

An Assessment of Dynamic Response Prediction for a High-Level Nuclear Waste Underground Repository

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1. INTRODUCTION

1.1 Overview

Requirements of 10CFR60 govern the design of an underground nuclear waste repository relative to safe operations, waste retrievability options, and integrity of natural geologic and engineered barriers. Specifically, design of the facilities to withstand the anticipated dynamic environment are of concern in this paper. It represents a brief summary of an extensive review that was recently compiled by the Center for Nuclear Waste Regulatory Analyses [Kana, et al, 1989], in support of the licensing activities of the Nuclear Regulatory Commission. That review should be consulted for more details and extensive reference lists.

Objectives of this work include establishment of the current state for prediction of underground response to seismic and other dynamic events. Capabilities of analytical and numerical models are evaluated, along with independent methods for establishing their validity. Specifically, key parameters are sought for establishing licensing positions on dynamic behavior of tuff media at the Yucca Mountain Nevada proposed repository site.

1.2 Underground repository concept

A conceptual description of the Yucca Mountain repository system is shown in Figure 1, which is taken from Chapter 6 of the Site Characterization Plan, Consultation Draft [1988]. The system can be seen to contain 1) central surface facilities which are designed to accept shipments of waste and provide maintenance capabilities; 2) underground facilities which provide the storage area for waste material canisters; and 3) a tuff pile which consists of a surface deposit of the material excavated to form the underground facilities and their access paths.

From the Site Characterization Plan it may be deduced that several components of the system are subject to seismic and other dynamic design considerations. Shafts and boreholes are nearly-vertical holes which may or may not be lined, and provide access to lower levels to transport materials or equipment. Tunnels, drifts, or ramps are nearly-horizontal underground rooms or passageways that also may or may not be lined, and form the main storage area, or provide access to and from this area. Various surface buildings can be important to safety. Ventilation systems must provide life support and remove heat generated by the waste material. A series of mechanical conveyors for both personnel and material are included. Finally a variety of miscellaneous equipment is necessary for operation of the facility.

Although the seismic resistance of all of the above components must be considered in design, generally the adequacy of supported equipment can be determined by procedures similar to those prescribed in IEEE Standard 344 [1987] for electrical equipment, and in ASME Standard for Mechanical Equipment [1986] for mechanical equipment. Furthermore, design of surface buildings can be accomplished according to various well-known structural standards and codes. On the other hand, seismic design of the first two categories of components which are constructed in a faulted, jointed, and fractured

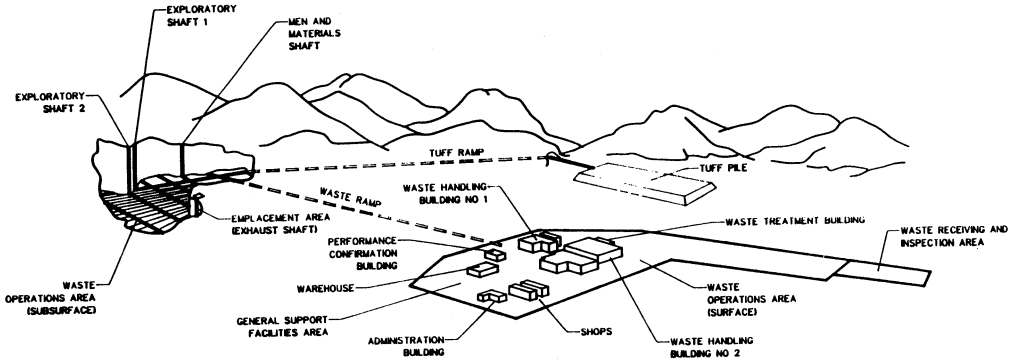


FIGURE 1
 PERSPECTIVE OF THE PROPOSED YUCCA MOUNTAIN REPOSITORY
 (FROM SITE CHARACTERIZATION PLAN, DRAFT-DOE/RW-0160, 1988)

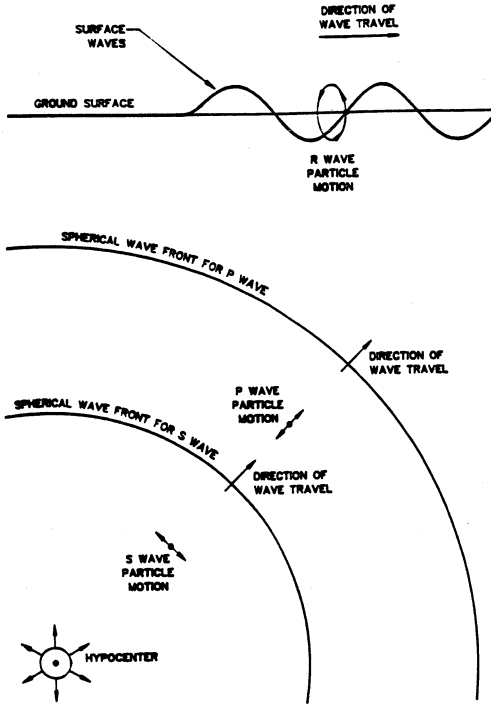


FIGURE 2
 SEISMIC WAVES. THE P AND S WAVES ARE BODY WAVES
 THAT ROTATE OUTWARD IN ALL DIRECTIONS
 FROM THE PLACES WHERE FRACTURES ARE OCCURRING
 (FROM GERE AND SHAH, 1984)

