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ABSTRACT

Large-scale underground experiment programs to examine excavation response have been performed at the Climax facility in Nevada and at the Colorado School of Mines. These two programs provided fundamental information on the behavior of rock and the effects of excavation; on instrument performance and configuration; and on the relationship between test geometry and test behavior. This information is being considered in the development of a major excavation response experiment to be carried out in the Canadian Underground Research Laboratory.

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1. INTRODUCTION

1.1 Significance of the Problem

The underground openings of a repository may affect the conditions of the host rock in two ways: through the response to the excavation of the repository, and through the response to the thermal load resulting from the emplacement of heat-generating waste. The region affected by the combination of these perturbations is called the **disturbed zone;** the region affected predominately by excavation is called the **excavation response zone.** This paper deals only with excavation response. The response to excavation is a combination of the damage to the rock caused by blasting or other means of excavation and of the redistribution of stresses around the newly created opening. The zone of excavation response is characterized by the creation of new fractures, by the opening or closing of existing fractures, or by the creation of a reduced-modulus or plastic zone around the opening.

The excavation response zone is important for two reasons. First, it may form a preferred pathway for the migration of radionuclides away from a repository. Kelsall et al. [1] suggest that the excavation response zone strongly affects ground-water travel times and flow through and around shaft and tunnel seals. The parameters that control the flow are the hydraulic conductivity of the zone, and to a lesser degree, its extent. Second, the US Nuclear Regulatory Commission [2] recommends that the disturbed zone should be the inner boundary for ground-water travel time calculations. Therefore, it is important to know the properties and the extent of the excavation damage zone. In order to know the properties and extent of the excavation response zone, we need to develop tools and techniques for characterizing its properties, and we need to understand the fundamental mechanisms that govern the creation of the response zone in order to minimize its effects and predict its performance and extent.

1.2 Purpose of this Paper

This paper describes the development of an Excavation Response Experiment for the Canadian Underground Research Laboratory (URL) which will contribute to our understanding of the characteristics and mechanisms of excavation response. We will summarize the information gained from earlier excavation response studies at the Spent Fuel Test - Climax and the Colorado School of Mines (CSM), identify some of the information needs that still exist or were raised as a result of these studies, and show how the information gained from the Climax and CSM studies is being used to guide the development of the URL experiment to satisfy these information needs.

2. RESULTS OF PREVIOUS STUDIES

2.1 Spent Fuel Test - Climax [3]

The Spent Fuel Test - Climax was conducted to investigate the feasibility of storage of spent reactor fuel assemblies at a plausible repository depth in a typical granite rock. The Climax facility was excavated at a depth of 420 m in a partially saturated quartz monzonite intrusive known as the Climax Stock. Wilder and Yow [4] report that the rock contains four prominent and four less prominent joint sets, with a total frequency of 0.9 to 2.2 joints/m, and three sets of shear zones. A primary technical objective of the experiment was to simulate the effects of thousands of emplaced spent fuel elements using only a small number of spent fuel elements and electrical heaters. One of the secondary objectives, and the only one with which we are concerned in this paper, was to compare the magnitude of displacement and stress effects from mining alone with that of thermally induced displacement and stress changes that occur as the result of heating.

In order to determine the effects of mining, a "Mine-By" experiment was conducted during the excavation of the test facility. The Mine-By Experiment was carried out by mining two outer drifts, installing instrumentation to monitor stress and displacement in the pillar between the drifts, and then mining a central drift through the pillar. Plan and section views of the Climax facility, showing the configuration of the Mine-By Experiment, are shown in Figures 1 and 2. Because the Spent Fuel Test was the primary objective of the Climax program, the design of the Spent Fuel Test strongly affected the configuration, instrumentation layout, and schedule of the Mine-by Experiment. After the Mine-By Experiment, the main part of the Spent Fuel Test was carried out by installing spent fuel elements and electrical heaters in the three drifts.

