictions with well-known performance. For this a number of different benchmark examples are required. One obvious way is to let the FEM model predict the tests used for evaluating the parameters.

So let the model predict triaxial tests, drained and undrained, compression tests and swelling tests. This has been done, but only to a limited extent. A swelling/compression test was compared with a FEM predicted similar test, SKB TR-95-20. However, the prediction and comparison were not presented in the same diagram. It was only concluded that the predicted behaviour was fairly good compared with the actual behaviour. The same can be said for a similar comparison for a triaxial test, in the same report.

The Canister Retrieval Test was close to a full scale test and here actual behaviour, regarding resaturation of the bentonite was studied and compared with modelling results. This was mainly done for the final stage, and little was possible to compare regarding the development with time of the homogenisation process. Some measurements were taken of how the swelling pressure changed with time, but the measurements were considered less reliable.

So in conclusion, much more could be done in terms of verifying the FEM model and probably also when it comes to optimizing the parameters in order to get a set of parameters that well describes the behaviour of the bentonite, when exposed to different actions.

As for prediction of and comparison with tests with different boundary conditions, several tests used for evaluating the parameters should be predicted by the model and compared with real performance. This should also be done for the tests on which the evaluation was based.

Based on the above suggested testing, some kind of optimization of the parameters could probably be made.

In TR-10-44, Sections 10.8 -10.10, parameters describing the mechanical behavior are given for the Code Bright and Abaqus models. Similar strategies should be illustrated for hydraulic and thermal properties.

It is desirable with some kind of quantification of to what degree the constitutive model is able to predict basic behavior. Ranges for suitable choices of parameters can probably be given.

It is easy to create a wishing list of tests that should or could be run in the laboratory illustrating different aspects of the expected behavior of the bentonite. A fair amount of testing has definitely been done, but it is probably advisable to extend that set of tests in order to get results so that the reliability of the FEM programs to predict actual scenarios are verified.

Below some type of tests are indicated, which probably fairly easily could be designed and run, addressing problems where the experimental background material is fairly limited or at least scarce.

- Homogenization tests, broken up at different times to study how the moisturization develops with time. It is important to verify that the time scale for these processes is reasonable as these form the basis for several other analyses.
- Element tests with different cavities, in order to investigate how well the FEM programs predict final distribution of densities and moisture content.
- Friction tests, where actual friction or adhesion between bentonite, at different densities, and bedrock and copper develops depending on e.g. swelling pressure.
- Penetration tests in apertures of probable size.
- Erosion tests where erosion is forced to appear as internal erosion and not only along the periphery, as has been the case in most tests reported so far.

Main conclusions

FEM model - a lot remains to be done in order to verify the accuracy of the FEM model as a tool suitable for prediction of the scenarios encountered.

Scatter – what type of scatter can be expected in the different parameters. What precision do you actually have in the prediction, regardless of what the accuracy is.

Accuracy – How well do the models actually predict what they actually claim?

- Due to the model itself,
- Are the parameters used actually valid for the material used? Clay content may vary between 75 and 90 % according to specifications.

Learn more about FEM

This verification of the FEM analyses are extremely important as the FEM analyses are the sole base for studying sinking, heave, shear, homogenization and saturation/drying, which are all discussed in Chapters 3 and 4 of this report.
These analyses are very important for the answer to the question whether the repository will fulfill the stipulated requirements or not.

3. “External” scenarios

Once the repository is in place and closed a number of different scenarios must be imagined and examined. The two major geological events are earthquake and glaciations. These two scenarios are discussed below.

3.1. Earthquakes

Earthquakes might affect the canister and the bentonite in two ways, one is shearing a local fracture intersecting a canister and the other possible external effect would be liquefaction,

3.1.1. Shear

Problem identification
An earthquake in the area close to the repository can induce shear movements in the bedrock which potentially could harm the canister. The bentonite will act as a cushion and thus the properties of the bentonite are crucial in the analysis. The static load of the ice should be superimposed on the stresses caused by shear.

The design value of the shear movement is 5 cm and an ice sheet of 3 km should be accounted for.

Modeling
The basic material model for behavior of the copper, cast iron and the bentonite were used. For the copper, creep was included in the analysis. Some attention was also given to the rate dependency of the properties of the bentonite.

The bentonite is assumed to be linear elastic, perfectly plastic, which is a fairly simple, but probably adequate model in this case.

