STUDIES OF THE SUBSURFACE EFFECTS OF EARTHQUAKES*

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Whenever use of subsurface facilities are comtemplated, no matter how deep or how passive these facilities are, the public perceives a risk from earthquakes. Incongrously, this risk is not as readily perceived for surface facilities where published observations indicate that damage is considerably greater.

As part of the National Terminal Waste Storage Program, the Savannah River Laboratory is conducting a series of studies on the subsurface effects of earthquakes. This report summarizes three subcontracted studies [Slide 1].

Earthquake Damage to Underground Facilities

The purpose of this study was to document damage and non-damage caused by earthquakes to tunnels and shallow underground openings; to mines and other deep openings; and to wells,

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shafts, and other vertical facilities [Slide 2]. This study by Terra Tek of Salt Lake City was published in November 1978 by the Savannah River Laboratory. The results were also presented at the Rapid Excavation and Tunneling Conference in Atlanta, Georgia, in June 1979.

In a study of 72 tunnels, no damage was reported below an acceleration of 0.2 g, which is a common design acceleration for surface facilities [Slide 3]. Some slight damage was reported between 0.2 and 0.5 g. Much of the damage reported above 0.5 g was near the tunnel portals or under shallow cover. Surface seismic motions may be 4 to 6 times greater than those in deep mines according to Japanese studies. Studies of water, oil, and gas wells after the Alaska earthquake of 1964 indicate that the only damage was caused by earth slides. Data from nuclear detonations provide a large quantitative data base on subsurface effects, but certain dissimilarities indicate that data may not be directly compared [Slide 4].

Earthquake Related Displacement Fields Near Underground Facilities

In the first study, the definition of damage was similar to that used for surface facilities, i.e., the disruption of the operation of the facility [Slide 5]. Although disruption may be significant during the operational phase of a repository for underground storage of nuclear waste, for the longer period of time that integrity of the facility is required, permeability enhancement is more important. Permeability is more likely to be enhanced by displacement than by acceleration. Thus, the second study, also performed by Terra Tek, and published by the Savannah River Laboratory, concentrated on the displacement fields due to earthquakes [Slides 6-10].

The study included an analysis of block motion, an analysis of the dependence of displacement on the orientation and distance of joints from the earthquake source, and displacement related to distance and depth near a causative fault as a result of various shapes, depths, and senses of movement on the causative fault [Slide 11].

Numerical Simulation of Earthquake Effects on Tunnels for Generic Nuclear Waste Repositories

The objective of this study was to use numerical modeling to determine under what conditions seismic waves might cause instability of an underground opening or create fracturing that would increase the permeability of the rock mass [Slide 12]. This study was done by Science Applications, Incorporated of Fort Collins, Colorado.

For this study, a model was developed that could simulate mechanical stresses and thermal stresses as well as seismic stresses and determine the strains, joint slip, and tensile fracture that might result from these stresses [Slide 13]. Three rock types were used: salt, granite, and shale. Most of the conditions that were stable through the heating phase of the repository were also stable through the seismic phase [Slides 14-30].

The model, thus far, has only been used to investigate generic situations, but the model should be validated by correlating its results with rock testing results [Slides 31 and 32].

SUBSURFACE EFFECTS OF EARTHQUAKES
SUBCONTRACTS

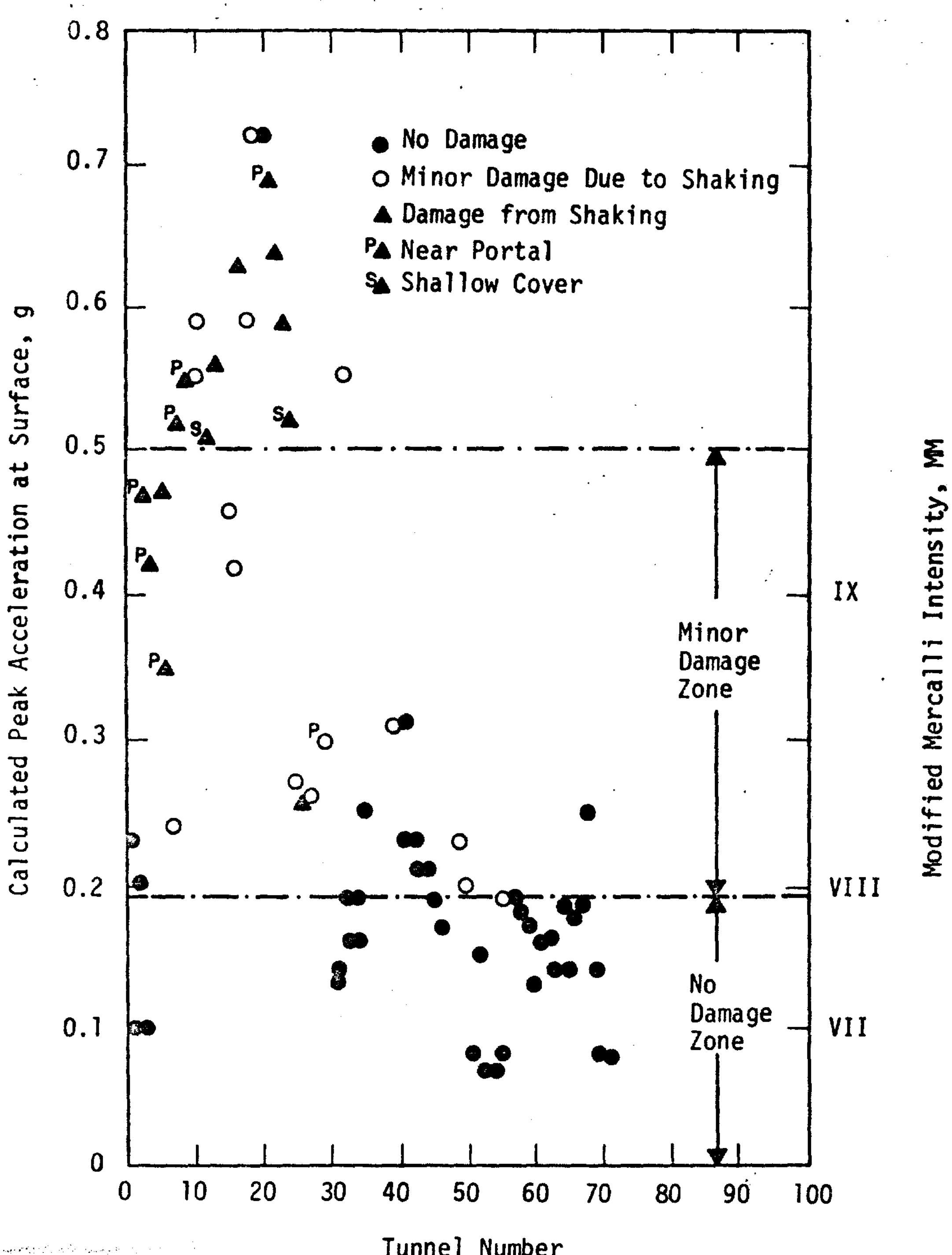
- EARTHQUAKE DAMAGE TO UNDERGROUND FACILITIES - TERRA TEK, SALT LAKE CITY, UTAH

- EARTHQUAKE RELATED DISPLACEMENT FIELDS NEAR UNDERGROUND FACILITIES - TERRA TEK, SALT LAKE CITY, UTAH

- NUMERICAL SIMULATION OF EARTHQUAKE EFFECTS ON TUNNELS FOR GENERIC NUCLEAR WASTE REPOSITORIES--SCIENCE APPLICATIONS, INC., FT. COLLINS, COLORADO

EARTHQUAKE DAMAGE TO UNDERGROUND FACILITIES

- PURPOSE: TO DOCUMENT THE DAMAGE TO UNDERGROUND FACILITIES CAUSED BY EARTHQUAKES
  - TUNNELS AND SHALLOW UNDERGROUND OPENINGS
  - MINES
  - WELLS
- PUBLISHED BY SAVANNAH RIVER LABORATORY AS DP-1513



Calculated Peak Acceleration at the Surface and Associated Tunnel Damage

EARTHQUAKE DAMAGE TO UNDERGROUND FACILITIES

CONCLUSIONS:

MORE DAMAGE IS REPORTED IN SHALLOW TUNNELS THAN IN DEEP MINES.

MOST DAMAGE IN TUNNELS IS NEAR THE PORTALS.

SUBSURFACE DAMAGE HAS OCCURRED NEAR EXISTING FAULTS OR FRACTURES.

WELLS AND SHAFTS ARE LESS SUSCEPTIBLE TO DAMAGE THAN SURFACE STRUCTURES.

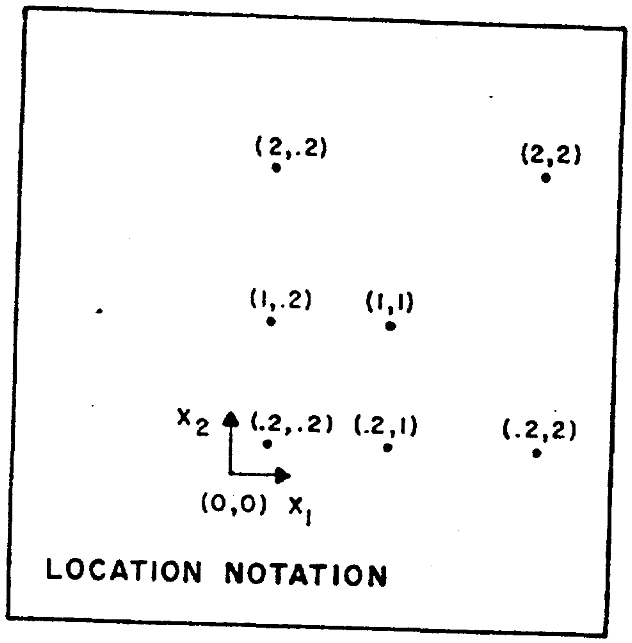
EARTHQUAKE RELATED DISPLACEMENT FIELDS NEAR UNDERGROUND FACILITIES

DAMAGE TO UNDERGROUND FACILITIES IS CAUSED PRIMARILY BY DISPLACEMENT - NOT ACCELERATION.

PURPOSE: EVALUATE DISPLACEMENT FIELDS AROUND A CAUSATIVE FAULT.

