SEISMIC DESIGN GUIDELINES
FOR
UNDERGROUND REPOSITORY FACILITIES

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SEISMIC DESIGN UNDERGROUND FACILITIES

ACKNOWLEDGEMENTS

based on SAND89-7065
Hardy and Bauer (1991)
(Drift Design Methodology)

CONTRIBUTORS

ASCE Committee
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SEISMIC EVALUATIONS

Repository design -- Layout of openings (orientation, depth)
-- Drift shape and size
-- Drift ground support system
-- Borehole size-length orientation
-- Borehole lining and plug
-- Drift backfill design
-- Seals design
-- Mining equipment selection
-- Waste emplacement operations

Performance assessment -- Evaluate mechanisms for radionuclide release
-- Seal performance

Issue resolution -- Licensing questions
-- State and local concerns
-- Technical Review Board
-- Peer review (NAS and others)
-- Professional societies

SEISMIC DESIGN OF UNDERGROUND REPOSITORY FACILITIES

TIME FRAME

Preclosure (0 - 100 yrs)	-- Worker health and safety (radiological, non-radiological), cask accident, rock falls -- Disruption to operations -- Program viability (cost, delays) -- Maintain retrieval option
Postclosure (100 - 10,000 yrs)	-- Container life -- Development of preferential pathways -- Overall system performance, containment and isolation -- Seal performance

COMPONENTS OF INTEREST

Ramps and shafts

Main access drifts

Emplacement drifts

Emplacement boreholes

Intersections

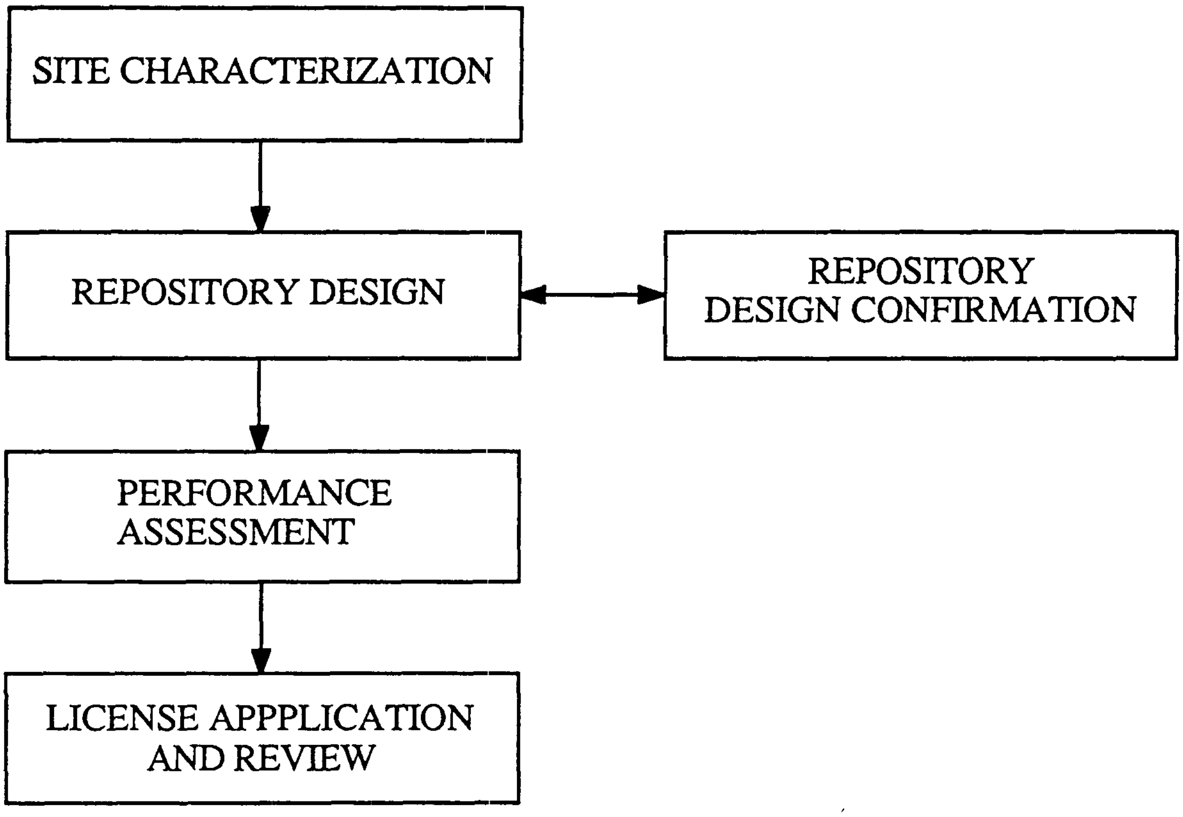
Quote from Owens and Scholl (1981)

...and because of the popular assumption that openings in rock are not vulnerable to earthquake motion, the current practice of earthquake engineering is poorly developed for structures in rock.

Perhaps another reason for this retarded development is that the static design in rock is largely dominated by empirical procedures.

