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EVALUATION OF LARGE-SCALE SEISMIC TESTING METHODS FOR ELECTRICAL SUBSTATION SYSTEMS

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SUMMARY

To evaluate the feasibility of three groups of experimental techniques to perform large-scale seismic testing for electrical substation systems, we compared quantitatively their waveforms with recorded acceleration records from the Landers and Northridge earthquakes. The three testing methods under investigation in this study were: (1) Shake table (10" and 2" displacement limit); (2) Underground explosive blasts based on data from the Nevada Test Institute (NeTI) facility at the Nevada Test Site; (3) Uncontrolled mining explosions based on data from the Black Thunder Mine (BTM) event of April 3rd, 1997. Based on the analysis results, it is concluded that full-scale experiments are difficult to perform with small (2" displacement limit) shake tables due to their inherent velocity and displacement limitations.). However, among the three groups of records, the analysis results for the large shake table (10" displacement limit) records are the closest to the results for their corresponding earthquake records. Regarding the NeTI facility, due to the large input energy generated by the detonation of the explosives, it is evident that specimens will dissipate energy through non-linear cyclic response, and will sustain considerable structural damage. Finally, the BTM small excitation duration prohibits energy dissipation through hysteretic cycles, and as a result the feasibility of large-scale seismic testing with uncontrolled mining explosions remains questionable.

INTRODUCTION

The objective of the present study, which was part of the PEER Lifelines Project 410, was to assess the capability of the proposed experimental methods to perform large-scale seismic testing for electrical substation systems. The waveforms of shake tables with 10'' and 2'' displacement limit, underground explosive blasts provided from the Nevada Test Institute (NeTI) [1], and uncontrolled mining explosions from the Black Thunder Mine (BTM) event of April 3rd, 1997 [2] were compared, in terms of their intrinsic characteristics and response parameters, with acceleration records from the Landers and Northridge earthquake.

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The Nevada Testing Institute (NeTI), a non-profit institution located in the state of Nevada, is founded to facilitate the use of the Nevada Test Site by researchers primary in University Institutions in U.S. and abroad. The main objective of NeTI is to develop advanced testing capabilities for the testing of earthquake hazard mitigation design and technologies related to seismic resistant engineering systems. Using the Repeatable Earth Shaking by Controlled Underground Expansion (RESCUE) technique for producing strong ground motion [3], the NeTI is developing a full-scale strong ground motion testing facility.

For the Black Thunder Mine (BTM) event of April 3,1997, the length of the explosive array was 1280 m. and the total weight of explosive estimated at 2.95 kilotons. The rows in the explosive array were triggered at 35-millisecond delays. The strong ground motion duration due to this detonation was about 6.0 seconds. A total of 25 accelerometers were fielded for this event. The accelerometers recorded radial, transverse, and vertical measurements at 50, 100, 150, 200, 300, 400 and 500 m. ranges from the explosive array.

The waveform comparison was based on record properties such as the peak absolute acceleration, duration, cumulative absolute velocity, Arias intensity, as well as their Fourier Spectra, response spectra for a linear SDOF system, constant ductility spectra and energy time histories for an elasto-plastic SDOF system. The analysis results for an elasto-plastic SDOF system are the main focus in this paper, since they underline the experimental techniques capability to subject specimens under strong excitation that can yield response beyond the elastic limits.

RECORD DATABASE

The following four groups of acceleration time history records form this study's database:
(1) Earthquake; (2) Shake Table (10 in. displacement limit, 2 in. displacement limit, Telcordia record);
(3) NETI; (4) Black Thunder Mine. The record ensemble with additional information on the data sources, filtering, and duration is given in Table 1.

The PEER Strong Motion Database [4] was the source of the earthquake acceleration data in the first group. From the six near field records (Table 1: R1-R6) two are from the Landers earthquake (1992/06/28), and four from the Northridge earthquake (1994/01/17).

To simulate the waveforms for the two shake table categories (displacement limit of 10 and 2 in.), the six earthquake records from the first group were processed twice (High Pass Ormsby filter) (Table 1: R7-R18).

The Telcordia record (Table 1: R19) is an industrial standard for seismic testing of telecommunication equipments. The test procedure [5, section 5.4] subjects equipment to follow the prescribed motion of the synthesized waveform by means of a shaker table. The acceleration time history waveform VERTEQII has been synthesized from several earthquakes, and for different building types and soil site conditions. The Telcordia record for earthquake risk zone 4, which has the highest acceleration among the risk zones, participated in this analysis.

From the three acceleration data records in the third group, two correspond to the Nevada Test Site test series:
- (R20) NTS, measured 1/7 scale prototype RESQUE source
- (R21) calculated full-scale acceleration time history of R20

The third record (R22) is a full-scale, multi-pulse, synthesized acceleration time history, which corresponds to the detonation of a series of RESQUE sources (provided by Mr. P. Gefken).

The fourth group of data consists of ground accelerations recorded during the Black Thunder Coal Mine blast event of April 3,1997 [Ref. 3]. The locations of the ground motion recording stations in this study with respect to the explosive array source are the following: vertical (50 m); radial (50, 100, 200, 300, 500 m.)

Table 1: Record database (R1-R28).