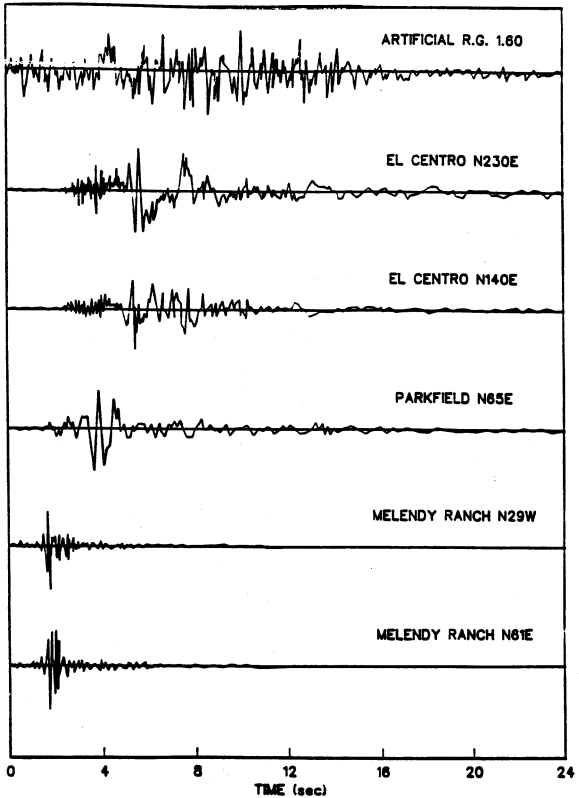


FIGURE 3
 HORIZONTAL CONTROL MOTION ACCELEROGRAMS
 (NORMALIZED TO 0.5G)
 (FROM LUCO et al, 1986)

rock mass and include underground structural supports, is not very well developed, and therefore is the primary subject of this report. Furthermore, because of their close relation with ground shock design, response to rockburst and underground explosions is also included.

1.3 Special features of the problem

In specifying suitable site conditions for a repository, 10CFR60.122 specifically requires consideration of natural phenomena and site conditions which could adversely affect achievement of the prescribed performance objectives. An important phenomenon which could conceivably affect both the short- and long-term performance of a repository is ground motion due to seismic activity. Similarly, ground motion due to underground nuclear explosions at the Nevada Test Site needs to be evaluated. Conceivably, ground motion from either source could cause rock displacements on the canister-, room- and repository-scales, any or all of which could violate the established repository performance objectives. For example, joint slip in a canister hole associated with seismically-induced ground motion might prevent canister retrievability. Falls of rock in repository emplacement rooms could result in canister damage, and increase staff exposure to radiation. Disruption of the geologic barrier after permanent closure by fault or joint displacement could significantly increase the gross permeability of the rock mass. In this regard, it is notable that dynamic soil-structure interaction schemes have been applied in the nuclear industry for some time. However, the nature of ground motion in the subsurface is different from that on the surface, and jointed rock exhibits constitutive behavior quite different from that of soil. Thus, experience gained in design analysis and performance prediction for surface structures founded on soil is not highly relevant to the problem of dynamic analysis of underground excavations in rock. Compared with the amount of attention devoted to dynamic analysis of ground structure interaction for surface structures, effort expended on observation and analysis of the dynamic performance of underground excavations and rock structures has been very limited.

2. CHARACTERIZATION OF GROUND MOTION

2.1 Source-generated ground motion

For the purpose of this report, seismic disturbances within the earth will be considered for natural earthquakes, explosions, and rockbursts. A general description of the ground motions which occur as a result of such events is given in Fig. 2. Energy release occurs at the underground hypocenter, or focus. For an earthquake, the energy is released by sudden rupture or movement of interacting surfaces which were subject to a gradual buildup of strain due to lockup and opposing creep at a ground fault of several possible types. For a rockburst, the source is excess shear stress, generated by mining, acting on natural or induced planes of weakness. For an explosion, the energy source is chemical or nuclear. In each case the magnitude (amplitude) of the resulting disturbance depends on the amount of energy present in the source at the time of the release event.