Testing
Apart from all the element testing of the bentonite and the copper, basically three model scale tests have been done, testing the interaction of the canister, bentonite and bedrock.

The results from the simulation obviously agreed very well with the experimental results, once the correct material properties for the copper at hand were obtained.

Adequacy
The model tests show very consistent results, in spite of the challenging measuring technique and data collection. When comparing with the FEM results the consistency is remarkable, especially as the same basic bentonite parameters were used as in all the other modeling.

The author of this technical note has found little reasoning for choosing the three planes, horizontal, 22,5^{o} angle to the vertical and vertical. It should be demonstrated that these are the critical design values.

All the simulations, and also the model test, were done for, or assumed ideal homogenized bentonite.

Nothing is said about shearing for unsaturated buffer, but this is probably an imaginary case as a glaciation period will not occur until the bentonite is well saturated.

Uncertainties pointed out by the author
Properties of the cemented buffer:
Old data on copper properties,
Contact elements no cohesion at tensile stress,
The size of the element mesh might affect the results,
Scatter in material properties not accounted for.

Conclusions
All the modeling is based on the assumptions about the constitutive model discussed in Chapter 2. Until the relevance of these assumptions has been more clearly verified, the conclusions must be regarded as tentative or preliminary. Accounting also for some inhomogeneity of the bentonite would be valuable in this case.

References

SKB TR-10-34. Hernelind J, Modeling and analysis of canister and buffer for earthquake induced rock shear and glacial load.

SKB TR-10-33. Börgesson L, Hernelind J, Earthquake induced rock shear through a deposition hole.

SKB TR-10-31. Börgesson L, Dueck A, Johannesson L-E., Material model for shear of the buffer. Evaluation of laboratory test results.

SKB TR-06-43. Börgesson L, Hernelind J, Earthquake induced rock shear through a deposition hole.

SKB TR-06-87. Earthquake induced rock shear through a deposition hole when creep is considered – first model.

SKB TR-04-02. Börgesson L, Johannesson L-E, Hernelind J,Earthquake induced rock shear through a deposition hole.

SKB TR-95-20. Börgesson L, Johannesson L-E, Hernelind J, Modeling of physical behavior of water saturated clay barriers.

SKB TR-86-26. Börgesson L, Model shear test of canisters with smectite clay envelopes in deposition holes.

3.1.2. Liquefaction

Problem identification
A loose and practically water saturated soil can, due to vibration or dynamic loading caused by an earthquake, temporarily lose its shear strength. If so happened, the canister could sink and eventually get in contact with the bedrock at the bottom.

Modeling
The phenomenon is usually associated with rather unified fine sand with well-rounded particles. The sand needs to be in a loose state and thus contractive so that, when exposed to dynamic loading it strives at compacting into a denser state. This requires that water is momentarily expelled and if the hydraulic conductivity is such that it prolongs the draining of the material large pore pressures will develop. As the total stress is practically constant, an increase in pore pressure results in a corresponding reduction in effective stress. The shear strength is a direct function of the effective stress and thus the strength of the material decreases. If this decrease is large enough, it could lead to a bearing capacity failure of the bentonite below the canister and the canister sinks.

Testing
No tests.

Adequacy
SKB concludes that liquefaction is not an issue for the bentonite with the specified properties. This is correct as the bentonite is in a very dense state and any shear, under the stresses at hand, would lead to a dilation of the soil which in turn is followed by a decrease in pore pressures and an increase in strength.

Consequences
None.

Conclusions
Liquefaction is not an issue.

References
SKB TR-00-18. Roland P, On the risk of Liquefaction of buffer and backfill.

SKB TR-06-38. Harrington J F, Birchall D J, Sensitivity of total stress to changes in externally applied water pressure in KBS-3 buffer bentonite.

3.2. Freezing

During glaciations the temperature will gradually decrease in the ground. Calculations indicate that a decrease down to a couple of degrees below zero, - 2 ^{o}C given as the extreme scenario, might occur at the depth of the repository.

3.2.1. Problem identification

A decrease of temperature of the bentonite below 0 ^{o}C will initially result in a decrease of swelling pressure. Eventually the swelling pressure will drop to 0 and the bentonite will then start to freeze accompanied by ice formation, which, if unrestricted, will result in a swelling of the bentonite. However, if expansion is restricted large compressive stresses will develop.

