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Application of Analytical Methods for Jointed Rock as Part of a Drift Design Methodology for the Yucca Mountain Project*

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by

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ABSTRACT

The Yucca Mountain Project, 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. Excavation stability will be required during construction, waste emplacement, retrieval (if required), and closure, covering a period of approximately 100 years. In order to incorporate a means of evaluating excavation stability in the design process, a drift design methodology has been developed. This methodology uses both empirical and analytical methods in conjunction with detailed descriptions of site conditions to evaluate a proposed design. At present, the emphasis is on analytical numerical methods because of the limited experience in tuff at elevated temperatures. This paper describes the proposed methods for analysis of systematically jointed, isotropically jointed, and widely spaced, discretely jointed rock masses. Loads resulting from in situ stress, thermal expansion, and seismic events are considered. Criteria for strength and failure of intact rock and the rock mass are applied to analysis results to assess the stability of proposed drift designs and to guide the design of the ground support system.

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Introduction

The Yucca Mountain Project is investigating the feasibility of locating a high-level nuclear waste repository at Yucca Mountain, Nevada. The conceptual design of the repository has shafts and ramps that provide access to the Topopah Springs formation, a welded tuff located approximately 200 to 300 m below the surface. Main access and emplacement drifts will be mined to allow waste disposal in either horizontal or vertical boreholes. The drifts must provide safe access for waste emplacement, inspection and maintenance following emplacement, closure, and possibly waste retrieval. These activities will take place over a period of approximately 100 years.

Because the emplaced waste gives off heat, the entire subsurface portion of the repository will be subjected to stresses resulting from thermal expansion of the rock in addition to those from seismic effects and excavation of the openings. Stability of the underground openings will be maintained by using appropriate excavation procedures and installing rock support reinforcement systems. To incorporate a means of evaluating excavation stability in the design process, a drift design methodology has been developed (Bauer and Hardy, 1990). This methodology uses both empirical and analytical methods in conjunction with detailed descriptions of site conditions to evaluate a proposed design. The site conditions (rock quality, etc.), will be developed during the site characterization phase of the project. However, at present, the emphasis is on analytical numerical methods because of the limited experience in tuff at elevated temperatures.

This paper describes the proposed methods for modeling rock-mass behavior in the vicinity of drifts in order to evaluate drift designs with regard to long-term stability. The numerical modeling methods include finite element, discrete element, and boundary element methods used in conjunction with a variety of constitutive models for rock with varying degrees of jointing. Because of the added complexity, ground support is often not modeled explicitly in the initial analyses, generally resulting in a conservative approach to design. However, after the initial design assessment, a ground support system is selected and the design is analyzed further to assess the effectiveness of the ground support system.

The following section provides the context for the discussion of analytical methods, i.e. it briefly summarizes the proposed drift design methodology is presented. The next section discusses the expected in situ stresses and thermal and seismic loadings as a preface to presenting the analytical methods used to evaluate drift designs subjected to these loads. Then the analytical methods and corresponding rock-mass models, along with the rationale for their application, are discussed in some detail. Finally, proposed failure and stability criteria for evaluating the analysis results are also presented.

Drift Design Methodology

The drift design methodology, developed by Bauer and Hardy (1990), is based on three principal steps for design: definition, analysis, and evaluation. Figure 1 shows a logic chart for the methodology, which is divided into two main sections. In the first part (Part A, Figure 1), preliminary drift designs (drift shapes and areas) are developed based on the functional and performance requirements and the results of initial parametric and tradeoff studies. Then analyses (both empirical and analytical) are performed and the stability of drifts is assessed without ground support. In the second part (Part B, Figure 1), a preliminary ground support system is selected based on the functional performance requirements and the results of the analyses done in Part A. Then the ground support plus the rock system is analyzed to assess ground support component loadings and drift stability. A final ground support system is selected when all design criteria are met by the drift and ground support system.

It is the block denoting "numerical analysis of drifts" in Part A of the methodology that is the focus of this paper. The analysis in Part A does not include the ground support. The intent is to verify that, for most of the expected ground conditions, the drift design (shape and size) is stable when subjected to the expected in situ, seismic, and thermal loads. The rock mass models developed for this analysis are based on preliminary data and expected site conditions. As an important part of the design philosophy, the predictions of rock-mass behavior and performance will be compared against the results of in situ tests and demonstrations as site characterization proceeds. These comparisons will form a basis for demonstrating model validity or for revising the model, if required.