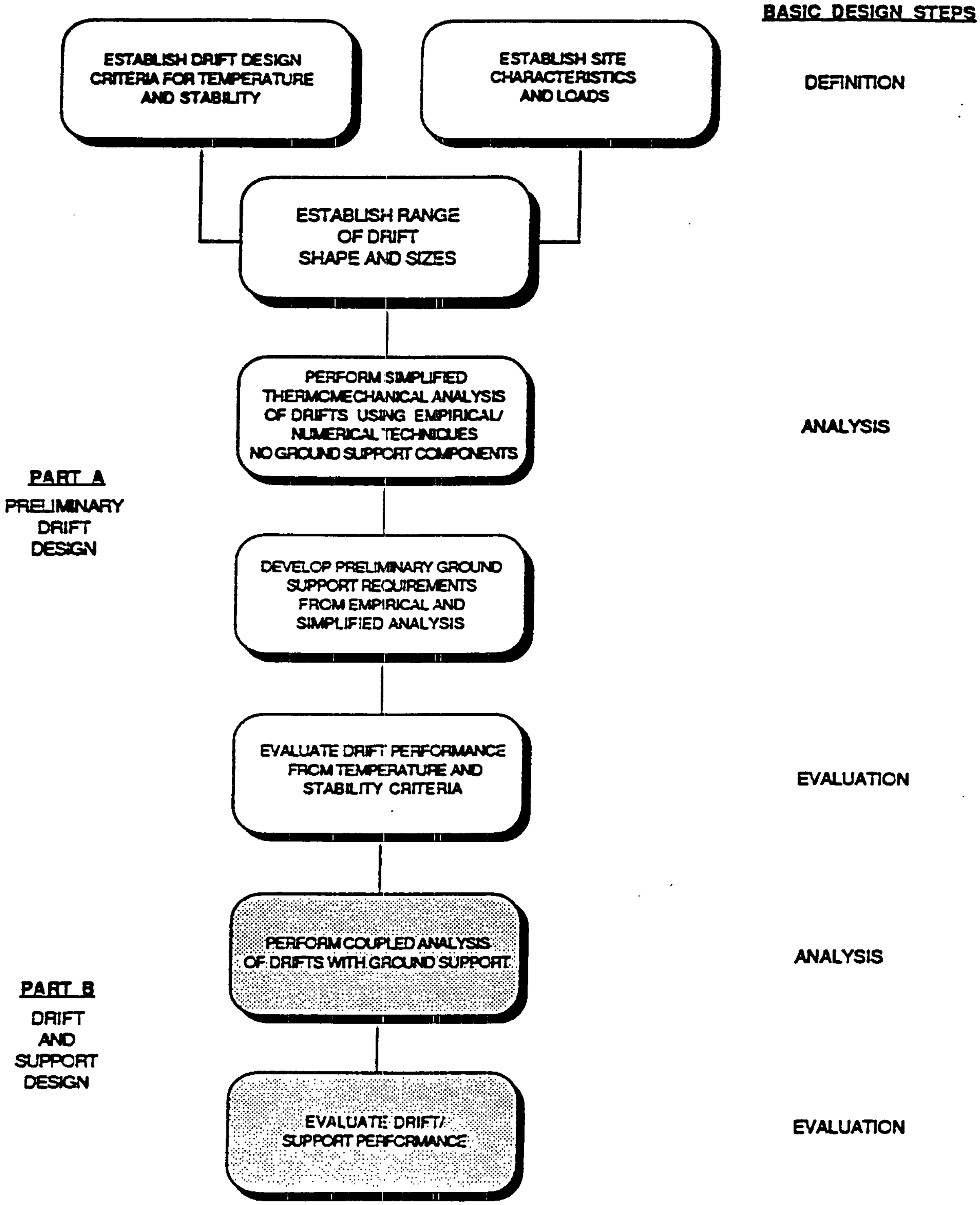
from Earthquake Engineering of Large Underground Structures, Report No. FHWA/RD-80/195, Federal Highway Administration, pp. 161-162.

OVERALL DESIGN PROCESSES



Note: Iterative process

DRIFT DESIGN METHODOLOGY



SEISMIC DESIGN METHODOLOGY
ESTIMATION OF SEISMIC LOADS

Deterministic

Probabilistic

Recommend: Probabilistic Method
Follow procedures proposed in Kennedy et al. (1990), UCRL 15910

SIMPLIFIED THERMOMECHANICAL ANALYSIS

Empirical	Analytical for Ground/Structure Interaction
Experience based "rules of thumb"	Quasi-static or dynamic analysis
Design charts	Finite-element stress analysis (or others)
	Ground support interaction
	Design based on safety factors for components
Problems	
Not well developed for seismic/thermal loads	Constitutive models unvalidated

GROUND SUPPORT DESIGN TO RESIST SEISMIC LOADS

Empirical

Grouted bolts

Wire mesh with bolts

Shotcrete (fibre-reinforced)

Reinforced concrete

Analytical

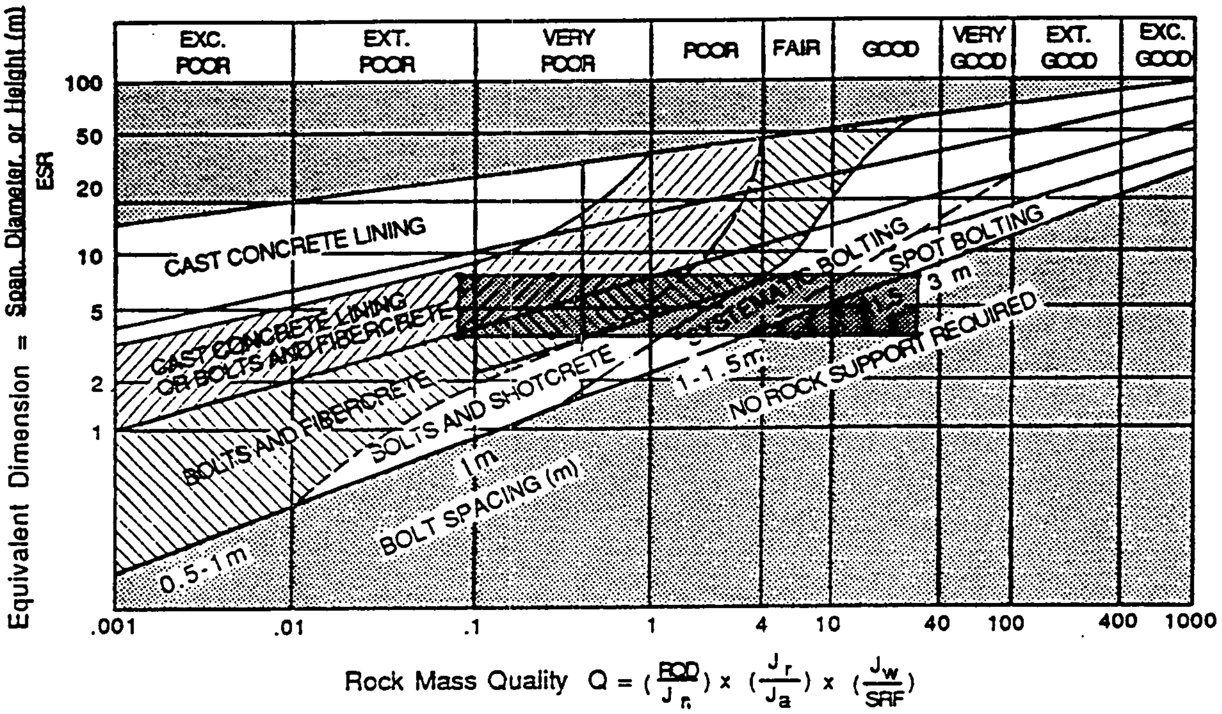
Quasi-static or dynamic analysis

Safety factor lower when considering load combinations that include seismic loads