Once energy release occurs, as shown in Fig. 2, seismic waves of several types emanate away from the hypocenter [Gere and Shah, 1984], and their character changes with distance of propagation, the type of material through which they pass, and interaction with the surface and other boundaries. Seismic waves associated with dynamic events are of two types: body waves and surface waves. Body waves account for energy transmission from its source in the interior of a rock mass, while surface waves are restricted to the vicinity of the ground surface. An important feature of surface waves pointed out by Asmis [1984] is that, because propagation velocity and frequency are less than that for the subsurface body waves, conservation of energy leads to higher amplitude motion in a soft layer. For this reason, the ground motion experienced by surface excavations and structures is distinctly different from that experienced by subsurface facilities. This has substantial implications for underground mines and similar facilities, since the shaft collar or portal for an adit must be designed to tolerate more intense ground motion than subsurface excavations.

Various texts and papers are available which describe seismology of the resulting complex earth motions at various depths and distances from the hypocenter. Here, we will only summarize the ground motions in terms of how they form the excitation or dynamic input to underground facilities. That is, we will be interested in the various ways that the motion at a point can be described, so that its effects on underground facilities can be predicted. Much of the discussion follows that previously reported by Asmis [1984]. In effect, at a given point in space within the earth, a time history of motions is formed by a complex combination of all the waves as they pass the given point. For example, an

earthquake motion at the surface quite distant from the hypocenter can be of rather long duration and comprised of three dimensional multifrequency components. However, several factors influence the exact nature of the motion.

One useful description of ground motion is provided by records of the time history of acceleration (such as Fig. 3), velocity, or displacement which are measured for a particular earthquake that occurs at a given site. Furthermore, given acceleration, the other records can be obtained by its successive mathematical integration. Regardless of what type of fault mechanism is involved, earthquake ground motion tends to be rather long in time duration, but the exact character is dependent on the distance to the hypocenter. The surface ground motion depicted in the first three accelerograms in Fig. 3, represent far-field earthquake surface motion [Luco, et al, 1986]. Near-field ground motion is represented by the lower three accelerograms in this figure. Generally they are much shorter in duration, and more pulse-like.

Another method of characterizing ground motion emphasizes the frequency content of the motion, by computation of the shock spectrum, or response spectrum from the corresponding time history. Pseudo relative velocity response spectra are shown in Fig. 4 for typical earthquake and ground shock events. Primary frequency content occurs in the amplified regions of each plot, although no information on duration can be obtained from the response spectrum. Thus, as is the case for application to surface structural design, use of the response spectrum for design of underground facilities is also limited to indication of frequency content and peak acceleration (or zero period acceleration) which occurs in the ground motion excitation. Furthermore, if the reciprocal of the basic frequency content (i.e., wavelength) of the transient is of the same order as the dimensions of the underground facilities, then phase information also becomes important, since the time history at one point on the structure can be different from that at another point on the structure.

Similar to how they occur in air, shock waves due to underground explosions are rather short duration pulses (similar to the lower curves in Fig. 3), so long as they are felt in a direct line relatively near the source [Vortman, 1979]. However, when reflections from the surface and other boundaries take place before they are felt, they tend to be smeared out to longer duration and frequency multiplications take place. A typical pseudo relative velocity response spectrum is shown in Fig. 4. Thus, amplitudes, frequency content, and durations are all subject to the location and distance of the sensing point from the source of energy release, as was the case for earthquakes. Therefore, the time histories tend to change from a relatively short to a somewhat longer duration transient random excitation, although the duration is usually less than that of earthquakes.

Seismic events in mines (called rockbursts when they result in excavation damage) are by far the most prolific source of information on the response of underground excavations to seismic loading. According to Johnston and Einstein [1988], there are two distinct modes of mine seismic activity. The first mode is associated with rock material rupture and the formation of new fractures adjacent to stope faces. In the second mode, seismic activity is associated with displacement on major natural geological features. In both cases, mine seismicity is related to local geology and rock structure, and the interaction of the mine structure and its induced stress field with the natural lithostatic, residual and tectonic stresses operating locally and regionally. It is notable that no systematic differences have been observed between mine seismic events and natural earthquakes. Thus, most of the physical and geomechanical principles which have been established for natural earthquakes also apply to mine seismic events and rockbursts. This is an extremely important observation, because it implies that observed underground mine response to rockbursts can be applied in predicting repository response to natural earthquakes.

