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

PRESENTATION TO THE NUCLEAR WASTE TECHNICAL REVIEW BOARD

SUBJECT: ANALYSIS OF STRAIN RELATED WATER-LEVEL FLUCTUATIONS

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ANALYSIS OF STRAIN RELATED WATER-LEVEL FLUCTUATIONS

OBJECTIVES

- ASSESS THE APPLICABILITY OF THESE ANALYSES FOR OBTAINING ESTIMATES OF ELASTIC AND HYDRAULIC PROPERTIES OF AQUIFERS AT YUCCA MOUNTAIN

- OBTAIN ESTIMATES OF ELASTIC AND HYDRAULIC PROPERTIES IN THE ABSENCE OF PERMITS REQUIRED FOR INJECTION OR PUMPING TESTS

STRAIN RELATED WATER-LEVEL FLUCTUATIONS

- ATMOSPHERIC LOADING
- EARTH TIDES
- EARTHQUAKES
- UNDERGROUND NUCLEAR EXPLOSIONS (UNEs)

SUMMARY OF INPUTS AND OUTPUTS FOR STRAIN ANALYSES

ATMOSPHERIC LOADING

INPUT: TIME SERIES OF WATER LEVELS AND BAROMETRIC PRESSURE

OUTPUT: VERTICAL PNEUMATIC DIFFUSIVITY
VERTICAL HYDRAULIC DIFFUSIVITY
BAROMETRIC EFFICIENCY

EARTH TIDES

INPUT: WATER LEVEL RESPONSE TO EARTH TIDES
AREAL STRAIN TIDE
BAROMETRIC EFFICIENCY

OUTPUT: AREAL STRAIN SENSITIVITY
POROSITY
MATRIX COMPRESSIBILITY
SPECIFIC STORAGE

SEISMIC ANALYSIS

INPUT: FLUID PRESSURE AND WATER-LEVEL RESPONSES TO SEISMIC EVENTS
SPECIFIC STORAGE

OUTPUT: PEAK DYNAMIC STRAIN
TRANSMISSIVITY

ANALYSES OF STRAIN RELATED WATER-LEVEL FLUCTUATIONS

ADVANTAGES

1) MAY ALLOW US TO OBTAIN PARAMETER ESTIMATES AT SEVERAL LOCATIONS WHERE PUMP TESTS WILL BE IMPRACTICAL, WHICH WILL HELP ASSESS SPATIAL VARIABILITY

2) ALLOWS COMPARISON OF PARAMETER ESTIMATES OBTAINED FROM STRAINS IMPOSED AT VARIOUS SCALES MUCH LARGER THAN THAT OF WELL TESTS

3) INEXPENSIVE - MOST OF THE REQUIRED DATA ARE ALREADY BEING COLLECTED FOR OTHER PURPOSES

ANALYSES OF STRAIN RELATED WATER-LEVEL FLUCTUATIONS
(CONTINUED)

DISADVANTAGES

1) PRESENTLY REQUIRES THAT BOREHOLES BE CASED TO THE WATER TABLE

2) THESE METHODS ASSUME A POROUS MEDIUM WHICH AT SOME SCALE IS PROBABLY INAPPROPRIATE

ATMOSPHERIC LOADING

THEORETICAL RESPONSES ARE EXPRESSED IN TERMS OF

- BAROMETRIC EFFICIENCY (BE)
- DIMENSIONLESS FREQUENCY (Q)

GOVERNING EQUATIONS ARE FROM VAN DER KAMP AND GALE (1983) AND WEEKS (1979)

ROJSTACER (1988b) DEVELOPED A PERIODIC STEADY-STATE SOLUTION FOR THE WATER-LEVEL RESPONSE TO ATMOSPHERIC LOADING IN AN OPEN WELL, CASED BELOW THE WATER TABLE, TAPPING A PARTIALLY CONFINED AQUIFER

ATMOSPHERIC LOADING
(CONTINUED)

- MEASURED TIME SERIES OF BAROMETRIC PRESSURE AND WATER LEVELS ARE ANALYZED USING CROSS-SPECTRAL ESTIMATION TECHNIQUES (BENDAT AND PIERSOL, 1986)

- THIS RESULTS IN VALUES OF BE AND Q IN CYCLES/DAY, WHICH ARE THEN PLOTTED AND MATCHED WITH THE BEST FIT THEORETICAL CURVE

ATMOSPHERIC LOADING
(CONTINUED)

