NUMERICAL MODELLING OF A CONTAINER EMPLACEMENT CONCEPT IN A DEEP GEOLOGICAL ENVIRONMENT

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ABSTRACT
The response of engineered compacted soils immediately following emplacement of used nuclear fuel containers in a deep geologic repository is a question of considerable importance for examining deep geological disposal concepts. A possible emplacement method described by Russell and Simmons (2003) involves several clay-based engineered barriers that are designed to support the containers both in the short-term during and immediately after placement and backfilling as well as in the long-term after closure of the facility. A modelling study was undertaken to qualitatively examine the undrained response of the unsaturated engineered soil barriers immediately following placement of the containers. A secondary purpose of the study was to undertake sensitivity analyses to identify parameters of greatest significance in the emplacement configuration in terms of their impact on the mechanical behaviour. The results of the modelling show that the unsaturated strength of the as-compacted materials plays an important role in the stability of the proposed configuration. The philosophical question of whether in-situ suction can be relied upon as a design variable in this short-term application is examined and discussed. Recommendations are made to address limitations identified in this modelling study as well as to explore the long-term behaviour after closure of the facility.

RÉSUMÉ
La réaction des sols compacts machinés toute suite après l'emplacement des récipients utilisés de carburant, dans un profond dépôt géologique, est une question très importante pour l'examination des concepts géologiques de profond disposition. Un méthode d'emplacement possible, décrit par Russell and Simmons (2003), inclus plusieurs barrières machinées qui sont composées d'argile avec l'intention de soutenir les récipients durant et immédiatement après la courte période du placement et du remblaiement, ainsi que la longue période après la fermeture du service. L'étude a été entreprise pour qualitativement examiner la pleine réaction d'une barrière de sol machiné insaturé immédiatement après l'emplacement des récipients utilisés de carburant. Le deuxième objectif de cette étude a été fait pour entreprendre des analyses sensibles pour identifier les paramètres significants de l'analyse de la configuration de l'emplacement en termes de l'impact sur le comportement mécanique. Les résultats du modèle démontrent que la force insaturée du tampon compacté joue un rôle important dans la stabilité de la configuration proposée. La question philosophique du fait que succion in-situ peut compter sur un plan variable dans cette courte application, a été examiné et discuté. Dernièrement, des suggestions ont été fait concernant la direction du modèle dans le futur pour aborder les limites identifiées durant cette étude, ainsi que l'exploration du comportement à long terme après la fermeture du service.

1. INTRODUCTION

The response of engineered barriers immediately following placement of used fuel containers in a deep geologic repository is a technical issue requiring examination. A possible concept for in-room emplacement of containers holding used nuclear fuel was described by Russell and Simmons (2003) and involves the assembly of several clay-based engineered barriers. The primary purpose of this study is to qualitatively assess the mechanical response of engineered barriers under undrained conditions immediately following emplacement of the containers using the published conceptual geometric arrangement. Changes in component shape, size or other characteristics would of course affect the results of a mechanical response analysis. A secondary purpose is to undertake sensitivity analyses to identify materials in the emplacement configuration of significance in terms of assessing their mechanical behaviour.

The scope of the modelling is to consider the short-term mechanical response of an in-room emplacement configuration immediately upon installation of containers. Recommendations are made regarding the direction of future analysis to address limitations identified in this study. These analyses are not intended to provide accurate quantitative information regarding the behaviour of the proposed repository geometry and configuration, rather they are intended to provide guidance in identifying important aspects regarding the proposed emplacement geometry and loading sequence. In many instances due to a lack of information, assumptions regarding materials properties are made to examine the qualitative behaviour of the various components. For an accurate quantitative model incorporating Thermal-Hydraulic-Mechanical (THM) response considerably more information regarding the behaviour of materials is required.

2. EMPLACEMENT MODEL DESCRIPTION

The cross-section of the waste emplacement room is described by Russell and Simmons (2003) and shown in Figure 1. The thick lines denote boundaries between material types while the thin lines show the interfaces between blocks of engineered materials as placed. The geometry of this emplacement concept was taken from an AutoCAD drawing and input into Sigma/W. Sigma/W is a commercial finite element computer program for load-deformation analysis of soil materials (Geo-Slope International 2001). The right half of the cross-section was modelled due to symmetry about the vertical centerline of the design. The finite element mesh used for modelling is shown in Figure 2.