2.2 Comparison of explosive and seismic ground shock

During the 1970's various investigations were performed to determine whether underground nuclear explosions could be used realistically to simulate earthquake events. Extensive discussions of this subject are given by Miscellaneous Paper S-71-17 of the U.S. Army Waterways Experimental Station [1972]. Although the results of their studies concentrated primarily on comparisons of damage effects, they are further useful in that they demonstrate essential differences in the two types of excitation, so that simulation of one type of event by the other is not generally practical. Among other differences, such as those associated with type of wave content for a given magnitude, the frequency content tends to be different depending on the distance of either of the events from the hypocenter, as was shown in Fig. 4. However, it is conceivable that some situations could exist where the explosive shock and

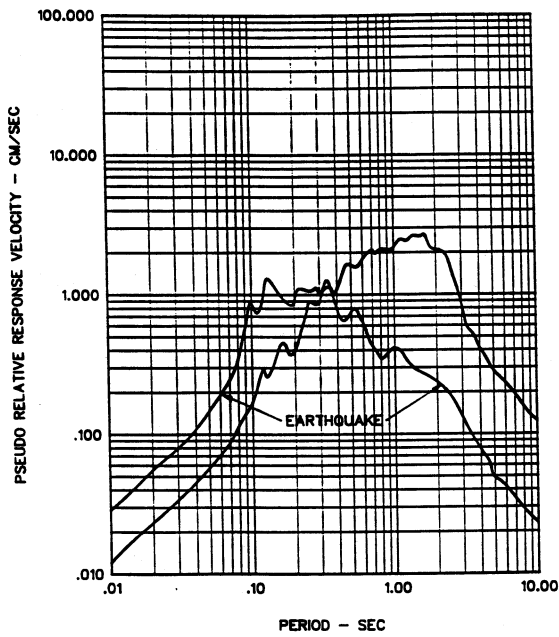


FIGURE 4
COMPARISON OF PSRV'S FOR HORIZONTAL COMPONENT
FOR EARTHQUAKE AND UNDERGROUND NUCLEAR EVENT C
(FOR VORTMAN, 1982)

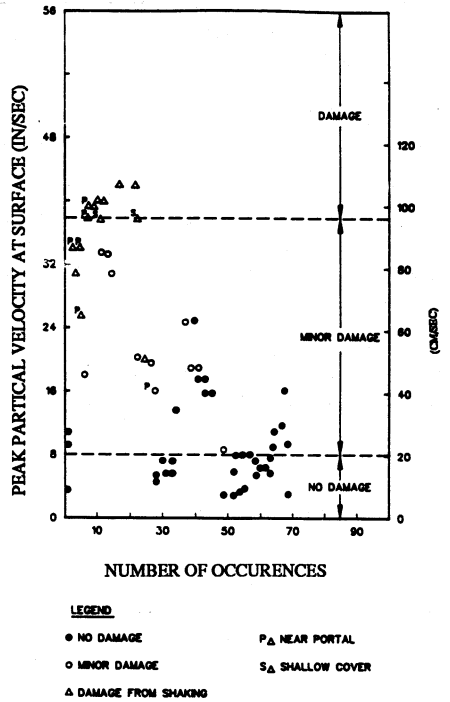


FIGURE 6
CALCULATED PEAK VELOCITIES AND ASSOCIATED
DAMAGE OBSERVATIONS FOR EARTHQUAKES
(FROM OWEN AND SCHOLL, 1981)

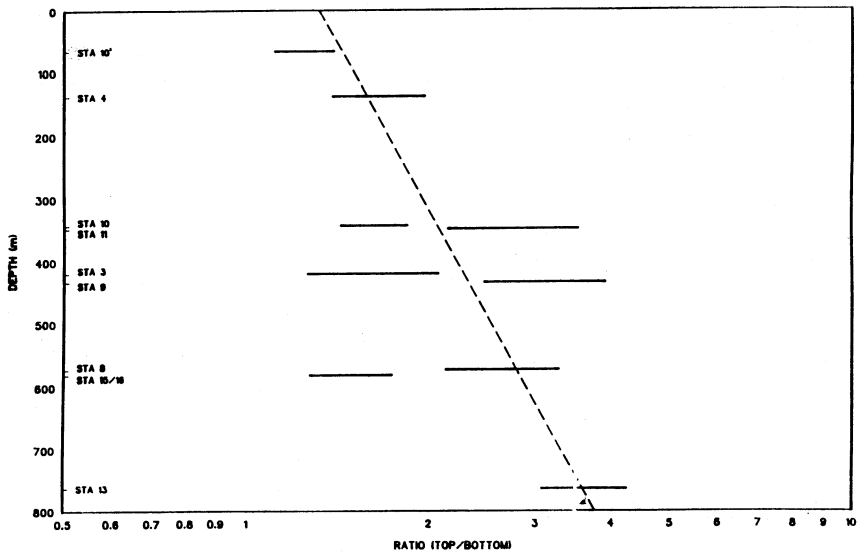


FIGURE 5
RATIO (TOP/BOTTOM) FOR "VECTOR" PSRV MEAN
VALUES PLOTTED VERSUS STATION DEPTH
(FROM VORTMAN AND LONG, 1982)

earthquake ground motions spectra are very similar. Nevertheless, the time duration of an earthquake is generally quite longer, and damage effects from repeated cycles of stress can be much more pronounced for earthquakes at a given magnitude level.