Records	Name	Type	Recording Source /Station	Data Source	Magnitude (M)	Focal Depth (Km)	Distance to Fault (Km)	Filtering	# Points	DT sec	Duration sec
1	Landers/ LCN260	EQ/Landers (1992/06/28)	SCE/ 24 Lucerne	PEER SMDB	7.3	9	1.1	HP 0.0 - LP 60.0	9625	0.005	48.12
2	Landers/ LCN345	EQ/Landers (1992/06/28)	SCE/24 Lucerne	PEER SMDB	7.3	9	1.1	HP 0.0 - LP 60.0	9625	0.005	48.12
3	Northr/ SCS142	EQ/Northridge (1994/01/17)	DWP/74Sylmar Convert.Sta.	PEER SMDB	6.7	19	6.2	unknown	8000	0.005	39.995
4	Northr/ SCE018	EQ/Northridge (1994/01/17)	DWP/75Sylmar Convert.Sta. East	PEER SMDB	6.7	19	6.1	unknown	8000	0.005	39.995
5	Northr/ RRS-288	EQ/Northridge (1994/01/17)	DWP/77 Rinaldi Receiving Sta.	PEER SMDB	6.7	19	7.1	unknown	2990	0.005	14.945
6	Northr/ PAR-L	EQ/Northridge (1994/01/17)	SCE/ 0 Pardee	PEER SMDB	6.7	19	-	HP 0.5 - LP 20	4425	0.005	22.12
7	Landers/ LCN260	Shake Table, 10" limit	SCE/ 24 Lucerne	PEER SMDB modified	7.3	9	1.1	HP 0.3	9625	0.005	48.12
8	Landers/ LCN345	Shake Table, 10" limit	SCE/24 Lucerne	PEER SMDB modified	7.3	9	1.1	HP 0.05	9625	0.005	48.12
9	Northr/ SCS142	Shake Table, 10" limit	DWP/74Sylmar Convert.Sta.	PEER SMDB modified	6.7	19	6.2	HP 0.3	8000	0.005	39.995
10	Northr/ SCE018	Shake Table, 10" limit	DWP/75Sylmar Convert.Sta. East	PEER SMDB modified	6.7	19	6.1	HP 0.3	8000	0.005	39.995
11	Northr/ RRS-288	Shake Table, 10" limit	DWP/77 Rinaldi Receiving Sta.	PEER SMDB modified	6.7	19	7.1	HP 0.5	2990	0.005	14.945
12	Northr/ PAR-L	Shake Table, 10" limit	SCE/ 0 Pardee	PEER SMDB modified	6.7	19	-	HP 0.05	4425	0.005	22.12
13	Landers/ LCN260	Shake Table, 2" limit	SCE/ 24 Lucerne	PEER SMDB modified	7.3	9	1.1	HP 0.8	9625	0.005	48.12
14	Landers/ LCN345	Shake Table, 2" limit	SCE/24 Lucerne	PEER SMDB modified	7.3	9	1.1	HP 0.4	9625	0.005	48.12
15	Northr/ SCS142	Shake Table, 2" limit	DWP/74Sylmar Convert.Sta.	PEER SMDB modified	6.7	19	6.2	HP 1.4	8000	0.005	39.995
16	Northr/ SCE018	Shake Table, 2" limit	DWP/75Sylmar Convert.Sta. East	PEER SMDB modified	6.7	19	6.1	HP 1.3	8000	0.005	39.995
17	Northr/ RRS-288	Shake Table, 2" limit	DWP/77 Rinaldi Receiving Sta.	PEER SMDB modified	6.7	19	7.1	HP 1.6	2990	0.005	14.945
18	Northr/ PAR-L	Shake Table, 2" limit	SCE/ 0 Pardee	PEER SMDB	6.7	19	-	HP 1.3	4425	0.005	22.12

				modified							
19	Telcordia	Shake Table	Synthetic	Telcordia GR-63-CORE	n.a.	n.a.	n.a.	-	6145	0.005	30.72
20	Measured NTS-5	NETI	NETI	Gefken transmittal 4/2001	n.a.	n.a.	n.a.	-	520	0.005	2.595
21	Scaled NTS-5	NETI	NETI	Gefken transmittal modified	n.a.	n.a.	n.a.	-	3638	0.005	18.185
22	Synthesized NTS	NETI	Synthesized	Gefken transmittal 4/11/2001	n.a.	n.a.	n.a.	-	10733	0.005	53.66
23	50m radial	Black Thunder Mine	BTM/ARA	ARA Report	n.a.	n.a.	n.a.	LP 80	1501	0.005	7.5
24	50 m vertical	Black Thunder Mine	BTM/ARA	ARA Report	n.a.	n.a.	n.a.	LP 80	1501	0.005	7.5
25	100 m radial	Black Thunder Mine	BTM/ARA	ARA Report	n.a.	n.a.	n.a.	LP 80	1501	0.01	15.01
26	200m radial	Black Thunder Mine	BTM/ARA	ARA Report	n.a.	n.a.	n.a.	LP 80	1501	0.01	15.01
27	300m radial	Black Thunder Mine	BTM/ARA	ARA Report	n.a.	n.a.	n.a.	LP 80	1501	0.01	15.01
28	500 m radial	Black Thunder Mine	BTM/ARA	ARA Report	n.a.	n.a.	n.a.	LP 80	1501	0.01	15.01

RECORD CHARACTERISTICS

The six quantities evaluated for the record ensemble were the following (Table 2):

- The peak absolute acceleration (PA), velocity (PV), and displacement (PD).
- The bracketed duration [D]. To measure bracketed duration corresponding to a given acceleration level, the first and last occurrences of accelerations equal to or larger than a prescribed value are marked on the acceleration trace. The time duration between these two markings is called bracketed duration (Bolt 1969; Page and others 1972). In this study, the bracketed duration corresponding to 0.05g acceleration is evaluated for the record ensemble.
- The Arias Intensity (AI) given by:

$$AI_{ij} = \pi / 2g \int_{0}^{t0} a_i(t) a_j(t) dt \qquad \text{(Eq.1)}$$

where t0: the record duration

$a_i(t), \alpha_j(t)$: Acceleration amplitudes of the orthogonal components

The AI (Arias, [6]) is a measure of seismic intensity and has a tensorial character (nine components); in this study the scalar value is used.

- The Cumulative Absolute Velocity (CAV) defined as the area under the absolute acceleration versus duration curve is given by:

$$CAV = \int_{o}^{t0} |\alpha(t)| dt \qquad \text{(Eq.2)}$$

Kennedy and Reed [7] originally proposed this parameter in a study sponsored by the Electrical Power Research Inst. It was used as an indicator for potential damage in nuclear power plants.

Later on, the method of calculating CAV was modified to remove the dependence on records of long duration containing low (non-damaging) accelerations [8]. The method to standardize the CAV calculation, which is adopted in this study, consists of calculating incrementally the parameter in 1 sec intervals. Each interval contributes to the sum only if it has at least one peak that exceeds the fixed acceleration level of 0.025g.

Table 2: Records characteristics.