The Climax Experiment subjected the rock to three loading phases: The mechanical unloading during the Mine-By test, the subsequent thermomechanical loading due to the spent fuel and electrical heaters, and the unloading during the cooldown following the removal of the spent fuel and heaters. Analyses by Wilder and Yow [5] show that the displacements caused by the mining/unloading are similar in magnitude to the displacements caused by the thermal/loading-unloading, but they are of a fundamentally different nature. The behavior during the thermomechanical loading phase appeared to be elastic, whereas during the Mine-By the deformations appeared to be controlled by the joints and shear zones in the rock. Also, the Mine-By response occurred with time as a function of mining and of yield in the rock mass; the thermal response occurred as a function of the heat transfer properties of the rock. Although rock mass behavior during cooldown was more difficult to assess because of curtailment of monitoring, the known differences may make the response to excavation in general harder to predict and to analyze than the response to heating.

The finite-element elastic continuum code ADINA was used to perform a pre-test estimate of the behavior of the Mine-By Experiment [6]. The ADINA results showed the pillars between the drifts expanding into the central drift, but the field measurements showed a narrowing of the pillars. The experiment was then modeled using the finite element model JPLAXD, which allows the inclusion of discrete joints, to see if the rock structure could account for the sign difference of the displacements [7]. However, the JPLAXD results for the pillars were also different in sign from the field measurements. Butkovitch [8] then showed that explosive expansion from the drill-and-blast mining of the central drift could account for some of the narrowing of the pillars. Although incomplete in some ways, this analysis indicates that models which simulate excavation merely through the removal of material do not account for all of the processes which control the deformation of the rock.

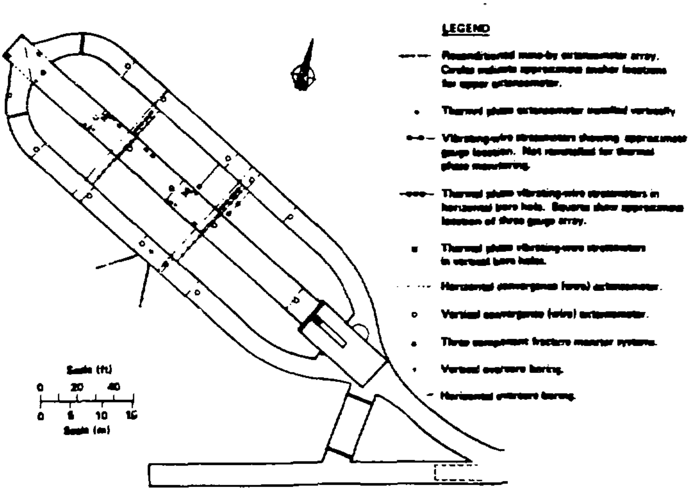

Figure 1 Plan view of the Climax facility, showing the two outer instrument drifts, the central mine-by drifts, and the location of the mine-by and thermal phase instrumentation.

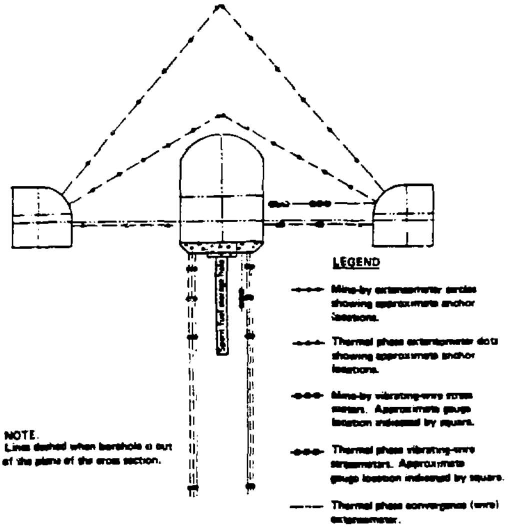

Figure 2 Section view of the Climax facility, showing the mine-by instrumentation in the pillars between the instrument drifts and the central drift.

Predictions of the response to heating using ADINA showed fairly good agreement with the measured displacements from the thermal phase of the experiment. This tends to confirm that the rock fractures controlled the excavation response but not the heating response.