THE MATCH YIELDS BE, R, $Q_{DIMENSIONLESS}$, AND $Q_{CYCLES/DAY}$ WHERE:

$$R = L^2\omega/2D_a$$

$$Q = Z^2\omega/2D$$

- L = DEPTH FROM LAND SURFACE TO THE WATER TABLE
- Z = DEPTH FROM THE WATER TABLE TO THE MONITORED ZONE
- D_a = VERTICAL PNEUMATIC DIFFUSIVITY
- D = VERTICAL HYDRAULIC DIFFUSIVITY
- ω = ANGULAR FREQUENCY (CALCULATED FROM $Q_{CYCLES/DAY}$)

SUMMARY OF MATCH PARAMETERS DETERMINED FROM BEST-FIT TO THEORETICAL ATMOSPHERIC LOADING MODELS

WELL/ MONITORED ZONE	DIMENSIONLESS FREQUENCIES [1]Q_u	Q	R	BAROMETRIC EFFICIENCY BE	HYDRAULIC DIFFUSIVITY D(mm^2/s)	PNEUMATIC DIFFUSIVITY D_a(mm^2/s)
UE-25c#1-ABOVE	[2]3.1f		6.3	0.80	4.23×10^4	2.34×10^4
UE-25c#3-ABOVE	3.1f		6.3	0.80	3.25×10^4	2.37×10^4
UE-25c#3-BELOW		6.3f	5.0	0.87	$1.81\text{-}3.86 \times 10^4$	2.96×10^4
USW H-4 - BELOW		[3]100f	[4]_____	0.80	[3]4.04×10^3	[4]_____
USW H-6 - BELOW		[3]20f	[4]_____	0.95	[2]2.35×10^3	[4]_____

[1]Q_u IS THE DIMENSIONLESS FREQUENCY FOR THE ATMOSPHERIC LEADING MODEL FOR AN UNCONFINED AQUIFER

[2]f IS FREQUENCY IN CYCLES PER DAY (CPD)

[3]THESE ARE BOUNDING ESTIMATES, A LOWER BOUND FOR Q, AND AN UPPER BOUND FOR D

[4]INDETERMINATE

EARTH TIDE ANALYSIS

- THE SOLID EARTH TIDE IS THE DISPLACEMENT OF THE PARTICLES OF THE EARTH DUE TO FORCES OF ATTRACTION OF PRINCIPALLY THE SUN AND MOON, AND ARE RELATED TO THE PHASES OF THE MOON AND CHANGING SEASONS

- MEASURED WATER-LEVEL RESPONSES TO EARTH TIDES ARE USED TO ESTIMATE

  - SPECIFIC STORAGE
  - MATRIX COMPRESSIBILITY
  - AREAL STRAIN SENSITIVITY
  - POROSITY

USING THE METHODS DEVELOPED BY ROJSTACZER AND AGNEW (1989)

EARTH TIDE ANALYSIS

(CONTINUED)

- BY MEASURING THE AMPLITUDE OF WATER-LEVEL FLUCTUATIONS IN RESPONSE TO EARTH TIDES AND BY ESTIMATING THE AREAL STRAIN TIDE FROM THE THEORETICAL TIDAL POTENTIAL (HARRISON, 1971), MATRIX COMPRESSIBILITY AND AREAL STRAIN SENSITIVITY OF THE WELL/ AQUIFER CAN BE ESTIMATED

