28 Mar 2001, 11:00 am - 11:45 am

Dynamic Soil Properties, Seismic Downhole Arrays and Applications in Practice

Ahmed Elgamal
University of California at San Diego, La Jolla, CA

Tao Lai
University of California at San Diego, La Jolla, CA

Zhaohui Yang
University of California at San Diego, La Jolla, CA

Liangcai He
University of California at San Diego, La Jolla, CA

DYNAMIC SOIL PROPERTIES, SEISMIC DOWNHOLE ARRAYS AND APPLICATIONS IN PRACTICE

Ahmed Elgamal, Tao Lai, Zhaohui Yang, and Liangcai He
University of California at San Diego
La Jolla, CA – USA – 92093-0085

ABSTRACT

Downhole arrays are deployed worldwide to record seismic ground response in near-surface strata. The information supplied by these arrays is increasingly becoming the basis for verification, and for development and calibration of predictive tools and design procedures. Advances in sensors and information technologies will further expedite this learning process, opening the door for worldwide sharing and collaboration. In this paper, the following topics are addressed: i) A summary of downhole array installations and data in the U.S. and in the Taiwan, Hualien and Lotung sites, ii) An overview of related current research efforts worldwide, iii) Downhole array system identification analyses for lateral and vertical site amplification, iv) Downhole array analyses related to liquefaction and availability of Internet websites for conducting online computations (**http://cyclic.ucsd.edu**), and v) Summary of findings, and needs towards future advancements.

KEYWORDS:

Soil Dynamics, Vertical Arrays, Downhole Arrays, Liquefaction, System Identification

INTRODUCTION

Currently, downhole arrays are being increasingly deployed on a worldwide scale. Numerous existing installations are active, and valuable recorded data sets are becoming available. Some of the recorded sets (e.g., those related to liquefaction) have received much attention, and have already yielded invaluable information. Many more arrays have recorded data from small tremors, and are awaiting the occurrence of significant earthquake excitation (from the engineering point of view). In this paper, sections are devoted to the following issues:

1. Summary of downhole arrays in the U.S. (and the Hualien and Lotung arrays in Taiwan). Downhole data sets from centrifuge testing investigations are also discussed.
2. Literature overview to demonstrate the wide interest in this area.
3. Sample analyses related to lateral and vertical seismic response at soft as well as stiff soil sites.
4. Downhole studies related to liquefaction and associated soil response.
5. Summary of findings and discussion of future needs.

In compiling this document, much information was generously provided by many colleagues in the US, Japan, Taiwan, Mexico, and New Zealand. This assistance has been of great value and is most appreciated (please see Acknowledgements).

SUMMARY OF EXISTING DOWNHOLE ARRAYS IN THE US (AND TAIWAN, HUALIEN AND LOTUNG ONLY)

Seismic downhole-array data provide a unique source of information on actual soil behavior and local site amplification effects. This section provides a summary of existing geotechnical arrays in the US as well as Hualien and Lotung in Taiwan. Some information about data availability is also provided. Table 1 lists general information according to the best knowledge available to the authors. Thereafter, brief summaries are provided for the following specific sites covering geotechnical information and/or earthquake histories:

1. Borrego Valley Downhole Arrays, California, USA
2. Campus Laboratory Collaborative (CLC) Arrays, California
3. El Centro Downhole Array, California, USA
4. Garner Valley Array, California, USA
5. Hollister Borehole Array, California, USA
6. La Cienega Downhole Array, California, USA
7. San Francisco Bay Area Bridge Borehole Arrays, California
8. San Francisco City Borehole Arrays, California, USA
9. SCEC Los Angeles Borehole Arrays, California, USA
10. Tarzana Downhole Array, California, USA
11. Treasure Island Geotechnical Array, California, USA
12. Wildlife Refuge Array, Imperial County, California USA
13. Hualien Arrays, Taiwan
14. Lotung Arrays, Taiwan

Table 1: Summary of Borehole Arrays in the US and Taiwan (Hualien and Lotung only).