Ground motion, both on the surface and at depth, is important in relation to the performance of, respectively, shaft collars and surface facilities, and the repository and its near-field rock. Thus, the reports by Vortman and Long [1982] are an important record of the surface and deep subsurface ground motion induced by nuclear explosions. For the measurement of surface and subsurface ground motion, subsurface measurement stations in boreholes were at depths ranging from 60 m to 762 m, in a total of six observation holes. Results from these data are shown in Fig. 5. Here, the peak vector acceleration is defined as the square root of the squared sum of the peaks for three orthogonal motion components [Vortman and Long, 1982]. The ratio of surface to underground peak vector value is developed as a function of depth for many different explosive experiments. The results indicate that accelerations diminish rapidly with depth. Similar trends were found for peak velocity and acceleration ratios. As shown in Fig. 6, some attempts have been made to associate damage levels with peak velocities. However, such schemes ignore duration of shaking, and are of limited use.

3. ANALYTICAL METHODS

3.1 Synthesis of jointed rock component

Analysis of the performance of rock around shafts, excavations, and other engineered structures requires prior definition of the strength, stiffness and stability parameters for the rock mass. Important parameters determining rock behavior are the constants relating stresses and strains in the elastic range, the stress levels at which yield, fracturing or slip occurs within the rock mass, and the post-peak stress-strain behavior of the fractured or "failed" rock.

Synthesis of a typical tuff rock mass segment at the Nevada repository site can be done in terms of an aggregate of jointed block component pairs, which is pierced by excavations. Furthermore, the joint properties along a connected series of joints have eroded with time, so that a fault is formed through the entire segment. Hence, the fundamental component for such an aggregate is two blocks with a common interface, as shown in the loading apparatus of Fig. 7. Whether the interface forms a normal joint or part of a fault is determined by the state of the interface. Mechanical properties for evaluation of the behavior of a block pair under typically anticipated loads are given in Table 1. The types of tests, appropriate to determine the corresponding properties are also listed. The apparatus shown in Fig. 7 pertains to the jointed-rock direct shear tests, although all other variables ultimately are necessary for describing the dynamic behavior of the jointed rock. Thus, any postulated analytical model of the fundamental component must empirically match experimental data obtained from various test conditions. No current model employs all of the variables listed in Table 1; thus, much remains to be done in model development.

Barton, et al [1985] have provided an empirical model which matches some behavior for tests under pseudostatic normal and shear loading. Typical results for normal and then shear loading are shown in Fig. 8. The results indicate a strong dependence of joint properties on the loading history. Thus, significant nonlinearity of shear strength and hysteresis is expected from cyclic shear loading. Unsatisfactory features of the Barton, et al model are emphasized in Fig. 8b. For practical application, the mobilization and attrition of surface roughness are represented in a piece-wise linear graphical form, rather than through a simple formal expression. Although this accounts for reduction in mobilized friction angle and hysteresis on cyclic loading, piece-wise linear representation results in a quite rough simulation of the load-displacement behavior. Such a coarse simulation may have adverse effects on modelling many cycles of shear load reversal.

The accumulation of joint damage (by erosion of surface roughness) observed in a single monotonic phase of shear displacement has major implications for dynamic behavior of joints, in which many cycles of shear displacement can occur. Studies by Brown and Hudson [1974] of the strength of jointed specimens of rock-like materials confirm that cyclic loading indeed results in pronounced reduction of the peak strength in the peak-residual behavior of joints. These experiments showed that catastrophic failure occurred when the accumulated deformation during the cyclic tests reached the load-displacement curve for failure obtained in a monotonic test. The effect is explicable on the basis of continuous damage accumulation during cyclic shear motion at joints.