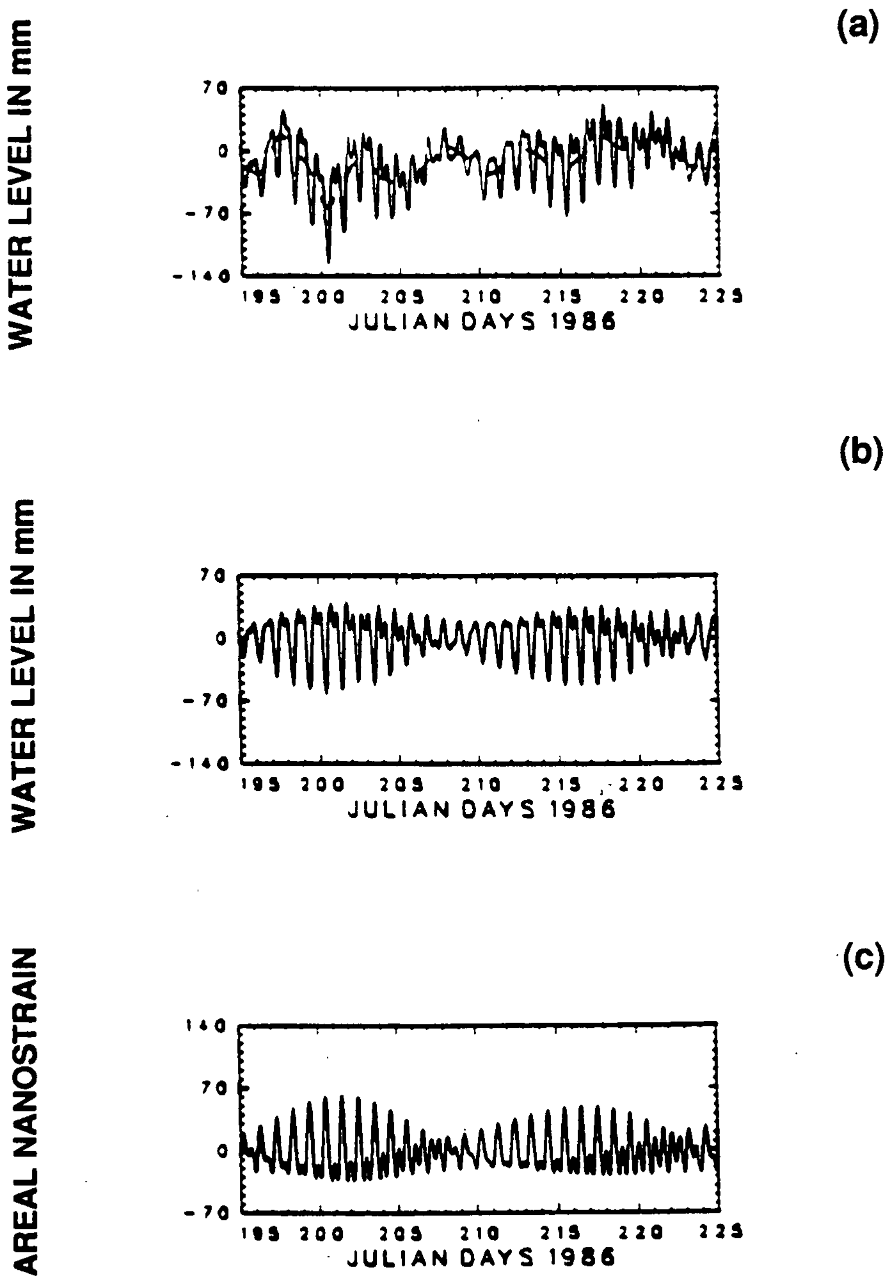
- USING A RELATION BETWEEN MATRIX COMPRESSIBILITY, BAROMETRIC EFFICIENCY, AND AREAL STRAIN SENSITIVITY, POROSITY AND SPECIFIC STORAGE CAN BE ESTIMATED

EARTH TIDE ANALYSIS

(CONTINUED)

- TIME SERIES OF WATER-LEVEL MEASUREMENTS ARE PROCESSED USING A LOW PASS, DIGITAL BUTTERWORTH FILTER. THE LOW PASS SIGNAL CONTAINS LONGER PERIOD ATMOSPHERIC INFLUENCES, AND IS SUBTRACTED FROM THE RAW DATA TO PROVIDE A REDUCED SERIES OF FLUCTUATIONS CONTAINING SHORTER FREQUENCY COMPONENTS INCLUDING EARTH TIDES AND DAILY ATMOSPHERIC EFFECTS

USW H-4-BELOW WATER-LEVEL TIME SERIES FOR A 30-DAY WINDOW OF THE (a) RAW AND LOW PASS, AND (b) REDUCED SIGNALS, SHOWN WITH (c) THE CALCULATED AREAL STRAIN TIDE



NOTE: FULL MOON JD 202, NEW MOON JD 217, 1/4 MOON JD 209

HGWFGP5P.125.NWTRB/6-25/27-91

EQUATIONS USED IN EARTH TIDE ANALYSIS

1. $W = -3\varepsilon_{2r}(1-2v)\gamma[(\rho g \beta(1+\nu))]^{-1}$

   W = WATER-LEVEL FLUCTUATION

   ε_{2r} = AREAL STRAIN TIDE

2. $A_s = W/\varepsilon_{2r}$

   A_s = AREAL STRAIN SENSITIVITY

3. $\beta = -3B(1-2\nu)/\rho g A_s[2\alpha B(1-2\nu)-3(1-\nu)]$

   β = MATRIX COMPRESSIBILITY

4. $\alpha = 1-\beta_s/\beta$ β_s IS ESTIMATED FROM LITERATURE

5. $B = 3(1-BE)/[2(1+\nu)+\alpha(1-BE)(1-2\nu)]$

6. $n = (\beta-\beta_s)(1-B)/B(\beta_f-\beta_s)$

   n = POROSITY

7. $S_s = \rho g[(\beta-\beta_s)\ (1-\lambda)+n(\beta_f-\beta_s)]$

S_s = SPECIFIC STORAGE

WHERE $\lambda=2\alpha(1-2\nu)/3(1-$ [illegible]