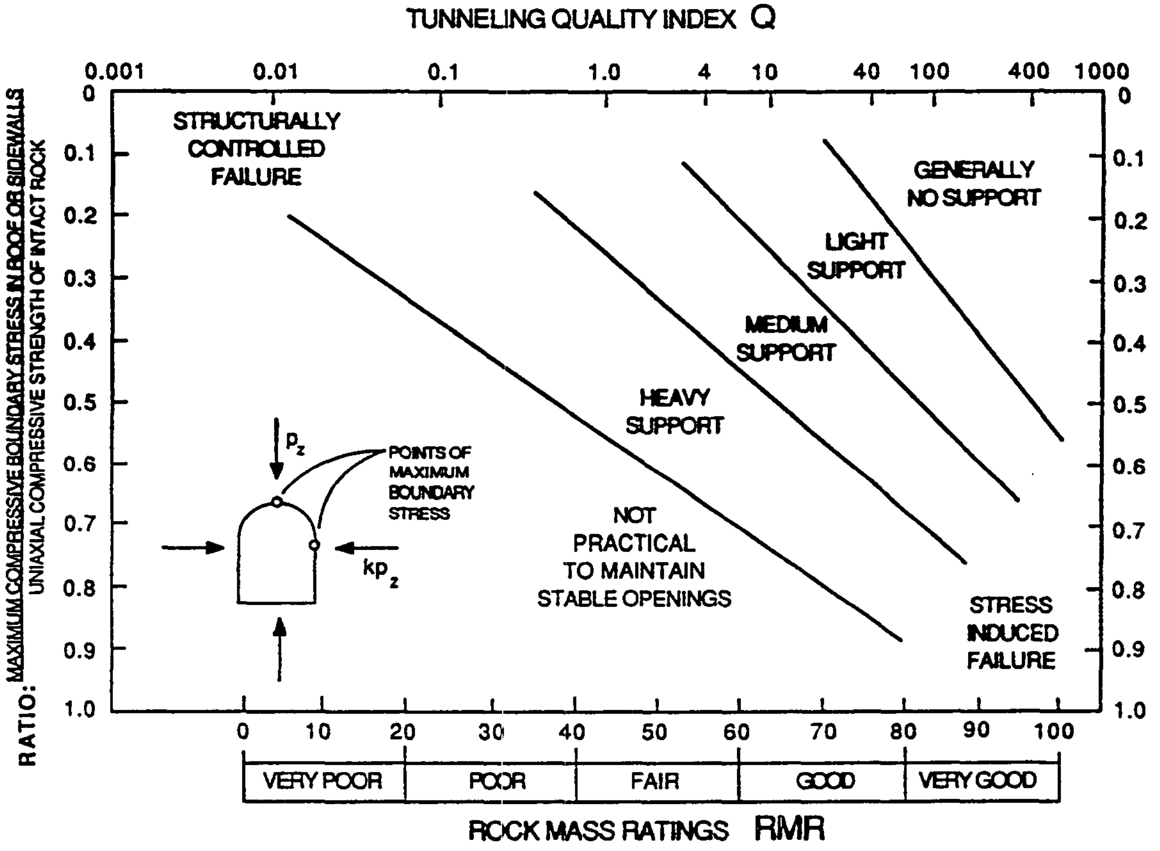
Accommodate Potential Displacement Across Faults

Inspection and Rehabilitation After Events

EMPIRICAL SCHEMES



Range of Rock Mass Quality, Q, Projected for Excavation Conditions at the Repository Horizon



Approximate Support Guidelines for Underground Excavations Proposed by Hoek (1981)

