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PRELIMINARY DRIFT DESIGN ANALYSES FOR NUCLEAR WASTE
REPOSITORY IN TUFF*

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INTRODUCTION

The Yucca Mountain Project (YMP), managed by the Nevada Operations Office of the U. S. Department of Energy (DOE), is examining the feasibility of siting a repository for high-level nuclear waste at Yucca Mountain, on and adjacent to the Nevada Test Site (NTS). The proposed repository will be excavated in the Topopah Spring Member, which is a moderately fractured, unsaturated, welded tuff. Excavation stability will be required during construction, waste emplacement, retrieval (if required), and closure to ensure worker safety. The subsurface excavations will be subject to stress changes resulting from thermal expansion of the rock mass and seismic events associated with regional tectonic activity and underground nuclear explosions (UNEs).

Analyses of drift stability are required to assess the acceptable waste emplacement density, to design the drift shapes and ground support systems, and to establish schedules and cost of construction. This paper outlines the proposed methodology to assess drift stability and then focuses on an example of its application to the YMP repository drifts based on preliminary site data. Because site characterization activities have not begun, the data base currently lacks the extensive site-specific field and laboratory data needed to form conclusions as to the final ground support requirements. This drift design methodology will be applied and refined as more site-specific data are generated and as analytical techniques and methodologies are verified during the site characterization process.

The work presented in this paper is part of an ongoing effort to improve the interface between analysis and design, to identify weaknesses in the available data, and to assist the site geomechanics characterization effort in identifying critical parameter needs. The numerical values used in the example, although based on data in the Reference Information Base (RIB) (DOE, 1989) are not necessarily representative of the site nor useful for design purposes.

DRIFT DESIGN METHODOLOGY SYNOPSIS

The drift design methodology, summarized in Figure 1, incorporates definition of design criteria, analysis, and evaluation. These three steps are first applied to unsupported drifts to assess shape and thermal loading, and once the shape and loading are judged to be acceptable, the ground support systems are designed. A brief overview of the methodology is provided here, with the data base for drift design and examples of design analysis provided in more detail.

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Figure 1. Drift design methodology logic.

Drift design criteria are established from the regulatory requirements, drift performance goals, and materials performance. The regulatory requirements from 10 CFR Part 60 require worker health and safety during construction, containment and isolation of the waste, and provision for waste retrieval if required. These requirements are discussed in the Site Characterization Plan (SCP) (DOE, 1988) and Hardy and Bauer ("Preliminary Drift Design Methodology for the Yucca Mountain Project," SAND89-0837, Sandia National Laboratories, in preparation), who developed specific criteria for drift design. Functional requirements for all drifts must be established based on the size of equipment, services in each drift, and ventilating air area requirements.

Collection and presentation of site-specific data is a central part of the site characterization process and required prior to final design and license application. This activity is included in the box labeled "Identify Site Characteristics Credible Range" in Figure 1. The drift design methodology identifies the parameters for design. Some site-specific design parameters will not be available until after exploratory drifts are excavated at the site; in the meantime, estimates of rock mass properties are based on core-hole data, laboratory tests, and engineering judgment developed from experiences in similar rock types.

The loads experienced by the drifts in the repository are from three primary sources: in situ or geostatic stresses, thermal loads, and transient dynamic loads from naturally occurring earthquakes or UNEs. The in situ stresses are projected to be relatively low with the horizontal stress 20 to 80% of the vertical stress. The thermally induced loads develop after the heat generating nuclear waste is emplaced and vary throughout the repository. The thermal load is a design variable and can be controlled by the selection of the waste emplacement configuration and emplacement density. The seismic loads from earthquakes or UNE origin are of short duration and infrequent. Characterization of the magnitude of potential earthquakes and UNEs is discussed by Subramanian (1988). The design earthquake acceleration is recommended to be 0.3 g with an extreme loading of 0.5 g. The UNEs are expected to be of lower magnitude.

Once the design criteria, site characteristics, and design basis loads are identified, candidate drift designs can be developed to meet the functional requirements of the drifts for various components of the repository. These candidate drifts are then analyzed and evaluated without the stabilizing effects of a ground support system.

Analysis of drift stability includes both empirical and numerical techniques. The empirical techniques, such as those proposed by Barton et al. (1974) and Bieniawski (1979), are of limited value in application to drifts acted upon by thermal and seismic loads and, hence, are useful only to assess ground support requirements and for design of unheated drifts. The method of Schmidt (1987) provides guidance as to the expected failure modes around the drift; the predominant mode should then be evaluated by appropriate analytical methods.