Important questions for the bentonite are the changes of the swelling pressure with time and temperature and also whether the process of freezing and swelling is reversible during repeated freezing and thawing.

3.2.2. Modeling

A thermodynamic model was developed and it was based on a sound theory. It shows that the swelling pressure decreases about 1.2 MPa/ ^{o}C below zero. Furthermore, it predicts that the swelling pressure at 0 ^{o}C is very important and that this determines the critical temperature, T_c, when the bentonite freezes.

3.2.3. Testing

Comprehensive tests have been made as element tests to investigate how the swelling pressure varies with temperature. It confirms the developed theory in great detail. The tests illustrate that the critical temperature, T_c, decreases according to the prediction and that the swelling pressure at 0 ^{o}C determines when the bentonite will freeze.

The tests also clearly illustrated that the process is completely reversible and that even after a number of freezing/thawing cycles the swelling pressure is regained.

3.2.4. Adequacy and consequences

No large scale tests were performed, as it was not regarded as necessary when the basic phenomenon is so well understood and modeled and also confirmed by element tests.

Part of the backfill might freeze, but will regain its swelling pressure after thawing. As no flow will occur while the bentonite is frozen and it will regain its swelling pressure after thawing, the process as such poses no threat to the barrier function.
It is concluded that some ice lens formation might occur in some boreholes sealed with bentonite. However, with the time scales involved the length of an ice lens will not exceed 10 cm, which is acceptable.

3.2.5. Conclusions

The area of freezing is comprehensively researched and the results are satisfactory. Permafrost and temperatures down to - 2 ^{o}C, as given as the design value, will not jeopardize the function of the buffer, backfill and the sealing of boreholes, as long as the design swelling pressures will prevail at 0 ^{o}C.

3.2.6. References

SKB TR-06-09. Long-term safety for KBS-3 repositories at Forsmark and Laxemar - a first evaluation. Main report of the SR-Can project.

SKB TR-09-14. Sundberg J. Back P-E, Ländell M, Sundberg A, Modeling of temperature in deep boreholes and evaluation of geothermal heat flow at Forsmark and Laxemar.

SKB TR-10-40. Birgersson M, Karnland O, Nilsson U, Freezing of bentonite. Experimental studies and theoretical considerations.

4. “Internal” scenarios

4.1. Settlement of the canister

4.1.1. Problem identification

The weight of the canister and the overlying bentonite results in a pressure at the bottom of the canister which is in the order of 0,5 MPa, and it is much lower than the swelling pressure of the saturated bentonite and sinking of the canister should not occur. However, under certain conditions the canister may settle/sink downwards due to creep phenomenon. If this sinking should be very large the canister could get in direct contact with the bedrock and this would violate the safety requirements.

4.1.2. Modeling

A creep model has been adopted, developed and tested. Laboratory testing confirms the model and the creep behavior can thus be adequately modeled. One drawback might be that creep is a process taking place during thousands of years and using the model means extrapolating testing results for long periods.

The material properties adopted for the modeling are comparable with what have been used in earlier analyses, apart from what were assumed for the friction angle for the bentonite and the friction at the rock wall. Especially the latter was assumed higher than in most of the earlier cases. This is, however, not important as it only affects the results insignificantly.

4.1.3. Testing

Model testing has been performed and results are extrapolated to very long times.

4.1.4. Adequacy

The buffer material is extremely dense and dilatant. It has been shown that a type of bearing capacity failure will not occur and that creep will be very limited if the density of the buffer is above a certain value, which is well below the required range of values for the buffer. The modeling implies that even densities as low as 1500 kg/m^3 at water saturation would give very small vertical displacement.

4.1.5. Uncertainties pointed out by the author

The assumptions made in the analysis are much on the safe side. Therefore I see no uncertainties on the unsafe side.

4.1.6. Conclusions

It has been demonstrated that sinking of the canister is not an issue, given that the bentonite fulfills the specified properties.

4.1.7. References

SKB TR-95-20. Börgesson L, Johannesson L-E, Sandén T, Hernelind J, Modeling of the physical behavior of water saturated clay barriers. Laboratory tests, material models and finite element application.

SKB TR-06-04. Börgesson L, Hernelind J, Canister displacement in KS-3V A theoretical study.

SKB TR-10-11. Åkesson M, Kristensson O, Börgesson L, Dueck A, THM modeling of buffer, backfill and other system components.

SKB TR-10-47. Buffer, backfill and closure process for the safety assessment SR-Site.