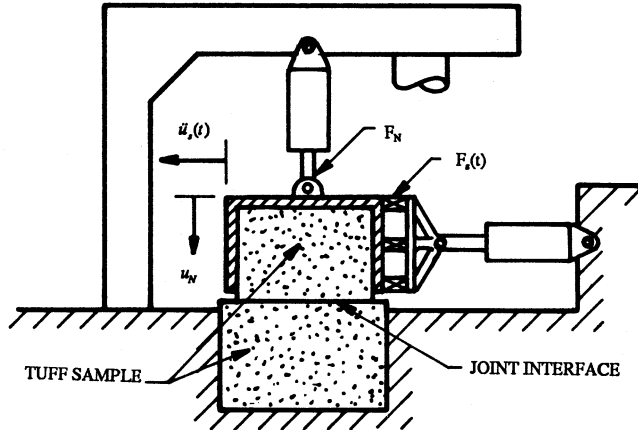


FIGURE 7
LOADING APPARATUS FOR DYNAMIC JOINT
NORMAL AND SHEAR TESTS

TABLE 1
MECHANICAL PROPERTIES FOR JOINTED ROCK EVALUATION

Variable	Description	Units	Type of Test
Basic Rock Material Tests			
σ_c	Unconfined Compressive Strength	Lb/in ² (MPa)	Uniaxial Compression
E	Youngs Modulus	Lb/in ² (MPa)	Uniaxial Compression
ν	Poissons Ratio	N/D	Uniaxial Compression
γ	Bulk Density	Lb/in ³ (Kg/m ³)	Weight Measure
T_o	Tensile Strength	Lb/in ² (MPa)	Brazilian Tensile
C	Material Cohesion	Lb/in ² (MPa)	Triaxial Compression
ϕ	Internal Friction Angle	Degrees	Triaxial Compression
Joint Characterization Tests			
JRC	Joint Roughness Coefficient	N/D	Inclination
JCS	Joint Wall Rock Compressive Strength	Lb/in ² (MPa)	Schmidt Hammer Rebound
JRW	Joint Roughness Wavelength	in (m)	Optical
l	Block Size	in (m)	Length Measure
Jointed-Rock Shear Tests			
C_j	Joint Cohesion	Lb/in ² (MPa)	Normal/Shear
ϕ_j	Joint Friction Angle	Degrees	Normal/Shear
F_n	Normal Static Force	Lb (kN)	Normal/Shear
u_N	Normal Static Displacement	in (m)	Normal/Shear
$\ddot{u}_s(t)$	Shear Acceleration History	in/sec ² (m/sec ²)	Normal/Shear
$F_s(t)$	Shear Force History	Lb (kN)	Normal/Shear

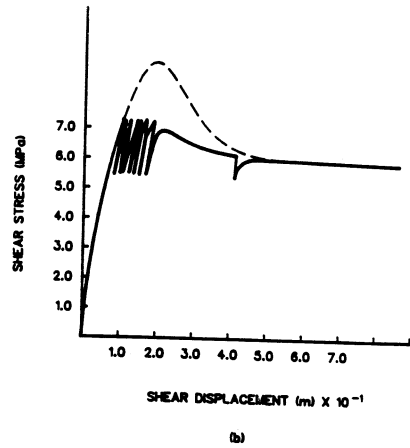
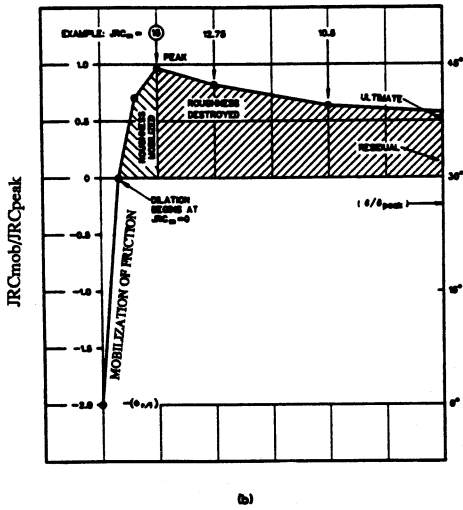
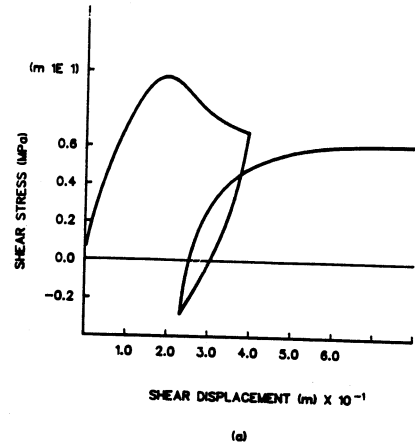
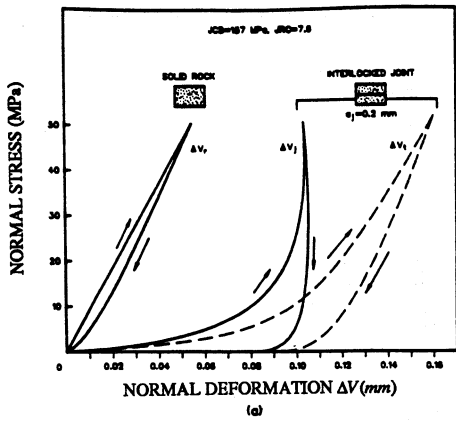