The following observations can be made about the Climax Mine-By Experiment:

- The effects of excavation are at least as significant as heating effects in rock response; excavation effects are probably harder to analyze due to the influence of rock structure
- The uncertainty in the modeling was due to a number of factors, the most important of which were the complexity of the rock structure, the initial failure to account for all important mechanisms in the excavation process, and the inadequate amount, and the failure, of important instruments. In particular, the absolute in situ stresses were uncertain at the time of the Mine-by, and stress monitoring instrumentation may have failed during the experiment.

2.2 Colorado School of Mines [9]

The Colorado School of Mines has carried out an investigation of excavation response in their Experimental Mine near Idaho Springs, Colorado. The objectives of this program were to develop and evaluate blast rounds intended to minimize blast damage to the rock, and to develop techniques for characterizing the nature and extent of excavation response in the rock surrounding an opening. The portion of the CSM Experimental Mine in which the program was carried out is situated in heavily foliated granitic gneiss with two major vertical fracture sets. A room 20 m long, 3 m high, and 5 m wide was excavated using blast rounds designed following the Swedish Langefors approach and Livingstone Cratering Theory. Vertical extensometers were installed in the roof next to the new face immediately following each round to attempt to capture the response to the excavation of the subsequent rounds. Following the excavation, six sets of seven 5 m boreholes were drilled radially outward from the room for the characterization of blast damage and excavation response. The configuration of the room and boreholes is shown in Figure 3.

Due to blast damage alone, the rock surrounding an opening would exhibit lower Rock Quality Designation (RQD), lower modulus, lower P and S wave velocities, and higher permeability. All of these characteristics except RQD are dependent on stress. During the removal of rock during excavation, the stresses that were previously carried by the opening are redistributed to the surrounding rock. This increase of stresses in the surrounding rock would lead to higher modulus, higher P and S wave velocities, and lower permeability. The favorable superposition of material and stress change characteristics could lead to a reduction in the deleterious effects or the extent of the excavation response zone. A characterization program was carried out in order to evaluate the success of the controlled blasting and to determine the characteristics of the

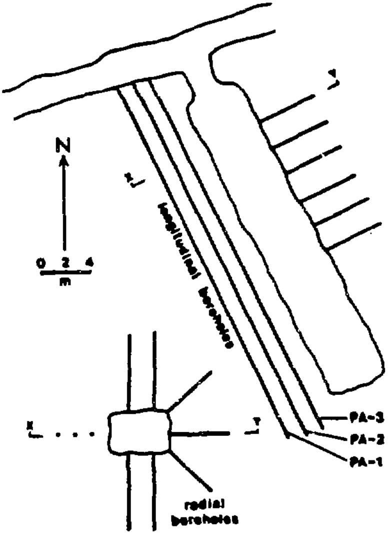

Figure 3 Plan and section views of the excavation response room in the CSM Experimental Mine, showing the location of the radial borehole arrays used to characterize the excavation response zone.

excavation response zone. The characterization consisted of:

- RQD indexing through examination of core and borehole walls
- Modulus determinations using the CSM cell (dilatometer)
- Crosshole ultrasonic velocity measurements
- Permeability measurements by nitrogen injection.

The characterization showed that the controlled blasting was successful in limiting blast damage to within 0.5 to 1 m from the wall of the excavation. What is more interesting, however, is the comparison of the results of the different characterization techniques. The CSM cell measurements, the ultrasonic velocity measurements, and the permeability measurements in general showed good agreement with one another on the extent and degree of disturbance of the excavation response zone. The RQD indexing showed relatively poorer agreement with the other three techniques. Zones in which the RQD indicated a higher degree of induced fracturing did not necessarily exhibit the lowest modulus, the lowest wave velocities, or the highest permeability. This indicates that, in determining the properties of the response zone, the number of fractures is less important than whether or not the fractures are open. Therefore it is logical that direct measurements of modulus, wave velocities, and permeability are more reliable than RQD determination for evaluating excavation response. The vertical extensometers installed in the roof provided little quantitative information on response to excavation because most of the response to each blast round had already occurred by the time each extensometer was installed.