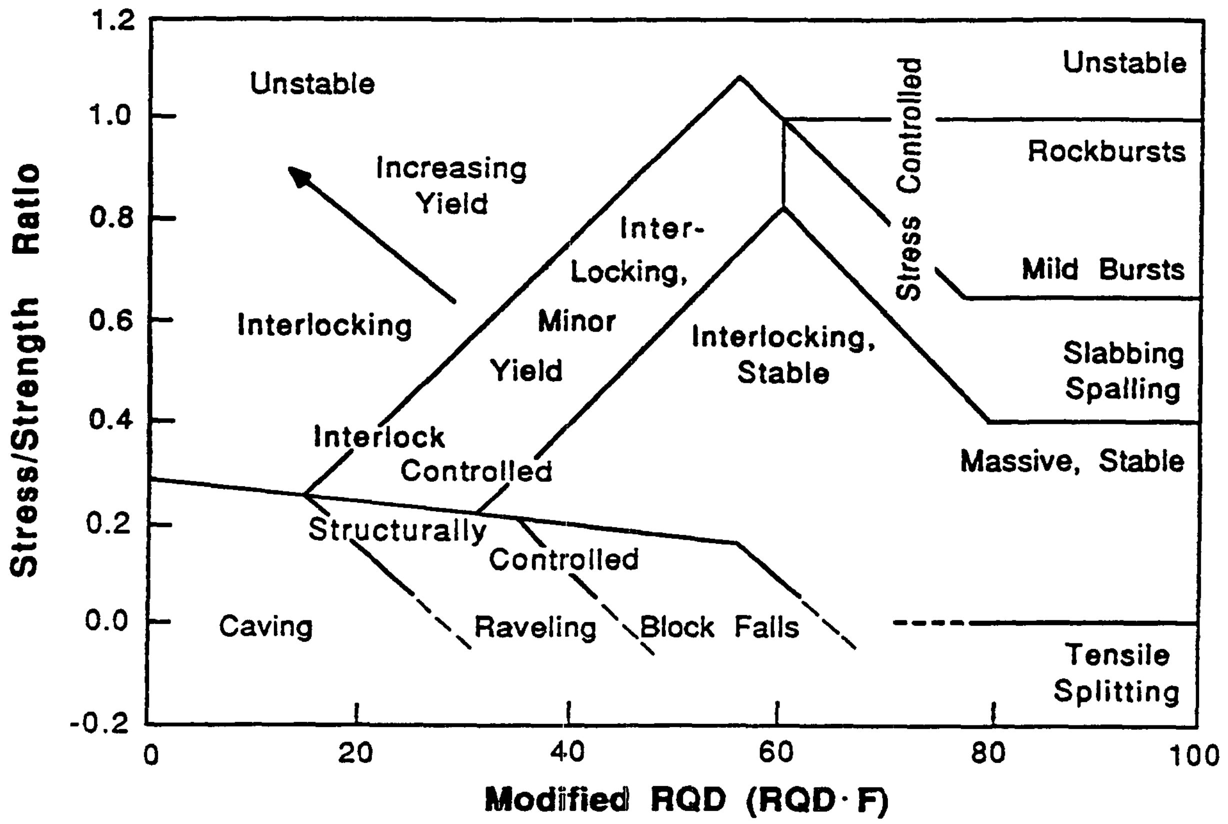
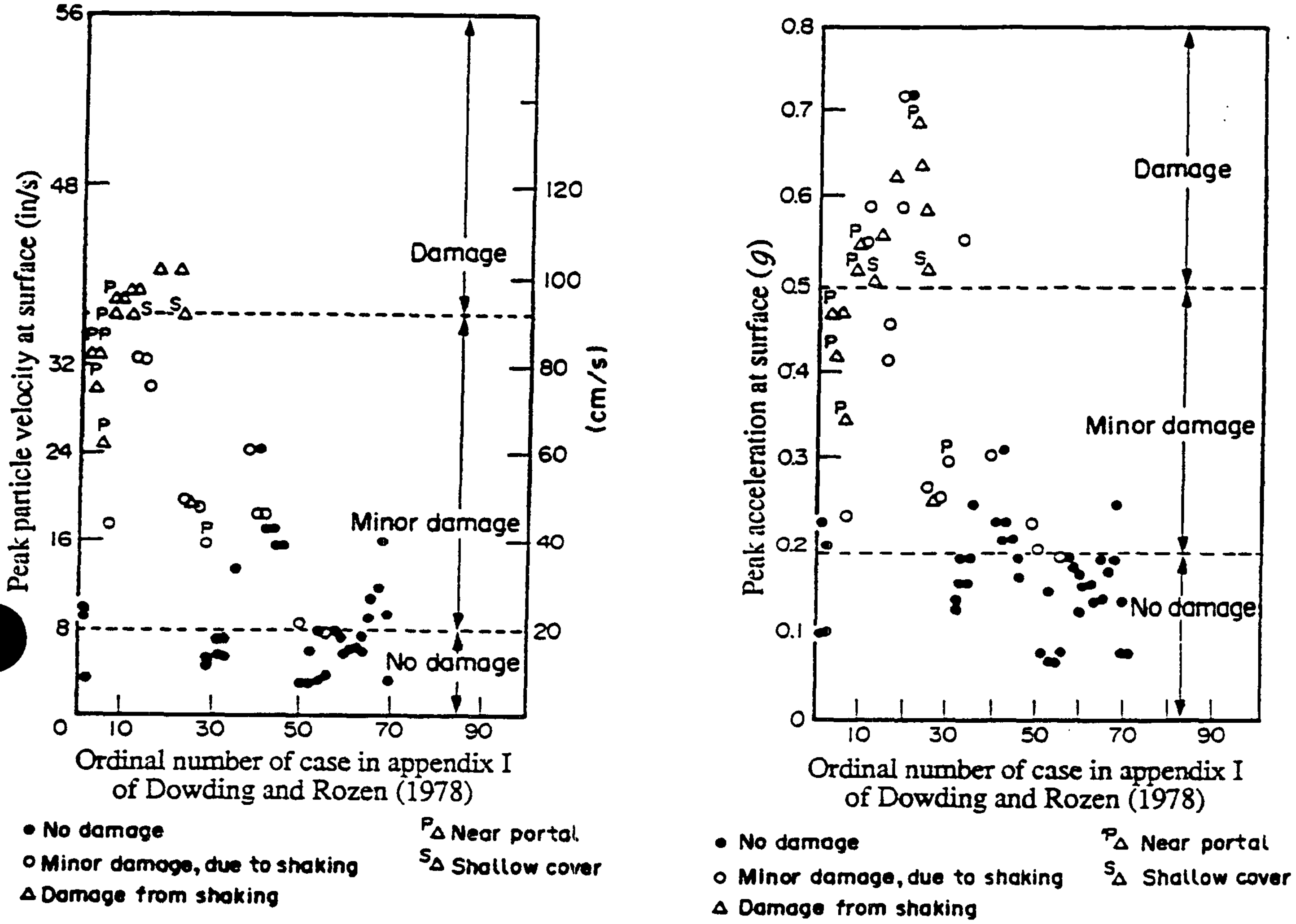
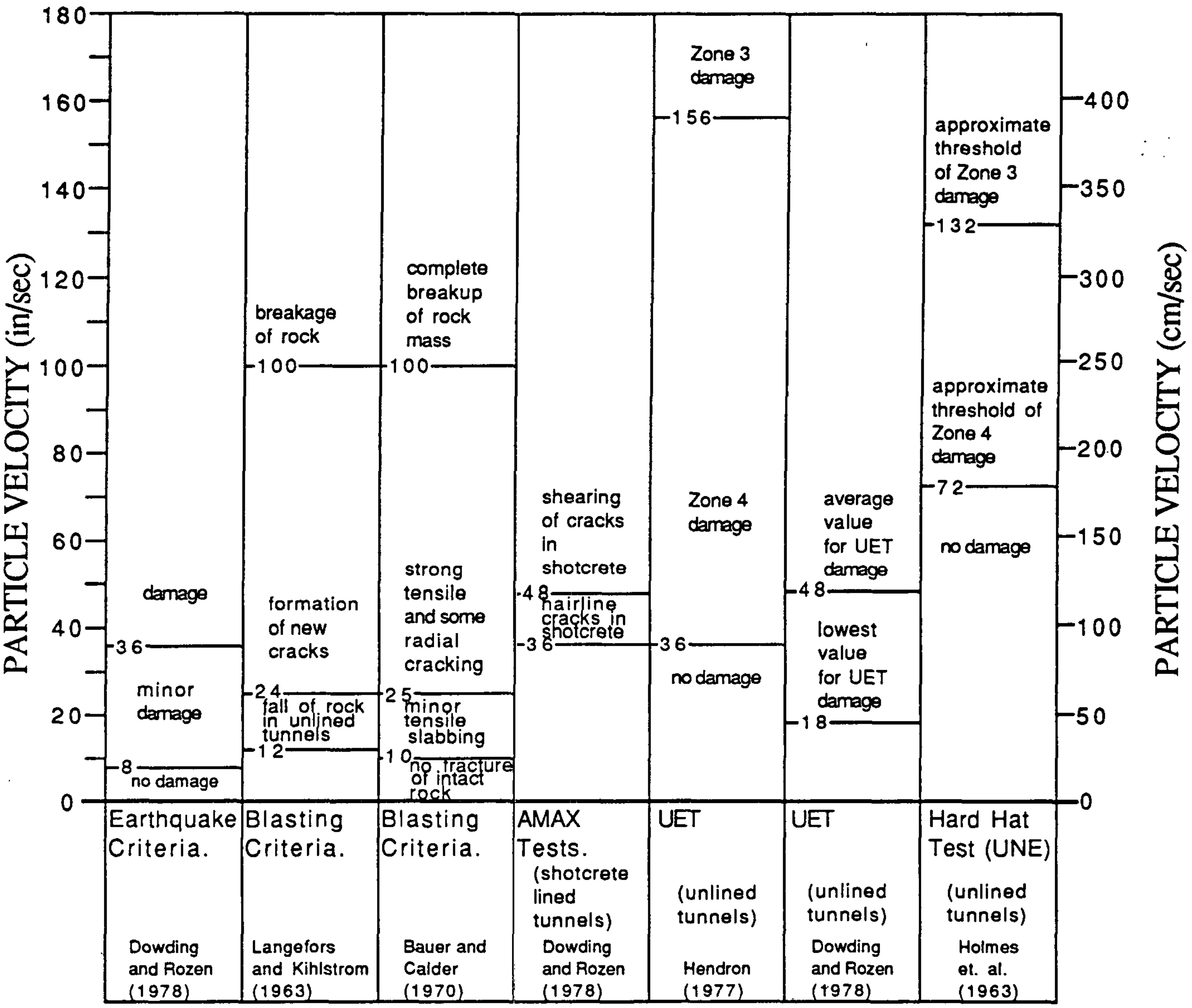