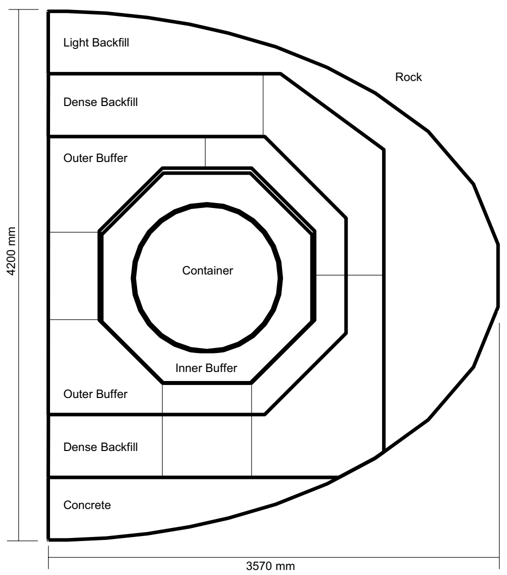

Figure 1: Model cross-section.

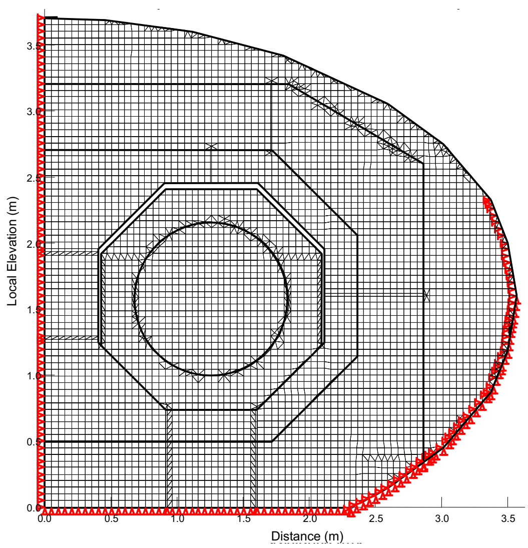

Figure 2: Finite element mesh.

The model developed is a two-dimensional plane strain model that is 1 m wide (into the page). The plane strain assumption assumes that the displacement perpendicular to the model cross-section is zero. The boundary conditions used in the model are also indicated in Figure 2. Due to symmetry the centerline of the model is defined as a fixed (i.e. zero) horizontal-displacement boundary while vertical movement is allowed. The concrete is assumed to be perfectly rigid and is not included in the mesh but serves as a zero vertical-displacement boundary. The boundary condition along the dense backfill-rock interface was modelled using slip elements to replicate the possibility that the soil might shear along the interface with the rock while normal stresses are maintained due to the rigid properties of the rock. Finally along the light backfill-rock interface no horizontal or vertical movement was allowed along the bottom half of the model indicating continuous contact. Along the top half free movement was allowed and following each run deformations were checked to ensure that the light backfill was not deforming into the rock which is not physically reasonable. If there was movement into the rock this was restrained incrementally until no deformation occurred into the surrounding rock.

The constitutive models used to define the behaviour of the engineered barriers were consistent throughout the analysis. For determination of the overburden stresses due to material self weight a linear-elastic model was used with a defined Young's Modulus and Poisson's Ratio. For all loading phases an elastic-perfectly plastic model was used. In addition to Young's modulus and Poisson's ratio a cohesion intercept and a friction angle are defined to denote yield and failure. In all cases the value used for cohesion intercept includes an apparent cohesion due to assumed soil suction being present in the material.

The effect of suction on the shear strength of the soil based on the traditional Mohr-Coulomb failure criterion is included by assuming a constant suction condition and then assessing the increase in shear strength at that level. The Mohr-Coulomb failure plane is three-dimensional based on the normal stress, shear stress and suction at failure. A section was cut at the plane of suction corresponding to the 'as-compacted' suction state. The influence of the suction and 'the true-cohesion-intercept' strength was assigned a single cohesion value in the model consistent with Krahn et al. (1989). The normal stress-dependent friction angle (ϕ) was assumed to be independent of suction.