It should be noted that this methodology is considered preliminary because it reflects only information gained through the conceptual design phase. The conceptual design is limited because there are no precedents for designing and constructing a nuclear waste repository and there is a lack of information from the site. To date only a limited number of boreholes have been drilled at the site, although plans for extensive characterization have been developed (DOE, 1988).

Expected Loads

In the analysis and evaluation of drift performance, near-drift stresses and displacements are calculated based on applied stresses and the assumed rock-mass behavior. Applied stresses from three different sources must be considered in designing the drifts: in situ or geostatic stress, thermally induced stress, and stresses resulting from seismic motion. The stress at the drift location, resulting from the superposition of stresses from the above mechanisms, can be used as an independent input to drift design if the rock mass remains essentially elastic after drift construction. However, if significant rock yielding, joint slip, or block fallout were to occur that might relieve the regional stress, the approach of superposition of the regional loads at the drift locations would be inaccurate but conservative. The approach of separating the loads (as the stress at the drift location) in the drift design is proposed because, by design, the rock mass will remain essentially elastic. The site has been selected based on its overall suitability for waste isolation and, in particular, its suitability for repository construction.

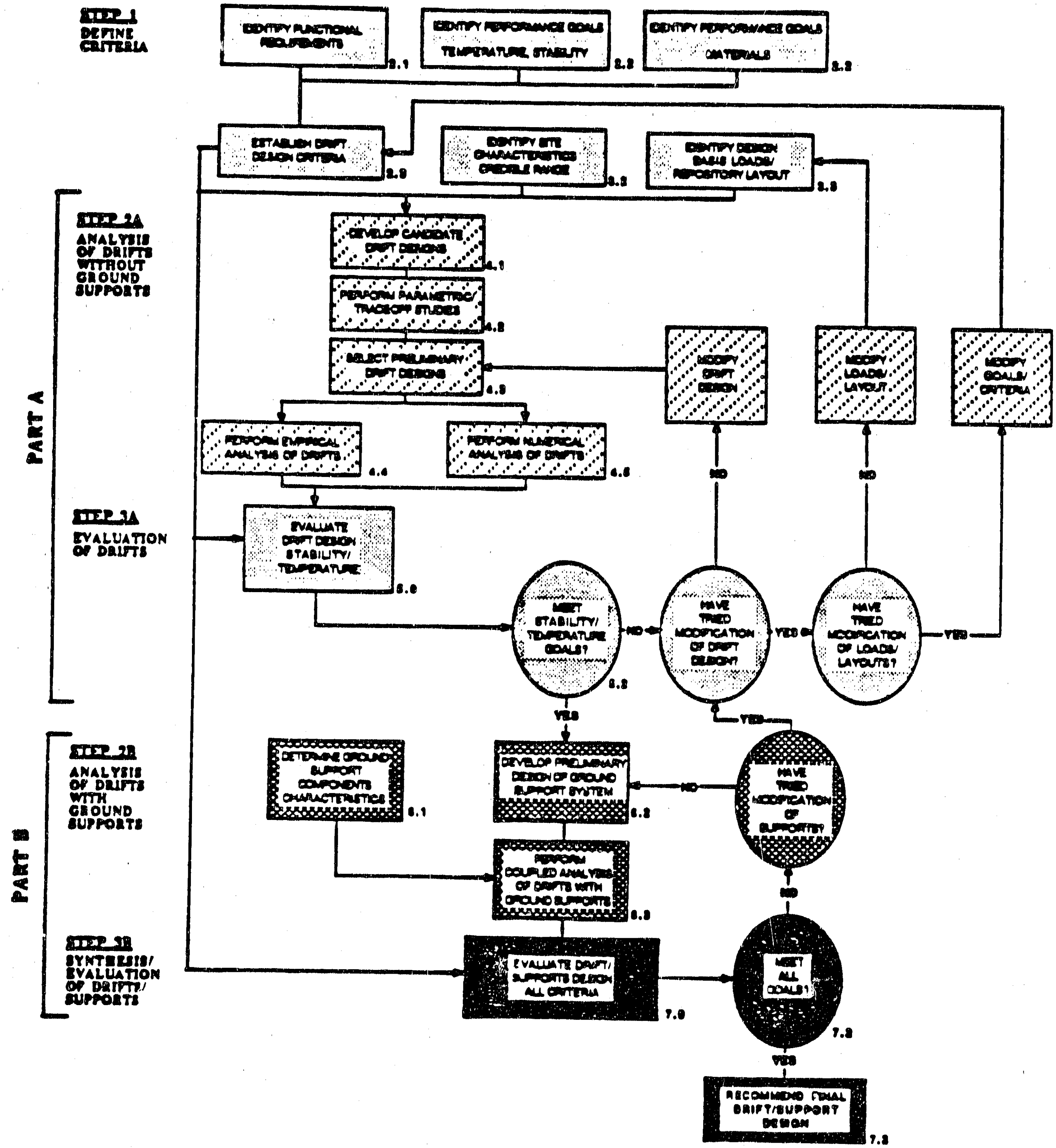

Figure 1. Logic Chart for Drift Design Methodology (from Bauer and Hardy, 1990).

Analytical Methods

In this section, analytical methods and the models used to describe the thermal and mechanical responses of the rock mass are discussed, including the criteria used to select models for particular classes of rock. Both analytical and empirical methods are proposed for assessing drift performance under repository conditions (Figure 1). Thermal conditions and thermal loads near the drifts are derived solely from numerical modeling, whereas empirical methods are used in conjunction with numerical methods to evaluate the effect of in situ and seismic stresses on drift stability. The particular criteria used to assess drift stability based on analytical results depend on the particular deformation mechanisms incorporated in the models used for the analysis. Thus, criteria that may be used to assess drift performance will differ from case to case depending on the particular models used in the analysis. All analyses are, of course, limited by the degree of understanding of the deformation and failure mechanisms, and the adequacy of material property data.

Thermal Modeling