Chart for Estimating Modes of Failure Around Drifts Proposed by Schmidt (1987)

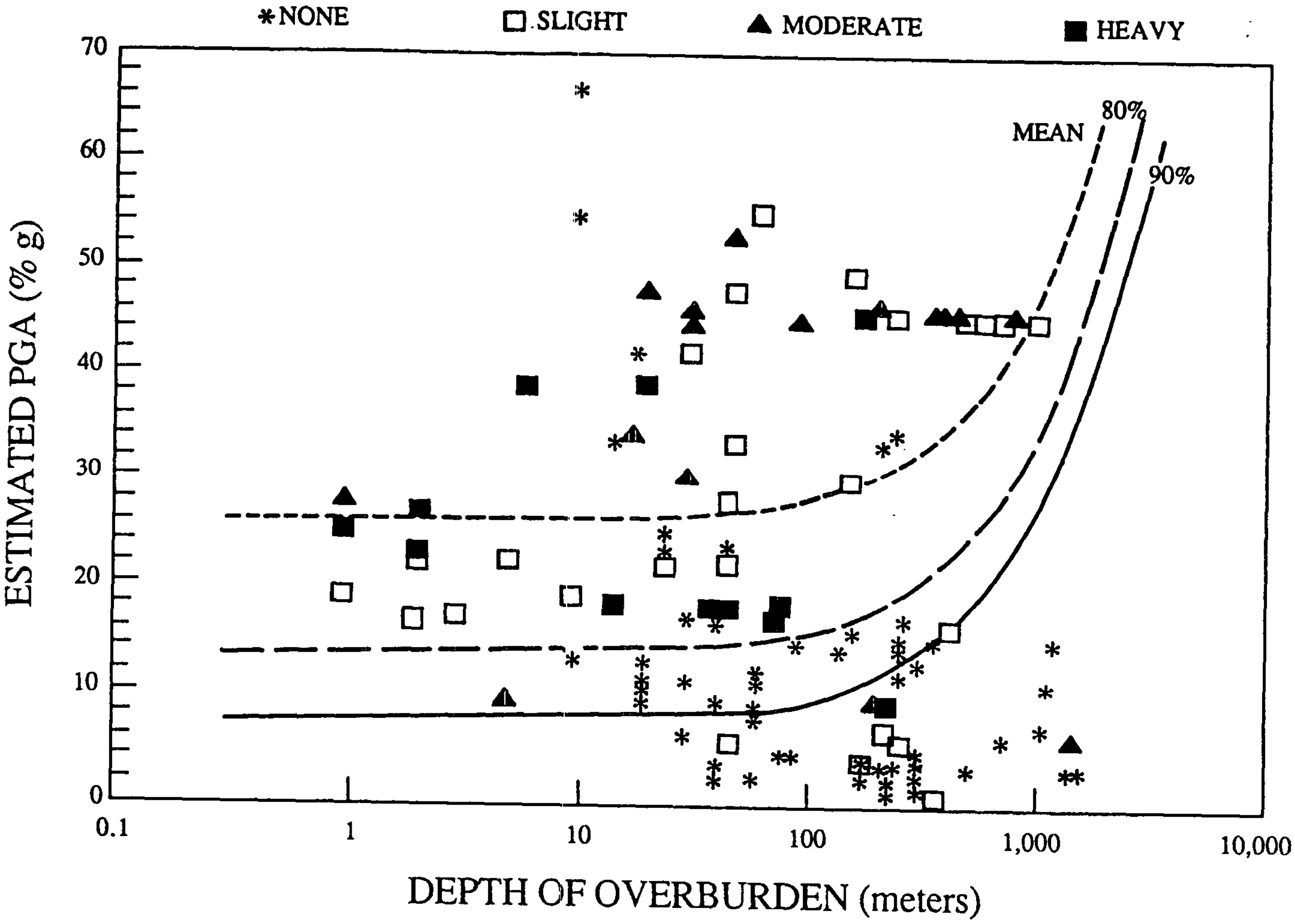


Calculated Peak Particle Velocities and Acceleration and Associated Damage Observations on Underground Openings



NOTE: "UET" = Underground Explosion Tests, conventional high explosives
"AMAX Tests" = Underground explosive tests at the Climax Molybdenum Mine, conventional high explosives
"UNE" = Underground Nuclear Explosive

Various Damage Criteria in Terms of Peak Particle Velocities (After Owen and Scholl, 1981)



Empirical Relation Between Damage to Underground Structures, Overburden Depth and Estimated Peak Ground Acceleration (PGA) (After Sharma and Judd, 1991)

SEISMIC DESIGN METHODS FOR UNDERGROUND OPENINGS

Quasi-Static

Estimated peak accelerations/ velocities

Strain

Stress (combinations of loads)