ESTIMATED VALUES USED IN EARTH TIDE ANALYSES

$\beta_f = 4.4 \times 10^{-10} Pa^{-1}$

$\beta_s = 1.72 \times 10^{-11} Pa^{-1}$

(FROM ZISSMAN (1933) FOR SUDBURY NORITE WITH COMPARABLE OVERBURDEN STRESS)

$\nu = 0.17$

(FROM PRICE (1982) AVERAGE ν FOR THE TRAM MEMBER AND LITHIC RIDGE TUFFS AT THE NEVADA TEST SITE)

PARAMETER ESTIMATES OBTAINED FROM EARTH TIDE ANALYSIS

WELL/ MONITORED ZONE	WATER-LEVEL AMPLITUDE A_{WATER} (mm)	STRAIN-TIDE AMPLITUDE A_{TIDE} (nε)	AREAL STRAIN SENSITIVITY (mm/nε)
UE-25c #1 ABOVE	5.15/1.88	17.17/12.55	0.30/0.15
UE-25c #3 ABOVE	4.98/1.63	17.17/12.55	0.29/0.13
UE-25c #3 BELOW	6.12/3.61	17.17/12.55	0.36/0.29
USW H-4 BELOW	14.8/12.2	17.76/13.26	0.83/0.92
USW H-6 BELOW	5.42/3.03	18.39/13.38	0.29/0.23

WELL/ MONITORED ZONE	MATRIX COMPRESSIBILITY $\times 10^{-11}$ β (Pa^{-1})	AQUIFER POROSITY IN PERCENT	SPECIFIC STORAGE $\times 10^{-11}$ S_s (mm^{-1})
UE-25c #1 ABOVE	5.68	27	13.6
UE-25c #3 ABOVE	5.88	29	14.4
UE-25c #3 BELOW	2.98	10	4.86
USW H-4 BELOW	2.57	6	3.17
USW H-6 BELOW	---	---	---

SEISMIC WAVES

SEISMIC RAYLEIGH WAVES FROM EARTHQUAKES AND UNDERGROUND NUCLEAR EXPLOSIONS PRODUCE AQUIFER DILATATION AND CONCOMMITANT FLUID PRESSURE DISTURBANCES

SEISMIC ANALYSIS

FROM COOPER et al (1965)

$$A=x_o/h_o=\{((1-(\pi r_w^2/T\tau)Kei\alpha_w) -4\pi^2H_e/\tau^2g)^2+((\pi r_w^2/T\tau)Ker\alpha_w)^2\}^{1/2} \quad (4)$$

where,

- h_e IS THE AMPLITUDE OF THE AQUIFER FLUID PRESSURE IN TERMS OF EQUIVALENT HEAD OF WATER,
- x_o IS THE AMPLITUDE OF THE WATER-LEVEL FLUCTUATION,
- H_e IS THE EFFECTIVE HEIGHT OF THE WATER COLUMN, H_e=H+3b/8,
  WHERE H IS THE HEIGHT OF THE WATER COLUMN IN THE WELL CASING, AND b IS THE THICKNESS OF THE AQUIFER OR LENGTH OF THE OPEN OR SCREENED PORTION OF THE WELL,
- r_w IS THE RADIUS OF THE CASING WHERE THE FREE-SURFACE WATER-LEVEL FLUCTUATES,
- g IS THE ACCELERATION DUE TO GRAVITY,
- τ IS THE PERIOD OF SEISMIC WAVE, $\tau=2\pi/\omega$ WHERE ω IS THE ANGULAR FREQUENCY OF THE WAVE,
- T IS THE AQUIFER TRANSMISSIVITY,