The evaluation process compares the results of analyses with the design criteria, and if all criteria are not met, then modification of drift shape and repository configuration is suggested. Not all geologic conditions are suitable for waste emplacement without ground support, and for the extremely poor ground conditions, consideration should be given to isolation of these drifts from thermal loads.

The second phase of analysis and evaluation to design the ground support system is beyond the scope of this paper, but will be presented by Hardy and Bauer.

DATA BASE FOR PRELIMINARY DRIFT DESIGN

The data base for preliminary design consists of core data from four cored holes near the repository location and laboratory test data from core and exposed rock from the host media (DOE, 1988; Chapter 2). The repository is proposed to be excavated in the TSw2, which is a thermomechanical unit of the Topopah Spring Member of the Paintbrush Tuff unit and is located at 200 to 300 m below the surface at Yucca Mountain. Outcrops of the TSw2 appear at Fran Ridge and Busted Butte located southeast and south of Yucca Mountain, respectively. Several test pits have been excavated at Fran Ridge, and visual observations from the exposures provide additional background on the expected conditions at the repository location.

The range of expected rock conditions at the repository horizon is broad, so no single analytical model is expected to be appropriate. The rock mass is expected to be highly jointed, with some variability in the degree of welding and porosity of the host medium. In some cases, blocky conditions can be expected, as can highly fractured zones. Discontinuum and continuum methods of characterization of the rock mass are expected to be useful. In the following examples, application of elastic, compliant joint model (CJM) (Chen, 1987), and elasto-plastic continuum models were used. All rock models were incorporated into the JAC finite-element code developed by Biffle (1984).

Rock properties important to drift design in a thermal environment include the thermal expansion coefficient and mechanical properties. The elastic and elasto-plastic models require equivalent rock mass elastic properties and strength characteristics. The CJM requires intact rock properties and mechanical properties of the joints.

Fundamental to the estimation of rock mass properties is the frequency, orientation, and continuity of jointing. The rock quality designation (RQD) provides an indication of the jointing intensity at a site. Figure 2 shows the RQD of core from TSw2 for the four cored holes near the repository location (Langkopf and Gnirk, 1986). The RQD for a 24-m section near the repository target horizon shows a uniform distribution from a very low RQD to 100% RQD. Some of the low RQD occurrences could be discounted because of poor drilling and handling techniques, but nonetheless, the design methodology must accommodate a wide range of ground conditions.

To accommodate a wide range of potential conditions, a procedure has been developed by Hardy and Bauer in which the expected conditions are grouped into five categories. These categories are based on the statistical range of RQDs shown in Figure 2. The range of each parameter in the empirical classifications of Barton et al. (1974) and Bieniawski (1979), presented by Langkopf and Gnirk (1986), and the RQD range indicated by Figure 2 were used to develop the five categories shown in Table 1. The rock quality ratings range from "extremely poor" to "good," or a rock mass quality (Q) range of from 0.08 to 29.60. The percentage of rock better than each individual rating is 95, 80, 60, 30, and 10.

The design rock mass rating (DRMR) in Table 1 was calculated by averaging the rock mass rating (RMR) and that calculated from Q using the equation

$$RMR = 9 \ln Q + 44.$$

Figure 2. The RQD in TSw2 for four cored holes near the YMP repository site (Langkopf and Gnirk, 1986).

Table 1. Derived mechanical properties for design methodology analysis for varying rock mass quality — equivalent-continuum approach.

Rock Mass Quality Indices				Rock Mass Strength (MPa)						
RQD (%)	Rock Mass Quality			Rock Quality Category	$\sigma_1 = A + B\sigma_3^C$			Drucker-Prager		Rock Mass Modulus (GPa)
	Q	RMR	DRMR*		A	B	C	K	α	
9	0.08	43.7	32.5	Ext. poor	2.7	9.3	0.60	0.78	0.22	3.7
22	0.34	49.8	42.1	Very poor	4.5	9.3	0.60	1.0	0.22	6.4
49	1.68	60.6	54.7	Poor	9.5	9.1	0.62	1.7	0.22	13.1
81	8.40	75.1	69.2	Fair	23.0	8.4	0.65	3.7	0.22	30.2
95	29.60	83.3	78.9	Good	43.0	7.9	0.67	6.7	0.21	30.4

*See text.

