ABSTRACT: The application of rock mechanics at nuclear waste repositories is a true multidisciplinary effort. A description and historical summary of the Waste Isolation Pilot Plant (WIPP) is presented. Rock mechanics programs at the WIPP are outlined, and the current rock mechanics modeling philosophy of the Westinghouse Waste Isolation Division is discussed.

1 INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is located in Southeastern New Mexico about fifty kilometers east of Carlsbad. The WIPP was authorized by Congress in 1979 (Public Law 96-164) to provide "...a research and development facility to demonstrate the safe disposal of radioactive wastes resulting from the defense activities and programs of the United States exempted from regulation by the Nuclear Regulatory Commission." The WIPP is intended to receive, handle, and permanently dispose of transuranic (TRU) waste. To fulfill this mission, the U.S. Department of Energy (DOE) is constructing a full scale facility to demonstrate both technical and operational principles of the permanent isolation of transuranic waste.

A variety of organizations are involved in the WIPP Project, including:

- The United States Department of Energy. The DOE is responsible for demonstrating whether defense-generated transuranic waste can be safely isolated in 225-million-year-old bedded salt formations located 655 meters below the earth's surface. The DOE's Carlsbad Area Office (CAO) manages the project.
- Sandia National Laboratories provides the research expertise to perform experiments and advise the DOE on scientific matters at the WIPP.
- Westinghouse Government and Environmental Services' Waste Isolation Division (WID) manages and operates the WIPP under contract with the DOE.
- The United States Environmental Protection Agency (EPA) is responsible for certifying whether radioactive and hazardous material disposal requirements are met.
- The state of New Mexico regulates the handling of hazardous materials and operations of the disposal facility.
- A variety of other agencies, committees, and panels at the federal, state, local, and private levels monitor progress at the WIPP and contribute to the project's development through regulation, review, and comment.

As is usual for undertakings of the magnitude of the WIPP, the project has passed through a long and somewhat complicated history. In 1955, the U.S. Atomic Energy Commission asked the National Academy of Sciences to study permanent disposal of radioactive wastes. After studying the issue, the Academy recommended disposal in salt deposits due to their low permeability and good containment properties. Initially a salt mine in Lyons, Kansas was selected as the potential site for a radioactive waste repository which was later abandoned. The salt formations of southeastern New Mexico were later identified as a potential site. In 1972, the DOE applied to the Interior Department for the withdrawal of the federal land surrounding the WIPP site from public use. Shaft sinking at the WIPP began in 1980 and most of the excavations were completed by 1984.

Several regulatory steps must still be completed before the WIPP can begin receiving waste. These are certification of compliance with EPA regulations concerning underground nuclear waste disposal, issuance of a Resource Conservation and Recovery Act (RCRA) permit by the state of New Mexico, and a No Migration Variance Determination for the disposal phase from EPA. Current schedules call for...
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completion of these steps in time to enable the DOE to declare the WIPP ready to receive waste by late 1997, with first waste receipt in April of 1998.

The WIPP underground facility consists of (1) the main shaft area and associated access drifts; (2) a waste emplacement area to the south of the main shaft area that consists of eight panels of seven rooms each to be used for the disposal of TRU radioactive waste (only Panel 1 is presently excavated); and (3) an experimental area for non-radioactive experiments developed to the north of the main shaft area. A schematic view of the underground facilities at the WIPP is shown in Figure 1.

The operating life required of the underground facility is thirty-five years after first waste receipt. Therefore, many of the access drifts must remain usable approximately until the year 2033.

2 GEOLOGY

The underground facility at the WIPP is located 655 meters (m) below the surface in bedded salt of the Permian Salado Formation of southeast New Mexico. The generalized stratigraphy, including the facility level, is given in Figure 2. Over 300 m of impermeable evaporate deposits separate the facility horizon from overlying sedimentary formations, and 600 m of evaporites lie below the facility horizon, providing a barrier against underlying limestones and sandstones.

The facility horizon lies within an evaporite sequence consisting of halite, argillaceous halite, and polyhalite (Figure 3). Observations indicate that these beds are laterally continuous. A persistent 50 to 80 centimeter (cm) thick bed of anhydrite and polyhalite, identified as Marker Bed 139 (MB139), lies about 1.5 m below the repository floor. Lateral variability in composition and thickness within this anhydrite bed exists at both the site and on the regional scale. Undulations up to 15 cm in the surface of MB139 have been observed in cores taken from the facility horizon. MB139 is underlain by clay E. Anhydrite "b," 6 cm thick, is about 2 m above the roof and is underlain by clay G. Anhydrite "a," about 20 cm thick, is about 3.9 m above the repository roof and is underlain by clay H. Clay I is located 7.2 m above the roof. Clay E, G, H, and I are all less than 2.5 cm thick. A diffused clay, clay F, is exposed in the ribs just below the roof. The mechanical properties of these clay seams are drastically different from the surrounding rock salt. In situ observations show that the clay seams have a high moisture content. Clay seams have negligible tensile strength and very low shear strength compared to the surrounding rock salt. Therefore, these clay seams constitute planes of weakness along which shearing and separation can easily take place. They also strongly influence the magnitude and orientation of the stress distribution around the openings. Compared to the surrounding rock salt, MB139 is a stiff and brittle layer. As the salt mass moves towards the excavation, stress concentrations develop in MB139. When these stresses reach a critical level, fractures develop in the marker bed, propagate up through the floor salt layer, and eventually may extend to the floor of the room resulting in floor heave.