3. MODEL PARAMETERS

Model parameters were selected to be representative of the materials proposed for the repository. The parameters required for the model include unit weight, Young's modulus, Poisson's ratio, cohesion (used to represent the combined effect of suction and 'true' cohesion) and friction angle. The following paragraphs outline the justification or assumptions made for the values used in the analysis. All parameters are summarized in Table 1.

Table 1: Model properties.

Name	Unit Weight (kN/m^3)	E (kPa)	ν	c' (kPa)	ϕ' (°)
Container	55.6	200,000	0.50	N/A	N/A
Inner Buffer	18.6	12,300	0.40	43.0	7.9
Outer Buffer	19.6	84,350	0.44	481.0	5.8
Dense Backfill	21.6	13,400	0.32	7.5	32.0
Light Backfill	16.7	13,000	0.36	N/A	N/A

N/A – not utilized in the models.

Unit weights for the model were calculated from information in McMurray et al. (2003) which summarized physical composition and as-emplaced properties of engineered barriers. The used fuel container was discretized (Figure 2) and assigned a linear-elastic model.

The strength properties used for the inner and outer buffer materials were extracted from published experimental data. Börgesson et al. (1995) reported results of drained and undrained triaxial tests on saturated MX-80 bentonite. The degree of saturation for the as-emplaced inner buffer was defined as 65% (McMurray et al. 2003). Test results on saturated MX-80 are assumed to provide a lower bound strength because the inner buffer will be placed in an unsaturated state. Young's modulus for the inner buffer was calculated by applying the secant method at 50% of the maximum deviator stress to the triaxial results. An average p' value was determined from initial modelling results to calculate a Young's modulus of 12,300 kPa. Börgesson and Hernelind (1999) reported strength values in terms of β (angle) and δ (intercept) for MX-80 bentonite. Through a regression of mean effective stress versus deviator stress the directly derived cohesion and friction angle are 43 kPa and 7.9° respectively.

Outer buffer is defined to be a mixture of equal dry weight proportions of sand-sized aggregate and Na-bentonite clay. Considerable test data generated by the Geotechnical Group at the University of Manitoba are available for the outer buffer. Specifically Wiebe (1996) and Blatz (2000) performed undrained tests on outer-buffer type materials compacted to Reference Buffer Material (RBM) parameters (Dixon and Gray 1985). Data from these tests were used to determine strength properties used in these analyses. The stiffness (i.e. Young's modulus) was determined in a manner similar to the inner buffer to be 84,350 kPa. The cohesion intercept and friction angle were directly interpreted from a deviatoric stress vs. mean stress plot. The strength parameters of the outer buffer in all analyses except as noted are c = 481 kPa and ϕ = 5.8°. The cohesion intercept value incorporates the effect of suction. Poisson's ratio was calculated from the friction angle to be 0.47 by using the Jaky equation (Jaky 1944). This technique was originally developed for saturated, isotropic soils and is assumed to be a best estimate.

The dense backfill strength properties for the model were determined using data from triaxial tests on a similar material to the proposed concept. The dense backfill presented by McMurray et al. (2003) is 70% crushed granite, 25% glacial lake clay and 5% Na-bentonite compacted to about 2.1 Mg/m^3 with 6% water content. The data were from consolidated drained and undrained triaxial tests with pore pressure measurement. In the proposed concept the dense backfill will be compacted in an unsaturated state and potentially have a higher cohesion intercept and stiffness (due to suction) compared with the specimens tested. The data used are the only triaxial test data available for the dense backfill type material. The stiffness from each triaxial test was plotted against the mean effective stress. The small mean stresses used in the application resulted in extremely low values of stiffness. Due to both the change in materials and unsaturated state of the dense backfill in the application the minimum value of stiffness determined from the saturated triaxial tests was considered by the authors to be more representative than the extrapolation outside the measured range. The stiffness of dense backfill used in all analyses is 13,400 kPa. A friction angle of 32° was determined from a plot of deviator stress versus mean effective stress of the unpublished tests. For cohesion intercept, a value of 7.5 kPa was assumed as a base case due to the blocks being placed in an unsaturated state and a sensitivity analysis was performed to examine its effect. The actual cohesion would likely be significantly higher than this assumed value.

