U.S. DEPARTMENT OF ENERGY
OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT

NUCLEAR WASTE TECHNICAL REVIEW BOARD
PANEL ON STRUCTURAL GEOLOGY & GEOENGINEERING

SUBJECT: SEISMIC VULNERABILITIES & SEISMIC DESIGN ISSUES: SUBSURFACE FACILITIES

(INCLUDING OBSERVATIONS FROM UNE'S AT NTS)

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Seismic Vulnerabilities of Tunnels
Outline

- Historical information
- Observations from UNE's at NTS
- Potential modes of failure:
  - Shaking
  - Spallation and flyrock
  - Discrete motion along "planes" of weakness
  - Inundation from perched water
  - Triggered rock bursts
- Summary

Tunnel Damage from Earthquakes

Historical Information - Sampling of US Literature

Source		Damage Indicators
Paper by Duke & Leeds Rand Symposium, 1959	-	". . . . .well constructed tunnels (even in epicentral region) but away from fault breaks can be expected to suffer little or no damage. . . ." Quote from p. 343
Paper by Dowding & Rosen ASCE 104: GT2, 1978	-	N ~~Do~~ damage < 0.~~1~~.9gg; < 0.67 FPS minor damage < 0.5g; < 3.1 FPS
Various papers in I.W. Marine ed., Proc. Wkshp. on Seis. Perf. of U/G Facil., 1981	-	Various
Report for FHWA/NSF by Owens & Scholl, 1981	-	Same empirical values as Dowding & Rosen but discusses implications & suggests analytical approaches
Paper by St. John & Zahrah in Tun. & U/G Space Tech., 2:2, 1987	-	Same empirical values as Dowding & Rosen but presents various analytical approaches

Tunnel Damage from Earthquakes
Historical Information - Sampling of US Literature
(CONTINUED)

Source	Damage Indicators
Paper by Sharma & Judd: Engineering Geology 30 (1991)	- Mean value: 0.36 g; 80% conf. lim.: 0.12 g; 90% conf. lim.: 0.07 g } But "In general, it appears that there is considerably less damage at depths greater than 50 M and no heavy damage below 300 M." Quote from p. 266

Tunnel Damage from Earthquakes
Historical Information

Information includes:

- Damage to tunnels in several rock types including soil
- Damage to unlined, brick lined, unreinforced and reinforced concrete lined, sets and lagging lined, etc. of tunnels with varying size and shape
- Damage to portals in addition to (or without) damage in associated tunnels
- Tunnels (e.g. Wright No. 1 in SFO 1906) damaged by direct fault offset
- Damage consisting of minor rock falls, creation of cracks in lining, roof caving, flooding and even possibly induced rock bursts, but of the 192 cases reported from 85 earthquakes, as emphasized by Sharma & Judd, there have doubtless been innumerable cases of <u>no damage and thus no reports</u>

Tunnel Damage from Earthquakes
Historical Information

Information generally excludes:

- Actual measurement of shaking parameters
- Actual response of tunnels
- Fundamental data on medium properties - say p-wave seismic velocity and presence of major features such as bedding and faulting

Summary - Historical Information

Historical experience is very broad and it indicates

- No damage at pk. surf. part. vel. < 0.67 FPS
- Minor damage at pk. surf. part. vel. < 3.1 FPS

Also

- Less damage for overburden depths > 50 M
- Essentially no damage for overburden depths > 300 M

Observations from UNE's at NTS

Plan View of Typical Group of UNE's at NTS

Elevation View of a Typical UNE at NTS

Photograph of a Typical Set of Sub-beds in Ash Fall Tuff at NTS

A Typical View of a Tunnel Ready for Testing in UNE at NTS

Tunnel Damage from UNE's at NTS

DNA's definition of damage levels for deep basing

Damage Level	Definition
I	No damage
II	Minor damage - passable, characterized by minor shotcrete and rock debris
III	Partial collapse - impassable, characterized by significant rock fall requiring mucking and placement of wire mesh
IV	Full collapse - impassable, characterized by major rock fall or invert upheaval requiring support and/or remining of tunnel

Typical Illustration of Type I Damage

Typical Illustration of Type II Damage

Typical Illustration of Type III Damage

Typical Illustration of Type IV Damage

Tunnel Damage from UNE's at NTS

Results of regression analysis

(From T.R. Kipp et al (1986), Assessment of Parameters Affecting Damage in Hardened Alcoves and Drifts Subjected to Ground Shock from Confined Underground Nuclear Explosions)

$$D = \frac{1180(OW)^{0.41}(GS)^{0.21}(GSO)^{0.23}}{(SR)^{1.24}(FP)^{0.04}(BRH)^{0.28}}$$