4.2. Swelling/uplift of the canister

4.2.1. Problem identification

Due to a lower modulus and probably also lower swelling pressure of the backfill compared to the buffer, the buffer might swell, lift the canister and the buffer might intrude into the backfill. This is not a problem as such, but it would, as a consequence, lead to a reduction in the buffer density and it could possibly violate the requirements.

4.2.2. Modeling

The modeling is based on the general conditions discussed in Chapter 2. It is sound and fairly uncomplicated. Again very homogenous conditions are assumed. On the other hand, inhomogeneities might not result in a much worse case.

4.2.3. Testing

The properties used for the FEM analysis are based on element testing and well researched. The model as such needs, as pointed out earlier, ought to be much better benchmarked. However, only limited tests have been made to investigate and verify the upwards movement of the canister, and thus most of the conclusions are based on the FEM analysis. This requires a number of assumptions, of which some seem to be somewhat arbitrarily chosen and certainly not verified by testing, which should be done. However most of the assumptions seem to be made on the safe side.

4.2.4. Uncertainties pointed out by the authors

Pellets filling at the bottom of the tunnel or whatever system that will be chosen eventually, should be included in the modeling but the effect will probably be rather insignificant, as it will be less than 8 cm thick.

Properties of the joints between the blocks are not very well known, nor is the saturation phase modeled.

4.2.5. Remaining issues to study

The friction between the deposition hole rock wall and the bentonite has a great influence on the model results. It is unclear where the basic model assumption 8.7^{o} comes from, possibly the lowest value obtained from all triaxial tests on bentonite, regardless of density. It is not quite clear, but it is probably so that the friction angle is assumed to vary with the swelling pressure and thus built into the model.

The author of this technical note has found little testing evidence for the choice of friction angle acting between the buffer bentonite and the deposition hole rock wall (although the author personally thinks it is larger so the assumption is made on the safe side). A test series investigating the friction angle at hand between the bentonite and the bedrock wall and also for the interface bentonite/copper should be performed and calculations should be made with respect to the so obtained results.

The influence of deviations from the base case has been studied for a number of combinations. However, the most detrimental one theoretically, but certainly not the most probable one has been omitted, that of low values of the backfill modulus combined with zero swelling pressure against the wall and a friction angle of 0. As this is not used, justifications for this should be given.

4.2.6. Conclusions

Complementary testing and analysis recommended.

4.2.7. References

SKB TR-10-11. Åkesson M, Kristensson O, Börgesson L, Dueck A, Hernelind J, Chapter 8, THM modelling of buffer, backfill and other system components.

SKB R-09-42. Börgesson L, Hernelind J, Mechanical interaction buffer/backfill.

SKB R-08-131. Johannesson L-E, Backfilling and closure of the deep repository.

SKB TR-06-12. Börgesson L, Johannesson L-E, Consequence of upward swelling from a wet deposition hole into a dry tunnel with backfill made of blocks.

4.3. Homogenisation/Mass redistribution of the buffer

4.3.1. Problem identification

Initially, the deposition hole will be carefully filled with buffer material. However the material is not completely homogenous for a number of different causes. There will for example be a gap between the canister and the buffer rings, a slot between the buffer and the bedrock will be filled with bentonite pellets. Furthermore larger inhomogeneities might occur due to erosion or piping and by flaws in the placing of the buffer. It has been assumed that one or several rings even might be missing, although the QA should guarantee that this will not happen.

It is thus important to study and investigate how the buffer will swell, fill the gaps and eventually get fairly homogenous again.

4.3.2. Modeling

A number of different scenarios have been investigated and all the calculations have been based on the constitutive models and findings discussed in Chapter 2 of this technical note. Three different modeling tools have been utilized and ample results are given.

One analysis, Case1_2e in Chapter 6 of SKB TR-10-11, did not converge. That test had a high friction between the bedrock wall and the buffer, but for stresses lower than 1 MPa, that might be a reasonable assumption.

4.3.3. Testing

One full scale test has been modeled, named the Canister Retrieval Test, CRT. After 5 years the test was dismantled and e.g. void ratios and water contents were determined and found to agree fairly well with the FE modeling. The monitored swelling pressures were far less than anticipated which was attributed to softer material surrounding the measuring device in the CRT.

Apart from the CRT very little testing investigating how the buffer will swell and fill a gap caused by erosion or faulty installation have been performed.