Limited information is available for the light backfill. This was not considered critical since it would be installed after the containers are placed and in these analyses serves as dead weight applied to the material below. Therefore a linear-elastic model is sufficient to analyze the material behaviour. Representative values of Young's modulus and Poisson's ratio are assumed due to the lack of any physical information. The light backfill is assumed to be 50% Na-bentonite clay and 50% crushed granite. For the purposes of these analyses the Young's modulus and Poisson's ratio are 12,900 kPa and 0.36 respectively.

4. NUMERICAL MODELLING

Several different scenarios were examined for the emplacement model. Initially a preliminary analysis using a model with outer buffer material parameters (Table 1) for all soils was performed to gain confidence that the model was responding appropriately. A number of scenarios were investigated using the initial model including complete loss of suction (cohesion) in the model and no lateral support along the centerline to simulate possible deformation mechanisms due to emplacement timing (one container at a time).

In all cases the modelling proceeded using the protocol described as follows unless explicitly stated otherwise. Prior to placement of the container the outer buffer and dense backfill were added except for the two blocks directly below the container (Figure 1) to determine the overburden stresses using a body load. Individual unit weights (Table 1) were used for each respective soil. Then the container and inner buffer loads were added to the overburden stresses. In this qualitative assessment, discussion of the models will focus on the deformation modes induced by container loading while reference will be made to notable stress distributions. Deformations for all cases were checked to ensure the inner buffer did not displace into surrounding outer buffer where independent interfaces exist. In selected scenarios the remaining outer buffer and dense backfill blocks and light backfill were added to model the stress field of the final configuration.

4.1 One Material Model – Base Scenario

To begin the modelling a base scenario was selected as a first step. For this case the entire model was assumed to have strength parameters of the outer buffer and all the sealing materials form a homogeneous, isotropic continuum. Outer buffer was chosen as a starting point since its strength and deformation properties are well defined. In addition the outer buffer has a high cohesion intercept (due to the in-situ suction) which limits yielding and provides straightforward interpretation of the results.

Prior to addition of the container at the bottom of the cross-section relatively little additional stress is being added by the body load of the sealing materials. Stress in the upper half of the model spreads laterally leaving vertical shaped contours for the distribution of vertical stress. This indicates that an arching mechanism develops within the material.

The weight of the inner buffer and container were then added as a body load. The dense backfill displaces outward as shown in Figure 3 and also deforms into the open area below the container. The stress concentrations at the corners of the inner buffer as well as along the dense backfill-rock interface on the bottom right side of the cross-section are of particular interest. From the displacement mesh it is apparent that the soil is trying to shear and displace along the rock interface but is being held in place by the imposed boundary conditions. Even though slip elements were added along the rock interface to allow slippage displacement stress concentrations were observed along the interface in all models. Yielding did not occur anywhere in this base case due to the high outer buffer cohesion used (due to suction).

Final vertical stresses following placement of the light backfill, outer buffer and dense backfill are shown in Figure 4. The stresses do not vary notably from the state after container placement following addition of the light backfill and lower blocks because most of the load is due to the container.

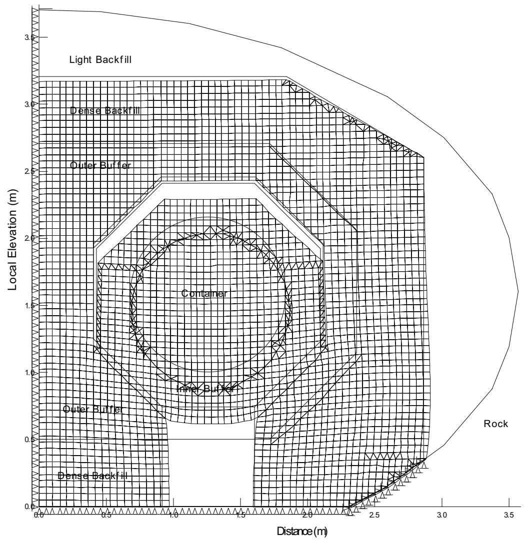

Figure 3: One material: displacement mesh (200x magnification).