Where:	D	=	Damage level
	OW	=	Opening width
	GS	=	Geological setting
	GSO	=	Ground shock orientation
	SR	=	Scaled range
	FP	=	Fault proximity
	BRH	=	Back and rib hardening

Tunnel Damage from UNE's at NTS

Results of regression analysis - caveats

256 cases included but all are for a particular <u>sequence</u> of ashfall tuff with sizes of openings, cross-sectional shapes and hardening as required for operations supported; - thus, use with caution for any other application

In other words, it works well for the purpose intended - design of alcoves, etc. at NTS - but data are still being accumulated

Tunnel Damage from UNE's at NTS

Results of regression analysis

Other parameters were considered, but it turned out they were either:

- Uncorrelated:
  BIP = Bed interface proximity
  IH = Invert hardening

- Or believed statistically significant but there were inadequate data:
  PSR = Preshock rock conditioning
  DP = Discontinuity proximity

Tunnel Damage from UNE's at NTS Studies for Deep Basing

Lining type	Hendron & Aiyer strain for damage limit = I (percent)
Safety bolts (~4x4)	0.5
Lt. patterned bolts & mesh	1.5
Hvy. patterned bolts & mesh	2.5
Composite integral	5.0 (@ int. surf.)
Backpacked	7.5 (@ rock surf.)

Tunnel Damage from UNE's at NTS
Studies for Deep Basing

Lining type	Hendron & Aiyer strain for damage limit = I (percent)	Indicated pk. vel. in medium (FPS) for p-wave with str. con. = 1	str. con. = 2	str. con. = 3
		38	19	13
Safety bolts (~4x4)	0.5	55	28	18
Lt. patterned bolts & mesh	1.5			
Hvy. patterned bolts & mesh	2.5			
Composite integral	5.0 (@ int. surf.)			
Backpacked	7.5 (@ rock surf.)			

Assumes pure p-wave - strain = $\frac{V_{max}}{C_p}$ with C_p = 7500 FPS @ NTS
with C_p = 11000 FPS @ Yucca Mt.

Note: For pure s-wave @ 45^0 incidence -

$$\text{Strain} = \frac{V_{max}}{2C_S} \pm 0.7 \frac{a_{max} r}{C_S^2}$$

usually negl.

$C_s \approx$ 4000 FPS @ NTS
$C_s \approx$ 6600 FPS @ Yucca Mt.

Tunnel Damage from UNE's at NTS
Studies for Deep Basing

Lining type	Hendron & Aiyer strain for damage limit = I (percent)	Indicated pk. vel. in medium (FPS) for p-wave with str. con. = 1	str. con. = 2	str. con. = 3
		38	19	13
Safety bolts (~4x4)	0.5	55	28	18
Lt. patterned bolts & mesh	1.5	110	56	38
Hvy. patterned bolts & mesh	2.5	190	94	63
Composite integral	5.0 (@ int. surf.)	380	190	130
Backpacked	7.5 (@ rock surf.)	560	280	190

Assumes pure p-wave - strain = $\frac{V_{max}}{C_p}$ with C_p = 7500 FPS @ NTS
with C_p = 11000 FPS @ Yucca Mt.

Note: For pure s-wave @ 45° incidence -

$$\text{Strain} = \frac{V_{max}}{2C_s} \pm 0.7 \frac{a_{max} r}{C_s^2}$$

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Tunnel Damage from UNE's at NTS Studies for Deep Basing

Caveats

- Although the data include results from granite and tuff, some influence of geologic setting must be considered

- A nuclear event involves a single major pulse with some higher frequency variations while a major earthquake typically is of longer overall duration with often more high frequency content

- Although there is p-wave dominance in UNE's, there are <u>significant</u> off-axis (s-wave type) motions

Indicated Capability to Withstand Earthquake Shaking at Yucca Mountain

Summary

- For safety bolts (~4x4 pattern) NTS data indicate a capability to withstand shaking up to 13 FPS

- Historical data indicates, at limits of damage:
  None 0.67 FPS
  Minor3.1 FPS but little below 50 M and essentially none below 300 M

- Indicated "raw" knock-down factor to account for caveats on NTS data, and/or caveats in historical indicators, ranges from

$$\frac{13}{0.67} = \underline{19} \quad \text{to} \quad \frac{13}{3.1} = \underline{4.2}$$