No	Station Name	Year Installed	Sensor Depths, *m*	Geology	Agency
1	Borrego Valley Downhole Array (1)	1993	0, 9.2, 19.4, 139, 238		Kajima, UCSB
2	CLC U.C. Riverside (1)	1998	0, 30, 100		UCCLC
3	CLC U.C. San Diego (1)	1997	0, 46, 91		UCCLC
4	CLC U.C. Santa Barbara (1)	1997	0, 75		UCCLC
5	El Centro Array (1) (3) (4) (6)	1998	0, 30, 100, 195	Deep alluvium	Caltrans, CSMIP
6	Eureka Array (1) (3) (4) (6)	1995-97	0, 19, 33, 56, 136	Deep soft alluvium	Caltrans, CSMIP
7	Garner Valley Downhole Array (1)	1989	0, 6, 15, 22, 50, 220,500,501		UCSB
8	Hollister Downhole Array (1)	1992	0, 10, 20, 50, 110, 192		UCSB
9	Los Angeles - La Cienega Array (1) (3) (4) (6)	1994-98	0, 18, 100, 252	Deep soft alluvium	Caltrans, CSMIP
10	SF Bay area Bridge - Bay Bridge (1)	1994-98	0, 3, 36.3, 57.6, 60.96, 150, 159.7		LLNL, Caltrans, UCB
11	SF Bay area Bridge - Dumbarton Bridge (1) Pier 01 Pier 27 Pier 44	 1993-94 1992-94 1994	 0, 1.5, 71.6, 228 189.2, pile cap 1.5, 62.5, 157.9	Rock	LLNL, Caltrans, UCB
12	SF Bay area Bridge - Golden Gate Bridge (1) (3)	1995	152	Rock	GGBD
13	San Francisco - Marina (2)		0, 30, 88 0, 30, 88 (Velocity)		USGS
14	San Francisco - Levi Plaza (2)		0, 8, 21, 42 42 (Velocity) 8, 21 (Pressure)		USGS
15	San Francisco - Embarcadero Plaza (2)		0, 10, 49, 79 79 (Velocity) 10, 49 (Pressure)		USGS
16	San Francisco - Bessie Carmichael School (2)		0, 10, 37, 90 90 (Velocity) 10, 37 (Pressure)		USGS
17	Tarzana - Cedar Hill B (1) (3)	1997	0, 60	Soil, rock	ROSRINE, Caltrans, CSMIP
18	Treasure Island Array (1) (3) (6)	1992-96	0, 7, 16, 31, 44, 104, 122	Fill, alluvium, rock	NSF, CSMIP
19	Wildlife Refuge Array (1) (4) (5)	1982	0, 7.5		USGS
20	Parkfield - Turkey Flat #2 (1) (3)	1987	0, 11, 23		Caltrans, CSMIP
21	Parkfield - Turkey Flat #1 (1) (3)	1988	0, 24		Caltrans, CSMIP
22	Los Angeles - Vincent Thomas Array East (1) (3) (4)	1998	0, 18, 46, 91	Deep soft alluvium	Caltrans, CSMIP
23	Los Angeles - Vincent Thomas Array West (two close sites combined) (1) (3) (4)	1998	0, 15, 30, 91, 189	Deep soft alluvium	Caltrans, CSMIP
24	Los Angeles - Stone Canyon Reservoir (1)	1998	0, 100		SCEC
25	Los Angeles - Griffith Park Observation (1)	1998	0, 100		SCEC
26	Los Angeles - Wonderland Ave. School (1)	1998	0, 60		SCEC
27	Los Angeles - Mira Catalina School (1)	1998	0, 30		SCEC
28	Los Angeles - Obregon Park (1)	1998	0, 70		SCEC
29	Central Fire Station, San Bernardino (1)	1995	0, 100		USGS
30	Cerritos College Police Station (1)	1995	0, 90		USGS
31	Hayward – San Mateo Bridge Array (3) (4)		0, 10, 23, 46, 91	Deep alluvium	Caltrans, CSMIP
32	Newhall - 14/5 Sep/OH (Ramp C) (4)		10, 30 in pile	Rock	Caltrans

33	Martinez - Benicia-Martinez Toll Bridge [4]		0, 10, 30	Rock	Caltrans
34	Crockett - Carquinez Toll Bridge [4]		0, 23, 46	Rock	Caltrans
35	Richmond - San Rafael [4]		9 (west), 0 (east)	Rock	Caltrans
36	San Francisco - SFOBB (west) [4]		Pier A: 0, 14, 40	Soil, rock	Caltrans
37	San Diego [4]		0, 9, 30, 91	Soil	Caltrans
38	San Diego - Coronado [4]		0, 9, 23, 46, 107	Soil	Caltrans
39	Alameda - Posey/Webster Tube [4]		0, 3, 15, 40	Soil	Caltrans
40	Colton - I-10/215 Interchange [4]		#1: 0, 18, 46, 91 #2: 0, 18, 46	Soil	Caltrans
41	Crowley Lake OC [4]		15, 30	Shallow soil	Caltrans
42	Taiwan – Hualien [7]		0, 5.3, 15.8, 26.3, 52.6	Stiff soil	EPRI, TPC, NRC
43	Taiwan – Lotung [8]		0, 6, 11, 17, 47	Soft soil	EPRI, TPC, NRC