FIGURE 8
JOINT MODEL: (a) NORMAL DEFORMATION,
(b) SHEAR DEFORMATION
(FROM BARTON, et al, 1985)

FIGURE 9
EXERCISING THE CONTINUOUS-YIELDING JOINT MODEL
(a) A SINGLE LOAD REVERSED CYCLE,
(b) CYCLIC LOADING
(FROM LEMOS, 1987)

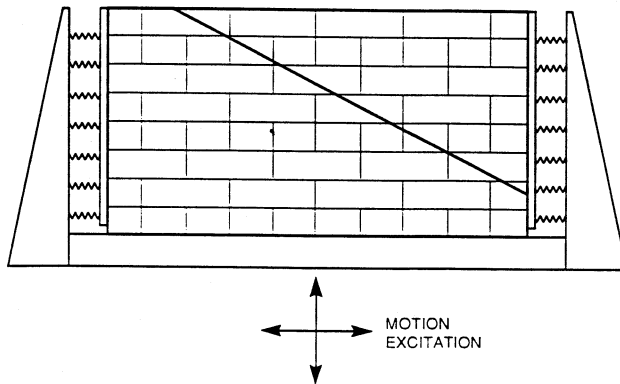


FIGURE 10
EXPERIMENTS WITH SCALE-MODEL FAULTED ROCK MASS SEGMENT

Observations that damage accumulation during joint shear needs to be modeled in a formal and consistent manner has led to the formulation of the continuous-yielding joint model [Cundall and Lemos, 1988]. This is designed to be a coherent and unified joint model, taking account of non-linear compression, non-linearity and dilation in shear, and a non-linear limiting shear strength criterion. The key elements of the model are that all shear displacement at a joint have a component of plastic (irreversible) displacement, and all plastic displacement results in progressive reduction in the mobilized friction angle. The capacity of this model to represent single episodes of shear load reversal, and the effects of cyclic loading, in a manner consistent with that reported by Brown and Hudson [1974], is illustrated in Fig. 9a,b.

The preceding discussion was concerned with the strength and deformation properties of joints under conditions of pseudostatic loading. Some dynamic shear tests on rough joints have shown that the shear strength of rough joints is velocity dependent, with the change in strength (either increase or decrease) being determined by the parent rock type. However, the results were not related to any conceptual or formal model of joint deformation mechanics. Thus, development of models for both ground shock and earthquake loading histories remains yet to be accomplished.

3.2 Analytical models and computer codes

In order to analyze the dynamic behavior of a jointed, faulted rock mass segment, an aggregate of the type shown in Fig. 10 may be considered. This aggregate is formed from a series of fundamental block pair components described in the previous section. It is recognized that the joint properties at original interfaces are quite different from those at the indicated fault line. However, the total aggregate can be built up by means of a suitable finite element computer code which accommodates the prescription of boundary properties according to the previously described models. Kana, et al [1989] provide a detailed description of a variety of codes by which this has been done to some extent or another. However, none of these reported efforts include all the advanced models of the type described in the previous section. Thus, significant development remains to be accomplished.

4. VALIDATION OF MODELS AND CODES

4.1 Need for validation

In rock mechanics practice, the need for validation of computational methods used in design of rock structures has been considered by Brady and St. John [1982], as well as others, who observe that unvalidated codes are virtually useless. They propose that code validation by field observations, reconciling field observations with model predictions, is complicated in rock mechanics practice by poor definition of the initial conditions in a rock mass. In these circumstances, validation may be conducted best by seeking correspondence between results of a benchmark physical model test and numerical modeling of the test. There are now many examples of the validation of computer codes in this way.

The particular need for validation of codes for dynamic analysis of underground excavations for nuclear waste isolation arises from the comparative novelty of the codes, the complexity of the processes involved in deformation of block-jointed media, and prevailing questions about the adequacy of the constitutive relations describing the dynamic behavior of rock joints and faults. There is also a stringent need, in geoengineering for underground isolation of waste, to ensure that computer codes can represent physical reality tolerably, independent of any questions about a capacity to characterize a rock mass or repository site adequately. For this reason, the main emphasis in validation of codes for dynamic analysis of repository design problems must be placed on execution of dynamic physical model tests, and related computational analysis.

4.2 Existing approaches

Two sets of studies illustrate the philosophy of experimental validation of a computational design code. The report by De Rouvray, et al, [1971] describes experimental and numerical studies of the static behavior of underground structures in jointed rock. Finite element methods were used in modeling non-linear joint behavior and the static performance of underground excavations in jointed rock. The work involved physical modeling of a highly idealized jointed rock mass with perfectly continuous joints, orthogonally oriented and equally spaced. The code used in the analysis was restricted to small strain for both intact material and joints. With current knowledge, the joint model was inadequate,

with unsuitable representation of damage accumulation during joint shear, no provision for hysteresis on load reversal, and stress independence of normal and shear stiffnesses. In spite of the limitations of the numerical model, fair qualitative correspondence was demonstrated between the results of numerical analysis and physical modeling of jointed media. This is explicable on the basis of the simple applied load path, which is not representative of that which develops during construction of an underground excavation. With the various reservations noted, the report is an instructive example of a philosophy for verification of computational analysis schemes.