EARTHQUAKE RELATED DISPLACEMENT FIELDS NEAR UNDERGROUND FACILITIES

- BLOCK MOTION PHENOMENA
  - GEOLOGICAL EVIDENCE
  - SEISMOLOGICAL EVIDENCE
  - SIMULATION EXPERIMENTS
  - MODELS - DISPLACEMENT RELATED TO JOINT ANGLE AND DISTANCE TO SOURCE
- STATIC DISPLACEMENT FIELDS OF EARTHQUAKES
  - DISPLACEMENT AS A FUNCTION OF DISTANCE AND DEPTH
  - EARTHQUAKE SOURCE RELATIONSHIPS
- MEDIUM EFFECT ON DISPLACEMENT SPECTRA OF SEISMIC WAVES



Location Notation for the Calculated Displacement Fields

CASE I - LONG, SHALLOW FAULT

DISPLACEMENT IN (MM DISPLACEMENT/METER SLIP ON FAULT)

VERTICAL STRIKE-SLIP FAULT

FAULT SEMI-LENGTH = 1.0

DEPTH TO TOP OF FAULT = 0.0

DEPTH TO BOTTOM OF FAULT = 0.10

RESULTANT SLIP

Z	(.2, .2)	(.2, 1)	(.2, 2)	(1, .2)	(1, 1)	(2, .2)	(2, 2)
0	140.5	104.9	6.0	16.5	18.2	4.3	5.3
.1	117.6	88.8	5.7	15.8	18.6	4.2	5.5
.5	16.6	16.9	4.2	11.1	15.5	4.2	5.7
1.0	2.8	4.4	2.5	5.5	9.0	3.7	5.2
2.0	.3	.8	.8	1.4	2.6	2.2	3.1
3.0	.1	.2	.3	.5	.9	1.1	1.7
4.0	0.0	.1	.2	.2	.4	.6	.9

EARTHQUAKE RELATED DISPLACEMENT FIELDS NEAR UNDERGROUND FACILITIES

CONCLUSIONS:

DISPLACEMENTS DECREASE RAPIDLY WITH DISTANCE FROM CAUSATIVE FAULT.

DISPLACEMENTS DECREASE RAPIDLY WITH DEPTH FOR LONG SHALLOW STRIKE-SLIP FAULTS.

DISPLACEMENTS DO NOT DECREASE AS RAPIDLY WITH DEPTH FOR SQUARE FAULTS WHETHER STRIKE-SLIP OR DIP-SLIP.

NUMERICAL SIMULATION OF EARTHQUAKE EFFECTS ON TUNNELS FOR GENERIC NUCLEAR WASTE REPOSITORIES

OBJECTIVE: TO USE NUMERICAL MODELING TO DETERMINE UNDER WHAT CONDITIONS SEISMIC WAVES MIGHT CAUSE INSTABILITY OF AN UNDERGROUND OPENING, OR CREATE FRACTURING THAT WOULD INCREASE THE PERMEABILITY OF THE ROCK MASS.

NUMERICAL SIMULATION OF EARTHQUAKE EFFECTS ON TUNNELS FOR GENERIC NUCLEAR WASTE REPOSITORIES

WORK ELEMENTS

- MODIFY AND COUPLE EXISTING NUMERICAL CODES FOR USE IN SIMULATING:

  EXCAVATION STRESS

  THERMAL STRESS

  SEISMIC STRESS

  JOINT SLIP

  TENSILE CRACKING

- SELECT INPUT SEISMIC MOTIONS

- SELECT MATERIAL PROPERTIES TO BE USED

- MAKE CALCULATIONS FOR SALT, GRANITE, AND SHALE VARYING JOINT PATTERN, IN SITU STRESS AND PORE PRESSURE

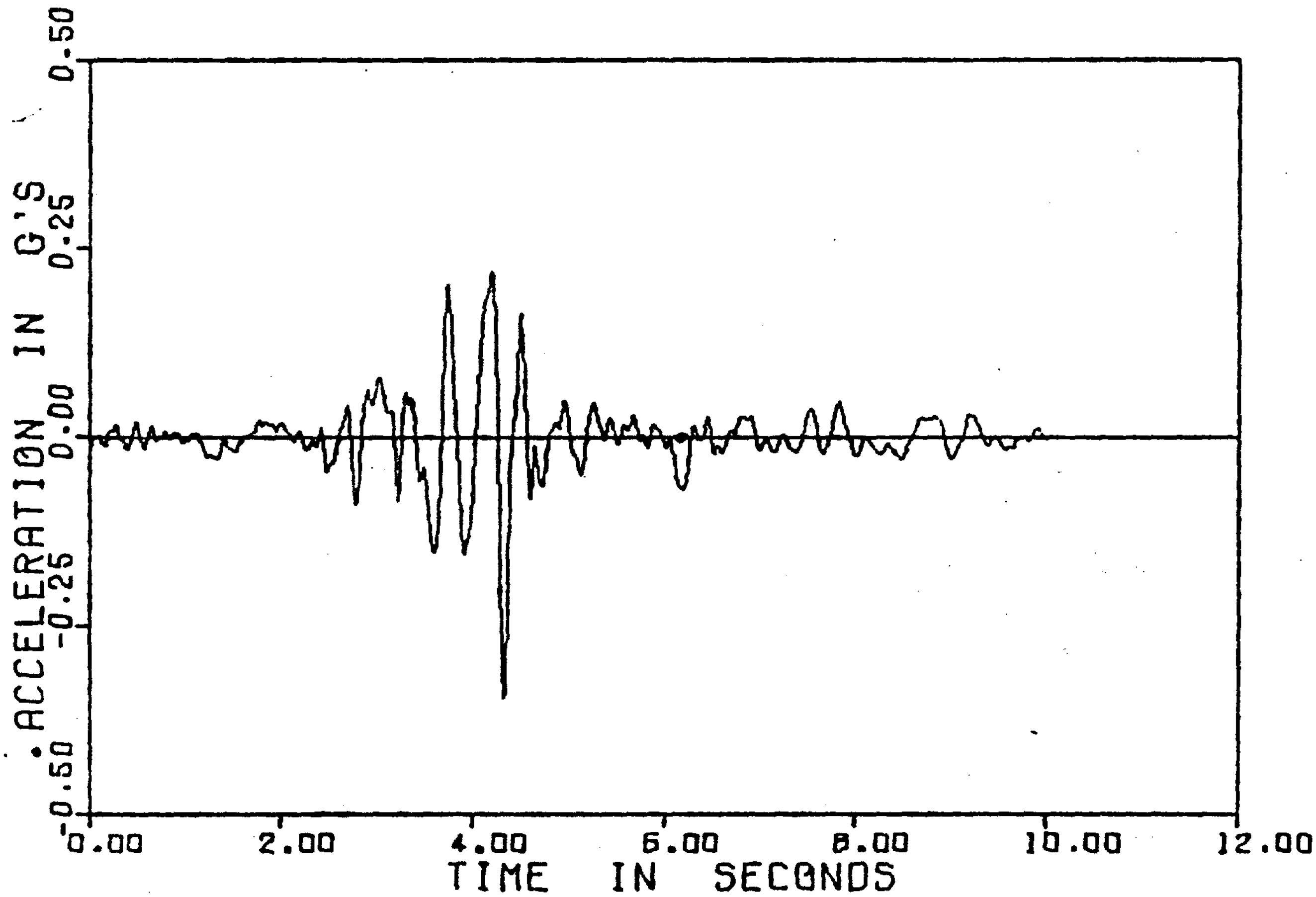
SELECTION OF INPUT SEISMIC MOTIONS

1. GENERATE ARTIFICIAL EARTHQUAKE AND CALCULATE THE SITE MOTION.

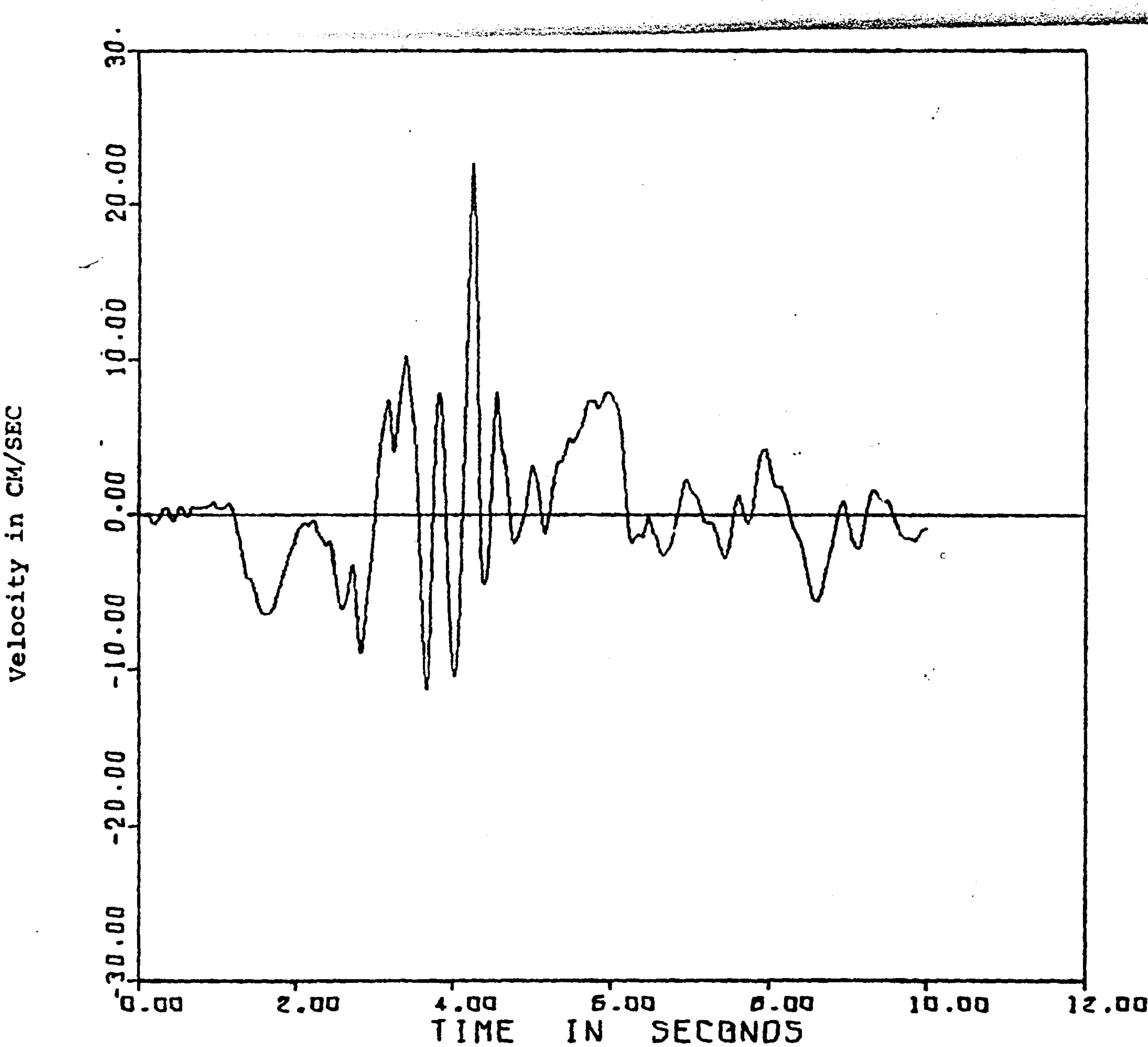
2. USE ACTUAL STRONG MOTION RECORDS FROM ROCK SITES.