Deformation quasi-static analysis

Ground support loads

Safety factors

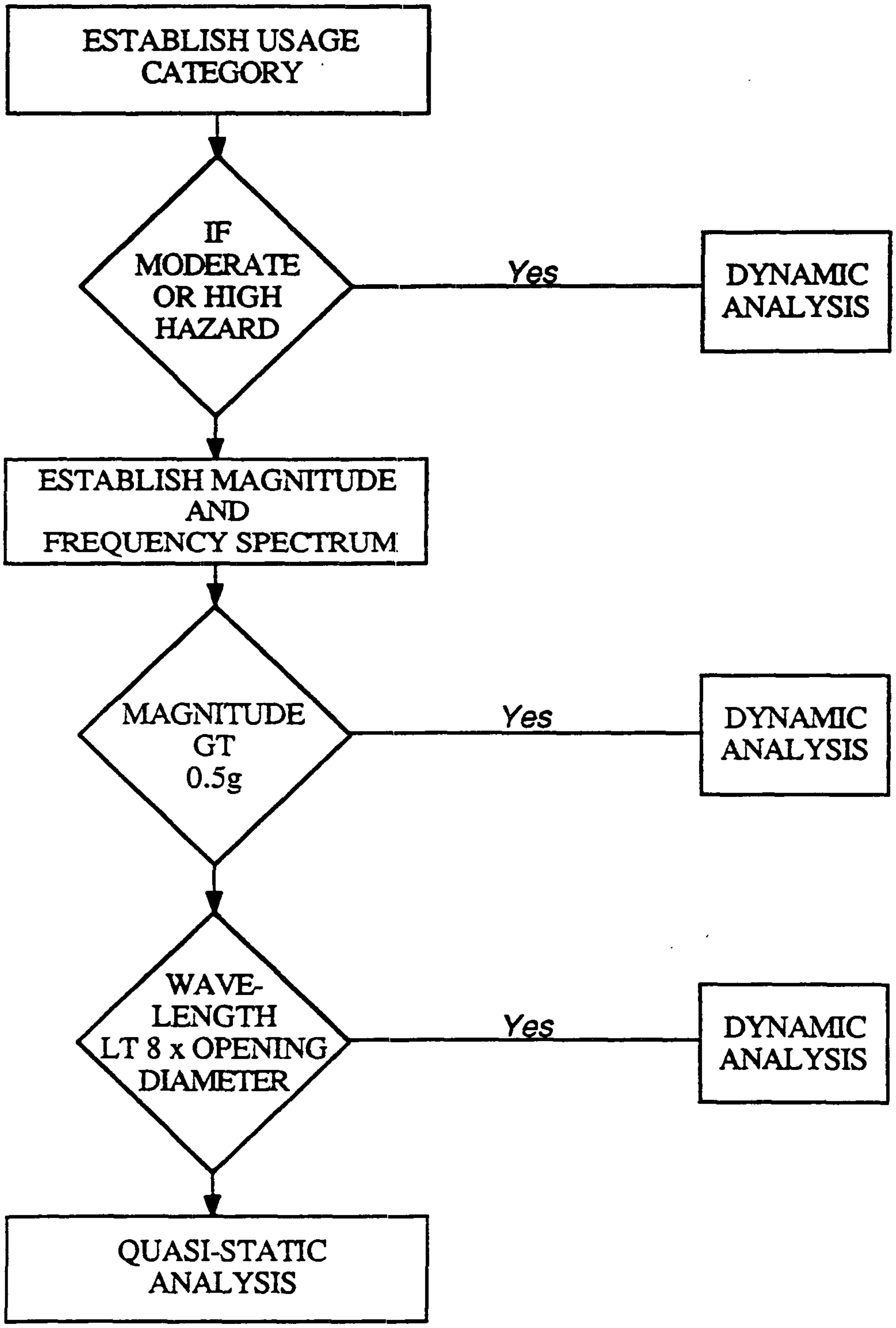
Dynamic Analysis

Earthquake response spectra

Dynamic analysis

Evaluation

REPOSITORY COMPONENT SEISMIC DESIGN DECISION TREE



SEISMIC DESIGN
QUASI-STATIC APPROACH

St. John and Zahrah (1987)	Aseismic Design of Underground Structures, National Science Foundation, ITA Working Group on Seismic Effects on Underground Structures
Subramanian, et al. (1990)	Exploratory Shaft Seismic Design, Basis Working Group Report, SAND88-1203
Richardson (1990)	Preliminary Shaft Liner Design Criteria and Methodology Guide, SAND88-7060
Hardy and Bauer (1991)	Drift Design Methodology and Preliminary Applicationf or the Yucca Mountain Site Characterization Project, SAND89-0837

QUASI-STATIC DESIGN OF UNDERGROUND OPENINGS

Structures that conform to ground motions (liner conforms to ground motion)	Structures that resist ground motion (ground/structure interaction important)
Appropriate for: • Flexible liners • Stiff host medium (most rocks)	Appropriate for: • Stiff liners • Soft host mediums (soft rocks, soils)
Example: Shaft liner in welded tuff	Example: Portal or ramp in unwelded tuff or surface soils

ANALYTICAL METHOD QUASI-STATIC LOADS

FREE-FIELD STRAINS CAUSED BY EARTHQUAKE EVENTS FOR STEEP ANGLE OF INCIDENCE

Wave Type	Free-Field Strains					
	ε_{xx}	ε_{yy}	ε_{zz}	τ_{xy}	τ_{yz}	τ_{xz}
P	$\frac{v_v}{C_p}\frac{\sin^2\theta}{\cos\theta}$	0	$\frac{v_v}{C_p}\cos\theta$	0	0	$\frac{v_v}{C_p}2\sin\theta$
SV	$\frac{v_h}{C_s}\sin\theta$	0	$\frac{v_h}{C_s}\sin\theta$	0	0	$\frac{v_h}{C_s}\frac{\cos 2\theta}{\cos\theta}$
SH	0	0	0	$\frac{v_h}{C_s}\sin\theta$	$\frac{v_h}{C_s}\cos\theta$	0

FREE-FIELD STRAINS CAUSED BY UNE EVENTS FOR SHALLOW ANGLE OF INCIDENCE

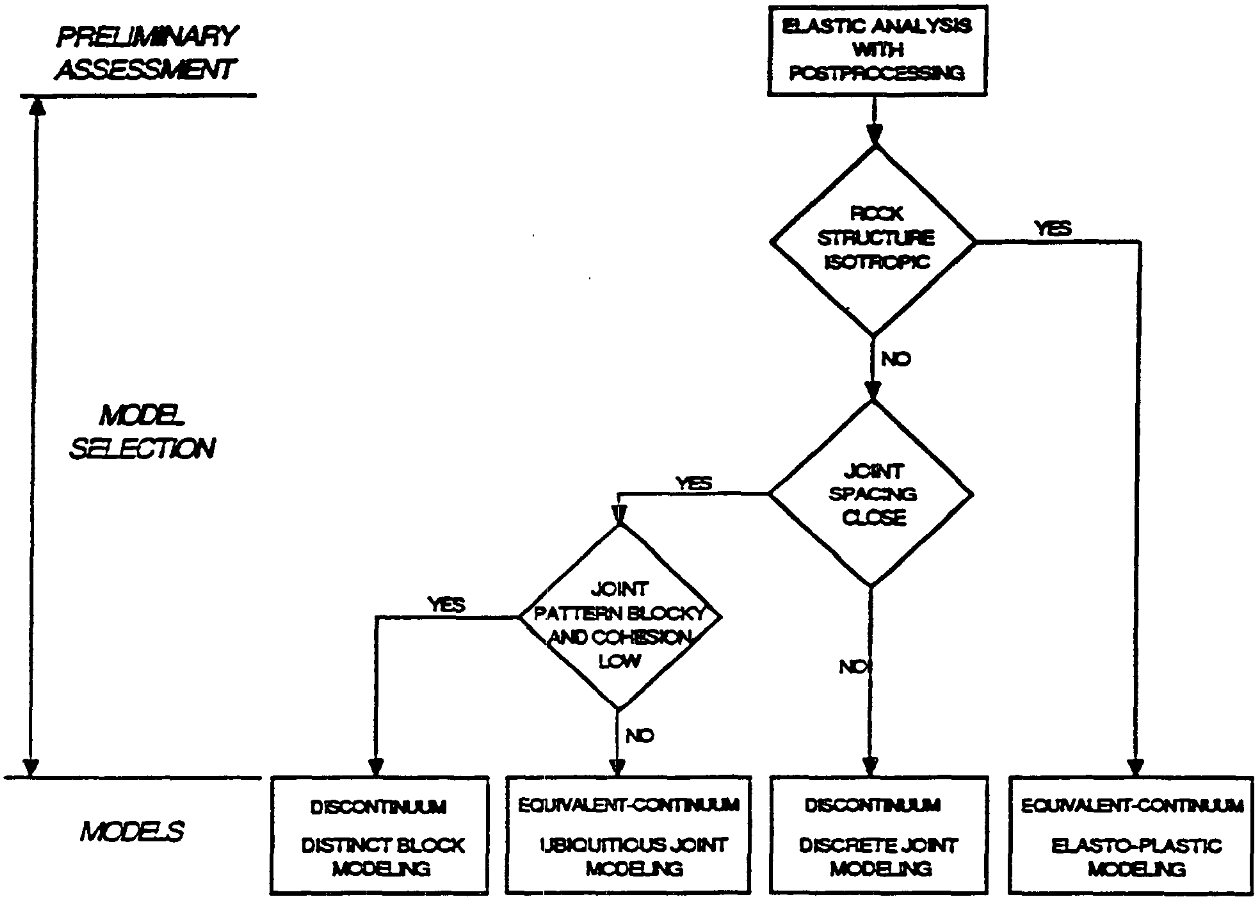
Wave Type	Free-Field Strains					
	ε_{xx}	ε_{yy}	ε_{zz}	τ_{xy}	τ_{yz}	τ_{xz}
P	$\frac{v_h}{C_p}\sin\theta$	0	$\frac{v_h}{C_p}\frac{\cos^2\theta}{\sin\theta}$	0	0	$\frac{v_h}{C_p}2\cos\theta$
SV	$\frac{v_v}{C_s}\cos\theta$	0	$\frac{v_v}{C_s}\cos\theta$	0	0	$\frac{v_v}{C_s}\frac{\cos 2\theta}{\sin\theta}$
SH	0	0	0	$\frac{v_h}{C_s}\sin\theta$	$\frac{v_h}{C_s}\cos\theta$	0