PA: Peak absolute acceleration
PV: Peak absolute velocity
PD: Peak absolute displacement
[D]: 0.05g Bracketed duration
AI: Arias Intensity
CAV: Cumulative absolute velocity

Records	Name	Type	PA (g)	PV (cm/s)	PD (cm)	[D] (sec)	AI (gsec)	CAV (gsec)
1	Landers/LCN260	EQ/Landers (1992/06/28)	0.727	146.5	262.7	33.255	0.711	2.535
2	Landers/LCN345	EQ/Landers	0.789	32.4	69.8	33.32	0.671	2.511
3	Northr/SCS142	EQ/Northridge (1994/01/17)	0.897	102.8	47.0	27.29	0.538	1.653
4	Northr/SCE018	EQ/Northridge	0.828	117.5	34.2	17.055	0.458	1.424
5	Northr/RRS-288	EQ/Northridge	0.838	166.1	28.8	13.095	0.751	1.675
6	Northr/PAR-L	EQ/Northridge	0.657	75.2	13.2	17.945	0.315	1.138
7	Landers/LCN260	Shake Table, 10" limit	0.685	78.06	25.89	33.255	0.689	2.51
8	Landers/LCN345	Shake Table, 10" limit	0.789	27.19	23.66	33.2	0.671	2.511
9	Northr/SCS142	Shake Table, 10" limit	0.892	85.75	20.2	27.64	0.537	1.636
10	Northr/SCE018	Shake Table, 10" limit	0.831	103.54	22.66	17.245	0.456	1.425
11	Northr/RRS-288	Shake Table, 10" limit	0.818	138.93	24.99	13.305	0.737	1.66
12	Northr/PAR-L	Shake Table, 10" limit	0.657	75.21	13.15	17.945	0.315	1.138
13	Landers/LCN260	Shake Table, 2" limit	0.689	36.23	4.52	33.255	0.662	2.469
14	Landers/LCN345	Shake Table, 2" limit	0.788	20.41	4.97	33.32	0.669	2.507
15	Northr/SCS142	Shake Table, 2" limit	0.594	40.87	4.56	12.84	0.233	1.009
16	Northr/SCE018	Shake Table, 2" limit	0.807	46.59	4.87	13.8	0.347	1.217
17	Northr/RRS-288	Shake Table, 2" limit	0.622	53.34	4.79	13.3	0.405	1.352
18	Northr/PAR-L	Shake Table, 2" limit	0.508	33.87	4.88	17.385	0.145	0.804
19	Telcordia	Shake Table Standard	1.65	103.1	12.78	29.98	7.151	8.072
20	Measured NTS-5	NeTI	3.467	58.1	4.68	2.3	0.511	0.362
21	Scaled NTS-5	NeTI	0.543	58.2	32.77	3.93	0.072	0.3
22	Synthesized NTS	NeTI	0.97	122.8	50.82	36.215	2.9	5.972
23	50m radial	Black Thunder Mine	2.871	18.95	2.09	7.365	1.363	1.286
24	50 m vertical	Black Thunder Mine	4.163	31.81	1.82	7.245	2.054	1.581
25	100 m radial	Black Thunder Mine	1.902	27.92	2.39	5.64	1.295	1.382
26	200 m radial	Black Thunder Mine	0.761	11.31	1.55	5.42	0.212	0.628
27	300 m radial	Black Thunder Mine	0.374	8.43	0.64	5.53	0.097	0.455
28	500 m radial	Black Thunder Mine	0.231	3.33	0.63	5.29	0.036	0.278

ANALYSIS FOR AN ELASTOPLASTIC SDOF SYSTEM

The governing equation for an inelastic system is given by:

$$m\ddot{u}(t) + c\dot{u}(t) + f_s(u(t), \dot{u}(t)) = -m\ddot{u}_s(t) \qquad \text{(Eq.3)}$$

For a certain deformation *u(t)*, the restoring depends on the prior history of motion of the system, and whether the deformation is currently increasing ($\dot{u}(t) > 0$) or decreasing ($\dot{u}(t) < 0$). To identify the system parameters that influence the deformation response *u(t)*, Eq.(3) is divided by the mass *m* to obtain

$$\ddot{u}(t) + 2\xi\omega_n\dot{u}(t) + \omega_n^2 u_y \tilde{f}_s(u, \dot{u}) = -\ddot{u}_s(t) \qquad \text{(Eq.4)}$$

where the function $\tilde{f}_s(u, \dot{u}) = \dfrac{f_s(u, \dot{u})}{f_y}$ (Eq.5)

describes the force deformation relation in dimensionless form. Eq.4 indicates that for a given support acceleration at time t, the system response depends on three system parameters: ω_n, ξ, and u_y, in addition to the force-deformation diagram.

Eq.4 can be rewritten in terms of the displacement ductility factor $\mu(t)$ by substituting:

$$u(t) = u_y\mu(t),\ \dot{u}(t) = u_y\dot{\mu}(t),\ \ddot{u}(t) = u_y\ddot{\mu}(t) \qquad \text{(Eq.6)}$$

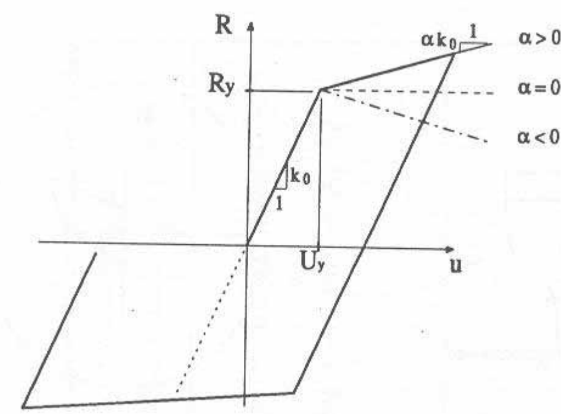


Figure 1: Bilinear Hysteretic Model

which results in

$$\ddot{\mu}(t) + 2\xi\omega_n\dot{\mu}(t) + \omega_n^2\tilde{f}_s(\mu, \dot{\mu}) = -\frac{\omega_n^2\ddot{u}_s(t)}{C_y \cdot g} \qquad \text{(Eq.7)}$$

where the coefficient C_y is given by $C_y = \dfrac{f_y}{m \cdot g}$ (Eq.8)

The acceleration, displacement and velocity values for the elastoplastic SDOF system are derived by analytical integration of the equation of motion, by assuming the piecewise linearity of the force-deformation relationship and the excitation time histories. (For a detailed explanation on the derivation of the inelastic SDOF response see Ref.9, Appendix 2).