STRONG MOTION RECORDS SELECTED FOR USE IN SIMULATION

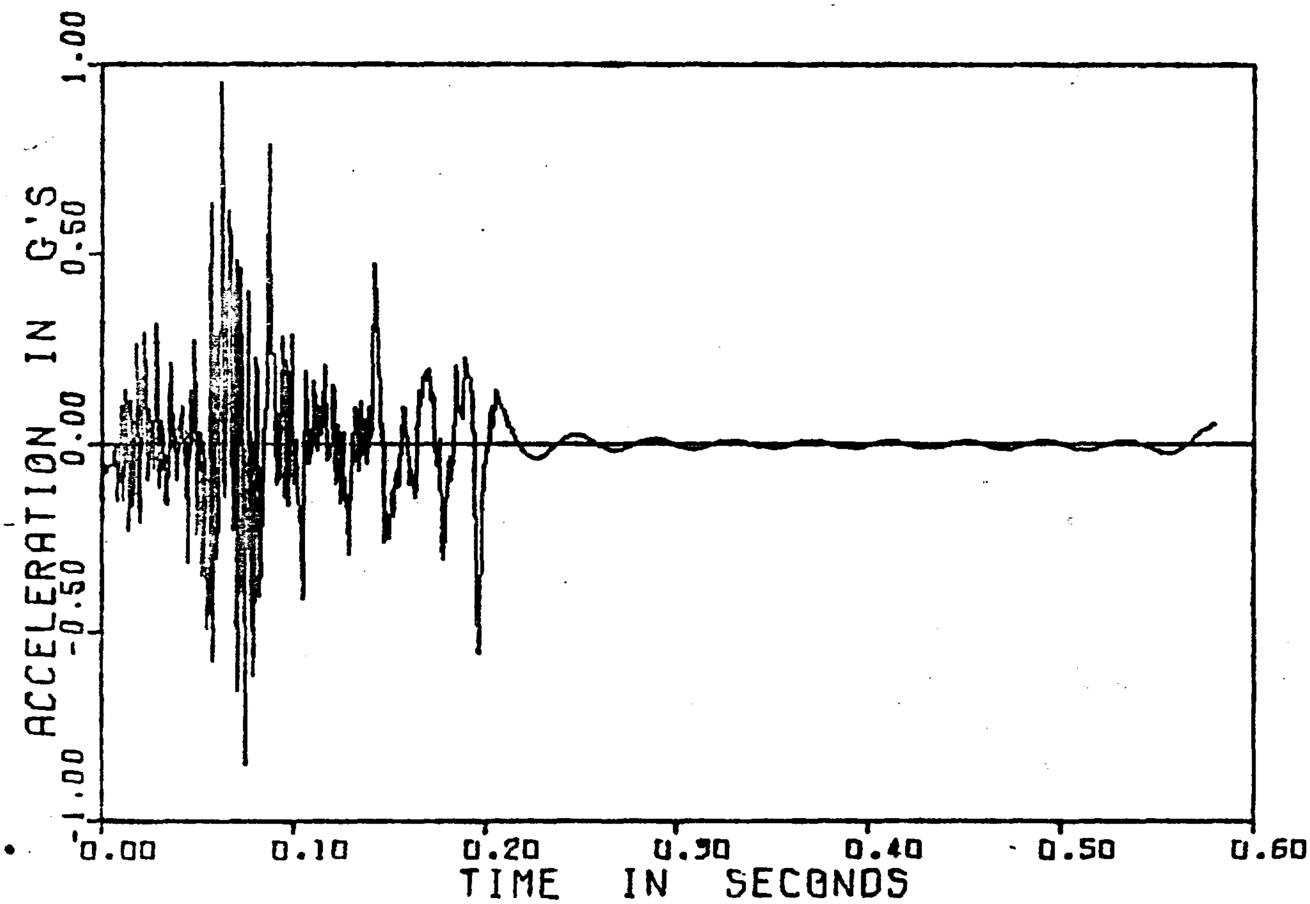
RECORD	EARTHQUAKE	DATE	MAGNITUDE (RICHTER)	PEAK ACCELERATION (g)
CDMG-6	OROVILLE, CA AFTERSHOCK	8/11/75	4.3	0.41
TEMBLOR	PARKFIELD, CA	1966	5.6	0.35
UNDERGROUND RECORD	EAST RAND PROPRIETARY MINES, SOUTH AFRICA	1978	1.5	0.95



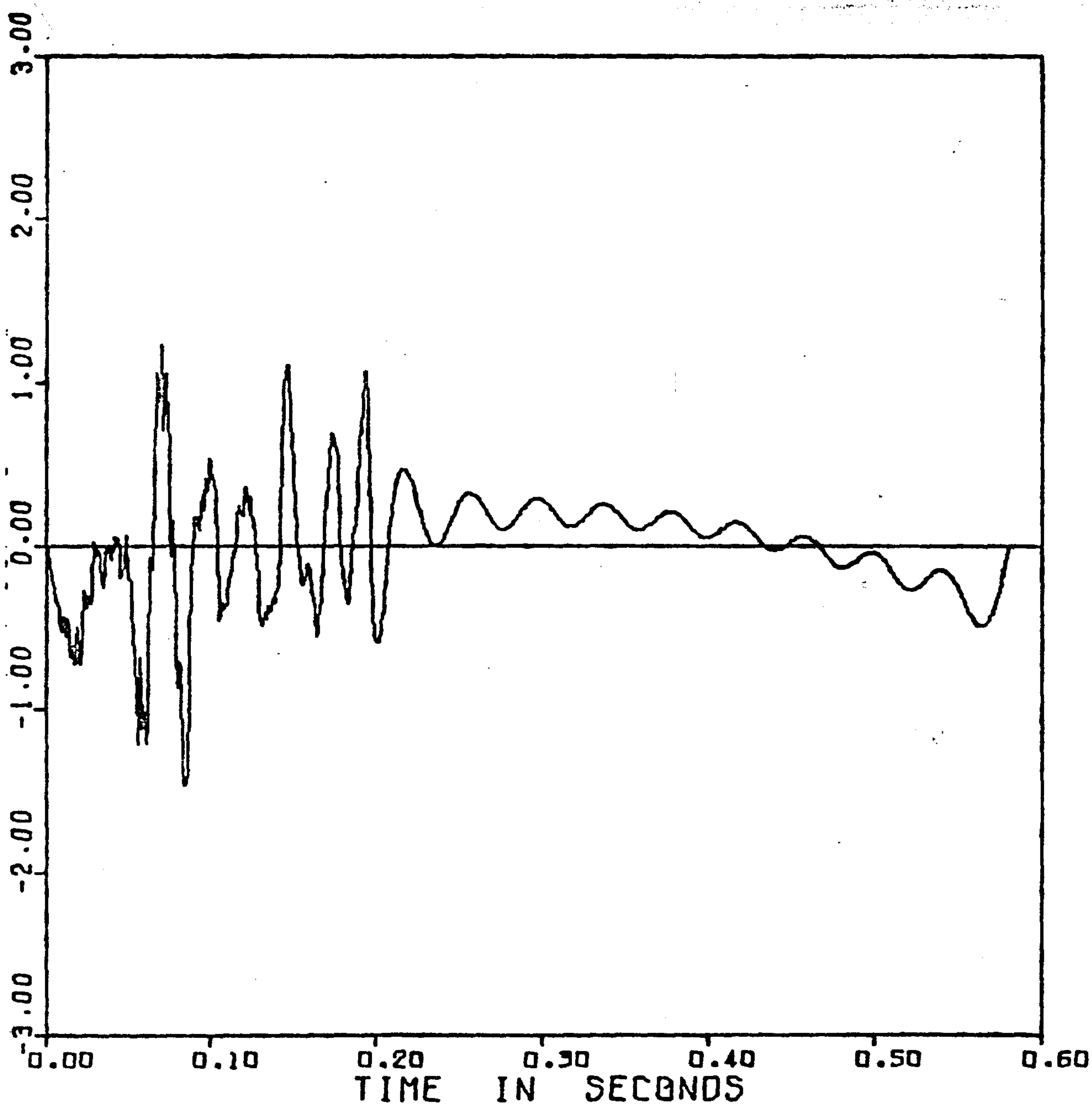
Acceleration Record of Temblor, Parkfield, 1966
- S25W Component