where v_h = *horizontal component of velocity in x direction*
v_v = *vertical component of velocity*
C_p = *compressional wave velocity*
C_s = *shear wave velocity*
θ = *angle of incidence (from vertical)*

COMBINATION OF LOADS

Initial Conditions	In situ± seismic
Preclosure (t=0-100 yrs)	In situ+thermal±seismic
Postclosure (t=100-10,000 yrs) (drifts+backfill, accesses+seals)	In situ+thermal (t=100-10,000 yrs)±seismic

Note: Thermal loads -- time and location dependent
Seismic loads -- location independent



Selection of Appropriate Rock Model for Design Analysis

SAFETY FACTORS FOR GROUND SUPPORT COMPONENTS

Load Type	Main Access Drift and Ramps		Emplacement and Other Access Drifts	
	Concrete/Shotcrete	Steel	Concrete/Shotcrete	Steel
In situ + Thermal	2.5	1.8	2.3	1.7
In situ + Thermal + Seismic	2.0	1.5	1.8	1.4

LIMITATIONS OF QUASI-STATIC METHOD

Does not accommodate rate-dependent phenomena.

Does not accommodate accumulated damage due to repeated cyclic loading.

Requires simplifying assumption for combination of wave types.

Does not incorporate dynamic inertial effects, particularly related to block motion.

DYNAMIC ANALYSIS FOR DESIGN

Comment -- Not commonly used in design of underground openings in rock

-- Methodology not developed

-- Dynamic code capabilities ahead of material properties knowledge

Need to evaluate -- Rate-dependent phenomena

-- Multliple loading cycles

-- Loosening of joints/blocks

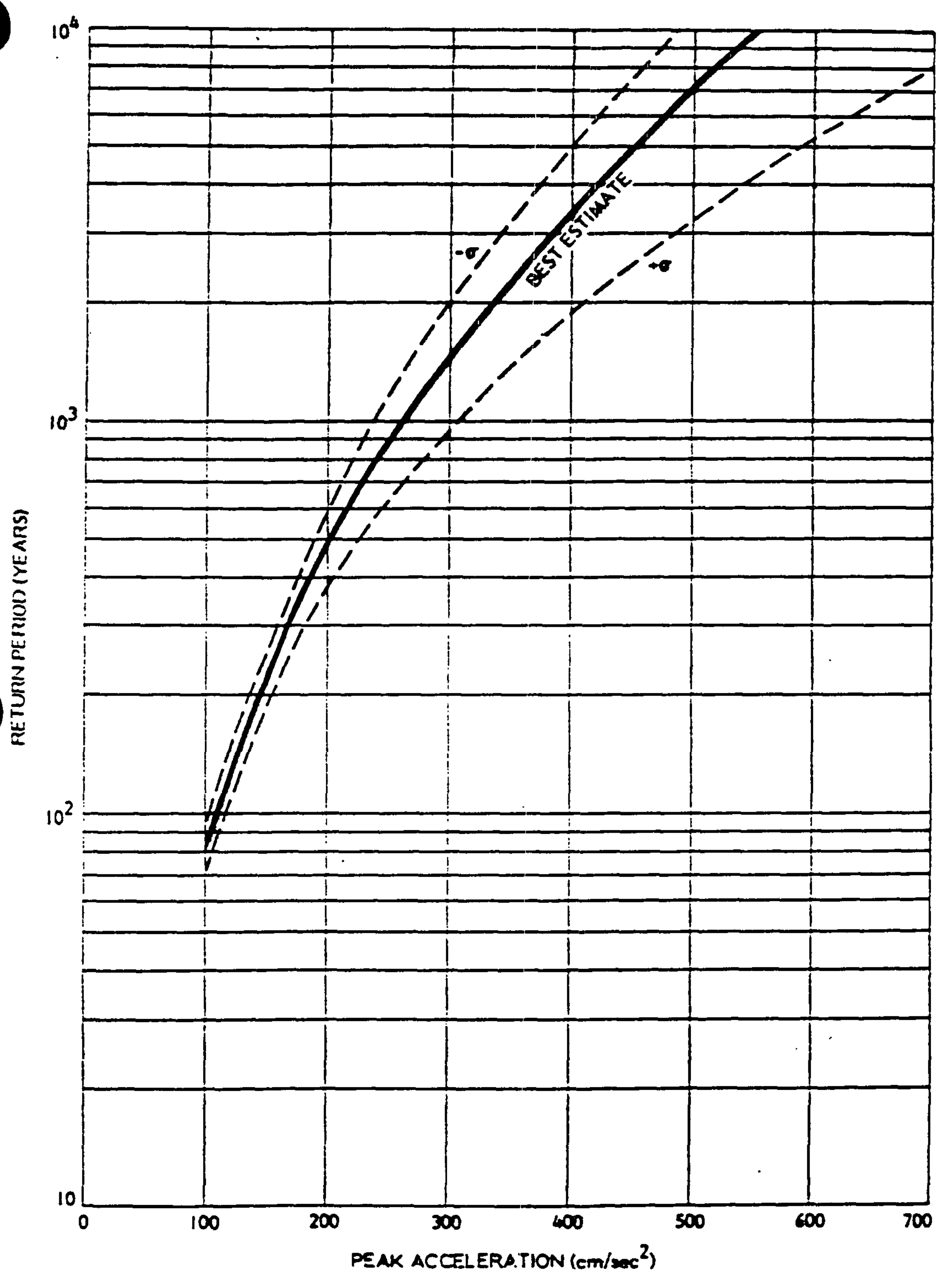
-- Validation of quasi-static assumptions

RECOMMENDATIONS

- An empirical database should be developed relating ground support/reinforcement performance to initial conditions and event magnitude in rock types similar to proposed repository host medium.