In this study, the analysis for an elastoplastic system (Fig.1; α = 0.0) was performed for period values ranging from 0.02 to 3.0 sec and the following parameters:

Strength Coefficient Cy = 0.25, *Damping ratio* ξ = 0.05 C_{cr}, *Weight = 1.0, Hardening ratio* α = 0

The peak absolute values for the acceleration, displacement and ductility factor for selective period values (T= 3.0, 1.0, 0.3, 0.2 sec) are given in Table 3.

Table 3: Peak absolute values for an elastoplastic system with 5% critical damping.

SA 3, SA 1, SA .3, SA .2: Peak absolute acceleration for period 3.0, 1.0, 0.3, 0.2 sec (g)
SD 3, SD 1, SD.3, SD .2: Peak absolute displacement for period 3.0, 1.0, 0.3, 0.2 sec (cm)
Duct 3, Duct 1, Duct .3, Duct .2: Maximum ductility for period 3.0, 1.0, 0.3, 0.2 sec

Records	Name	Type	SA3	SA 1	SA .3	SA .2	SD 3	SD 1	SD .3	SD .2	Duct3	Duct1	Duct.3	Duct.2
1	Landers/ LCN260	EQ/Landers (1992/06/28)	0.795	0.744	0.841	0.823	74.43	18.14	3.43	3.1	1.331	2.956	22.893	12.482
2	Landers/ LCN345	EQ/Landers	0.807	0.853	0.909	0.861	26.46	7.57	2.16	1.08	0.473	1.219	3.873	4.336
3	Northr/S CS142	EQ/Northridge (1994/01/17)	0.996	1.09	0.589	0.567	41.06	32.1	10.1	8.67	0.734	5.168	18.069	34.915
4	Northr/S CE018	EQ/Northridge	1.029	1.062	0.916	0.799	63.56	26.45	11.4	10.77	1.137	4.258	20.387	43.343
5	Northr/R RS-288	EQ/Northridge	1.05	1.017	0.959	0.896	58.42	31.24	25.3	18.34	1.045	5.029	45.253	73.825
6	Northr/P AR-L	EQ/Northridge	0.708	0.895	0.466	0.363	16.34	22.62	7.78	5.28	0.292	3.641	13.919	21.274
7	Landers/ LCN260	Shake Table, 10" limit	0.821	0.779	0.809	0.802	53.36	13.18	2.2	2.5	0.954	2.122	3.923	10.06
8	Landers/ LCN345	Shake Table, 10" limit	0.807	0.853	0.908	0.86	26.35	7.57	2.17	1.04	0.471	1.219	3.877	4.191
9	Northr/S CS142	Shake Table, 10" limit	0.998	1.096	0.583	0.566	35.53	35.1	10.28	7.49	0.635	5.651	18.39	30.142
10	Northr/S CE018	Shake Table, 10" limit	1.021	1.065	0.901	0.773	70.42	27.34	11.7	10.96	1.26	4.401	20.909	44.095
11	Northr/R RS-288	Shake Table, 10" limit	0.969	1.014	0.944	0.882	38.96	28	21.55	18.9	0.697	4.507	38.548	76.047
12	Northr/P AR-L	Shake Table, 10" limit	0.708	0.896	0.466	0.363	16.33	22.62	7.78	5.29	0.292	3.642	13.925	21.281
13	Landers/ LCN260	Shake Table, 2" limit	0.702	0.802	0.783	0.78	6.66	7.67	2.79	2.59	6.665	7.672	2.787	2.589
14	Landers/ LCN345	Shake Table, 2" limit	0.795	0.856	0.917	0.859	16.24	7.32	1.94	1.12	0.29	1.179	3.468	4.51
15	Northr/S CS142	Shake Table, 2" limit	0.618	0.668	0.501	0.45	5.02	15.25	4.57	2.81	0.09	2.456	8.169	11.308
16	Northr/S CE018	Shake Table, 2" limit	0.83	1.045	0.822	0.817	4.96	12.11	10.08	9.32	0.089	1.95	18.032	37.491
17	Northr/R RS-288	Shake Table, 2" limit	0.632	0.802	0.763	0.617	5.01	11.52	4.1	4.39	0.09	1.855	7.34	17.678
18	Northr/P AR-L	Shake Table, 2" limit	0.528	0.661	0.542	0.294	5.56	11.62	3.42	1.15	0.099	1.871	6.113	4.631
19	Telcordia	Shake Table	1.691	1.896	1.66	1.608	14.11	21.92	14.71	14.04	0.252	3.528	26.327	56.491
20	Measure d NTS-5	NeTI	3.461	3.445	3.349	3.245	4.51	3.9	2.81	2.56	0.081	0.628	5.02	10.291
21	Scaled NTS-5	NeTI	0.532	0.522	0.322	0.28	38.18	10.02	3.58	2.51	0.683	1.614	6.406	10.086
22	Synthesiz ed NTS	NeTI	1.143	0.809	0.649	0.622	82.7	90.79	39.79	43.02	1.479	14.615	71.173	173.129
23	50m radial	Black Thunder Mine	2.878	2.88	2.776	2.942	3.64	0.77	0.99	0.84	0.065	0.125	1.769	3.39
24	50 m vertical	Black Thunder Mine	4.17	4.178	4.263	4.47	3.14	1.16	0.91	2.85	0.056	0.187	1.621	11.463
25	100 m radial	Black Thunder Mine	1.9	1.905	2.175	2.128	1.269	0.765	0.631	0.888	0.023	0.123	1.141	3.589
26	200 m radial	Black Thunder Mine	0.761	0.764	0.662	0.839	1.027	0.516	0.796	0.978	0.018	0.083	1.424	3.943
27	300 m radial	Black Thunder Mine	0.375	0.382	0.61	0.646	0.568	0.427	0.878	0.483	0.01	0.069	1.575	1.943
28	500 m radial	Black Thunder Mine	0.231	0.233	0.319	0.401	0.312	0.295	0.248	0.311	0.006	0.047	0.444	1.267

The peak absolute accelerations (SA) for the earthquake (R1-R6) and the corresponding large shake tables (R7-R12) have almost equal values; for the small (R8-R13) shake table records the SAs are slightly reduced. The Telcordia (R19), measured NETI (R20), and the BTM (R23, R24, and R25) records, they all have larger SA values than the earthquake records.