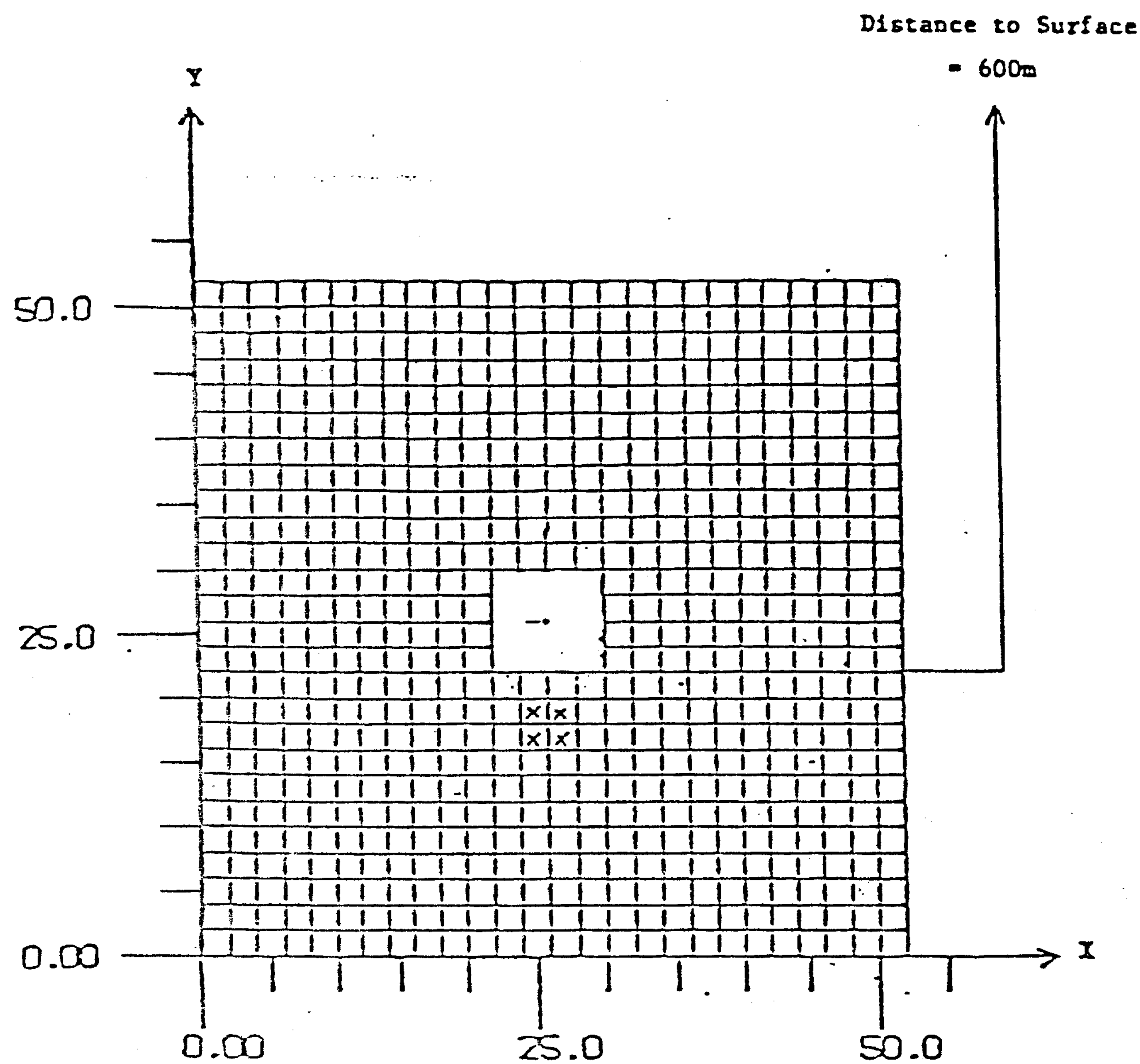
Velocity Record of Temblor, Parkfield, 1966
- S25W Component



Acceleration Record of the East Rand Proprietary Mines, South Africa, 1978 - Longitudinal Component



Velocity Record of the East Rand Proprietary Mines, South Africa, 1978 - Longitudinal Component



KEY

[X] Zones Simulating Canister Heating

Notes

1) Tunnel (or room) dimensions are 8m X 8m.
2) Bottom of tunnel is 600m below surface i.e. top of grid is 570m below the surface.

ASSUMPTIONS COMMON TO ALL ROCK TYPES

DEPTH - TUNNEL 600 M

OVERBURDEN STRESS - 1 PSI/FT

NATURAL TEMPERATURE - 35°C

WASTE - 10 YR OLD SPENT FUEL

THERMAL LOADING - 5 KW CANISTERS 6.5 M APART IN TUNNELS 52 M APART, 60 KW/ACRE

SEQUENCE -

0 YR	EXCAVATION
0.5 YR	WASTE EMPLACEMENT, HEATING
5.5 YR	EARTHQUAKE

NO BACKFILL, NO VENTILATION

NUMERICAL SIMULATION OF EARTHQUAKE EFFECTS ON TUNNELS FOR GENERIC NUCLEAR WASTE REPOSITORIES

Parameters Studied

Rock Type

- Salt
- Granite
- Shale

Earthquake Loading

Oroville,	M = 4.3,	Acc. 0.41 g
Parkfield,	M = 5.6,	Acc. 0.35 g
Mine Tremor,	M = 1.5,	Acc. 0.95 g

In Situ Stress

- Horizontal = Vertical
- Horizontal = 2 Vertical
- Horizontal = 1/2 Vertical

Joint Geometry

- None - Salt
- 1 m Apart - Granite
- 1 m x .2 m - Shale

Stratigraphy

- Homogeneous

Pore Pressure

- None - Salt
- Atmospheric Cavern to Hydrostatic in 12 m
- Atmospheric Cavern to Hydrostatic in 30 m

DEFINITION OF DAMAGE/FAILURE

$$\text{FAILURE} = \frac{\text{DEFORMATION}}{\text{TUNNEL DIMENSION}} > 5\%$$

DAMAGE IS A DELETERIOUS CHANGE BUT MAY OR MAY NOT LEAD TO FAILURE.

1. A FRACTURE THAT CROSSES A CALCULATIONAL ZONE (2 M)

2. JOINT SLIP > 1 CM PER JOINT

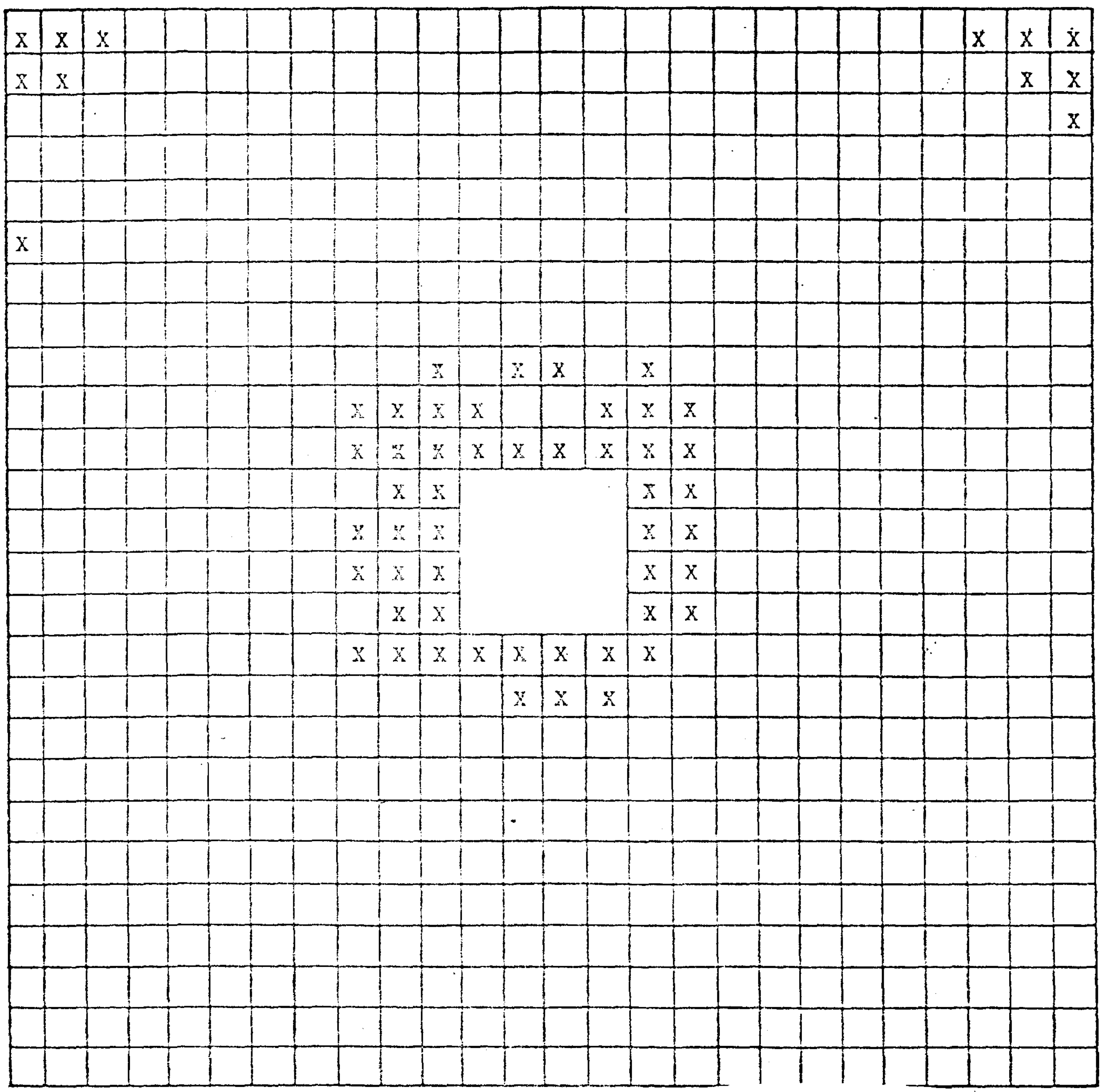
3. CRACK OPENING > .2 CM.

4. NEW THROUGHGOING CRACKS > 2 TUNNEL DIAMETERS

NUMERICAL SIMULATION OF EARTHQUAKE EFFECTS ON TUNNELS FOR GENERIC NUCLEAR WASTE REPOSITORIES

SALT

Simulation/ Property	Run 1	Run 2	Run 3	Run 4	Run 5
Joint Geometry (No Joints)	X	X	X	X	X
Pore Pressure (No Pore Pressure)	X	X	X	X	X
In Situ Stresses ($\sigma_H = \sigma_V$ All Cases)	✓	✓	✓	✓	✓
Fault	X	X	X	X	Large Diagonal Fracture
Thermal Loading	✓	✓	✓	X	✓
Earthquake	Oroville .41 g	Parkfield .35 g	ERPM .95 g	Oroville .41 g	Oroville .41 g
Results	No Damage	No Damage	Velocities Amplified, Cracks Develop, Deformation, Significant Damage	No Damage	No Damage