- Quasi-static design method should be evaluated relative to instrumented case study in similar rock type to that of proposed repository host medium.

- A methodology should be developed and demonstrated to accomodate relevant dynamic effects using dynamic fully-interactive analysis.



Earthquake Hazard at the Nevada Test Site,
Area 410, Nevada

Maximum Horizontal Ground Surface Accelerations at DOE Sites from Kennedy et al. (1990)*

DOE Site	Hazard Annual Probability of Exceedance 2×10^{-3}	 1×10^{-3}	 2×10^{-4}
Bendix Plant	.08	.10	.17
Los Alamos Scientific Laboratory	.18	.22	.38
Mound Laboratory	.12	.15	.23
Pantex Plant	.08	.10	.17
Rocky Flats Plants**	.13	.15	.21
Sandia National Laboratories, Albuquerque	.17	.22	.38
Sandia National Laboratories, Livermore, Ca	.41	.48	.68
Pinellas Plant, Florida	.04	.05	.09
Argonne National Laboratory-East	.09	.12	.21
Argonne National Laboratory-West	.12	.14	.21
Brookhaven National Laboratory	.12	.15	.25
Princeton National Laboratory	.13	.16	.27
Idaho National Engineering Laboratory	.12	.14	.21
Feed Materials Production Center	.10	.13	.20
Oak Ridge National Laboratory, X-10, K-25, and Y-12	.15	.19	.32
Paducah Gaseous Diffusion Plant	.33	.45	*
Portsmouth Gaseous Diffusion Plant	.08	.11	.17
Nevada Test Site	.21	.27	.46
Hanford Project Site	.09	.12	.17
Lawrence Berkeley Laboratory	.55	.64	*
Lawrence Livermore National Laboratory (LLNL)	.41	.48	.68
LLNL Site 300-854	.32	.38	.56
LLNL Site 300-834 & 836	.28	.34	.51
Energy Technology And Engineering Center	.53	.59	*
Stanford Linear Accelerator Center	.45	.59	*
Savannah River Plant	.08	.11	.19

* Value not available from Reference 1 and must be determined for High Hazard facilities at these sites.

** Bedrock slopes at Rocky Flats. This value is surface acceleration at an average soil depth at this site.

Note: Values given in this table are largest peak instrumental accelerations. Maximum vertical acceleration may be assumed to be 2/3 of the mean peak horizontal acceleration (see Section 4.4.1 for a discussion of earthquake components and mean peak horizontal acceleration).

*<u>Design and Evaluation Guidelines for Department of Energy Facilities Subjected to Natural Phenomena Hazards</u>, Prepared for the Office of the Assistant Secretary for Environment, Safety & Health, Office of Safety Appraisals, United States Department of Energy.

PERFORMANCE GOALS FOR EACH USAGE CATEGORY

(from Kennedy et al., 1990, UCRL 15910)

Category	Performance Goal	Performance Goal Annual Probability of Exceedance
General Use	Maintain occupant safety	10^{-3} of the onset of major structural damage to the extent that occupants are endangered
Important or Low Hazard	Occupant safety, continued operation with minimal interruption	5×10^{-4} of facility damage to the extent that the facility cannot perform its function
Moderate Hazard	Occupant safety, continued function, hazard confinement	10^{-4} of facility damage to the extent that the facility cannot perform its function
High Hazard	Occupant safety, continued function, very high confidence of hazard confinement	10^{-5} of facility damage to the extent that the facility cannot perform its function

USAGE CATEGORY GUIDELINES
(from Kennedy, 1990, UCRL 15910)

Usage Category	Description
General Use Facilities	Facilities that have a non-mission-dependent purpose, such as administration buildings, cafeterias, storage, maintenance and repair facilities which are plant- or grounds-oriented.
Important or Low Hazard Facilities	Facilities that have mission-dependent use (e.g., laboratories, production facilities, and computer centers) and emergency handling or hazard recovery facilities (e.g., hospitals, fire stations).
Moderate Hazard Facilities	Facilities where confinement of contents is necessary for public or employee protection. Examples would be uranium enrichment plants, or other facilities involving the handling or storage of significant quantities of radioactive or toxic materials.
High Hazard Facilities	Facilities where confinement of contents and public and environment portion are of paramount importance (e.g., facilities handling substantial quantities of in-process plutonium or fuel reprocessing facilities). Facilities in this category represent hazards with potential long-term and widespread effects.

EXAMPLE OF COMBINATION OF LOADS
YUCCA MOUNTAIN SITE
(from Hardy and Bauer, 1991)

Rock Mass Quality Category	In situ Stress			Seismic Stress			Thermal Stress			Combined In situ, Thermal, and Seismic		
	σ_{xx}	σ_{yy}	σ_{zz}	σ_{xx}	σ_{yy}	σ_{zz}	σ_{xx}	σ_{yy}	σ_{zz}	σ_{xx}	σ_{yy}	σ_{zz}
1	4.2	3.5	7.0	0.7	0.3	0.8	2.6	1.7	-0.6	7.5	5.5	7.2
2	4.2	3.5	7.0	1.3	0.6	1.4	4.6	3.0	-1.0	10.1	7.1	7.4
3	4.2	3.5	7.0	2.7	1.2	2.9	9.6	6.3	-2.2	16.5	11.0	7.7
4	4.2	3.5	7.0	6.1	2.8	6.7	21.6	14.3	-5.0	31.9	20.6	8.7
5	4.2	3.5	7.0	6.2	2.8	6.7	21.8	14.4	-5.0	32.2	20.7	8.7

SUMMARY OF EARTHQUAKE EVALUATION GUIDELINES
(from Kennedy et al., 1990, UCRL 15910)

	Usage Category			
	General Use	Important or Low Hazard	Moderate Hazard	High Hazard
Hazard Exceedance Probability	2×10^{-3}	1×10^{-3}	1×10^{-3}	2×10^{-4}