(1). Archuleta and Steidl (1998)
(2). Borcherdt *et al.* (2000)
(3). Graizer *et al.* (2000)
(4). Personal contact, Caltrans, Thomas Shantz and Clifford Roblee (Dec. 2000)
(5). Copy of this USGS data is available, contact elgamal@ucsd.edu
(6). Selected data sets available at ftp://ftp.consrv.ca.gov/pub/dmg/csmip/GeotechnicalArrayData/
(7). Tang *et al.* (1991), Yang *et al.* (1995a,b)
(8). Tang (1987)
Caltrans (California Department of Transportation)
CSMIP (California Strong Motion Instrumentation Program, Anthony Shakal and Vladimir Graizer)
EPRI (Electric Power Research Institute, H.T. Tang)
GGBD (Golden Gate Bridge District)
Kajima (Kajima Engineering and Construction, Inc.)
LLNL (Lawrence Livermore National Laboratory)
NRC (Nuclear Regulatory Commission, Herman Graves)
NSF (National Science Foundation)
ROSRINE (Resolution of Site Response Issues from the Northridge Earthquake, Caltrans, Clifford Roblee)
SCEC (Southern California Earthquake Center)
TPC (Taiwan Power Company)
UCB (University of California at Berkeley)
UCSB (University of California at Santa Barbara, Ralph Archuleta and Jamie Steidl)
UCCLC (University of California Campus-Laboratory Collaboration, LLNL, Francois Heuze)
USGS (US Geological Survey)

Borrego Valley Downhole Arrays (Archuleta and Steidl 1998)

The Borrego Valley downhole array, deployed by Kajima Engineering and Construction Corp. and Agbabian Associates (Dr. Robert Nigbor) in 1993, is located near San Jacinto Fault in Southern California. In this array there are four borehole instruments extending to a depth of 238*m*, and a remote rock site that includes a borehole sensor. At the main station, the shear wave velocity ranges from about 300m/s at the surface to 750*m/s* at the 230*m* granite interface (where it jumps to 2500*m/s*). The water table is at 92*m* depth (Archuleta and Steidl 1998).

Campus Laboratory Collaborative (CLC) Arrays (Archuleta *et al.* 2000b)

The Office of the President of the University of California (UCOP) initiated a program to install borehole arrays at a number of University of California campuses (Francois Heuze, P.I., LLNL). The program started in March 1996 as a partnership between four campuses of the University of California – Los Angeles, Riverside, San Diego, and Santa Barbara - and the Lawrence Livermore National Laboratory (LLNL). The current studies focus on the Riverside, San Diego, and Santa Barbara downhole arrays. Each of the boreholes is logged for P and S wave velocities, and for the collection of undisturbed samples (Archuleta and Steidl 1998, Minster *et al.* 1999, and Archuleta *et al.* 2000b). A number of low amplitude tremors were recorded at all these sites (contact: Dr. Francois Heuze at heuze@llnl.gov).

El Centro Downhole Array (Graizer *et al.* 2000)

The El Centro site consists of a deep soft alluvium profile, with shear wave velocities (Norris 1988) increasing from approximately 150*m/s* near the surface to 450*m/s* at a depth of 100*m* (silt, sand and clay). Surveys for P and S-wave velocities were performed by Caltrans. Table 2 lists 5 small amplitude earthquakes recorded at the surface, 30 and 100*m*.

Table 2: Earthquakes recorded by El Centro Geotechnical Array (after Graizer *et al.* 2000).