2.3 Observations on the Climax and CSM Experiments

If we are to use the Climax and CSM Experiments as guides in the development of future excavation response experiments, we may make the following observations:

1. *In order to understand the phenomena, important parameters must be measured directly rather than inferred from some other parameter or effect.* If permeability is an important parameter, we should measure permeability rather than determine the RQD. Stress change and displacements should both be determined explicitly rather than inferring one from the other.

2. It is essential that there be adequate numbers of instruments, and that the instruments be in the right locations and of sufficient resolution for measuring the critical parameters. There are three ways of installing instruments for evaluating excavation response: from a remote location prior to and in the direction of the eventual excavation; from within an opening as it is being excavated; and from within an opening after excavation has been completed. Each of these methods is probably necessary for capturing the total response to excavation. For example, both drift convergence (from within an opening) and pillar displacement (from a remote location) need to be measured to determine the complete response of the pillar.

3. The computer models that we use to evaluate the results of the experiment must adequately represent the processes that determine the behavior of the physical system. If our goal is to determine

the change in hydraulic conductivity due to excavation response, itmay not be adequate to calculate stress change or even change in fracture aperture, because the relationships between stress, aperture change, and conductivity might not be adequately understood for a deforming fracture.

4. The field environment that will contain the experiment must be fully characterized so that all characteristics and structural features that could affect the behavior of the experiment are known. The modelers must know the location and significance of these features so that they may correctly account for them in their analyses.

To put these observations in other words, we must measure the right parameters, we must measure them correctly, our computer models must deal with the parameters correctly in analyzing the problem, and we must understand the field situation that determines the behavior of the experiment. We will describe in the rest of this paper how the development of the Excavation Response Experiment for the URL is dealing with these issues.

3. PLANNING THE URL EXCAVATION RESPONSE EXPERIMENT

3.1 Summary and Objectives

The URL Excavation Response Experiment (ERE) is being developed as a part of a cooperative experimental program between Atomic Energy of Canada Limited and the United States Department of Energy. The actual planning of the experiment is being carried out by a group consisting of representatives from AECL, DOE, Lawrence Livermore National Laboratory (LLNL), Lawrence Berkeley Laboratory (LBL), and the University of Alberta. The exact configuration of the ERE has not yet been determined. Very generally, the experiment will probably consist of a drift several meters in diameter excavated parallel to, or intersecting at some angle, a hydraulically conductive fracture or system of fractures. The test will include several galleries overhead and alongside the central drift from which instrumentation will be installed to monitor the response of the rock an fractures to the excavation of the central drift.

The test development group has given particular attention to rigorously defining the objectives of the ERE so that it meets the programmatic needs of both AECL and DOE. Rigorous and concise definition of the experiment objectives is also an immense help to designing the experiment itself, as distractions from the primary needs arising from secondary or tertiary needs can be eliminated. The objectives for the URL ERE are:

- To evaluate our ability to predict the mechanical and hydrological response of the rock mass to excavation in a rock mass containing a range of fracturing, and to assess the limitations of our ability to predict, and to improve our ability to predict, these responses

- To determine the geomechanical and hydrological properties of the rock mass and their coupling

- To study the response of the rock mass in terms of fundamental mechanisms governing fluid flow and rock mass deformations. Specifically, to study and extend our understanding of:

  - excavation-induced fracturing
  - stress dependence of fracture permeability.

We will now discuss how the ERE is being developed to meet each of these objectives.

3.2 Planning the ERE

Objective: Evaluate and improve predictive ability

The first step in evaluating our modeling capability was to assess the state of the art. LLNL surveyed computer models available in the US and Canada to see if any of them had the capability of modeling excavation response in fractured rock. They found that, while several codes could handle discrete fractures or large deformations, none of them could explicitly treat the all-important hydrologic response and highly non-linear fracture deformation in a coupled fashion. LLNL then proceeded with the development of a three-dimensional hybrid boundary element-finite element code named GENASYS (Geotechnical Engineering Analysis System) which would allow the calculation of coupled deformation and fluid flow response of a fractured rock mass subject to excavation. AECL and the University of Alberta are improving existing finite element and boundary element codes for application to the ERE. This intimate involvement of the development of models in the process of designing the experiment ensures that the output of the experiment will be meaningful to the modelers.