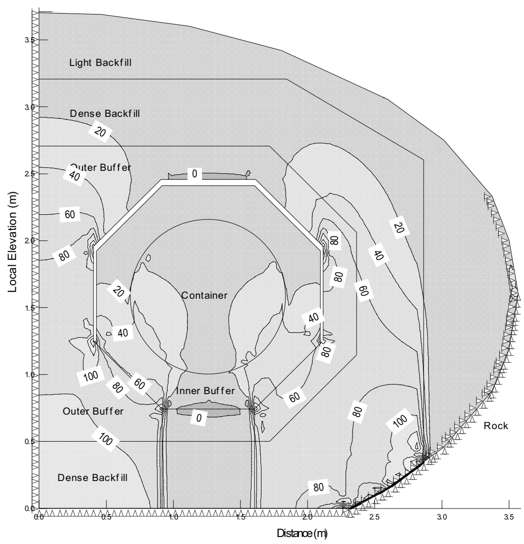

Figure 4: One material: final vertical stresses (kPa).

This model using one material strength without distinct block interfaces provided an understanding of how the engineered sealing materials might react as one unit. It also showed stress concentrations at the corners of the keyhole and the distribution of vertical stresses.

4.2 One Material Model – Block Behaviour

The next model scenario incorporates the soil being placed in discrete individual blocks while maintaining a single strength for all materials modelled. This model is constructed to account for the materials being placed in blocks as reported by Russell and Simmons (2003). In this model one material strength (outer buffer) is used for all sealing materials. Both compression and tension slip elements are used to simulate the interfaces between blocks as shown in Figure 1. Compression slip elements allow shear displacements with extremely small compression movements while tension slip elements allow both shear and separation of the adjacent blocks. The joints had to be assigned before the model was run and were checked after each run to ensure that the compression elements were actually in compression and tension elements were in tension. The interfaces between the outer buffer and the dense backfill were not modelled with slip elements. Stress concentrations occur along the horizontal joints on the left side of the model as well as the vertical joints above the container. The top layers of dense backfill and outer buffer act like beams as they experience tension along the bottom of the vertical joints.

The deformed mesh following placement of the inner buffer and container is shown in Figure 5. Once again due to the assigned high cohesion intercept yielding was not evident at any point in the model. The mode of deformation shown in the deformed mesh (Figure 5) shows the dense backfill and outer buffer on the left side of the model being pushed into the keyhole. Also horizontal displacement occurs at the horizontal joint on the right side of the model.

This model shows how individual blocks will affect the mode of deformation for linear-elastic behaviour since no material yields. The results show areas of stress concentrations due to interface geometry under loading from the container and inner buffer.

4.3 One Material Model - Loss of Suction

The third model considers a scenario where the suction component of shear strength is removed. In terms of the model parameters this means that all materials are modelled with a cohesion intercept equal to 0 kPa. The overburden stresses were similar to the previous model using the block construction. When the model is run with zero cohesion and $\phi = 5.8^{o}$ a stable solution cannot be reached. This is interpreted to mean that the material properties result in an unstable condition. This could also be interpreted as uncontrolled yielding with the material strength unable to be mobilized in supporting the applied container load. To determine the point at which convergence would occur the cohesion was reduced in increments from its initial value to 200, 100, 50, 40, 30 and 20 kPa. Yielding is not observed until the cohesion intercept equals 50 kPa. A typical deformed mesh is shown in Figure 6 for cohesion intercept equal to 30 kPa.

Several observations can be made from lowering the cohesion intercept. Decreasing the cohesion intercept from 200 to 40 kPa results in minimal change to the vertical stress distribution except for a slight increase in the lower part of the model. When cohesion is lowered to 20 kPa model instability is apparent and the model results are not considered to be physically meaningful. Since frictional strength is not available the soil yields and deforms plastically until the plastic strain energy required to reach a stable position is mobilized. The top of the model subsides, the lower left side of the keyhole shifts into the gap and the right side of the dense backfill bulges out with the top block pushing farther than the bottom. It is important to note that settlement of the container and inner buffer into the 'keyhole' increases as the cohesion intercept is decreased. This combined with the lower left side shift could impact installation of the final blocks.