No.	Date yr/mo/dy	Time(UTC) hh:mm:ss	M_L	Lat	Long	Depth (*km*)	Epic dist. (*km*)	PGA, (*g*)			Acc. Recorded at Depth, *m*
								D270	D360	UP	
1	99/07/24	02:01:26.0	3.9	32.770	115.560	15.4	10.6	0.015 (Lateral)			
2	99/10/16	09:46:44.1	7.1	34.594	116.271	6.0	216.0	0.015	0.014	0.009	0, 30, 100
3	00/04/09	10:48:09.7	4.3	32.692	115.392	10.0	10.4	0.042	0.033	0.008	0, 30, 100
4	00/06/14	19:00:20.0	4.2	32.896	115.502	5.1	14.6	0.014	0.012	0.007	0, 30, 100
5	00/06/14	21:49:18.0	4.5	32.884	115.505	4.9	13.5	0.008	0.008	0.008	0, 30, 100
Epic dist. (Epicenter distance) Selected data sets available at ftp://ftp.consrv.ca.gov/pub/dmg/csmip/GeotechnicalArrayData/											

Garner Valley Array (Archuleta and Steidl 1998)

The Garner Valley experiment (Mohammadioun and Gariel 1996) is sponsored jointly by the US Nuclear Regulatory Commission and the French Institut de Protection et de Surete Nucleaire (IPSN). This site is located in a seismically active area of southern California 7*km* east of the San Jacinto fault and within 35km of San Andreas fault (Archuleta *et al.* 1992). The array consists of three-component accelerometer stations at the surface and within the ground at depths of 6, 15, 22, 55, 220, 500 and 501*m*. It includes five surface instruments in a linear array, and a remote rock site that includes a surface and a shallow (30*m*) borehole sensor along with pore pressure transducers (Archuleta and Steidl 1998). At this location, the upper 18*m* of soil are followed by weathered granite (up to 45*m*), with solid granite bedrock thereafter. Shear-wave and P-wave velocity tests were conducted along with Standard Penetration and laboratory soil sample tests (Pecker 1995). The outcome of analyses of 218 recorded weak seismic motions was found to be in agreement with in-situ low-strain shear wave velocity measurements (Archuleta *et al.* 1992, and Mohammadioun and Pecker 1994). In addition, a damping mechanism proportional to the power 0.68 of the frequency was identified (Pecker 1995).

Hollister Borehole Array (Archuleta and Steidl 1998)

Agbabian Associates installed the Hollister Earthquake Observatory in 1991 with funding from Kajima. In 1998, Kajima Corporation donated this array to the University of California, Santa Barbara. It is located in the Salinas Valley of Southern California where alluvium overlies Tertiary sandstone overlying a granitic basement. The array consists of six accelerometers at the main station and three at remote rock stations – one on granite, one in the Tertiary sandstone and one in a borehole at 53*m* depth (Archuleta and Steidl 1998).

La Cienega Downhole Array (Graizer *et al.* 2000)

Sponsored by Caltans, the array was installed to study the seismic response of a deep soil geologic structure in Los Angeles near the Santa Monica freeway (I-10) at La Cienega. The site consists of recent fluvial deposits of about 30m in thickness over marine deposits (sands, silts, clays and gravels). P and S-wave velocity surveys performed by Caltrans (suspension logging method) and the USGS indicate a 140*m/s* shear wave velocity near the surface with an increase to about 600*m/s* at a depth of 100*m* (Graizer *et al.* 2000). Eighteen earthquakes have been recorded at this site (Table 3).

San Francisco Bay Area Bridge Borehole Arrays (Hutchings *et al.* 1998)

This is a cooperative project between LLNL, UC Berkeley and Caltrans for instrumenting bridges in the San Francisco Bay region (Hutchings *et al.* 1998). A description of two borehole arrays is given in Table 1 (Bay Bridge and Dumbarton Bridge). The purpose of these arrays is to (Archuleta and Steidl 1998): 1) develop realistic predictions of strong ground motion at multiple input points along long span bridges; 2) examine ground motion variability in bedrock; 3) calibrate soil response models; 4) develop bridge response calculations with multiple support input motions; 5) evaluate the seismicity of potentially active faults in the San Francisco Bay; and 6) record strong ground motion.

San Francisco City Borehole Arrays (Borcherdt *et al.* 1999, 2000)

Four integrated borehole arrays and ten surface installations were deployed in the city of San Francisco, California to measure the seismic response of soft-soil deposits. Evidence of liquefaction during past earthquakes has been documented at three of the four sites (Embarcadero Plaza, Levi Strauss Plaza, Winfield Scott School in the Marina district, and Bessie Carmichael School). The borehole arrays extend through thick layers of soft water-saturated soils of Holocene age and older more consolidated soils of Pleistocene age into bedrock at depths up to 100*m*. Surface installations were configured in pairs to provide comparative surface measurements of soft soils and nearby rock (Borcherdt *et al.* 2000).