- This strongly suggests that shaking produces no problems at Yucca Mountain for openings with safety bolts (~4x4 pattern) but, of course, we must remain cognizant of the need for special reinforcement in unusual circumstances even for static loadings

Potential Modes of Failure Due to Earthquakes

Potential Modes of Failure Due to Earthquakes

- Spallation and flyrock
- General structural failure from shaking
- Local structural failure:
  - From shaking due to weaker generalized zones
  - By discrete motion along faults, bedding planes or other localized discrete features
- Inundation from perched water
- Triggering of <u>incipient</u> rock bursts

Potential Modes of Failure Due to Earthquakes

- Spallation and flyrock

- Local structural failure:

  - By discrete motion along faults, bedding planes or other localized discrete features

- Inundation from perched water

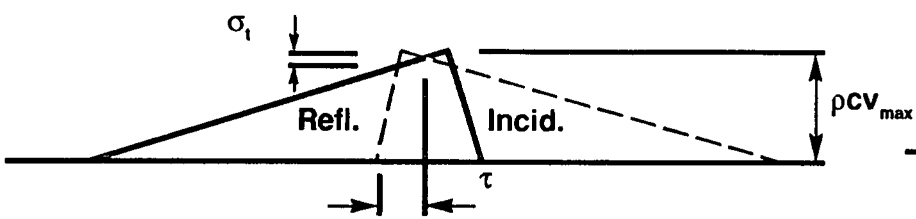
- Triggering of incipient rock bursts

Spallation and Flyrock

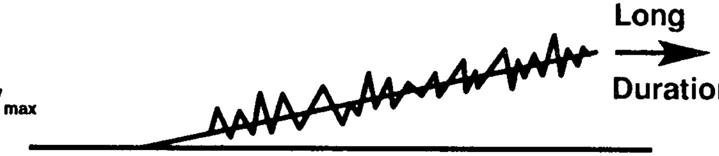
Spallation and Flyrock

Scoping of Problem and Experience from UNE's

EARTHQUAKE



UNE's



If:

V_{max} = 5 FPS (pk. vel. in med.)
σ_t = 100 PSI (eff. tens. str.)
$\rho = 2\ ^{gm}/_{cc} \rightarrow$ 125 PCF (unit wt.)
f = 60 CPS (assumed dom. freq.)

Then:

τ = 1.6 ft. (spall thkns.)
for 6"x6"x1.6' spall, KE = 72 ft. lb.

And:

2 crossing wires each with 4' span must deflect 4" to 6" (depending on their diam. and yld. strength) at their ctrs. to absorb this kinetic energy

Only 1 case in ~500 where flyrock is likely mode of failure

Summary: Protection from flyrock - if it occurs - is readily provided by wire mesh

Discrete Motion Along "Planes" of Weakness

Typical Illustration of a Pre-fabricated Test Structure Ready for Transportation to Underground Tunnel Complex

Illustration of a Strong Structure in which Displacement on a Pre-existing Fault Caused the Damage Shown. Note Gage Mounts at Mid-length of Structure to Give a Reference when Viewing the Two Following Photographs

Illustration of a Much Weaker Structure Subjected to the Same Loading as that in the Preceding Photograph but with No Fault Intersecting the Structure

View of a Backpacked Structure which was Subjected to Twice the Loading as Imposed on those Structures in the Two Preceding Photographs

Illustration of the Exterior of the Pre-fabricated Structure shown in the Preceding Photograph before the Test Structure was Transported Down the Tunnel and Inserted in the Test Bed

"Block Motion"
Summary

- If discrete relative motions of large magnitude occur on faults or bedding planes, as examples, there are ready solutions to provide protection

Inundation from Perched Water

Inundation from Perched Water
Scoping of Problem and Summary

(Ref. J. Sweet & J. L. Merritt, "Subterranean Water Management Study. . ." BMO-TR-86-17, 11 March 1986)

- Used true effective stress model (SATURN prog.) with crit. state
- Single crack intersecting circular tunnel
- Solutions assumed triangular shaped wave applied at far-field with 6,000 PSI peak, ~ 40 msec. rise time & ~ 1.5 sec. duration for most cases (3 prob. w/ 1/2, 1/4 & 1/8 x pk. str.)
- Variables:
  - Sat. med. w/no crack and w/blk. mod. of fluid varied to account for air filled pores from prob. to prob.
  - cracked cases:
    * Angle of crack rel. to dir. of str. wave prop.
    * Tunnel size (8' and 16' diam.)
    * Crack thickness
    * Bulk mod. of porous material to that of grains
    * Crack permeability
    * Crack porosity