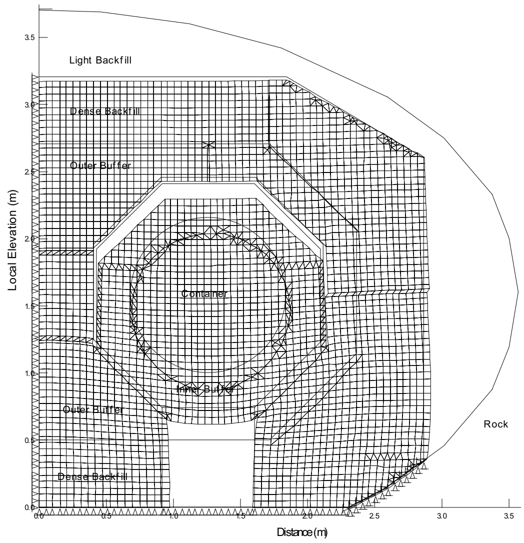

Figure 5: One material with blocks: deformed mesh (200x magnification).

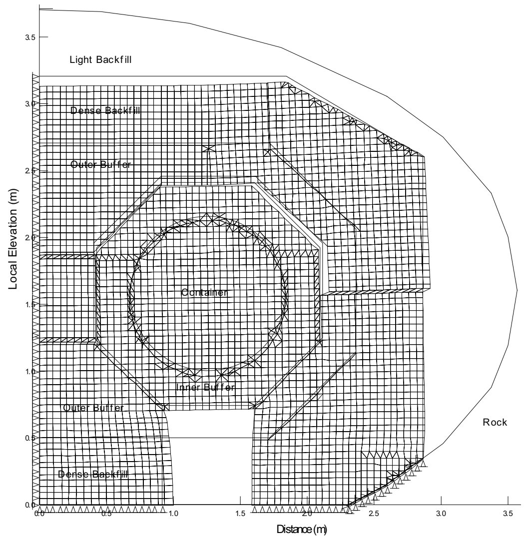

Figure 6: Loss of suction: deformation mesh for cohesion intercept = 30 kPa (2x magnification).

This model shows the effect of the 'as-compacted' suction on the undrained shear strength required in the used fuel container emplacement configuration. It is clear that suction in the material is important for the proposed emplacement strategy.

4.4 Blocks Installed Below Container

Analysis was performed to determine the final conditions following installation of the blocks below the inner buffer. In the repository following installation of these lower blocks the inner buffer and container will continue to settle until the system equilibrates, however time-dependent consolidation is outside the scope of this modelling exercise. This model is not an exact representation but it provides a qualitative examination of the final stress and displacement distributions. Only one material model (i.e. outer buffer) is used for all sealing materials allowing comparison with most of the models in this paper.

The same finite element mesh was used as in previous models except that the lower two soil blocks were also discretized. There is almost no change to the overburden stresses from the previous model. The only changes are the stress distributions in the lower zone due to existence of the key material. Next the container and inner buffer load are added. The main differences in the stress distribution between this model and the one material model occur below the inner buffer. Vertical and horizontal stresses are reduced in the outer buffer and dense backfill because there is now more material (two lower blocks) to carry the same amount of load. Above the lower blocks there is little noticeable difference in the stresses between the two models as anticipated.

The properties of the model with the lower blocks installed are modified to determine the effect of the suction-dependent-cohesion for cohesion intercept values of 50, 40, 30 and 20 kPa. The deformation mesh for cohesion equal to 30 kPa is shown in Figure 7. Considering the deformation meshes (Figure 6 and Figure 7) the general shapes are similar however less vertical deformation is observed at the top of the mesh with the lower blocks installed. As in the earlier cohesion-reduction model both deformation and yielding increase with decreasing cohesion intercept. Less yielding and deformation is observed in this model due to the extra material available.

4.5 One Material Model - No lateral Support

This analysis investigates the scenario where the blocks are assumed to have no lateral support along the centerline due to one container being placed prior to the second container in the other half of the cross-section. This scenario has the adjacent container emplacement cavity empty. The barrier materials on the left side of the emplacement room are assumed to not contribute to the lateral support at the centerline of the cross-section. One material model has been used for all materials in the model and suction was maintained at the as-compacted value of 481 kPa to isolate the influence of the centerline boundary condition being removed. Previous models are based on the assumption that no horizontal movement is allowed along its centerline. This lateral fixed boundary condition is removed to simulate a free-standing block structure that can displace horizontally. The finite element mesh is similar to other models except for the change in the selected boundary condition.