$\alpha_w = r_w(\omega S/T)^{1/2}$, WHERE S IS THE AQUIFER STORAGE COEFFICIENT,

Ker AND Kei ARE KELVIN FUNCTIONS OF ORDER ZERO

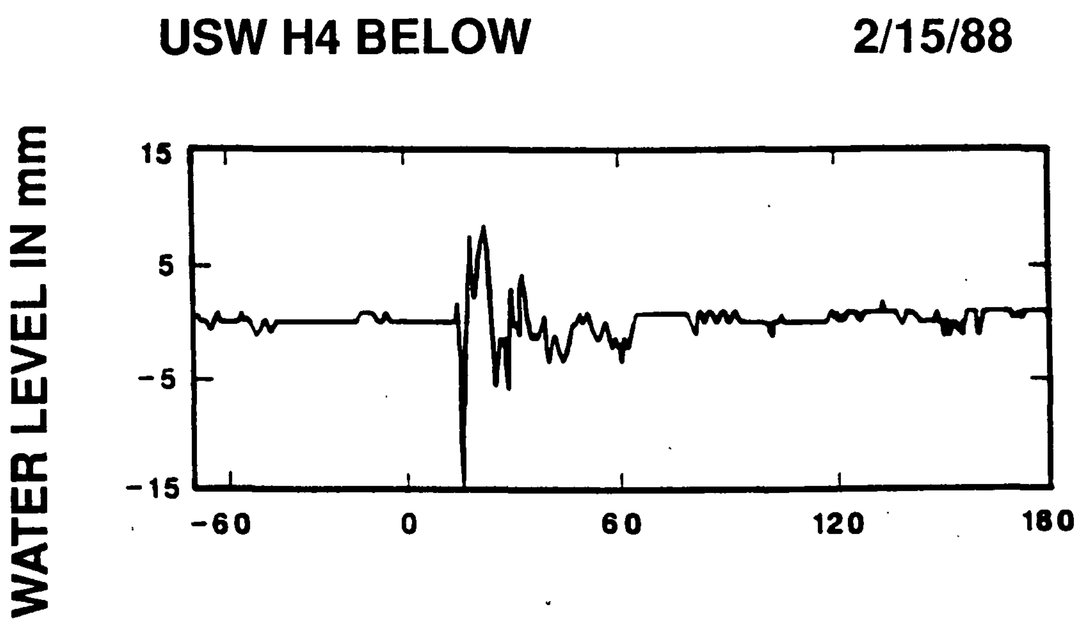
SEISMIC ANALYSIS
(CONTINUED)

WHEN "SHUT IN" FLUID PRESSURE RESPONSES TO SEISMIC WAVES ARE MEASURED, AND WHEN AREAL STRAIN SENSITIVITIES ARE KNOWN FROM EARTH TIDE AND ATMOSPHERIC LOADING ANALYSIS, PEAK DYNAMIC STRAIN ASSOCIATED WITH THE SEISMIC EVENT CAN BE CALCULATED BY

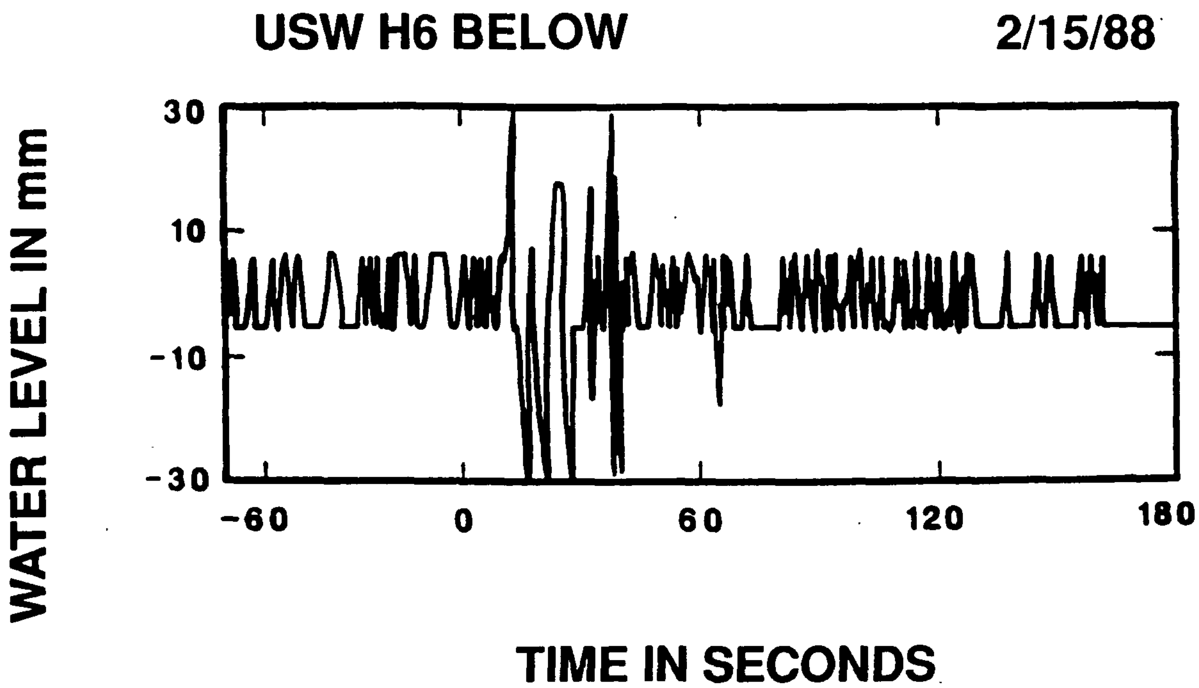
$$H_o = A_S * \varepsilon_n$$

WHERE H_o = FLUID PRESSURE RESPONSE
A_s = AREAL STRAIN SENSITIVITY
ε_n = PEAK DYNAMIC STRAIN
(IN NANOSTRAIN 10^{-9})