The large peak absolute displacement (SD) values imply significant inelastic behavior. The synthesized NETI (R22) has the largest SD values, and the BTM (R23-R28) records the smallest among the record ensemble. The ductility demand for short period systems (T < 0.3 sec) is very large for the given strength coefficient ($Cy = 0.25$). This result implies that these systems should be designed for a yield strength f_y the same as the strength required by the system to remain elastic; otherwise the inelastic deformation and ductility demand may be excessive.

Constant Ductility Spectra for an elastoplastic SDOF system

In design applications, the effect of yielding is to reduce the value of the design loads below those required for elastic behavior; the magnitude of this reduction being a function of the degree of inelastic behavior that can be tolerated by the system. The system's ductility capacity is given by the system's ductility factor μ. For a specified system's ductility capacity, the construction of the constant ductility spectra allows the determination of the yield strength fy, which is necessary to limit the ductility demand imposed by the excitation to the system's inherent allowable ductility.

In the present study, constant ductility spectra for ductility factor μ = 4 are constructed for the record ensemble and are presented in Figs.2 – 4. An interpolating procedure is necessary to obtain the yield strength of an elastoplastic system for a specified ductility factor, since the response of a system with arbitrarily selected yield strength will seldom correspond to the desired ductility value [8, Section 7.5.3]. The data from Figs.2 – 4 demonstrate the strength demand imposed by the ground / shake table motion on a system with ductility capacity μ =4.0.

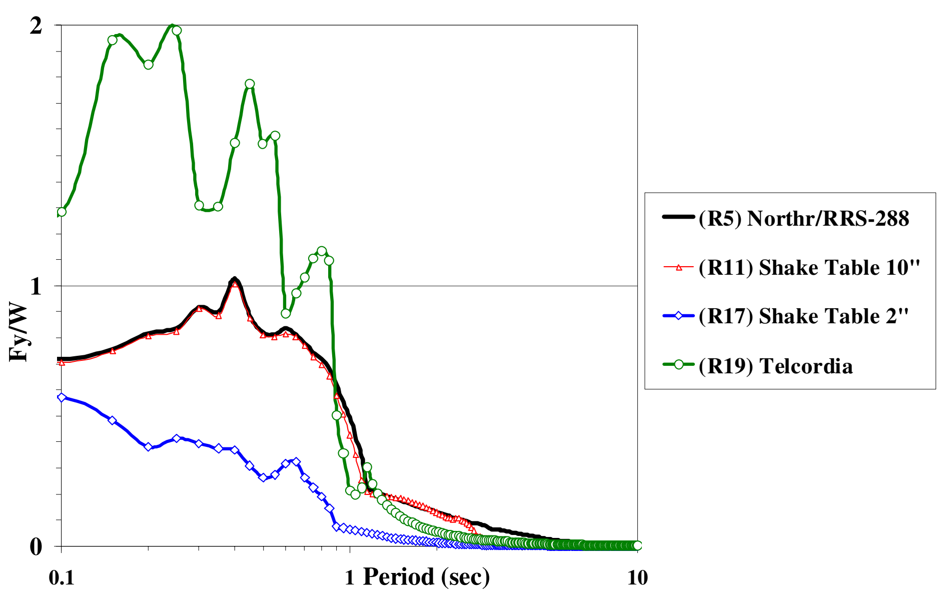


Figure 2: Constant ductility spectra for the Northr/RRS-288 (R5, R11, R17) and Telcordia (R19) records (Ductility = 4.0)

The two spectra for the Northr/RRS-288 and the shake table 10" coincide through the period value 3.0 sec (Fig.2). The 2"shake table has significantly smaller values. The Telcordia record imposed the largest yield strength value from the record ensemble ($f_y max = 1.981$ W for period T = 0.25 sec) on the elastoplastic system under consideration, and it is the only record which its spectrum values exceeded those from the North/RRS record for the range of period values 0.1 – 0.9 sec.).

Fig.3 depicts the constant ductility spectra for the NETI records. The yield strength values for the synthesized NETI record fluctuate between the North/RRS-288 values for the smaller period range (0.1 – 1.0 sec) and exceed these values for the larger period range (1.0 – 10.0 sec). The measured NeTI record spectrum exceeds the North/RRS spectrum only in the small period range (0.1 – 0.15 sec) and for the period range (0.15 –10.0 sec) the measured NETI spectrum values are almost 10 times smaller than the yield strength values for the North/RRS-288.