There is a strong need for further testing, simple and idealized, on the element scale as well as for a prototype, which should give indications on how well the model predicts true behavior.

Furthermore little testing is done regarding the friction between the buffer and copper and the bedrock wall, respectively.

4.3.4. Adequacy

The testing program needs to be extended regarding swelling into a cavity, friction between the bentonite and the copper and to the bedrock wall, respectively.

4.3.5. Consequences

For some of the cases modeled, the limiting requirements were not fulfilled.

4.3.6. Remaining issues to study

Experimental verification of a number of basic cases regarding expansion in to an existing cavity remains to be studied.

4.3.7. Conclusions

Further testing is needed regarding expansion into a cavity, friction between bedrock wall and the buffer and perhaps a more nuanced modeling of the internal friction as a function of stress.

4.3.8. References

SKB TR-95-20. Börgesson L, Johannesson L-E, Sandén T, Hernelind J, Modeling of the physical behaviour of water saturated clay barriers.

SKB TR-10-11. Åkesson M, Kristensson O, Börgesson L, Dueck A, THM modeling of buffer, backfill and other system components.

SKB TR-11-01. Long-term safety for the final repository for spent nuclear fuel a Forsmark. Volume I, II and III. Chapters 10.3.8, 10.3.9 and 10.4.8.

4.4. Homogenisation/Mass redistribution of the backfill

4.4.1. Problem identification

The saturation and homogenization process under ideal conditions were discussed in Chapter 2 of this report. Also for the backfill voids due to improper handling during placing of backfill blocks or flaws in the procedure for placing of the pellets can occur. However no such cases were investigated numerically. This might not be a great problem, but should be given some attention, especially inadequate filling of pellets.

4.4.2. Modeling

The modeling of the backfill is rigorous regarding homogenization of the blocks and pellets for the ideal geometries given. However, no modeling of how inadequate filling of the spacing between the blocks and the tunnel walls is included, nor are any missing blocks accounted for in the analysis.

4.4.3. Testing

Testing for the general understanding of the homogenization process is adequate, but very little is done regarding testing of actual behavior.

4.4.4. Uncertainties pointed out by the author

The data used for the material is based on results from tests on MX-80, while the present design assumes Milos BF. Further testing should be made to give proper data for the reference material.

The predictive capability of the model is somewhat limited as several of the parameters used in the modeling are density dependent, while this is not incorporated in the model at hand.

4.4.5. Conclusions

More modeling of preexisting voids in the backfill needs to be investigated, theoretically as well as experimentally.

4.4.6. References

SKB TR-10-11. Åkesson M, Kristensson O, Börgesson L, Dueck A,
THM modeling of buffer, backfill and other system components.

4.5. General references

SKB TR-10-47. Buffer, backfill and closure process report for the safety assessment DR-Site, Chapters 3 and 4.

SKB TR-11-01. Long-term safety for the final repository for spent nuclear fuel a Forsmark. Volume I, II and III. Chapters 10.3.8, 10.3.9 and 10.4.8.

5. Other processes – Erosion and piping

Erosion and piping is referred to as the process when flowing water removes and transport soil particles away from their original positions. The process can be caused by mechanical action, due to flow rate and the viscosity of the fluid or it can be caused by some chemical interaction between the fluid and the soil/gel/sol material.

5.1. Chemical erosion

Chemical erosion is dealt with by other reviewers and actually not a part of this THM review task. However, there are some assumptions made in SKB TR-09-34 and TR-09-35, which are of extreme importance and relates to the HM phase. It concerns the phenomenon of bentonite intrusion into an aperture and how far this intrusion will reach. Neretniks et.al. in TR-09-35 assumes no friction between the bentonite and the wall, irrespectively of the density and swelling pressure. This leads to intrusion of the bentonite of tens or even hundreds of meters. Börgesson et.al., in TR-09-34, assuming swelling pressures and friction angles from observations in laboratory tests, arrives at intrusions of a few millimetres up to a centimetre depending on the size of the aperture. The assumption made by Neretniks et. al. is not realistic, although it probably leads to a serious overestimation of the chemical erosion rate.

5.2. Mechanical/Physical erosion

The subject of mechanical erosion is complicated as even small, hardly detectible inhomogeneities will govern the flow paths of the flowing liquid. It can thus, not readily be modelled by a homogenous continuum material. Thus it must heavily rely on experimental investigations and observations. Thereby some sort of critical gradients can probably be established and different erosion phenomena studied and hopefully understood.