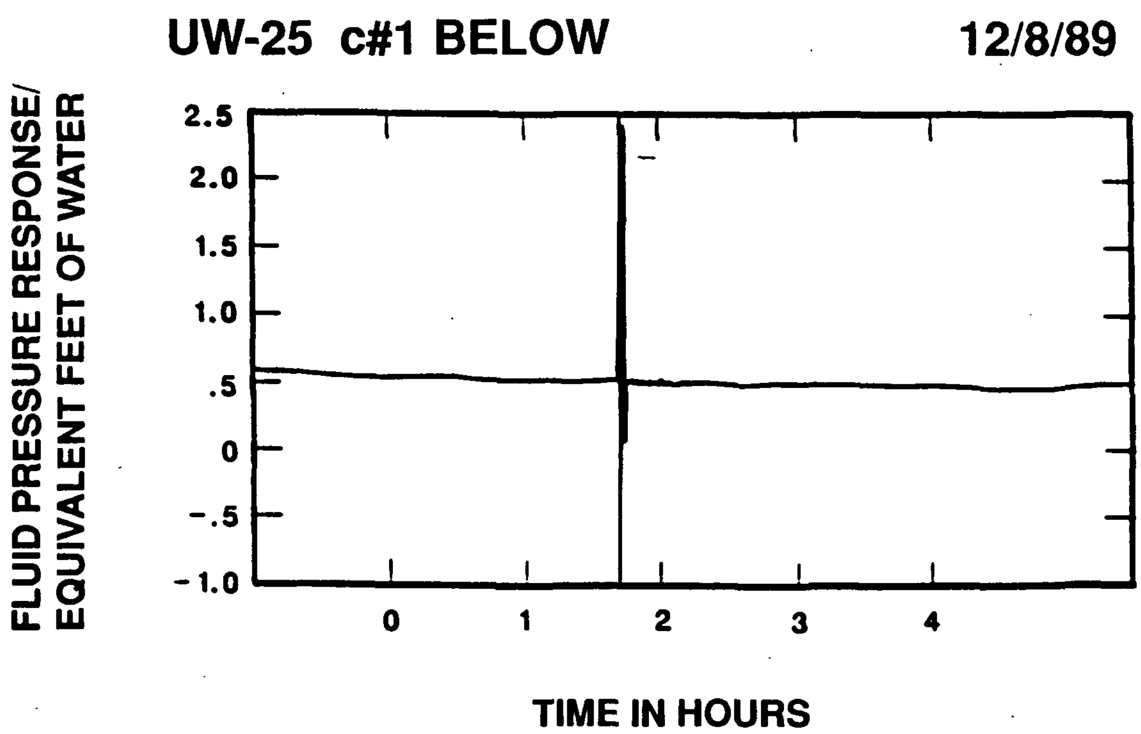
UNDERGROUND NUCLEAR EXPLOSION
MAGNITUDE 5.3



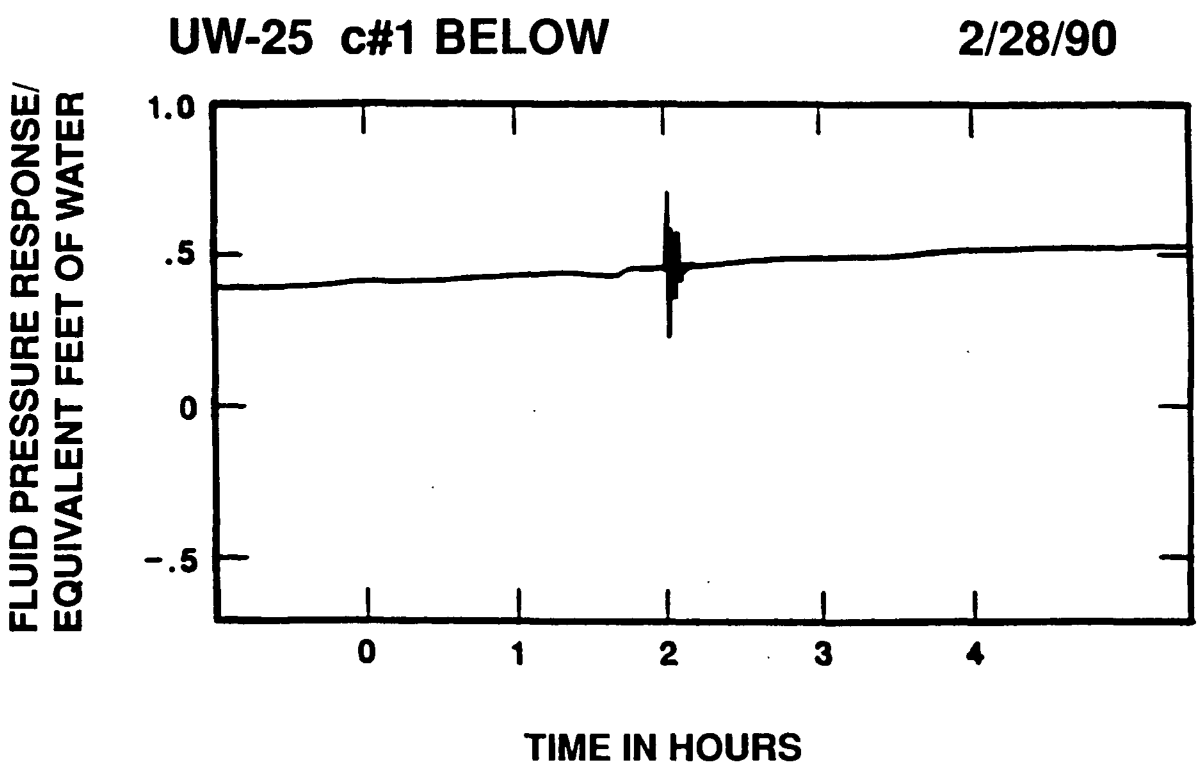
UNDERGROUND NUCLEAR EXPLOSION
MAGNITUDE 5.3