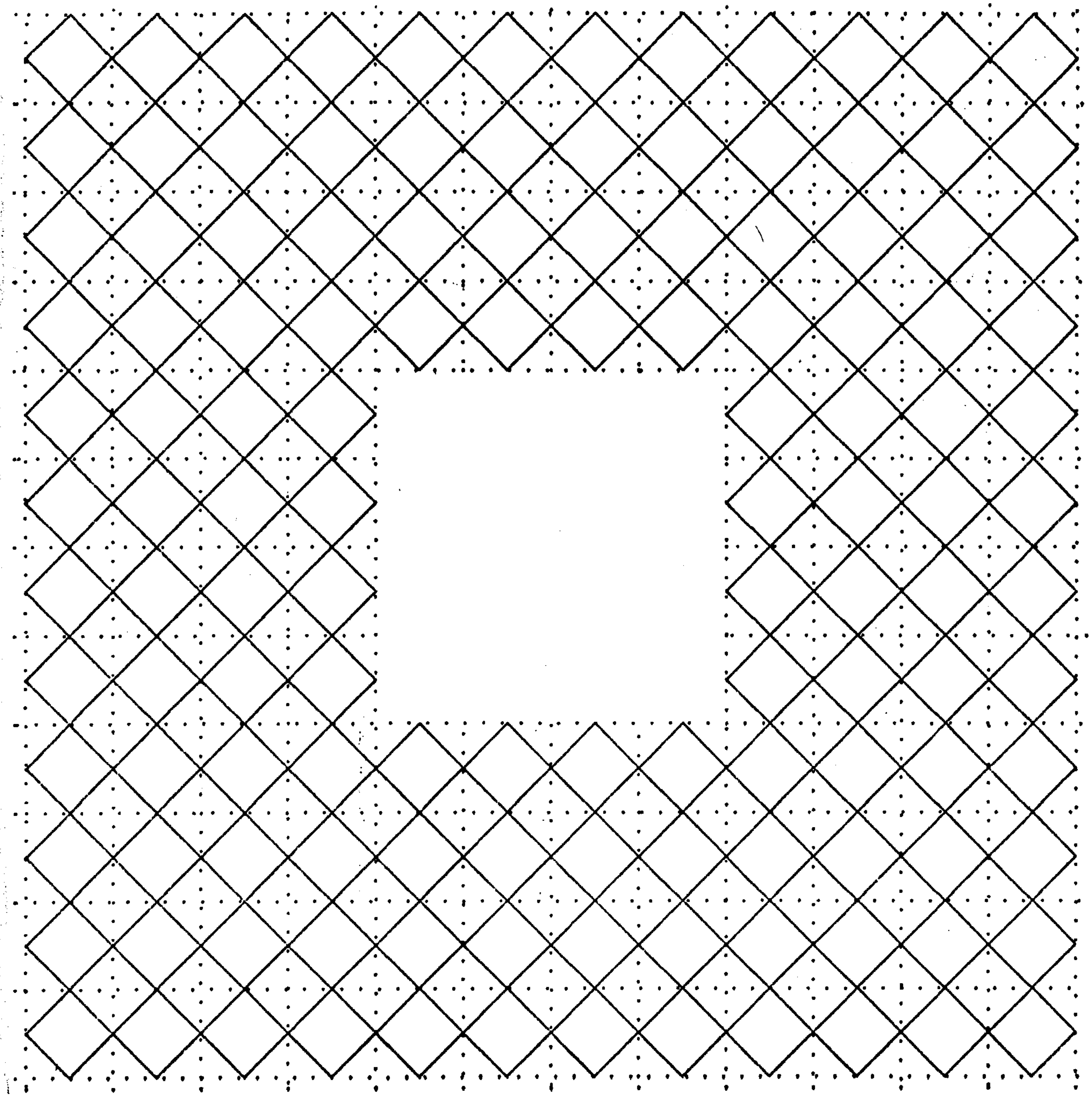


Zones with cracks (indicated by an X) after 0.138 s of earthquake motion in salt, Case 3.

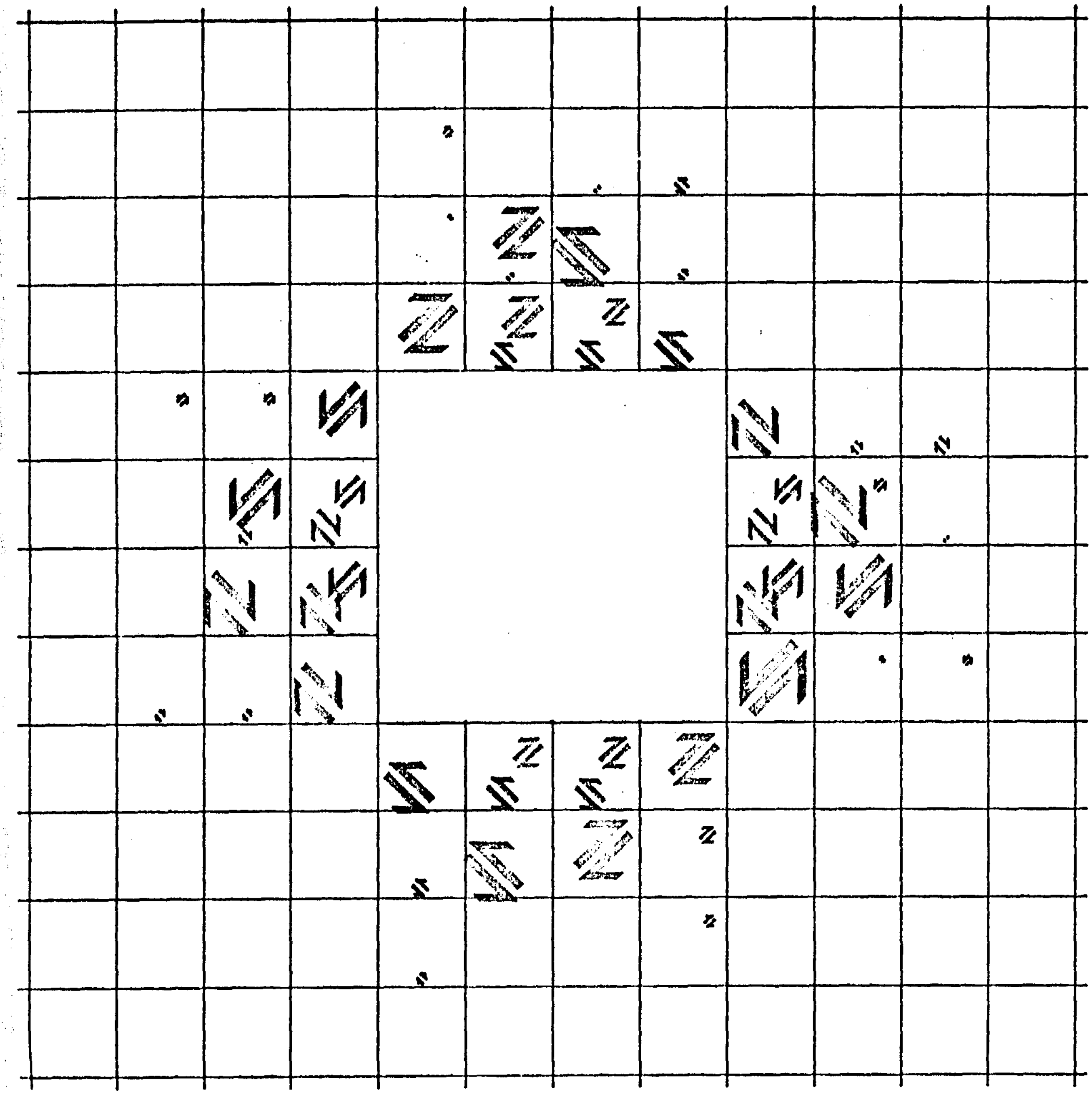
NUMERICAL SIMULATION OF EARTHQUAKE EFFECTS ON TUNNELS FOR GENERIC NUCLEAR WASTE REPOSITORIES

GRANITE

SIMULATION/PROPERTY	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	RUN 6	RUN 7	RUN 8
JOINT GEOMETRY	1 M x 1 M	1 M x 1 M	1 M x 1 M	1 M x 1 M	1 M x 1 M	1 M x 1 M	1 M x 1 M	1 M x 1 M
PORE PRESSURE	X	X	X	H_1	H_2	X	X	X
IN SITU STRESSES	$\sigma_H = \sigma_V$	$\sigma_H = 1/2\sigma_V$	$\sigma_{H_1} = 2\sigma_V$ $\sigma_{H_2} = 2\sigma_V$	$\sigma_H = \sigma_V$	$\sigma_H = \sigma_V$	$\sigma_H = \sigma_V$	$\sigma_{H_1} = 2\sigma_V$ $\sigma_{H_2} = \sigma_V$	$\sigma_{H_1} = 1.5\sigma_V$ $\sigma_{H_2} = 1.5\sigma_V$
THERMAL LOADING	✓	✓	✓	✓	✓	✓	✓	✓
EARTHQUAKE	OROVILLE 0.41 g	OROVILLE 0.41 g	OROVILLE 0.41 g	OROVILLE 0.41 g	OROVILLE 0.41 g	ERPM 0.95 g	OROVILLE 0.41 g	OROVILLE 0.41 g
RESULTS	NO DAMAGE	NO DAMAGE	DAMAGE DURING HEATING PHASE THROUGH JOINT SLIP	NO DAMAGE	NO DAMAGE	SUBSTANTIAL DAMAGE DUE TO CRACKING AND JOINT SLIP	DAMAGE DURING HEATING PHASE THROUGH JOINT SLIP	NO DAMAGE