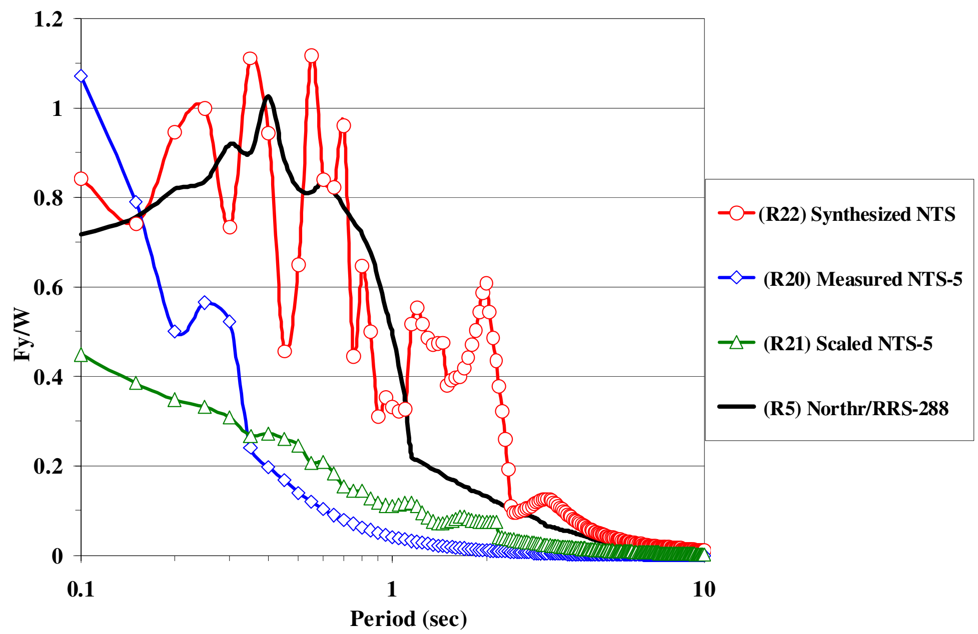
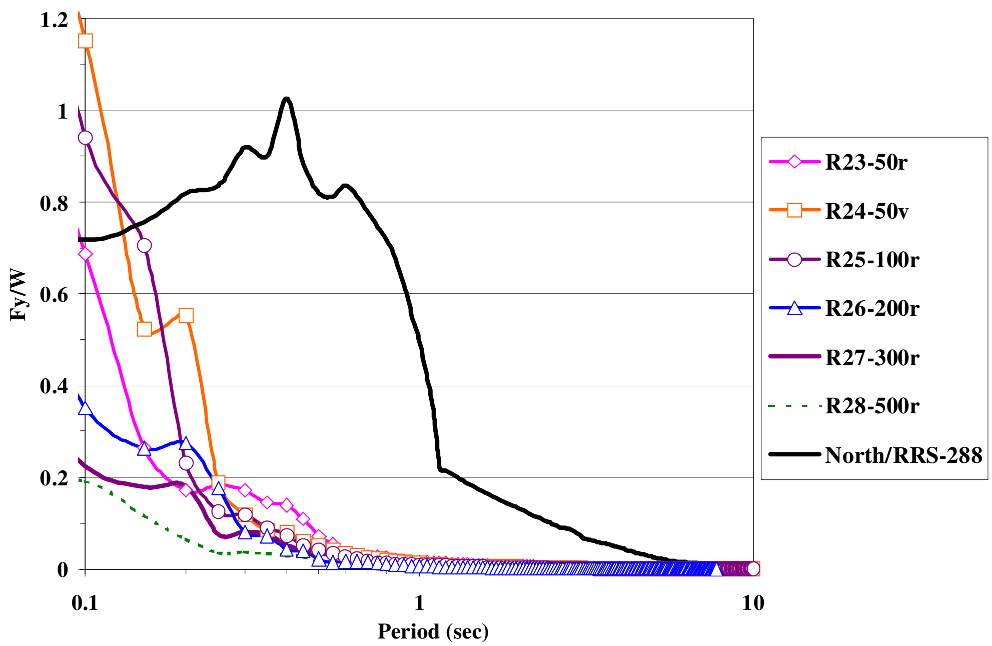


Figure 3: Constant ductility spectra for the NETI records (Ductility = 4.0)

Finally the constant ductility spectra for the BTM records and the Northr/RRS-288 spectrum are presented in Fig.4. The Northr/RRS-288 spectrum envelops all the BTM spectra for period values T > 0.15 sec and it is observed that the yield strength values for all the BTM records are significantly smaller than the spectrum values for the Northr/RRS-288 record.

Figure 4: Constant ductility spectra for the BTM records (Ductility = 4.0)



Energy Balance Equation

Mainly both viscous damping and yielding dissipate the earthquake input energy to an inelastic system. The energy balance equation is obtained by integrating the equation of motion for a SDOF inelastic system, with respect to the relative displacement u(t)

$$m\ddot{u}(t) + c\dot{u}(t) + fs(u(t),\dot{u}(t)) = -m\ddot{u}_g(t) \qquad \text{(Eq.9)}$$

$$\int_0^u m\ddot{u}(t)du + \int_0^u c\dot{u}(t)du + \int_0^u f_s(u(t),\dot{u}(t))du = -\int_0^u m\ddot{u}_g(t)du \qquad \text{(Eq.10)}$$

or by using the notation $du = \frac{du}{dt}dt = \dot{u}dt$ the above equation can be rewritten

$$\int_0^t m\ddot{u}(t)\dot{u}dt + \int_0^t c\dot{u}(t)\dot{u}dt + \int_0^t f_s(u(t),\dot{u}(t))\dot{u}dt = -\int_0^t m\ddot{u}_g(t)\dot{u}dt \qquad \text{(Eq.11)}$$

The right side of the equation is the system's total energy input E_I (t). Since the term $\dot{u}$ is the relative velocity the corresponding input energy is also relative. The first term of the left side of Eq.11 is the kinetic energy of the mass associated with its motion relative to the ground:

$$E_K(t) = \int_0^t m\dot{u}(t)\ddot{u}(t)dt = \left|\frac{1}{2}m\dot{u}^2(t)\right|_0^t = \frac{1}{2}m\dot{u}^2(t) - \frac{1}{2}m\dot{u}^2(0) \qquad \text{(Eq.12)}$$

The second term of the left side of Eq.11 is the energy dissipated by viscous damping

$$E_D(t) = \int_0^t c\dot{u}^2(t)dt \qquad \text{(Eq.13)}$$

The third term of the left side of Eq.11 is the sum of the energy dissipated by the recoverable elastic strain energy E_S (t) and the irrecoverable hysteretic energy through yielding E_Y (t).

Based on these energy quantities the energy balance equation of the system can be rewritten as

$E_I(t) = E_K(t) + E_D(t) + E_S(t) + E_Y(t)$ (Eq.14)

To compute the energy terms, the integration over time has to be broken into the number of constant linear loading time intervals. A discussion on the analytical integration of motion and the evaluation of the energy terms can be found in Ref. 10.

Energy Time Histories

For each record, the energy time histories (kinetic, damping, elastic, yielding) for an elastoplastic system with 5% critical damping and strength coefficient equal to 0.25 (Cy = yield strength/ weight, weight =1.0) were calculated. Table 4 summarizes the maximum damping, yielding, and total energy values at the end of the excitation, along with the participation percentages for the damping and yielding to the dissipation of the input energy for period values 0.2, 0.3, 1.0 and 3.0 sec., and for the following seven records: (1) Earthquake - Landers / LCN260 (R1), (2) Shake Table 10" - Landers / LCN260 (R7), (3) Shake Table 2" - Landers / LCN260 (R13), (4) Telcordia (R19), (5) Measured NTS-5 (R20), (6) Synthesized NTS (R22), (7) Black Thunder Mine 50 m radial (R23).