SCEC Los Angeles Arrays (Archuleta and Steidl 1998)

A major initiative by the Southern California Earthquake Center (SCEC) was undertaken to deploy borehole instruments throughout Southern California. The ultimate goal is to place approximately 10 borehole instruments in and around the Los Angeles basin in order to quantify the incoming wave field for studying basin effects as well as local site effects. Five of these sites have been drilled, sampled, logged and cased for instrumentation (Archuleta and Steidl 1998).

Table 3: Earthquakes recorded by La Cienega Geotechnical Array (after Graizer *et al.* 2000).

No.	Date yr/mo/dy	Time(UTC) hh:mm:ss	M_L	Lat	Long	Depth (*km*)	Epic dist. (*km*)	PGA, (*g*)			Acc. Recorded at Depth, *m*
								D90	D180	UP	
1	95/06/26	08:40:28.9	5.0	34.390	118.670	13.3	47.6	0.011	0.009	0.002	0, 18, 100
2	97/03/18	15:24:47.7	5.1	34.970	116.820	1.8	176.7	0.003	0.003	.0007	0, 18, 100
3	97/04/04	09:26:24.5	3.3	33.980	118.350	4.2	6.7	0.076	0.058	0.013	0, 18, 100
4	97/04/04	09:35:09.5	2.4	33.990	118.360	4.5	6.4	.010 (Lateral)			
5	97/04/05	14:33:25.3	2.5	33.990	118.360	4.1	6.4	0.021	0.013	0.003	0, 18, 100
6	97/04/26	10:37:30.7	5.1	34.370	118.670	16.5	45.8	0.015	0.014	0.002	0, 18, 100
7	97/04/27	11:09:28.4	4.9	34.380	118.650	15.2	45.7	0.006	0.006	0.001	0, 18, 100
8	98/01/12	06:36:24.9	3.4	34.190	118.470	11.3	19.1	0.005	0.008	0.001	0, 18, 100
9	98/04/15	20:13:21.6	3.2	34.100	118.260	9.2	13.0	0.008	0.013	0.002	0, 18, 100
10	98/05/05	18:14:08.6	1.9	34.050	118.390	9.2	1.9	.012 (Lateral)			
11	99/06/17	01:11:50.1	3.0	34.010	118.220	8.5	15.2	0.012	0.011	0.003	0, 18, 100, 252
12	99/06/29	12:55:00.8	3.8	34.010	118.220	8.0	15.2	.042 (Lateral)			
13	99/10/16	09:46:44.1	7.1	34.594	116.271	6.0	203.6	.035 (Lateral)			
14	99/10/16	09:59:35.1	5.8	34.682	116.285	5.8	205.0	.007 (Lateral)			
15	99/11/30	18:27:02.1	3.3	34.121	118.417	2.8	10.1	.017 (Lateral)			
16	99/11/30	18:46:27.1	3.1	34.125	118.416	2.8	10.5	.011 (Lateral)			
17	00/08/01	19:53:19.4						0.025	0.037	0.004	0, 18, 100, 252
18	00/09/16	13:24:41.3						0.021	0.062	0.005	0, 18, 100, 252
Epic dist. (Epicenter distance)											
Selected data sets available at ftp://ftp.consrv.ca.gov/pub/dmg/csmip/GeotechnicalArrayData/											

Tarzana Downhole Array (Graizer *et al.* 2000)

The Tarzana site is located on a gentle 20m high hill, about 500*m* in length by 130*m* in width. This site has been drilled and logged to a depth of 100*m* by Agbabian Associates (sponsored by CSMIP), and the accelerometers were installed at surface and at 60*m* depth. Low shear-wave velocities (about 200*m/s*) were found in the top 4*m*, with decomposed shale from 4 to 12*m*. Highly to slightly weathered shale of the Modelo formation followed from 12*m* to 100*m* depth. Gypsum crystals were observed in the drill cuttings near 6*m* depth. Velocities increased gradually to near 750*m/s* around 80*m* depth, except in zones of hard shale (Darragh *et al.* 1997). The hill is well drained with a water table at a depth of 17*m*. Table 4 lists 11 earthquakes recorded at this array.

Table 4: Earthquakes recorded by Tarzana Array (after Graizer *et al.* 2000).