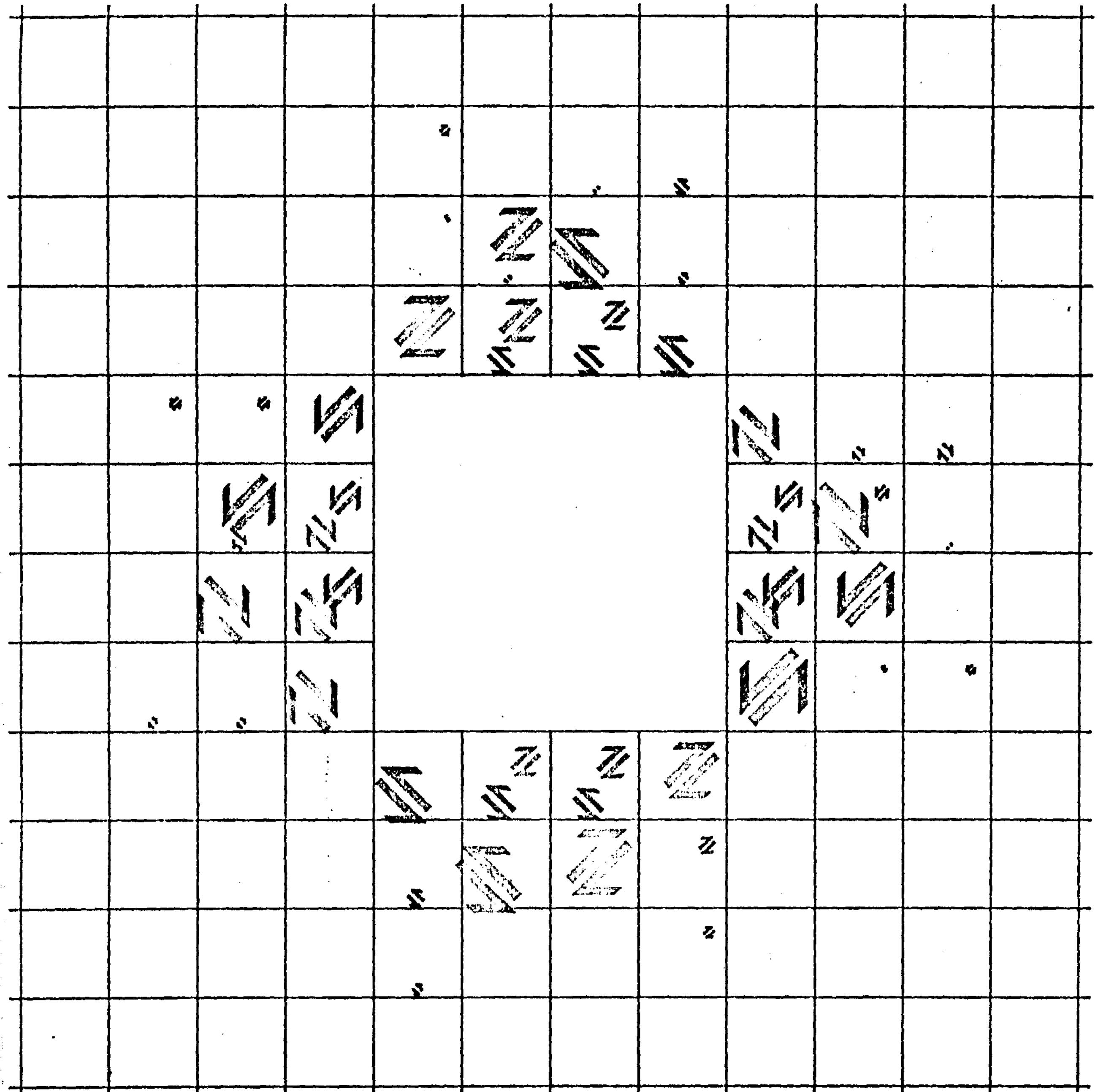
STEALTH MESH FOR GRANITE
(INTERIOR ZONES ONLY)