Inundation from Perched Water
Scoping of Problem and Summary

(CONTINUED)

- **Results:**
  - Nominal case produced total inflow of 5 ga. of H_20 per ft. of length of tunnel (or 5,000 gal. for 1,000' of tunnel) for 16' diam. 2 gal./ft. for 8' diam. w/6,000 PSI applied; 0.8 gal/ft. for 16' tunnel with 750 PSI applied. With infinite permeability in crack, total inflow was 59 gal. per ft. in 16' diam. tunnel w/6,000 PSI applied
- **Summary:**
  - If perched water is a problem, pumping will suffice during construction; grouting will be adequate for long term

Triggered Rock Bursts

Triggered Rock Bursts
Scoping of Problem and Summary

- Experience in deep mines (primarily in India and South Africa)
  - Prior to ~ 1970 rock bursts caused severe damage and loss of life
  - Studies in South Africa indicated principal problem was locally higher than normal compressive stresses typically associated with faulting
  - Problem has largely disappeared by planning stope development to avoid regions of suspected or measured excessive compressive stress

Triggered Rock Bursts
Scoping of Problem and Summary

(CONTINUED)

- **Conditions at Yucca Mountain:**
  - Details of tectonic stress still being developed
  - Lithostatic stress (ρgh) is about 1,600 PSI at 2,000 ft
  - Unconfined compressive strength is in range of 6,000 to 10,000 PSI
  - If we assume a stress concentration factor of 2.8 around a circular opening, lithostatic conditions will produce a max. stress of about 4,500 PSI; thus an earthquake must produce a stress of at least 1,500 PSI around such an opening to cause concern. Tectonic stresses, non-linear behavior in solid rock, jointing, etc. makes the problem more complicated, but zones of weakness will naturally receive special attention for even static loading.

- **Summary:**
  - Triggered rock bursts appear unlikely and normal design for static loads will suffice

Summary

- Providing safety bolts (~4x4 pattern) w/wire mesh gives adequate protection from shaking and spallation

- Criteria still are in development, but there are ready solutions to withstand potential "block motions" - discrete displacements along localized (~ planar) regions of weakness

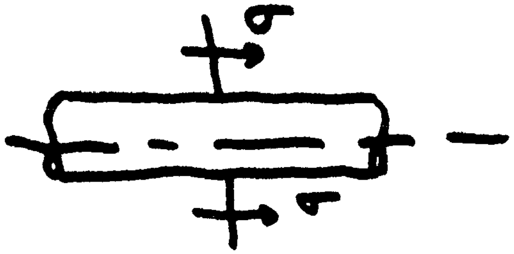
- Inundation from perched water is highly unlikely, but can be easily mitigated if of concern

- Triggering of incipient rock bursts seems highly unlikely at this site at the proposed depths

J. Merritt

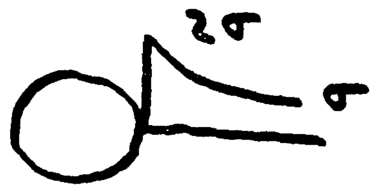
STRAIN (STRESS) GRADIENTS

P-WAVE :

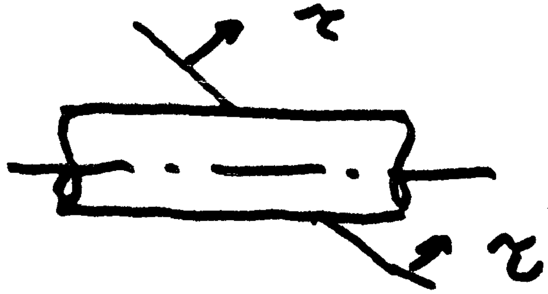


AXIAL – NO GRADIENT

CIRCUM :



S-WAVE :



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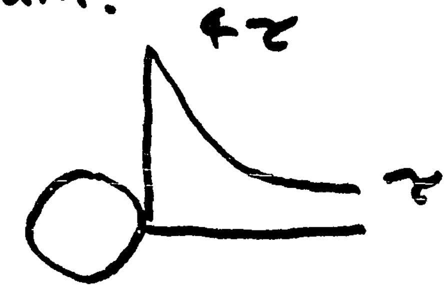

<u>CONVENTIONAL</u> REINFORCED CONC. :

$$\left.\begin{array}{l}\text{NO GRADIENT} \rightarrow \text{FAIL. STRAIN} \approx 0.0015 \\ \text{FLEXURE} \rightarrow \text{FAIL. STRAIN} \approx 0.003\end{array}\right\} \text{ACI 318-89}$$