The results show that the energy supplied to the elastoplastic system is being dissipated throughout the excitation time history mainly by viscous damping and hysteretic behavior (when yielding occurs). In addition, the input energy for the same record varies according to the system's period as it is expected. The system's period also affects the damping, inelastic and kinetic energy participation percentages to the total input energy dissipation.

For the earthquake record R1-Landers/LCN260, more than 50% of the input energy is being dissipated by hysteretic behavior for small period systems (T = 0.2, 0.3 sec). For the larger period range, the yielding percentage decreases while both the dissipating damping and kinetic energy increase. The same energy time history trends with the R1-Landers/LCN260 record are also observed for the corresponding 10" and 2" shake table records. It is interesting to note that for both shake table excitation records and period value T =3.0 sec., no yielding occurs and the elastoplastic system dissipates the input energy mainly by damping, and also kinetic and elastic energy by a smaller percentage.

For the R19-Telcordia record yielding is the main energy dissipater for period range T = 0.2 -1.0 sec. with a high percentage ratio ranging from 65% to 70%. For period value T = 3.0 sec. no yielding occurs.

The response of the elastoplastic system under consideration to the R20-NETI measured NTS-5 record exhibits high inelastic energy values for periods T = 0.2, 0.3 sec. and no hysteretic behavior for period T >=1.0 sec. On the other hand, hysteretic behavior is observed for the R22-NETI synthesized record and periods T =1.0 and 3.0 sec. In addition, the inelastic are higher than the damping percentages for systems with T < 1.0 sec.

From the BTM group of records, energy time history results for the R23-BTM 50 m. radial are presented. The lowest total energy input values from the seven records under consideration were observed for R23. Mainly damping is dissipating the excitation energy. There is a significant decrease in inelastic energy as the period increases and there is no nonlinear behavior for systems with T > 1.0 sec.

Table 4: Maximum Energy quantities at the end of excitation.

Max Ed / unit mass: maximum damping energy / unit mass, at the end of excitation
Max Ey / unit mass: maximum yielding energy / unit mass, at the end of excitation

Max Ei / unit mass: maximum total input energy / unit mass, at the end of excitation

Records	**Max Ed / unit mass 1000 (cm/sec)^2**				**Max Ey / unit mass 1000 (cm/sec)^2**				**Max Ei /unit mass 1000 (cm/sec)^2**			
	0.2sec	**0.3 sec**	**1.0 sec**	**3.0 sec**	**0.2sec**	**0.3 sec**	**1.0 sec**	**3.0 sec**	**0.2sec**	**0.3 sec**	**1.0 sec**	**3.0 sec**
(R1) Landers/LCN260	1.86	2.05	3.551	11.563	3.818	3.002	2.98	4.542	5.679	5.052	6.532	16.118
Participation to the total input energy (%)	32.76	40.58	54.37	71.74	67.24	59.42	45.63	28.18				
(R7) Landers/LCN260	1.822	2.067	3.589	12.404	3.571	2.679	1.763	0	5.394	4.747	5.353	12.415
Participation to the total input energy (%)	33.78	43.54	67.04	99.91	66.20	56.43	32.93	0				
(R13) Landers/LCN260	1.86	2.128	3.653	0.224	3.528	2.515	0.556	0	5.388	4.644	4.21	0.224
Participation to the total input energy (%)	34.52	45.82	86.77	100	65.48	54.15	13.21	0				
(R19) Telcordia	52.628	45.969	35.549	6.518	96.522	104.197	65.829	0	149.15	150.17	101.802	6.518
Participation to the total input energy (%)	35.28	30.61	34.92	100	64.71	69.39	64.66	0				
(R20) Measured NTS -5	0.83	0.968	0.352	0.074	1.868	2.074	0	0	2.699	3.089	0.382	0.088
Participation to the total input energy (%)	30.75	31.34	92.15	84.10	69.21	67.14	0	0				
(R22) NeTI Synthesized	16.653	19.209	23.211	94.628	42.745	58.711	95.774	45.904	59.399	77.921	118.986	140.637
Participation to the total input energy (%)	28.03	24.65	19.51	67.28	54.86	75.35	80.49	32.64				
(R23) BTM 50 m radial	0.679	0.546	0.089	0.043	0.945	0.297	0	0	1.625	0.845	0.09	0.051
Participation to the total input energy (%)	41.78	64.61	98.88	84.31	58.15	35.15	0	0				

Total Input Energy for selective records

Table 5 summarizes the total input energy percentages for four period values (T = 0.2, 0.3, 1.0, 3.0 sec.) with respect to the earthquake Landers /LCN260 record (R1).

The 10” Shake table record (R7) has smaller reduction percentages values than the 2” Shake table (R13) for the four period values. For both records though, the energy results are the closest to the earthquake record (R1) as expected since their acceleration time histories are filtered versions of the (R1) record.

The input energy values for the Telcordia record (R19) exceed significantly the earthquake values for periods of 0.2, 0.3 and 1.0 sec. For the period of 3.0 sec a reduction percentage of ~ 60% is observed with respect to the earthquake total energy input.

The measured NTS-5 (R20) record has large reduction percentages for T = 0.2 and 0.3 sec. For period values T = 1.0 and 3.0 sec the total input energy values are so minor that we can infer about the elastoplastic system that will remain undisturbed. On the other hand, the input energy values originated from the synthesized NeTI (R22) record exceed by 8 to 18 times the earthquake values for all the periods and are the largest among the record ensemble for T >1.0 sec.

Finally, the smallest total input energy values and the largest reduction percentages from the group of seven records resulted from the BTM 50 m radial record (R23). This result indicates that the intensity of the BTM explosion is too weak to produce significant excitation similar in magnitude to an earthquake excitation, for elastoplastic systems with period T > 0.2 sec.

Table 5: Total Input Energy percentages for selective records with respect to (R1).