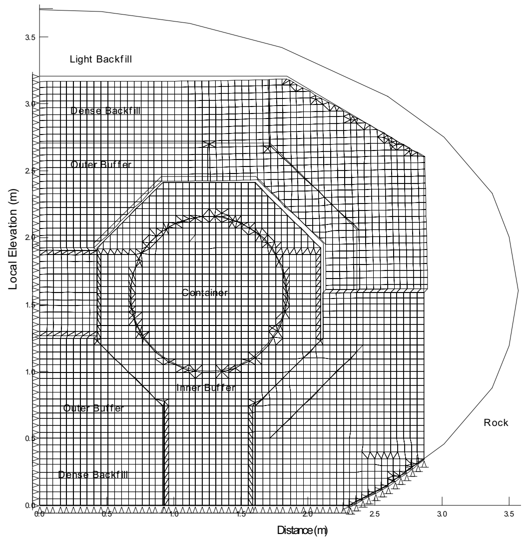

Figure 7: Lower key blocks added: deformation mesh for cohesion intercept = 30 kPa (3x magnification).

The overburden stresses initially imposed are different in that the vertical stresses are more uniformly throughout the domain as compared to the model with lateral confinement. Specifically the vertical stresses are higher in the left side of the keyhole and there is a large stress concentration above the keyhole. There are also higher horizontal stress concentrations along the top of the model and near the vertical joint in the outer buffer directly above the keyhole.

Following overburden stress analysis container loading proceeded as usual. The resulting displacement mesh is shown in Figure 8. The stress concentrations are magnified following loading and in general stress levels have increased. The deformed mesh also shows interesting behaviour. The entire mesh moves to the left now as the loading rebounds from the angled support. There are shear movements in the horizontal joints on the left side of the model as there is no horizontal support. For this scenario the overall stability of the model could be improved by adding the light backfill prior to container loading. The light backfill would resist movement of the outside blocks (the right and top soil blocks in the model) however this would not affect the middle blocks (lower left side of the model) which would still be free to move.

This model showed possible implications of loss of lateral support during container emplacement. This could occur if only one container was placed or if the entire block system shifted to one side due to lack of lateral support.

4.6 Multiple Material Model

Following understanding gained in the previous analyses the strength parameters for each of the sealing materials (Table 1) were applied to the block model. The model and mesh are the same as previous models (Figure 2). Compared to the one material parameter model the results show that the cohesion intercept of the dense backfill zone affects the stress distribution. Also, the vertical stress concentrations are greater and the shape of the contours has changed. Large horizontal tensile and compressive forces exist on the left side of the keyhole.

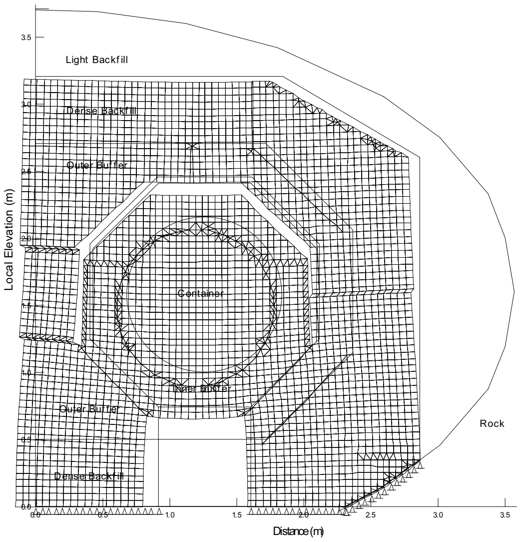

Figure 8: No lateral support: deformation mesh (100x magnification).

The container and light backfill loading proceeded as normal following determination of the overburden stresses. The deformation mesh is shown in Figure 9. Because the cohesion intercept of 7.5 kPa was assumed for the dense backfill a sensitivity analysis was performed while holding the friction angle constant. As the cohesion intercept is lowered deformation and yielding in the dense backfill increase. The solution did not converge when the cohesion intercept was lowered to 5.0 kPa. The loss-of-suction model previously discussed showed that materials with no cohesion generally result in numerical instability due to excessive deformations. The greater friction angle in the dense backfill and suction-induced-cohesion in the outer buffer is not enough to support the container. Also, settlement of the container and inner buffer increases as the cohesion intercept is decreased which could impact placement of the blocks in the key slot below the container/inner buffer assembly. The light backfill and the rest of the outer buffer and dense backfill were not added to this model since the results are dependent on the cohesion intercept of the dense backfill.