Analytical and numerical simulations of laboratory experiments on small-scale tunnels in jointed rock were compared by Rosenblatt and DeAngelo [1980]. The studies were based on the DIABLO HAWK underground nuclear test in jointed tuff at the NTS. The study was performed in three stages. In the first stage, an analytical solution was developed which defined the far-field, static load level at which joint slip will begin around a circular tunnel. In the second stage of the study, dynamic analysis was performed using the code WAVE-L, a Lagrangian code. The intact rock was simulated as an elastoplastic material with a Drucker-Prager yield surface and non-associated flow rule. Slide lines were used to simulate joint behavior. In the third stage of the study, static analyses performed with the WAVE-L code were compared directly with results of the laboratory tests. The comparison was reasonably good near the springline but poor at the crown-invert. Joint slip regions in laboratory tests, indicated by deformations of a thin tunnel lining, corresponded to the region predicted by the analytical solution performed in the study's first stage.

It is notable that neither of these studies, one static and one dynamic, examined effects such as repetitive cyclic loading. However, they describe a broad general philosophy supporting code verification and qualification for geodynamic modeling, design and performance assessment studies.

4.3 Proposed approach

Development of an advanced jointed rock component model and validation of its use for prediction of dynamic response for a faulted tuff rock mass segment requires a relatively elaborate procedure, such as depicted in Fig. 11. The extensive review reported by Kana, et al [1989] has indicated that sufficient full scale experimental data exists for measurements of response at various depths to underground nuclear tests in certain locations at Nevada Test Site. Thus, by comparison with this data, codes developed to include the advanced component analytical models can be validated by using the appropriate boundary conditions and excitations. The success of this approach will depend on the fidelity of the full scale data available.

At the same time it appears that no such full scale data exists for earthquake excitations. Therefore, a scale model approach to validation is proposed for this case. Advanced component analytical models will be developed by means of earthquake motions imposed for full scale specimens tested in the apparatus of Fig. 7. Subsequently, similar tests will be conducted with scale models to verify that physical scaling introduces no distortions. Then, a physical scale model of a jointed, faulted rock mass segment will be tested as shown in Fig. 10. The results will account for variations in load paths and the presence of tunnels, which cannot be included in the component tests. Thus, a measure of response will result for controlled, simulated earthquake conditions, which cannot be achieved in full scale.

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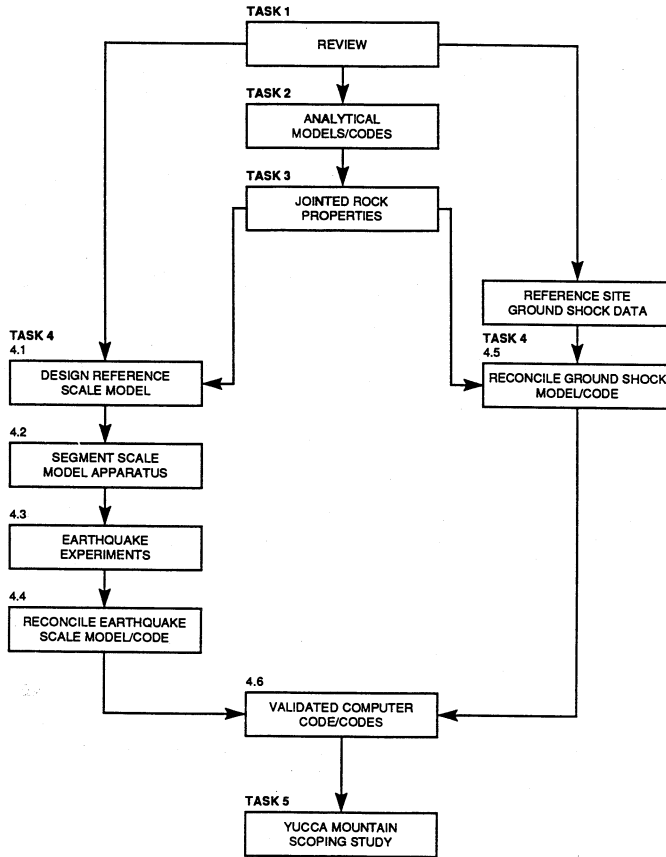


FIGURE 11
SEISMIC ROCK MECHANICS PROJECT PLAN

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