3 ROCK MECHANICS AND NUCLEAR WASTE

Nuclear waste repository investigations currently support a large portion of rock mechanics analysis and design as well as research. However, the nature of these projects are different from traditional rock mechanics projects. These facilities are designed and built under tighter control and scrutiny because of the potential hazards they present to the public. Furthermore, because the nuclear waste remains radioactive for thousands of years, the current regulations require a design that ensures safety of the public and the environment for ten thousand years. This performance requirement is unprecedented for any other man-made structure.

Rock mechanics efforts at the WIPP are divided into two areas. One concentrates on the design and maintenance of the underground excavations during the operating period. This work is primarily the responsibility of Westinghouse Waste Isolation Division (WID). This effort aims to maintain safe working conditions until the underground facility is permanently sealed. The other major rock mechanics program concentrates on the long-term performance of the repository over the ten thousand year regulatory period. This is primarily Sandia National Laboratories' responsibility. Performance assessment considers the behavior of the entire repository system and its environment as a whole. The performance assessment calculation determines the probability of release of radioactivity greater than that permitted by the regulations outside site boundaries over ten thousand years. All possible processes or occurrences that could affect the performance of the repository, everything from meteor strikes and renewed glaciation to human intrusion, are being considered. However, processes and occurrences that are below a probability cut-off are not used in the calculation. In this effort, rock mechanics analyses are combined with analyses from many other fields, including hydrogeology, chemistry, geochemistry, and nuclear engineering, to name a few.
Rock mechanics contribution to the performance assessment calculation is ultimately manifested through the results of numerical models. Similarly, numerical models are an important component of the rock mechanics studies that deal primarily with the operational period. In today’s practice, rock mechanics modeling is frequently expected to deliver exact solutions to the posed problems. Each model is a simplification and abstraction of the actual case which is in fact a complex function of many variables. The determination of which parameters are important and which can be sacrificed to calculational simplicity is often a difficult question.

Starfield and Cundall (1988) present a methodology for rock mechanics modeling based on the work of Holling (1978). They classify rock mechanics as a data-limited field in the sense that a great deal of relevant data is usually unavailable or cannot be easily obtained. Because of the complexity and multidisciplinary nature of nuclear waste repositories, it may seem logical to think that more details infer a better model. However, the “bigger and better” model in turn requires more input data which in turn needs more field and lab measurements, all of which are potential sources of error in the model. As more detail is incorporated into the model, the intellectual control on the model can become lost and engineering judgment may no longer provide independent verification. As the model becomes more complex, it becomes increasingly difficult to determine why the model behaves as it does and whether the model is accurately simulating real physical mechanisms. Starfield and Cundall emphasize that the purpose of modeling data-limited problems should be to gain understanding and to explore potential trade-offs and alternatives, rather than to make absolute predictions. Modeling can sometimes make the most significant contributions to knowledge of a rock engineering project by providing understanding of the sensitivity of the results to changes in the parameters and assumptions. This is the primary use of WID’s rock mechanics models. However, the nature of the project requires that the accuracy of the model be assessed in some way.

4 ROCK MECHANICS MODELING AT THE WIPP

The main rock mechanics modeling program used by WID is Fast Lagrangian Analysis of Continua (FLAC) (Itasca, 1995). FLAC is a two-dimensional finite difference program that was developed by Peter Cundall and Itasca Consulting Group, Inc., to solve a wide range of complex problems in mechanics. The WIPP Reference Creep Law constitutive model (Krieg, 1984) is built into FLAC. Prior to FLAC, WID primarily used a commercial version of VISCOT (INTERA, 1983) which also incorporated the Reference Creep Law. FLAC has been used by WID for rock mechanics analyses since 1991.

To determine the adequacy of WID’s models, we must define the purpose of the models. The purpose of the WID models can be summarized as follows:

- Prediction of the future performance and stability of the existing underground excavations;
- Comparison of excavation design alternatives;
- Investigation of the deformation mechanisms affecting the past performance of existing excavations.