Thermal modeling is done on at least two different scales, drift scale and repository scale. The analytical method and the details of the thermal model depend on the analysis scale. However, it is assumed that the primary heat transfer mechanism in all cases is conduction. In the partially saturated tuff at the repository horizon, thermal conduction appears to be independent of the local joint structure. Some (more detailed) analyses take into account the effect of the pore water, especially in the boiling transition region (near $100^{\circ}C$). In most cases, this effect is analyzed by making the thermal conductivity a function of temperature to account for the energy transfer resulting from boiling of pore water. Other heat transfer mechanisms, such as radiation and convection in the drifts, are also incorporated into near-field analyses by assuming the drift contains a conductive material with an equivalent conductivity that accounts for radiative and convective effects at the drift walls.

For thermal modeling on a repository scale, the details of the drifts can be neglected, but the sequencing of the emplacement of heat sources and the temporal decay of those sources are important components of the model. In this case, two- and three-dimensional numerical methods employing superposition of semianalytic solutions to finite line and planar heat sources are used. In these solutions, the conductivity of the rock must be constant, and the solution region is assumed to be infinite or semi-infinite. These thermal analysis methods are often combined with a simple numerical method, such as the boundary integral method, for solving the associated structural boundary value problem where the strains due to thermal expansion are incorporated in the analysis as an additional boundary condition. Repository-scale analyses are usually performed to determine the temperature history for 1) emplacement drifts near the boundary of a panel, 2) midpanel drifts and 3) the mains, where the thermal loads are asymmetric with respect to the drift axis and depend on the emplacement sequence, and hence, on repository-scale factors.

Thermal modeling on a more local drift scale usually incorporates the details of the drift geometry and the emplacement boreholes. Finite element modeling is generally preferred for these cases because of its flexibility how it represents the geometry and how it can incorporate additional detail into the thermal model, including temperature dependent conductivities, and account for radiative and convective heat transfer. These methods are used to determine the thermal loading component for waste emplacement drifts in the interior of an emplacement panel because, for some time after waste emplacement, the thermal load depends primarily on the heat sources in the drift and those in neighboring drifts. Thus, using symmetry to construct analysis regions that simulate infinite arrays of emplacement drifts is relatively easy and represents a good approximation to actual geometry. In addition, drift-scale modeling can be used to assess the effects of ventilation changes on the local temperature fields.