There are a few, vastly different scenarios regarding erosion that must be identified and investigated. One pertains to initial conditions, when the buffer and backfill bentonite yet not is saturated and gaps still exists between blocks and within the volumes filled with pellets. An inflow of water might then easily cause erosion. In a second case when the bentonite has swelled and is fairly uniform, high gradients can still cause internal erosion, if preceded by piping. A special case, which needs much attention, is that of the stability of the backfill blocks and pellets in the tunnel, before a plug is manufactured and can seal off the tunnel, so that the pore pressure can start building up and stop the erosion.

Some tests have been reported, but it is stated in one of SKB’s reports (SKB R-06.80, page 19) that “The uncertainties are considerable regarding both the influence of the rock hydrology and the ability of the buffer to resist these processes” and also concluded that “The knowledge of when piping and erosion occur and the consequences are not enough known today”.

Some tests of the saturation phase in the tunnel have been performed, but more testing is needed to understand and master the necessary procedures to limit erosion during the construction phase.

5.3. References:

SKB TR-10-11. Åkesson M, Kristensson O, Börgesson L, Dueck A, THM modeling of buffer, backfill and other system components.

SKB R-06-80. Börgesson L, Sandén T, Piping and erosion in buffer and backfill materials.

SKB TR-09-34 . Birgersson M, Börgesson L, Hedström M, Karland O, Nilsson U, Bentonite erosion.

SKB TR-09-35. Neretniks I, Liu L, Mormo, L, Mechanisms and models for bentonite erosion.

6. The real production line

Most results and conclusions drawn so far are based on calculations and test results obtained from carefully performed tests on very homogenous material, mainly prepared on a small scale in the laboratory and under carefully monitored conditions. When the repository will be built and successively filled with canisters and bentonite blocks and pellets, the scale will be vastly different. All parts of the production, including mining of the bentonite, transportation, preparation (homogenisation and drying/wetting), compaction, mechanical shaping, storing, transportation and final placing must be performed to the specified conditions. This will require a rigorous plan for quality assurance, monitoring and documentation, which will form enormous proportions of the entire disposal procedures.

Many of the different phases and actions are well known from other similar industrial applications and should easily be modified to meet the special requirements stipulated for this application. There are, however, many procedures and processes still requiring extensive developing work. It is also stated that samples will be taken and that a specific strategy will be developed for this. This is not a small task and it is mandatory to have a well-defined strategy for how many samples shall be taken in each case. How should this be done randomly enough? Moreover it is important to specify the acceptance and rejection criteria, and what the actions will be in case of unsatisfactory results.

A detailed plan of how this QA system shall be designed and work must be demonstrated. Furthermore a robust plan for how the capacity for the production and placing at the rate necessary for the deposition of the number of canisters per month also needs to be demonstrated.

Many of the different stages, from mining to final placements, seem well illustrated on the drawing board, but not all of them have yet been tested in full scale, and certainly not at a production rate that will be necessary once the repository is under construction.

References

SKB TR-10-15. Design, production and initial state of the buffer.

SKB TR-10-16. Design, production and initial state of the backfill and plug in deposition tunnels.

SKB R-06-73. Johannesson L-E, Nilsson U, Deep repository-engineered barrier systems.

SKB TR-10-44. Åkesson M, Börgesson L, Kristensson O, SR-Site Data report.

SKB TR-08-59. Wimelius H, Pusch R, Backfilling of KBS-3V deposition tunnels.

7. Main review findings

7.1. Benchmarking of finite element modelling (FEM)

Mainly two FEM codes have been utilized, Clay/tech and Code_Bright. For the latter model a scheme for how the modelling parameters are evaluated is given, but for the other model this information is not that clearly indicated. The THM testing in the laboratory is extensive and forms the basis for evaluating the parameters needed for the FEM modelling. Some comparisons of predictions and performance can be found in SKB TR-95-20, but requires quite some replotting of experimental results and modelled results. These comparisons on the element scale should be made to a much greater extent in order to validate how well the code models different aspects of the bentonite behaviour.

The results from FEM calculations are also compared for the CRT, but show mostly the modelled and predicted water contents and densities, which are important parameters. However it would be useful with some parameter study, in order to see how sensitive the calculation results are to moderate variations in the assumptions of the parameters of the analysis.