All of the above involve assessment of rock mass behavior in response to excavation. In most cases, WID models are assessed on a comparative basis. One modeled excavation behaves more or less favorably than another excavation. In these cases, the model results are more important comparatively than absolutely. For example, less importance is placed on the magnitude of the shear strain in the roof beam of a model than on the fact that one of several model scenarios shows twice as much shear strain in the roof beam as in the other scenarios. This procedure is adequate for comparison of excavation alternatives and investigation of the deformation mechanisms. However, it is of less value for the prediction of future behavior. In this case, accurate quantitative results are vital. Limited prediction of future behavior can be achieved through comparison. For example, if the shear strain in hypothetical Model A is twice that of Model B in a particular time, it can be confidently concluded that the excavation simulated by Model B will probably remain stable longer than the excavation simulated by Model A.

WID therefore uses rock mechanics models primarily on a comparative basis which is adequate and appropriate for most of our requirements.

The primary use of WID rock mechanics models is to assess the excavation stability. Currently, WID several indicators of stability:

- Vertical and horizontal convergence rates;
- Clay seam separation and offset rate;
- Degree of roof beam fracturing.

Convergence and clay seam movement are easily and regularly measured in the field and predicted in the models. The degree of roof beam fracturing is more abstract and difficult to quantify. However, general fracture patterns leading to instability have been identified. Although fracture and failure modeling are not currently included in any of the WID models, simple measures of the propensity of the rock to fracture have been identified. It has been observed that the accumulation of the shear strain in the models correspond to large-scale fracturing observed in the roof, floor, and walls of the excavations (Francke and Saeb, 1995).
The field data is inherently variable from location to location. Vertical convergence rate measurements taken in apparently near-identical excavations can vary widely. For instance, in Panel 1, the first storage panel mined at the WIPP, the average vertical convergence rates at the centers of the seven rooms ranged from 5.3 cm/year to 9.0 cm/year during the fifth year after excavation of each room. For the purpose of the two-dimensional, single-room FLAC model, the seven rooms are identical. They would all be modeled the same and hence would give the same results. This example refers to excavations that are in the steady-state creep regime. Rooms with advanced fracturing can have even greater closure rate variations.

In 1994, a 1350 metric ton roof fall occurred in an abandoned opening at the WIPP. This roof fall was expected and was closely monitored up to the moment it occurred. The twelve convergence meters installed in this room recorded order of magnitude differences in vertical convergence rate before the expected roof fall. The differences in the convergence and convergence rates among seemingly identical locations is most likely caused by variation in the material properties. This is very difficult to accurately simulate if subtle details are found to be important. As a result, the expected model accuracy should not be better than the variability seen in the field data. If the field data show 50% variation in a measurement, the model results for that measurement should be considered to be valid only to within 50% of the calculated value, unless the source of the variation could be identified and successfully modeled.

An exercise in model comparison and sensitivity was conducted using the program VISCOT. Several models were used to simulate a WIPP room. Figure 4 shows the result of the simulation. Case A uses the Reference Creep Law and clay seams that are allowed to open. Case B was generated by Sandia National Laboratories using the M-D law and clay seams that do not open (Callahan and DeVries, 1991). Case 3 shows VISCOT results using the M-D law without clay seams. The other lines on Figure 4 are field measurements from the WIPP rooms with the same dimensions as the modeled room. Another modeled case using the VISCOT code with the M-D law and clay seams that are allowed to open was also run for this study, but the results, which were as much as 400% greater than the others, are not shown on Figure 4. This example illustrates the effect of different constitutive models. Furthermore, this example emphasizes the sensitivity of the result to assumptions regarding clay seams and their ability to open. The cases modeling joints capable of opening show substantial increase in the roof-to-floor convergence relative to the cases that do not allow joint opening. This shows the importance of modeling key aspects of geology and its appropriate numerical simulation, however minute.

5 SUMMARY AND CONCLUSIONS

Nuclear waste repositories worldwide support a large proportion of research and engineering in the area of rock mechanics. Due to their complexity and importance, nuclear waste repositories draw from various fields including, but not limited to, hydrogeology, chemistry, geochemistry, and nuclear engineering. These projects are required to provide for the protection of the environment for thousands of years, which is unprecedented for any other man-made project. Modeling is the only way to predict the short and long term performance of these repositories. However, modeling has its own limitations. Modeling for the nuclear waste repositories should evolve from simple to more complex models. However, intellectual control of input and analysis must be maintained, especially over the more complex models. It must be recognized that the results of the models can vary with the variability of the input, as was seen in the case of the WIPP storage rooms.

Based on this philosophy, rock mechanics modeling at WID is used to investigate the major mechanisms responsible for the deformation and fracturing around the underground excavation. In most cases, WID models are used to assess the stability of underground excavations on a comparative basis and to conduct parametric and sensitivity studies.

6 REFERENCES

Figure 1. The underground facilities at WIPP.
Figure 2. Generalized WIPP site stratigraphy.


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Figure 4. Comparison of Model Results To Field Data
Figure 3. WIPP facility horizon stratigraphy.

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