Rock-Mass Structural Modeling

For structural modeling of the rock mass, several classes of constitutive models are available. The nature of the rock jointing and the scale of interest relative to the jointing pattern are the principal factors used in selecting a model (or set of models) and analytical method for assessing drift performance. The selection logic proposed in the drift design methodology is given in Figure 2. Elastic analyses using finite elements or boundary elements are almost always performed as a first step. These analyses assume that the rock is isotropic and homogeneous with a deformation modulus indicative of the rock mass. The results of the initial elastic analyses are postprocessed using various rock strength, joint strength, and rock-mass strength criteria to assess the potential for selected modes of rock or joint failure and to evaluate the sensitivity of rock stresses to rock mass parameters or changes in thermal conditions resulting from different waste emplacement configurations. Once this is done, further analysis can be done taking into consideration more of the details of the rock structure. These analyses use one or more of four classes of models shown in Figure 2. The lowest tier of blocks in Figure 2 summarize, for each class of models, the analysis methods, the material (rock) models, the principal input data required for the material models, and the type of strength or failure criteria applicable to the deformation modes incorporated in the model. The four model classes are described briefly below.

Elasto-Plastic - The elasto-plastic continuum models assume rock-mass properties similar to the isotropic elastic models, but they incorporate stress redistribution and yielding to maintain the stress condition within the yield criterion. Yielding of the rock mass occurs when the yield condition, which is a function of stress and material parameters, is equal to zero. Plastic strains are introduced when the material is in the plastic state. The yield condition for rock is generally based on either the Mohr-Coulomb or Drucker-Prager relations for frictional materials. In the application of elasto-plastic models, the zones where yield has occurred are identified and the magnitude of the compressive strains are monitored. In interpreting the results of the analysis, a maximum compressive strain criterion is proposed to assess the extent of failure and to assess the need for ground support.

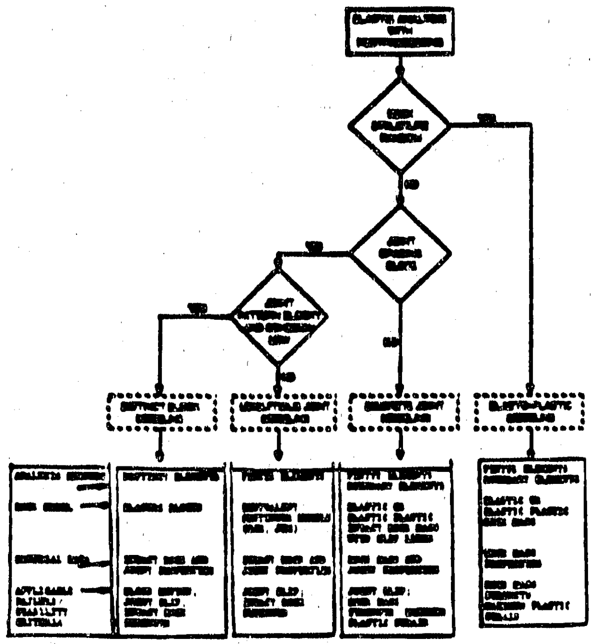

Figure 2. Selection of Appropriate Rock Model for Design Analysis

Discrete Joint - Discrete joint modeling is used where the rock structure and fracturing are essentially isotropic except for a small number of prominent joints or discontinuities (faults) that are believed to play a significant role in the deformation of the rock mass. In these cases, the rock mass is modeled using the elastic or elasto-plastic models described above. Finite element and boundary element methods allow for the introduction of discrete joints through the use of slip lines, shear-zone elements, or other numerical techniques. Frictional and normal closure behavior of the model joints can be prescribed on an individual basis, i.e. each slip line can have different properties.

Ubiquitous Joints - As the number of joints in the analysis region increases, modeling joints individually becomes impractical. Further, highly jointed rock, where the jointing is not random but occurs in distinctly oriented sets, is not well modeled by assuming elastic behavior, either isotropic or anisotropic. The deformation of the joints, both in normal closure and in shear, can be highly nonlinear and anelastic. In these cases, ubiquitous- or smeared-joint models are used. The advantage of these models is that the rock is treated as a continuum, but the effect of the oriented joint sets is explicitly accounted for. Models such as the Compliant Joint Model (CJM) (Chen, 1987) and the Joint Empirical Model (JEM) (Blanford and Key, 1990) assume the relationship between normal stress on the joint and normal closure of the joint is hyperbolic. The CJM assumes a bilinear shear stress/shear strain relationship with the initiation of slip governed by a Coulomb friction strength envelope. The JEM adopts the empirical approach of Barton (1982) to describe joint shear. For these equivalent continuum models, yielding within the rock mass is limited to slip along the joints. A separate criterion must be established to determine the limiting stresses allowed in the intact rock. This criterion for crushing or splitting of the intact rock could be similar to the yield criterion used for the elasto-plastic analysis or a criterion based on effective extensile strain (Stacey, 1981) can be used.