In order to allow the planning group to check the progress of the model development, AECL made available the results of a small excavation response experiment they performed during the development of the 240 m level of the URL. The results of this experiment, called the Room 209 Experiment, are reported elsewhere in this workshop [10]. Each modeling group attempted, using the best available characterization information, to predict the results of the Room 209 Experiment prior to the release of the data from that experiment. This exercise provided extremely valuable practice for the development of the models and of the ERE. It should help ensure that the modelers request as input only those parameters that are capable of being measured in situ, and that those responsible for installing and operating the test instrumentation provide data in a form that is useful to the modelers.

Model development and improvement will continue until about 1990 to ensure that adequate codes are available prior to implementation of the experiment. Once the test location has been fully characterized, the modelers will use the information from the characterization to perform a blind prediction of the results of the ERE. Comparison of the predictions with the actual field results will constitute the most rigorous possible test of our ability to model the process of excavation response.

Objective: Determine geomechanical and hydrological properties

The ERE will affect a volume of rock on the order of 10^6 cubic meters. It therefore provides one of our best chances of determining large-scale rock mass mechanical and hydro-mechanical properties. This process starts with the intensive characterization of the test environment. All material properties, in situ conditions, and structural features that might affect the behavior of the experiment need to be determined and understood. In particular, any anisotropy in material properties needs to be understood to allow three-dimensional analyses. Comparison of test response to pre-test conditions will then help in confirming such large-scale parameters as fracture stiffness, rock mass deformation modulus, and stress and permeability tensors.

In order to capture the response of the experiment, the test instrumentation must measure the correct parameters, be in the correct locations, and be able to survive the excavation process. LLNL is now performing thorough pre-test scoping calculations to determine regions of maximum response and maximum gradients to guide the selection of instrument locations. Different drift and instrument configurations will be evaluated to determine which combination of drift, fracture, and stress directions provides the maximum measurable local hydrologic response.

Even though the experiment will seek to maximize hydrologic response, it is important to remember that the installation of instrumentation required to monitor a test of this magnitude is likely to cause a significant hydrologic response of its own. AECL is currently developing instruments which will combine displacement and hydrologic measurements in the same borehole, thus reducing significantly the number of boreholes required to instrument the ERE. The zone of greatest interest in determining excavation response is the zone closest to the opening. This zone is of greatest interest because it experiences the highest gradients and the greatest impacts due to blasting, which also makes this zone the harshest environment for instruments. AECL and DOE are evaluating displacement instrumentation in order to develop a system with a gage length short enough to capture the gradients and robust enough to survive the impacts that occur close to the excavated opening. These developments are described elsewhere in this workshop [11].

Objective: Study fundamental mechanisms governing rock mass response

As we have seen with the Climax Mine-By Experiment, the complexity of the test environment can contribute to the uncertainty in the interpretation of the test results. In order to avoid masking the fundamental response of the rock mass, the test environment for the ERE will be kept as simple as possible. The ground conditions at the URL range from massive intact rock to rock with several fractures per meter. The rock volume that will contain the ERE will be carefully selected in order to allow the observation of the effects of excavation on a single fracture and, if our modeling capabilities are sufficiently advanced at that time, on a simple fracture network. This will minimize the number, and the accompanying uncertainty, of simplifying assumptions required for the analysis.

The Climax and CSM Experiments showed that blasting and stress redistribution may produce distinct responses in the rock mass. If permitted by cost constraints and by test geometry, the ERE may use machine excavation in addition to drilling and blasting for part of the excavation. Comparison of the response to blasting to the response to machine excavation will allow the separation of the effects of blasting from the response to stress redistribution.

The mechanical and hydraulic response of the rock mass, and especially of any fractures, will be monitored during the excavation of the test drift. Following excavation, a characterization program will be performed from inside of the test drift to determine blast damage and near-field changes in material properties. Comparison of the pre-test conditions, the response during excavation, the post-test conditions, and the predicted response form the modeling groups will help us to determine the mechanisms which govern the creation and the characteristics of the excavation response zone.

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