This DRMR was used to calculate the rock mass strength using the average of that determined from the methods of Hoek and Brown (1988) and Yudhbir et al. (1983). A curve of the power law form was fit to the average of these two strength algorithms (see Table 1). The Drucker-Prager yield surface parameters were estimated to be compatible with the power law form. Table 1 also lists the rock mass modulus estimated from the DRMR using the algorithm of Hoek and Brown (1988). For the good rock, the laboratory value of elastic modulus was used for the rock mass modulus. Poisson's ratio, rock mass density, and the thermal expansion coefficient were assumed to be constant and independent of rock mass quality. These parameters will vary throughout the repository depending on such parameters as porosity, degree of welding, and jointing.

Postprocessing elastic analytical results requires a knowledge of the rock mass and joint strengths. The joint strengths are also required for nonlinear modeling of discrete or ubiquitous jointing. For the Coulomb joint strength model, the frictional characteristics (ϕ) and cohesion (C) might vary with rock quality, and the persistence of joints can be expected to vary from one joint set to another with rock mass quality. The estimates of these parameters for vertical and horizontal joints are shown in Table 2. The length-weighted average of the joint frictional properties accounts for the discontinuous nature of the joints as suggested by Brown (1971).

Table 2. Joint strength properties for design analysis for varying rock mass quality.

Rock Quality Category	Basic Frictional Properties						Weighted Average* Joint Frictional Properties			
	Joint Persistence χ		Intact Rock		Joints		Vertical		Horizontal	
	Vertical	Horizontal	C_r (MPa)	ϕ_r (degrees)	C_j (MPa)	ϕ_j (degrees)	C (MPa)	ϕ	C (MPa)	ϕ
Ext. poor	0.975	0.475	19	21	0.01	13	0.5	13	10	17
Very poor	0.9	0.4	22	23	0.04	17	2.3	17	13	21
Poor	0.8	0.3	26	26	0.08	22	5.3	23	18	25
Fair	0.65	0.15	32	32	0.14	31	11.0	31	27	31
Good	0.55	0.05	36	35	0.18	36	16.0	36	34	35

* $C = \chi C_j + (1 - \chi) C_r$, and $\phi = \chi \phi_j + (1 - \chi) \phi_r$.

The compliant joint model (Chen, 1987) defines the joint normal stress (σ_{nn}) closure (u) relationship by

$$\sigma_{nn} = \frac{A_n u}{u_{max} - u},$$

where A_n is the half-closure stress, and u_{max} the maximum joint closure. Both A_n and u_{max} can be expected to vary with joint conditions. Table 3 lists the preliminary range of parameters selected for the repository drift design example. The A and u_{max} range is compatible with that previously reported [Sandia National Laboratories (SNL), 1987]. The joint frequencies were calculated from the RQD values using the method of Hudson and Priest (1979). The joint shear stiffness, K_j , range of from 10^3 to 10^6 MPa/m was broadly based on the data compiled by Barton (1982) on joint shear stiffnesses.

EXAMPLE APPLICATION

The example application is for a waste emplacement drift with waste emplaced in a vertical borehole in the floor of the room. The drift geometry and waste emplacement configuration is from the Site Characterization Plan - Conceptual Design Report (SCP-CDR) (SNL, 1987). The areal power density (APD) at emplacement is 57 kW/acre using 8.5-yr-old waste. The example uses the two-dimensional finite-element model with either elastic, elasto-plastic, or compliant joint rock models for the five categories of rock shown in Tables 1 through 3. Analysis was completed out to 100 yrs after waste emplacement. The temperature field was developed using a finite-element code assuming no heat loss to the ventilation system. During the operational period, the maximum impact of the thermal loads around the drift was experienced.

Results from the analysis are evaluated to assess the extent of overstress zones either for yield of the rock mass or slip along joints. Criteria used to evaluate analytical results, include:

- the maximum compressive strain associated with yield of the elasto-plastic continuum,
- the potential for splitting of intact rock by assessing the extensile strain (for CJM),

Table 3. Joint properties for design analysis using CJM approach.