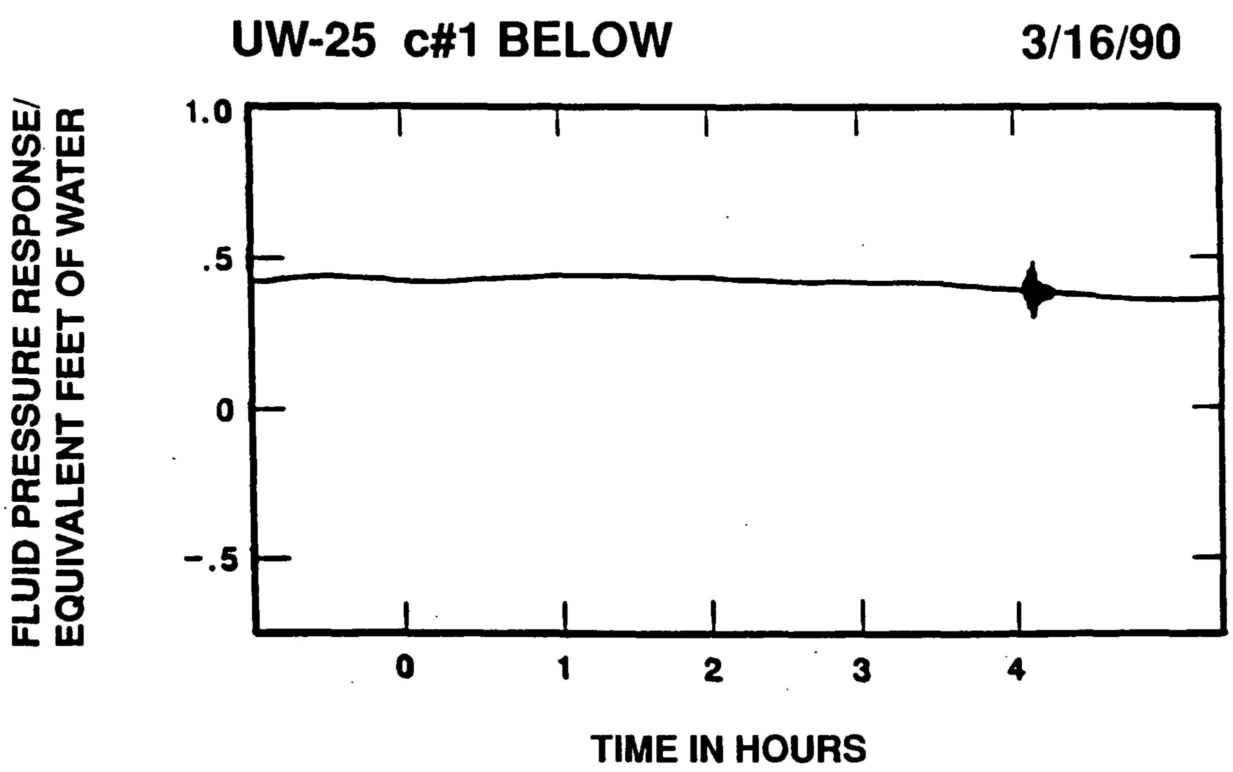
UNDERGROUND NUCLEAR EXPLOSION
MAGNITUDE 5.5