GRANITE 750 CYC

MAXIMUM SLIP IS 1.20 mm

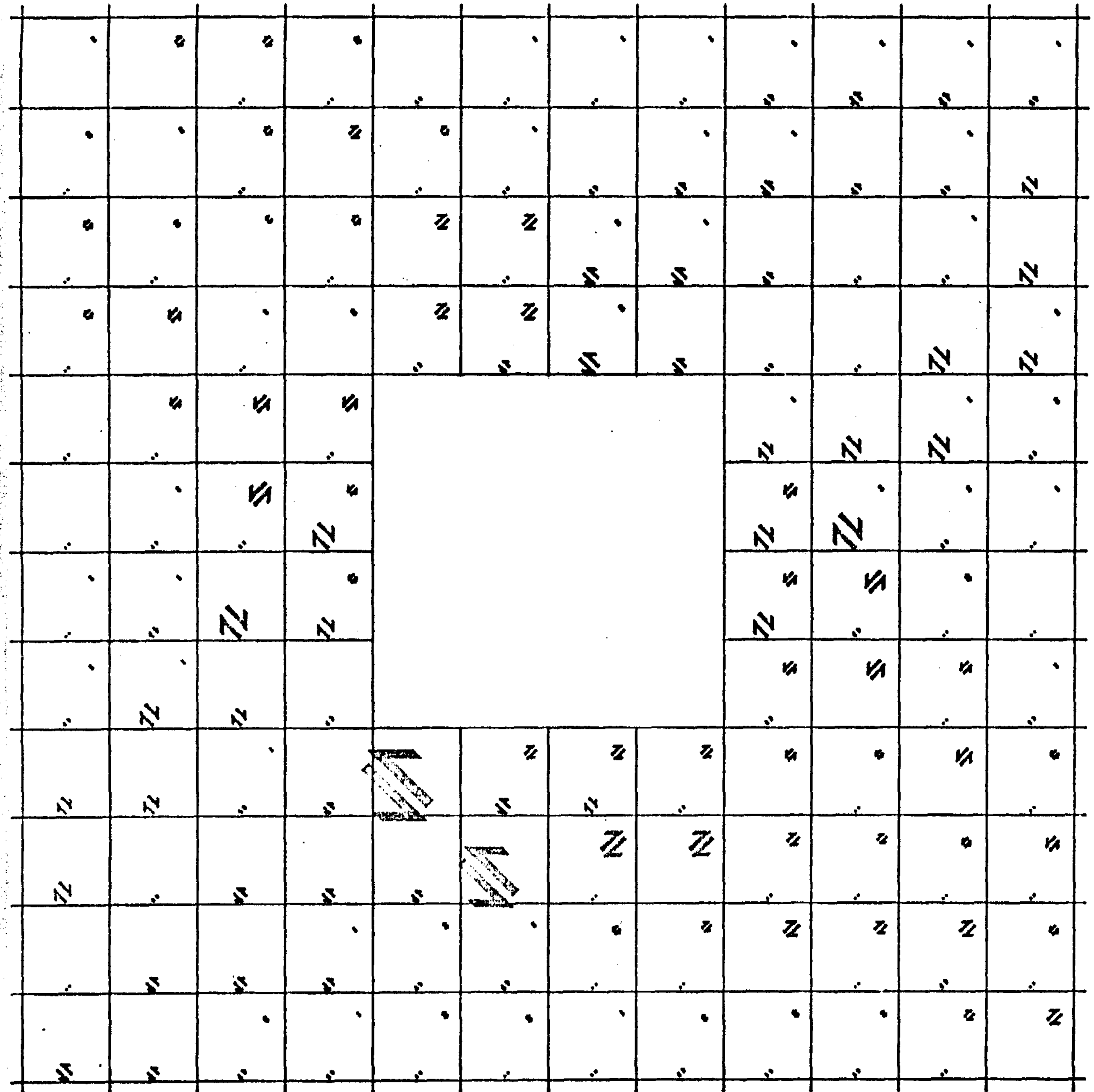
NET RELATIVE SLIP
SINCE TIME ZERO
PER JOINT (NOT ZONE TOTAL



GRANITE 3 S ORO

MAXIMUM SLIP IS 1.20 mm

NET RELATIVE SLIP
SINCE TIME ZERO
PER JOINT (NOT ZONE TOTAL



GRANITE SL ERPM

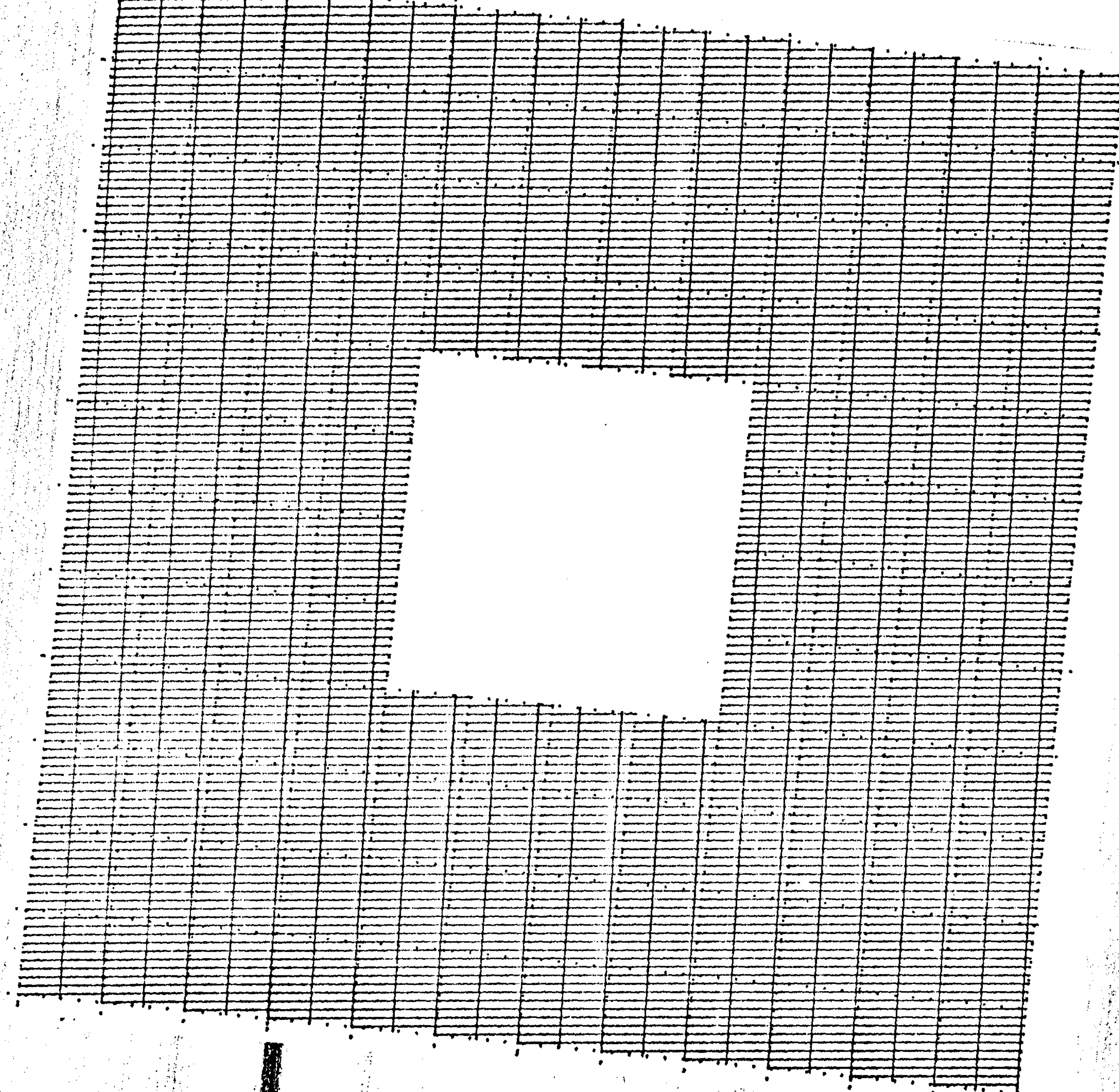
MAXIMUM SLIP IS 30.00 mm

NET RELATIVE SLIP
SINCE TIME ZERO
PER JOINT (NOT ZONE TOTA

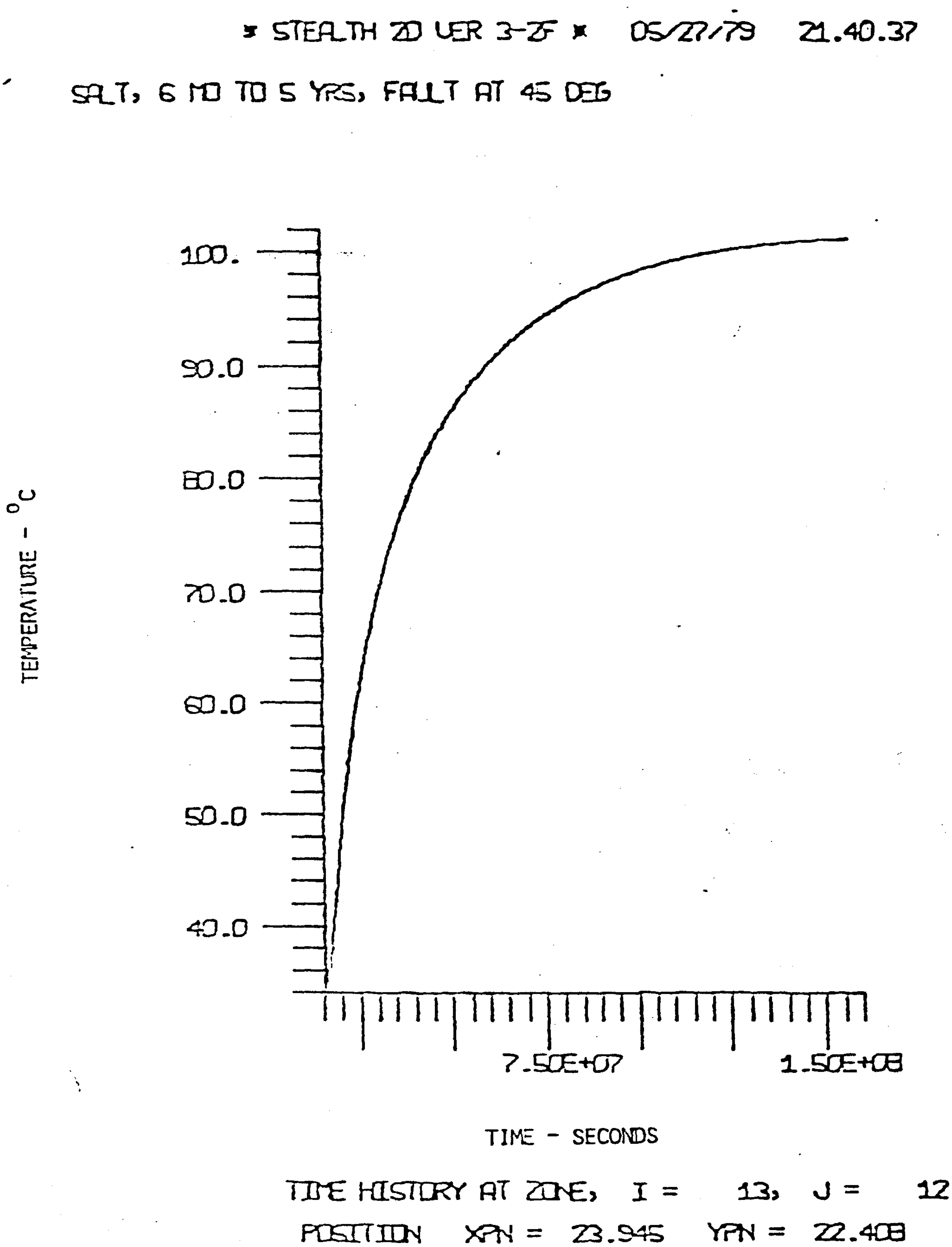
NUMERICAL SIMULATION OF EARTHQUAKE EFFECTS ON TUNNELS FOR GENERIC NUCLEAR WASTE REPOSITORIES

SHALE

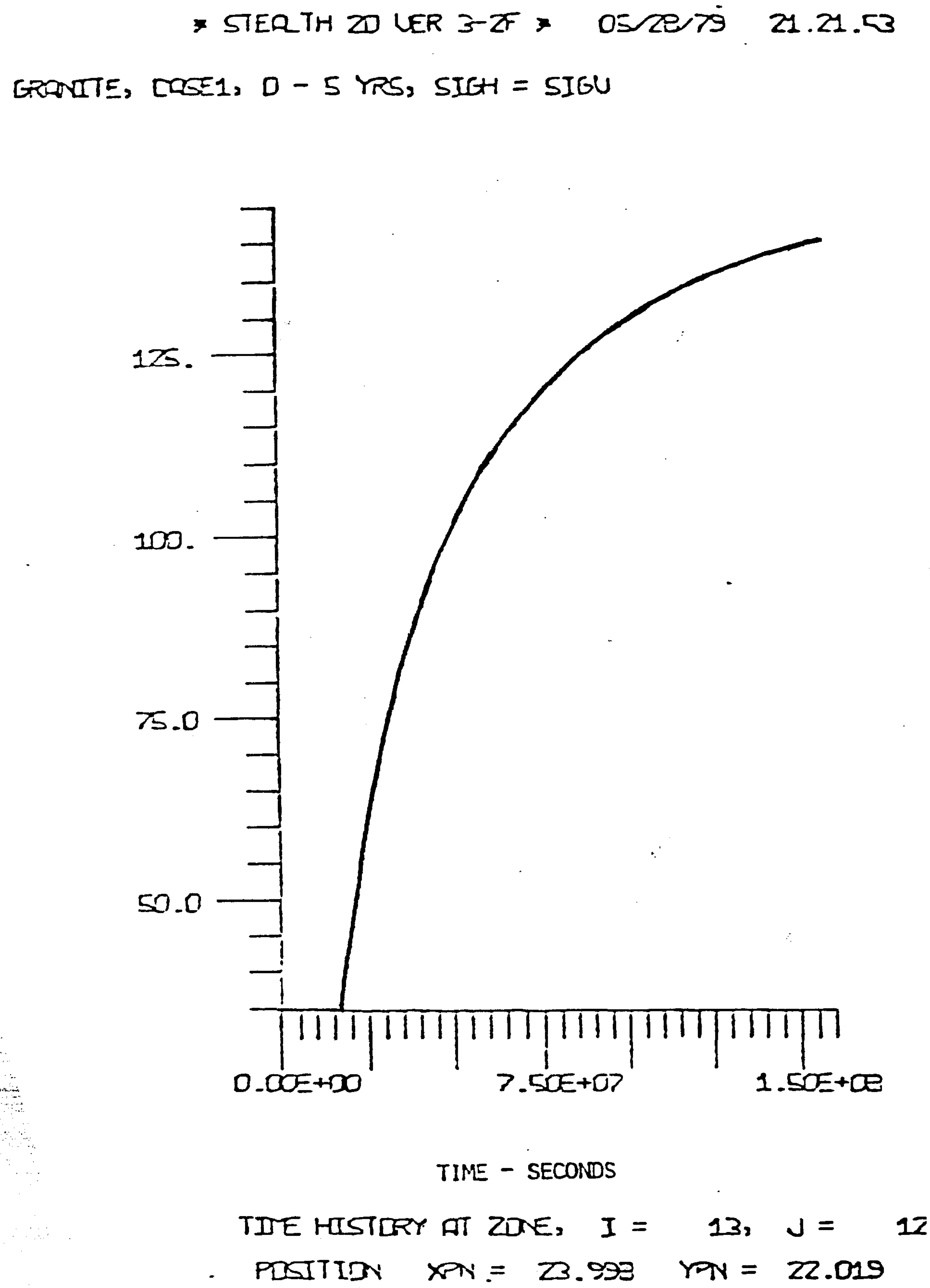
SIMULATION/PROPERTY	RUN 1	RUN 2
JOINT GEOMETRY	1 M X .2 M	1 M X .2 M
PORE PRESSURE	X	H_1
IN SITU STRESSES ($\sigma_H = \sigma_V$ ALL CASES	✓	✓
THERMAL LOADING	✓	✓
EARTHQUAKE	OROVILLE 0.41 g	OROVILLE 0.41 g
ANISOTROPY	✓	✓
RESULTS	STABLE THROUGH HEATING PHASE UNSTABLE DUE TO EARTHQUAKE	DAMAGE DURING HEATING PHASE



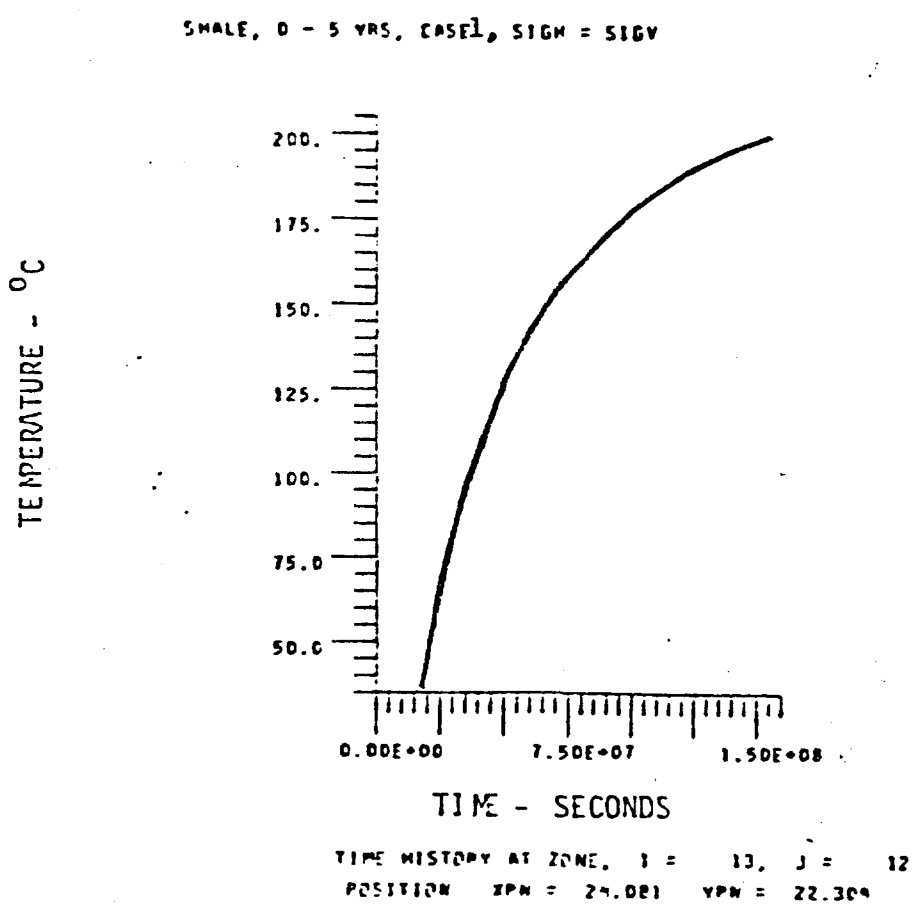
STEALTH MESH FOR SHALE
(INTERIOR ZONES ONLY)