Distinct Blocks - Distinct element methods require a complete geometric description of the blocks composing the rock mass, as well as a knowledge of the joint and intact rock properties. The behavior of the joints or contacts between blocks can be represented by a Mohr-Coulomb strength criterion with joint stiffnesses being either constant or dependent on stress or displacements. The uniqueness and utility of the method is derived from the fact that the blocks can deform, rotate, translate, and split to form new blocks, depending on the applied forces. The key to applying this modeling technique is in the geometric representation of the joint system and the blocks formed by the intersection of those joints.

Strength and Failure Criteria

The strength and failure criteria used in the initial assessment of drift performance and ground support selection depend on the models used and, hence, the deformation and failure mechanisms assumed in the analysis. The general criteria listed in Figure 2 include strength criteria for intact rock and the rock mass, yield criteria for the rock mass, and a criterion for maximum allowable joint or fault slip. Some criteria that are proposed for use in the reference case in assessing the analytical results are noted below. Variability of ground conditions can be expected based on the variability in jointing, porosity, and degree of welding and must be accounted for in the drift design.

Intact rock and rock mass strength - A maximum extensile strain criterion proposed by Stacey (1981) can be used to assess the potential for intact rock fracture or crushing. The proposed limiting extensile strain for welded tuff from the repository horizon is 0.0004, as determined from laboratory test data available to date. Several other empirical criteria for intact rock and rock mass strength have been proposed for drift evaluations, including those developed by Yudbir et al. (1983), Hoek and Brown (1980), and Ramamurthy (1986). The reference information base, developed for project use, suggests strength envelopes for intact rock and the rock mass based on the average values derived from the above three empirical criteria.

Joint Slip - Few studies exist to assist in establishing limits for joint slip that would be compatible with ground support design methods. Continuum joint models, such as CJM, predict average joint slip over a computation cell. A preliminary assumption for joint slip is that if it is limited to less than 0.01 m, then the opening will remain stable or require only light support.

Plastic strains - Maximum allowable compressive strain is similar in concept to the maximum allowable strain adopted in ultimate load design methodology in concrete. Preliminary estimates suggest that a limit of 0.8% compressive plastic strain (from elasto-plastic models) may be appropriate for maintaining drift stability.

Evaluation of Stability

The results needed for evaluating the drift include the temperatures, stresses, and displacements about the drift resulting from various combinations of in situ, thermal, and seismic loads. The principal evaluation method is to develop safety factors relative to the stability criteria. For example, a safety factor for rock mass failure can be computed as the ratio of the failure stress (from one of the above-noted criteria) to the computed stress at each point in the analysis region. Contours of safety factors can then be plotted. Similarly, safety factors for joint slip, intact rock failure, and other potential failure mechanisms can be computed and plotted, depending on the models used in the analysis.

To evaluate the suitability of drift design, two sets of criteria must be met. The first set relates to the conditions of the rock mass under the imposed loads and the second to the practicality of installing a ground support system to support yielded or failed rock. The details of these evaluations are beyond the scope of this paper; however, in general, regions of potential yield or failure (those with safety factors less than 1.0) need to be limited to what a reasonable ground support system can be expected to support. This is taken to be the dead weight of failed rock (with a factor of safety of at least 1.5). Final stability evaluations must include an evaluation of the entire system, i.e. rock mass plus ground support, to insure that reasonable factors of safety for both the rock mass and ground support system are achieved.

Summary and Conclusion

A preliminary drift design methodology has been developed to define a method and criteria by which the stability of underground repository drifts in tuff can be assessed and the ground support system designed. Because site-specific data, at present, is sparse, the initial evaluations proposed in the methodology emphasize the use of analytical methods. Although empirical and observational methods are part of the overall approach, their contribution to the drift design is limited at this stage of the repository design. In this paper, emphasis has been placed on showing how thermal and mechanical analysis methods can be incorporated and utilized in the design process. An integral part of the methodology must include testing of both the empirical and analytical methods employed by comparing results from in situ tests and demonstrations with predictions of the design analyses.

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