EARTHQUAKE
LOS ANGELES, CALIFORNIA
MAGNITUDE 5.5



EARTHQUAKE
LA PAZ, MEXICO
MAGNITUDE 5.9



WATER LEVEL AND FLUID PRESSURE RESPONSES TO SELECTED EARTHQUAKES AND UNDERGROUND NUCLEAR EXPLOSIONS

	UNDERGROUND NUCLEAR EXPLOSIONS		EARTHQUAKES	
	2/15/88	12/8/89	2/28/90	3/16/90
C#1	---	1263 mm	144 mm	43.3 mm
H4	23.2 mm	---	---	---
H6	58.5 mm	---	---	---

THE RESPONSE IN C#1 IS "SHUT IN" FLUID PRESSURE

PEAK DYNAMIC STRAIN

- THE PEAK DYNAMIC FLUID PRESSURE RESPONSE (H_o) IN UE25-C#1 TO THE UNE OF 12/08/89 WAS 1.26 METERS

- THE STATIC-CONFINED AREAL STRAIN SENSITIVITY (A_s) FOR THE M_2 TIDE FROM UE-25-C#3 BELOW WAS .36mm/NANOSTRAIN

$$H_o = A_s * \varepsilon_n$$

$$1263\text{mm} = .36\text{mm/NANOSTRAIN} * \varepsilon_n$$

$3.51x10^{3}(1x10^{-9})=3.51x10^{-6}$ PEAK DYNAMIC STRAIN

- THE LOS ANGELES EARTHQUAKE (2/28/90) CAUSED A PEAK DYNAMIC STRAIN OF $4.0x10^{-7}$

- THE LA PAZ MEXICO EARTHQUAKE (3/16/90) CAUSED A PEAK DYNAMIC STRAIN OF $1.20x10^{-7}$

FLUID PRESSURE RESPONSE

- THE PEAK DYNAMIC STRAIN FROM UE25-C#1 (FROM 12/8/89) WAS 3.51×10^{-6} (STRAIN)

- THE STATIC-CONFINED AREAL STRAIN SENSITIVITY FROM EARTH TIDE ANALYSIS FOR USW-H4 WAS .83mm/NANOSTRAIN

$$H_o = A_s * \varepsilon_n$$

$$H_o = .83\text{mm/NANOSTRAIN} * 3.51 \times 10^3 \text{ (NANOSTRAIN)}$$

$$H_o = 2.91 \text{ METERS}$$

AMPLIFICATION FACTOR

- THE AMPLIFICATION FACTOR (A) EQUALS THE WATER-LEVEL RESPONSE (X_o) OVER THE FLUID PRESSURE RESPONSE (H_o)

- FOR USW-H4, THE OPEN WATER-LEVEL RESPONSE (X_o) TO THE UNE OF 2/15/88 WAS 23.2mm

- $A = X_o/H_o = 23.2/2.91 \times 10^3 = 7.97 \times 10^{-3}$

ESTIMATE OF TRANSMISSIVITY FROM SEISMIC ANALYSIS

FOR USW-H4

$A = 7.97 \times 10^{-3}$ - USING THE C#1 FLUID PRESSURE RESPONSE

$S_s = 3.17 \times 10^{-10}$ (mm^{-1}) - FROM EARTH TIDE ANALYSES

SOLVING COOPER'S EQUATION FOR T YIELDS

1.05 m^2/d

THIS COMPARES TO 7.88 m^2/d ESTIMATED FOR THE SAME INTERVAL FROM A BOREHOLE FLOW SURVEY (WHITFIELD et al., 1985)

CONCLUSIONS

- ANALYSIS OF STRAIN RELATED WATER-LEVEL FLUCTUATIONS APPEARS TO BE A VIABLE METHOD FOR OBTAINING ESTIMATES OF AQUIFER PROPERTIES AT SOME BOREHOLES NEAR YUCCA MOUNTAIN

- ON SITE STRAIN MONITORING WOULD ENHANCE THE ANALYSIS BY ELIMINATING THE NEED TO USE THE THEORETICAL TIDAL POTENTIAL FOR ESTIMATING THE AREAL STRAIN TIDE WHICH MAY BE INFLUENCED LOCALLY BY FAULTS

- SOME BOREHOLES NEAR YUCCA MOUNTAIN WOULD BE EFFECTIVE COMPONENTS OF AN AREAL STRAIN MONITORING NETWORK IF COUPLED WITH IN SITU STRAIN MONITORS

FUTURE PLANS

- EXPAND MONITORING OF FLUID PRESSURE RESPONSES TO INCLUDE ADDITIONAL BOREHOLES

- INCORPORATE ADDITIONAL STRIP-CHART RECORDERS FOR TRUE CONTINUOUS MONITORING TO TAKE ADVANTAGE OF EARTHQUAKES AND UNANNOUNCED UNEs