This model shows the importance of suction in the proposed emplacement strategy. With a cohesion intercept of 5 kPa for the dense backfill the model would not converge meaning it cannot gain the required strength to support the container and block configuration. As the cohesion intercept is decreased the frictional strength cannot be mobilized by the increase in stress from the container until extremely large deformations occur.

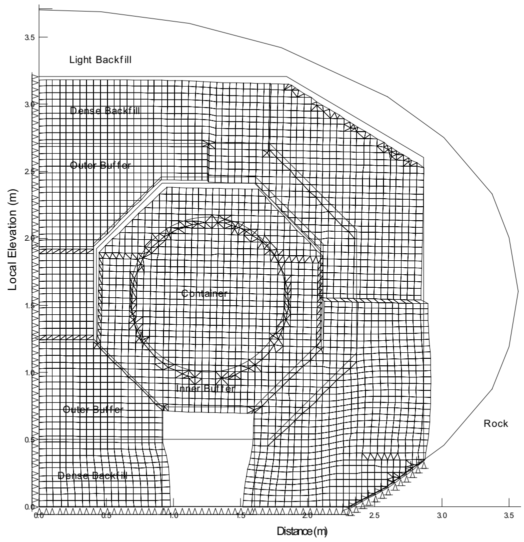

Figure 9: Actual strengths: deformation mesh with dense backfill cohesion intercept = 7.5 kPa (3x magnification).

5. DISCUSSION

Preliminary numerical modelling of an in-room emplacement configuration immediately after placement of the containers has been conducted. Selection of the undrained short-term strength parameters for the various materials has been discussed in detail along with a variety of scenarios used to examine the various components of the geometry and materials proposed for the repository. The results demonstrate the importance of as-compacted suction in the material strengths. In addition the interface behaviour has been shown to be a critical feature in terms of the material response to the container loading. The final results indicate a need for more detailed material property information for a number of the materials proposed in the in-room emplacement configuration.

6. CONCLUSIONS

This paper describes analysis performed using a model developed to represent one possible assemblage of sealing system components for an in-room emplacement option within a deep geologic repository. The model examined a number of scenarios designed to qualitatively evaluate the impact of various design variables on the performance of the repository. It is important to note that this modelling is a first step to analyzing the configuration presented. Results show that the configuration is stable using best estimates of material parameters. Further material information is required to confidently model behaviour quantitatively. In addition the interface behaviour has been shown to be a key consideration in terms of understanding the deformation and stress distribution in the underground environment. Further experimental work and numerical modelling are required to demonstrate quantitatively that the post emplacement mechanical behaviour can be reliably assessed to ensure safety for the short and longer-term.

7. RECOMMENDATIONS

Based on the analyses, recommendations can be made to both improve and validate the current model. This model only considers the mechanical response of the clay-based engineered barriers while ignoring any thermal and hydraulic responses. The containers could have surface temperatures as high as 90° C (Dixon et al. 2002) within a short time of their placement in the repository. The energy released will change the water content and temperature of the materials surrounding the containers. Mechanical properties of materials are affected by temperature and water content (suction) and must be accounted for in future THM models.

Secondly further work must be performed to better define the thermal, hydraulic and mechanical properties of the dense backfill, inner buffer and light backfill, including properties for the unsaturated state. Properties of the outer buffer are relatively well defined based on work performed at the University of Manitoba. Some strength and stress-strain properties used in this modelling were assumed from testing on materials that are not the same composition as in the proposed repository and unsaturated properties had to be assumed from tests on saturated materials, in some cases. Effects of temperature, water content, degree of saturation and confining pressure must be investigated to entirely understand the response of the engineered barriers following emplacement. Moreover, the effects of interfaces, including those between blocks of sealing materials on the thermal, hydraulic and mechanical evolution of the emplacement room sealing system must continue to be explored.

Finally once the above measures have been accomplished a transient model should be completed which considers the time-dependent response of the materials. The current model only considers the period immediately following emplacement and ignores any longer-term time-dependent responses. The time-dependent model would combine the THM responses of all the engineered soils and then finally their interaction with the surrounding rock.

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