Rock Quality Category	Joint Frequency		Compliant Joint Parameters		
	Vertical (per meter)	Horizontal (per meter)	A (MPa)	u_{max} (mm)	K_j (GPa/mm)
Extremely poor	37	1.00	1.93	0.034	51
Very poor	26	0.71	1.70	0.029	200
Poor	16	0.43	1.40	0.023	400
Fair	7	0.20	0.95	0.013	700
Good	3	0.08	0.65	0.006	900

- the potential for compressive failure of intact rock (for CJM), and
- extent of excessive slip along joints.

Conditions around the drift are considered unacceptable if economic and practical ground support systems cannot be designed to support the yielded rock. After the preliminary assessment of ground support needs based on the analysis outlined above and the empirical evaluation, the compatibility of the ground support system and the rock under these changing thermal environments must be evaluated. This can be achieved by directly modeling shotcrete and bolts or by assessing the strain compatibility of the ground support system with the rock deformation determined from the above analysis. Such analysis, presented in Hardy and Bauer, has shown that shotcrete would be unacceptable in the emplacement drifts and that unbonded bolts or low modulus bolts would be required.

To illustrate the significance of the range of rock models on the stress environment around the drift, results of the analysis are presented in Tables 4 and 5. Table 4 shows the horizontal stress in the crown of the drift for the three rock models, and Table 5, the depth of overstress or yield for the elastic and elasto-plastic models, all for 100 yrs after waste emplacement. Figures 3, 4, and 5 show the crown horizontal stress history for the three rock models. The results for the elastic rock model indicate the sensitivity of the predicted stress change to the rock mass modulus. Yielding of the rock mass relieves the high stress buildup in the crown, but as Table 5 shows, the extent of yield is insignificant (less than 0.65 m or 2 ft in the crown). The stress results of the CJM indicate that the joint normal stiffness has only a limited effect on the rock mass response compared to that of the elastic analysis for the good rock conditions. This suggests that in the CJM, the joint stiffnesses are not as compliant as predicted by the rock mass modulus algorithm for the lesser quality rock categories.

Table 4. Horizontal stress in the drift crown in MPa, 100 yrs after waste emplacement.

Rock Quality Category	Rock Model		
	Elastic	Elasto-Plastic	CJM
Extremely poor	13.6	6.5	64.3
Very poor	20.3	8.7	78.9
Poor	37.1	14.5	79.0
Fair	80.1	30.6	82.0
Good	80.1	53.7	82.4

Figure 6 shows zones of active joint slip predicted by the CJM for the extremely poor rock after 100 yrs of heating. The horizontal joints intersecting the floor and haunch slip, but the magnitude of slip along individual joints is predicted to be less than 2 mm.

OBSERVATIONS

Preliminary indications from available data, field exposures of the host medium, and empirical based algorithms suggest that the mechanical properties of the host medium vary widely. The drift design methodology must address this variability and provide ground

support systems compatible with the exposed conditions and expected impacts of thermal and seismic loads. The example estimated rock properties derived from the laboratory core data and empirical algorithms suggest that the rock mass strength may vary from 2 to 25% of the laboratory strength, and the equivalent rock mass modulus range from 10 to near 100% of the intact laboratory modulus. Incorporating these and specific joint deformation and strength properties in the drift design methodology indicate that the lower modulus of the poorer quality rock results in lower thermally induced stress than for the high-quality rock masses. It is, thus, not a simple task to identify rock conditions that might not be suitable for waste emplacement or requiring reduced thermal loads. In fact, for the poorer quality rock, it can be shown analytically, at least, that most rock stability problems may be encountered during construction and that heating of the rock mass enhances drift stability.

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Table 5. Emplacement drift yield zones from elastic and elasto-plastic analyses.

Rock Quality Category	Crown		Wall	
	Elastic* (m)	Elasto-Plastic (m)	Elastic* (m)	Elasto-Plastic (m)
Extremely poor	0.24	0.65	0.82	2.36
Very poor	0.33	0.65	0.49	1.63
Poor	0.42	0.65	0.33	1.01
Fair	0.57	0.65	0.91	2.36
Good	0.33	0.33	0.82	1.04

*Depth of overstress area using the power law strength equation from Table 1.

Figure 3. Crown horizontal stress history from elastic rock mass model.

Figure 4. Crown horizontal stress history from elasto-plastic rock mass model.

Figure 5. Crown horizontal stress history from CJM.

Figure 6. Area of joint slip predicted by CJM for extremely poor rock (scale in meters).

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