Records	**Total Input Energy percentages with respect to record (R1) (%)**			
	0.2 sec	0.3 sec	1.0 sec	3.0 sec
(R7) Landers/LCN260	-5.02	-6.04	-18.05	-22.97
(R13) Landers/LCN260	-5.12	-8.08	-35.55	-98.61
(R19) Telcordia	*+2,526*	*+2,872*	*+1,458*	-59.56
(R20) Measured NTS -5	-52.47	-38.85	-94.15	-99.45
(R22) NeTi Synthesized	*+945.94*	*+1,442*	*+1,721*	*+772.5*
(R23) BTM 50 m radial	-71.38	-83.27	-98.62	-99.68

Ratio of the hysteretic over the total dissipated energy

In Fig. 5 the graphs of the ratio of the hysteretic (E_Y) over the total dissipated energy ($E_K + E_D + E_S + E_Y$) at the end of the excitation for the seven selective records are presented. It is evident that the Synthesized NeTI record (R22) has the largest ratio values for periods larger than 0.2 sec. High hysteretic ratio values are also observed for the measured NeTI (R20) record for periods up to 0.6 sec.

The graphs for both the large (R7) and the small (R13) shake table records follow closely their corresponding earthquake Landers LCN/260 (R1) graph until ~ the period of 0.3 sec, and for larger period values (T >0.3 sec) fall under the earthquake graph. The Telcordia (R19) envelops the earthquake Landers

LCN/260 (R1) graph for the period range of 0.3 - 1.1 sec, and for period values larger than 1.1 sec the ratio values decrease following a steep slope.

The smallest hysteretic ratios among the seven records are observed for the BTM 50 m radial (R23), which indicate that mainly kinetic and damping energy dissipate the excitation input. The graph also implies that systems with period values larger than 0.5 sec will behave linearly and remain in the elastic region.

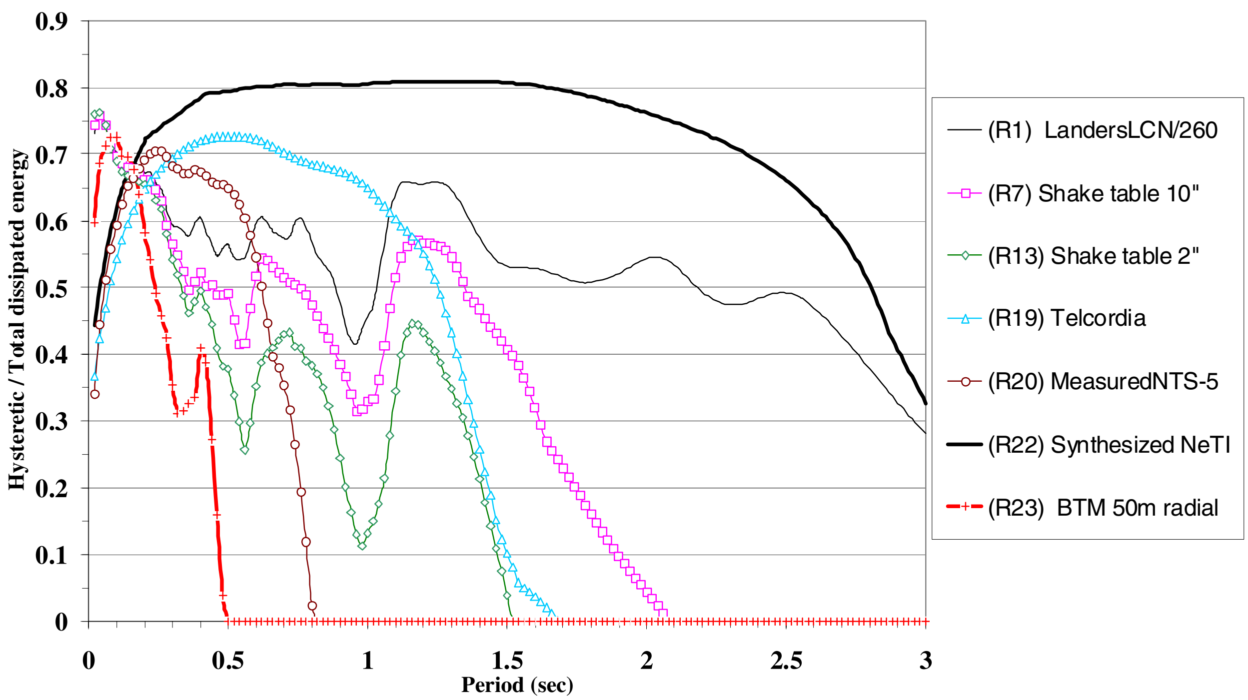


Figure 5: Ratio of the hysteretic energy over the total dissipated energy at the end of the excitation for a selective group of records (Cy = 0.25, 5% cr. damping).

CONCLUSIONS

Based on the records characteristics and the analysis findings we can draw the following conclusions for the capability of the experimental methods under consideration to perform large-scale seismic testing:

Shake tables (10” and 2” displacement limit, Telcordia)

The earthquake records and the corresponding shake table (10” displacement limit) have almost identical values for the peak acceleration, Arias intensity and cumulative absolute velocity. Their linear response spectra values are also identical throughout the spectrum (Note: Results from the linear analysis are not presented in this paper due to the length limitation). From all the testing methods examined in this study, the results of the analysis for the large shake table (10” displacement limit) records are the closest to the results for the corresponding earthquake records. Full-scale experiments are difficult to perform with small (2” displacement limit) shake tables due to their inherent velocity and displacement limitations.

The Telcordia record has the largest total input energy for period values 0.2 and 0.3 sec from all the records. Specimens subjected to the Telcordia excitation can reach response values beyond their elastic limit and valuable insight into their non-linear behavior can be gained. However, the low-frequency portion of theTelcordia record can only be implemented with long-stroke shake tables.

NeTI

More information is needed regarding the quantitative correlation between the number of the explosive RESQUE sources, the intensity of the triggered excitation and the level of the potential structural damage to the specimens. Due to the large input energy generated by the detonation of the explosives, it is evident that specimens will dissipate energy through non-linear cyclic response and will sustain considerable structural damage. The RESQUE technique can also be fielded around existing structures to test the dynamic characteristics of actual full-scale structures in situ.

BTM

The total input energy for the mine blast records attenuates rapidly with increasing distance from the explosive source. Only experiments in less than a 100 m. radius from the source will have significant excitation. Full-scale experimentation remains difficult, since the total input energy from a BTM record, even the 50 m. radial, is significantly smaller than the total earthquake energy. Small excitation duration prohibits energy dissipation through many hysteretic cycles. This kind of excitation is appropriate for large- to medium--scale experiments (1/4 to 1/10).

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