It is also important that this benchmarking is rigorously done, as the reliability of many of the key scenarios later modelled are heavily depending on the fact that the FEM model closely models many different aspects of the bentonite behaviour.

7.2. Homogenisation

The basic assumptions, as discussed in Chapter 2, results in a model that can predict how homogenisation of the bentonite will occur under different boundary and testing conditions. There is, however, a lack of experimental data to verify the performance. This area should be complemented with ample testing, aiming at obtaining data on how the homogenisation, under different boundary conditions, will develop with time. This is required on the element scale as well as for larger tests, almost of prototype scale.

7.3. Resaturation

Resaturation of the buffer is a key issue for the whole function of the bentonite as a barrier. When modelling the negative pore pressures in the yet unsaturated bentonite, the negative pore pressures will ‘suck’ water into the bentonite until it is practically saturated. In a very dry hole, the bentonite might get a very low degree of saturation due to the temperature increase close to the buffer. Some testing results indicate that this material will not saturate until an external pore pressure is applied. The resaturation of the buffer under different boundary conditions, and degrees of saturation needs to be further investigated.

7.4. Erosion/Piping

The understanding and modelling of erosion and piping are not very extensive and much testing and model development need to be done.

7.5. Real life

Many of the different stages, from mining of the bentonite to the final placement of the blocks and pellets, seem to be well illustrated on the drawing board, but far from all of them have been tested in full scale, and certainly not at the production rate that will be necessary once the repository is under construction.

Apart from development of machinery, methods and procedures there is a need for finalizing sampling strategies and acceptance and rejection criteria for the different phases of the whole production line.

8. Recommendations to SSM

Needless to say, SSM should require that SKB carefully considers the questions raised in Chapter 7 of this report, Main review findings.

There exists a lot of element testing results, but SSM should request clarifications regarding how well the FEM codes Code_Bright and ClayTech are able to model different phases of clay behaviour. SKB should probably perform some more element tests, as class A predictions. That implies that the FEM modelling results are delivered to SSM before the actual testing is done. It might be wise to decide what tests to perform in a dialogue between SKB and SSM.

Another clarification regarding the ClayTech model would be to produce a clear scheme for the choice of parameters, similar to what is given for Code_Bright in SKB TR-10-44, Figure 10-15, page 61. It would also be helpful if SKB to a certain extent discuss the compromises necessary when choosing the parameters for the models.

Along the same line, more comparisons between modelling results from Code_Bright and Abaqus would be helpful when judging the accuracy of the two models.

SSM should probably do some further FEM modelling in order to be able to appreciate the results presented by SKB. Thereby it will be possible to see the effect on the results of different choices of input values. A parameter study will give valuable information of the expected precision of the prediction and also which parameters contribute most to the uncertainties.

Homogenisation seems to be well understood, but more testing, on an element scale as well as for the prototype should be requested by SSM.

Resaturation and erosion/piping are two areas where SSM should require more testing and modelling before the phenomena can be regarded as mature.

Finally, SKB needs to demonstrate that the whole chain of elements, from mining of the bentonite to final placing of the bentonite and closure of the repository, can be performed satisfactory. This also includes sampling strategies, methods, rejection and acceptance criteria.

APPENDIX 1

Coverage of SKB reports

Table 1:1

Reviewed report	Reviewed sections	Comments
SKB TR-86-26. Börgesson L., Model shear test of canisters with smectite clay envelopes in deposition holes.		Background information
SKB TR-95-20. Börgesson L, Johannesson L-E, Sandén T, Hernelind J, Modelling of the physical behaviour of water saturated caly barriers.	The entire report	
SKB TR-00-18. Pusch R, On the risk of Liquefaction of buffer and backfill.		Background information
SKB TR-04-02. Börgesson L., Johannesson L-E, Hernelind J, Earthquake induced rock shear through a deposition hole.		Background information
SKB TR-06-04. Börgesson L., Hernelind J, Canister displacement in KS-3V A theoretical study.		Background information
SKB TR-06-09 Long-term safety for KBS-3 repositories at Forsmark and Laxemar - a first evaluation. Main report of the SR-Can project.		Background information
SKB TR-06-12. Börgesson L., Johannesson L-E, Consequence of upward swelling from a wet deposition hole into a dry tunnel with backfill made of blocks.	The entire report	
SKB TR-06-38. Sensitivity of total stress to changes in externally applied water pressure in KBS-3 buffer bentonite J F Harrington, D J Birchall.		Background information
SKB TR-06-43. Earthquake induced rock shear through a deposition hole. Börgesson, L., Hernelind, J.	The entire report	
SKB R-06-73. Johannesson L-E, Nilsson U, Deep repository-engineered barrier systems.		Background information
SKB R-06-80. Börgesson L, Sandén T, Piping and erosion in buffer and backfill materials.	The entire report	
SKB TR-06-87. Earthquake induced rock shear through a deposition hole when		Background information