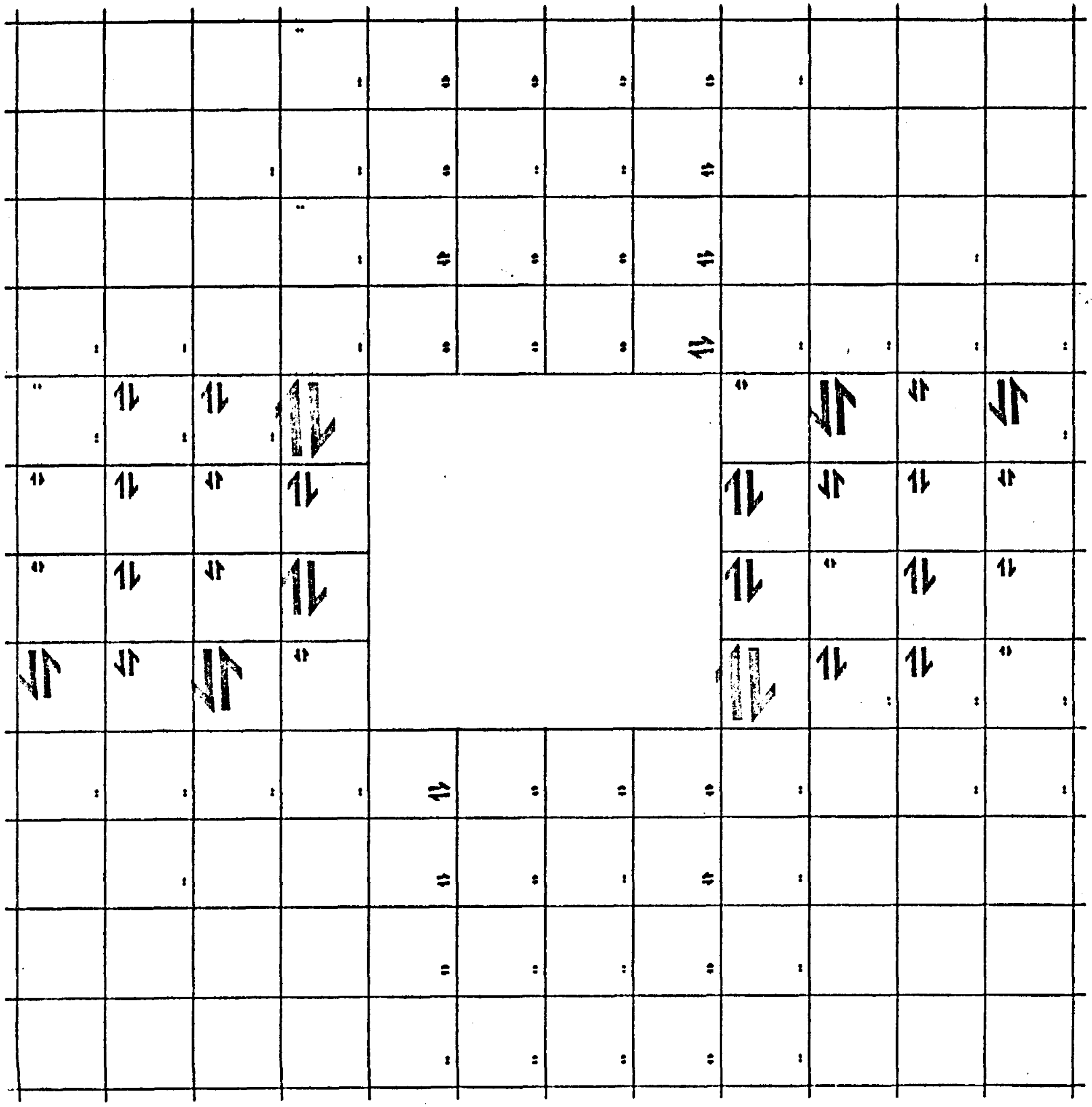
Temperature history adjacent to the heat source in salt (Case 5).



Temperature history adjacent to the heat source in granite (Case 1).



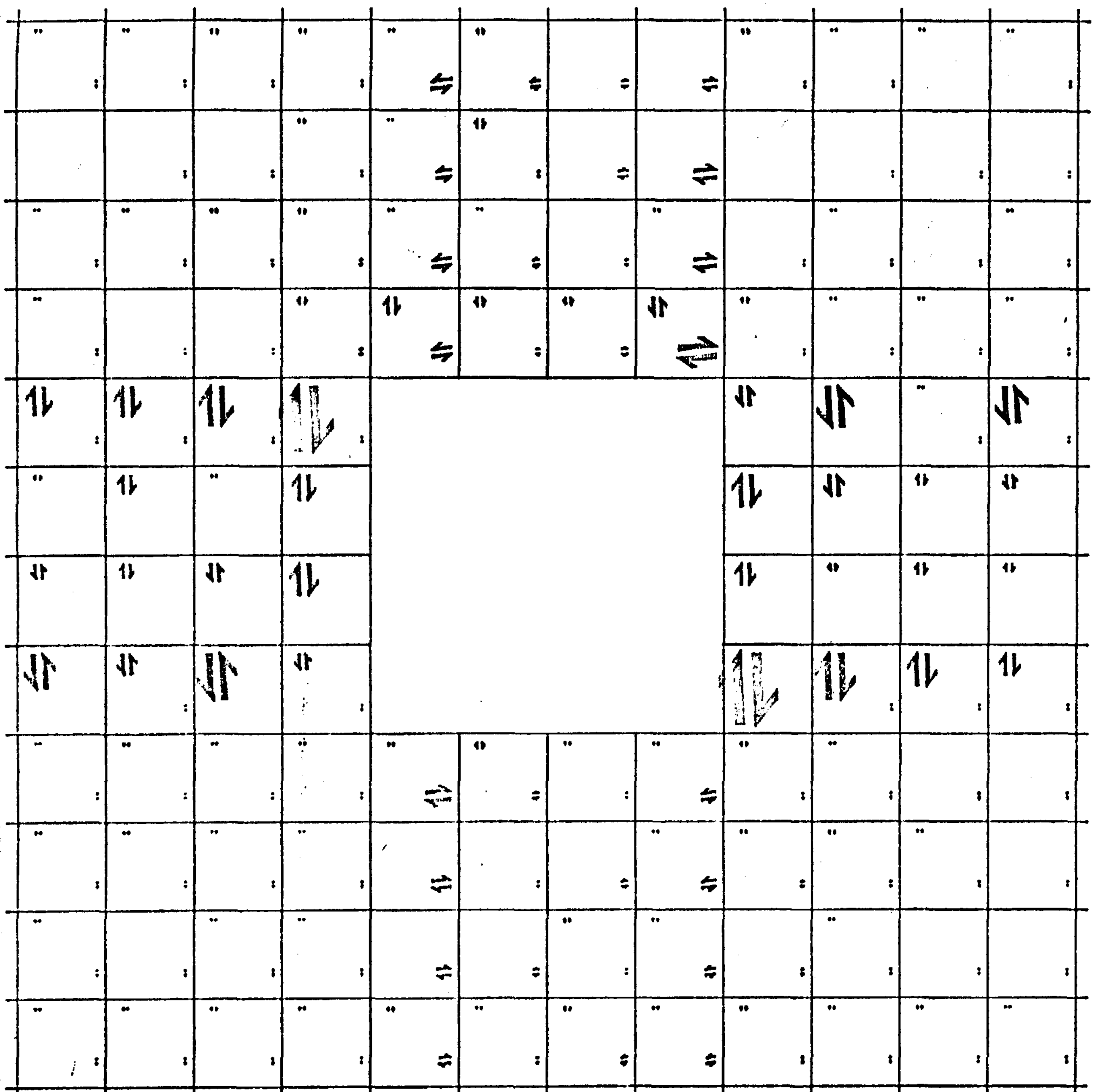
Temperature history adjacent to the heat source in shale (Case 1).



SHALE 800 CYC

MAXIMUM SLIP IS 49.00 mm

NET RELATIVE SLIP
SINCE TIME ZERO
PER JOINT (NOT ZONE TOTAL)



SHALE POST ORO

MAXIMUM SLIP IS 120.00 mm

NET RELATIVE SLIP
SINCE TIME ZERO
PER JOINT (NOT ZONE TOTAL

NUMERICAL SIMULATION OF EARTHQUAKE EFFECTS
ON TUNNELS FOR GENERIC NUCLEAR WASTE REPOSITORIES

CONCLUSIONS:

IN SITU STRESSES ARE IMPORTANT PARAMETERS TO MEASURE IN SELECTING A REPOSITORY SITE.

THERMAL STRESSES ARE GENERALLY MORE RESTRICTIVE THAN EARTHQUAKE STRESSES.

THE STABILITY OF SHALE REPOSITORIES REMAINS TO BE DEMONSTRATED.

NUMERICAL SIMULATION OF EARTHQUAKE EFFECTS ON TUNNELS FOR GENERIC NUCLEAR WASTE REPOSITORIES

CONTRIBUTIONS TO STATE-OF-THE-ART:

- DEVELOPMENT OF INPUT EARTHQUAKE MOTIONS
- DEVELOPMENT OF MATERIAL MODELS TO INCLUDE IN SITU STRESS, HEAT, AND WATER SATURATION
- FIRST TWO-DIMENSIONAL SIMULATION OF AN EARTHQUAKE WAVE PASSING THROUGH A TUNNEL
- DEVELOPMENT OF A JOINT SLIP MODEL
- DEVELOPMENT OF A 2-D TENSILE FAILURE MODEL THAT MONITORED THE OPENING AND CLOSING OF CRACKS

RESEARCH NEEDS

- MODEL VALIDATION THROUGH LABORATORY TESTS
- ADDITIONAL DEVELOPMENT OF MATERIAL PROPERTIES
- COMPARISON WITH FIELD TESTS
- INCREASED USAGE WITH OTHER PARAMETER VALUES AND FOR SITE SPECIFIC CASES
- VALIDATION OF HYDRAULIC FRACTURING TECHNIQUE FOR DETERMINING IN SITU STRESS