creep is considered – first model.		
SKB TR-08-59. Wimelius H, Pusch R, Backfilling of KBS-3V deposition tunnels.		Background information
SKB R-08-131. Johannesson L-E, Backfilling and closure of the deep repository.		Background information
SKB TR-09-14. Sundberg J, Back P-E, Ländell M, Sundberg, A, Modeling of temperature in deep boreholes and evaluation of geothermal heat flow at Forsmark and Laxemar.		Background information
SKB TR-09-34. Birgersson M, Börgesson L, Hedström M, Karland O, Nilsson U, Bentonite erosion.		
SKB TR-09-35. Neretniks I, Liu L, Mormo L, Mechanisms and models for bentonite erosion.		
SKB TR-09-42. Mechanical interaction buffer/backfill. Börgesson, L., Hernelind, J.	The entire report	
SKB TR-10-11. Åkesson M, Kristensson O, Börgesson L, Duek A, THM modelling of buffer, backfill and other system components.	Chapters 2-11	
SKB TR-10-15. Design, production and initial state of the backfill and plug in deposition tunnels.		
SKB TR-10-16. Design, production and initial state of the backfill and plug in deposition tunnels.	The entire report	
SKB TR-10-31. Börgesson L, Dueck A, Johannesson L-E, Material model for shear of the buffer. Evaluation of laboratory test results.	The entire report	
SKB TR-10-34. Hernelid J, Modelling and analysis of canister and buffer for earthquake induced rock shear and glacial load.		Background information
SKB TR-10-40. Birgersson M, Karnland O, Nilsson U, Freezing of bentonite. Experimental studies and theoretical considerations.	The entire report	
SKB TR-10-44. Åkesson M,,Börgesson L, Kristensson O, SR-Site Data Report – THM modeling of buffer, backfill and other system components.	The entire report	
SKB TR-10-47. Buffer, backfill and closure process for the safety assessment SR-Site.	The entire report	
SKB TR-11-01. Long-term safety for the final repository for spent nuclear fuel a Forsmark. Volume I, II and III.	Chapters 10.3.8, 10.3.9 and 10.4.8.	

APPENDIX 2

Suggested needs for complementary information from SKB

Gaps

1. Experimental verification of the FEM models through a number of benchmarking examples, on the element level as well on a prototype scale.
2. Erosion/piping. This pertains to mechanical internal piping as well as chemical piping. More testing is required both regarding erosion in the long perspective and regarding the pre-closure situation, particularly in the backfill.
3. Homogenisation of the buffer and the backfill has been demonstrated for rather ideal situations by testing and modelling. Larger gaps or irregularities have only been analyzed by modelling and needs to be complemented by more testing. Thereby the modelling results can hopefully be verified.
4. Statistical treatment of parameters in the FEM modelling in order to a certain extent verify uncertainties.

Clarifications

1. Resaturation process is thoroughly treated in many respects but needs clarifications regarding repeated wetting and drying.
2. Information on how the parameters for the ClayTech model are determined. A scheme similar to what is given for the Code_Bright would be helpful.

Need of further analyses (and testing)

1. Benchmarking is rather straight forward, but probably will result in indication of areas where further analyses is needed.
2. Resaturation.
3. The FEM models used will probably need to be extended or modified and thereby further analyses are needed.
4. All areas above, where gaps have been indicated, probably require more analyses.

APPENDIX 3

Suggested review topics for SSM

1. Erosion/piping.
2. Verification of the constitutive models used in Code_Bright and Abaqus finite element programs.
3. Sensitivity analysis for the constitutive models used in Code_Bright and Abaqus finite element programs.
4. Sensitivity analysis for the different scenarios modelled by FEM.
5. Resaturation. Basic phenomena and congruence of prediction and performance.
6. Design, production and initial state of the buffer and the backfill. Feasibility and QA.

2012:30

The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 270 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

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