No.	Date yr/mo/dy	Time(UTC) hh:mm:ss	M_L	Lat	Long	Depth (*km*)	Epic dist. (*km*)	PGA, (*g*) Lateral direction
1	98/01/04	09:11:45.1	3.3	34.200	118.640	3.5	10.7	.009
2	98/01/05	18:14:06.5	4.3	22.950	117.710	11.5	79.6	.004
3	98/01/12	06:36:24.9	3.4	34.190	118.470	11.3	6.8	.030
4	98/01/15	22:54:08.1	3.0	34.260	118.430	10.6	14.7	.006
5	98/03/11	12:18:51.8	4.5	34.020	117.230	14.9	121.3	.006
6	98/05/01	21:02:37.8	3.8	34.350	118.670	14.2	24.5	.015
7	98/06/03	05:22.50.6	3.0	34.120	118.480	7.7	6.7	.026
8	98/09/24	11:41:42.7	2.6	34.110	118.590	6.0	7.6	.007
9	98/11/11	05:40:28.9	2.5	34.160	118.500	11.3	3.1	.011
10	99/04/11	09:09:19.0	3.6	34.350	118.580	2.3	21.5	.007
11	99/10/16	09:46:44.1	7.1	34.594	116.271	6.0	213.6	.055
Epic dist. (Epicenter distance)								

Treasure Island Geotechnical Array (de Alba *et al.* 1994)

Treasure Island is a 160 ha reclaimed (man-made) island located in the San Francisco bay. It was constructed in the 1930's (Pease and O'Rourke, 1995 and Power *et al.* 1995) of hydraulic fill over natural sand and Bay Mud. The fill (about 12*m* thick at the array location) is in a relatively loose condition, and is susceptible to liquefaction. Geologic formation at Treasure Island (including the upper loose hydraulic fill) is similar to that of nearby Marina District in San Francisco (Pease and O'Rourke, 1995, 1997). At both locations, widespread liquefaction with devastating consequences was documented during the 1989 Loma Prieta Earthquake (Pease and O'Rourke, 1995 and Power *et al.* 1995). In the vicinity of the Treasure Island array, sand boils indicative of site liquefaction were observed (Hryciw *et al.* 1991, Darragh *et al.* 1993, and Finn *et al.* 1993). The array site was instrumented in 1992 by the California Strong Motion Instrumentation Program, and the National Science Foundation (de Alba *et al.* 1994). Among the main goals of installing this array (within a framework of a U.S. Geotechnical Test Site Network, Benoit and de Alba 1988) were: (1) to gather seismic data that would elucidate the mechanism of rock-motion amplification by deep soil deposits in the San Francisco area, and (2) to document the mechanisms of site liquefaction in the upper hydraulic fill strata (de Alba *et al.* 1994). The Treasure Island Geotechnical Array consists of six triaxial accelerometers located at the surface, 7, 16, 31, 44, 104 and 122*m* depths; and 6 piezometers located within the top 12*m* reclaimed hydraulic fill (de Alba *et al.* 1994, Shakal and Petersen 1992). Since the array installation, low amplitude data from 7 earthquakes have been recorded (Table 5). Site characterization and estimated P and S-wave velocity are described in Gibbs *et al.* (1992), Darragh *et al.* (1993) and de Alba *et al.* (1994).

Table 5: Earthquakes recorded by Treasure Island Geotechnical Array (after Graizer *et al.* 2000).

No	Date yr/mo/dy	Time(UTC) hh:mm:ss	M_L	Lat	Long	Depth (*km*)	Epic dist. (*km*)	PGA, (*g*)			Acc. Recorded at Depth, *m*
								D360	D90	UP	
1	93/01/16	06:29:35.0	4.8	37.018	121.463	7.9	120.4	0.014	0.013	0.004	0, 7, 16, 31, 44, 104
2	94/06/26	08:42:50.3	4.0	37.916	122.286	6.6	12.6	0.020	0.013	0.006	0, 7, 16, 31, 44, 104
3	96/05/21	20:50:20.2	4.5	37.359	121.723	8.1	77.3	0.009			
4	98/08/12	14:10:25.1	5.4	36.753	121.462	9.2	143.8	0.005	0.005	0.001	0, 7, 16, 31, 44, 122
5	98/12/04	12:16:07.8	4.1	37.920	122.287	6.9	13.0	0.013	0.012	0.006	0, 7, 16, 31, 44, 122
6	99/08/18	01:06:18.9	5.0	37.907	122.687	6.7	29.0	0.016	0.015	0.010	0, 7, 16, 31, 44, 104, 122
7	00/09/03	08:36:30.0	5.2	38.377	122.414	9.4	61.4	0.007	0.008	0.003	
Epic dist. (Epicenter distance) Selected data sets available at ftp://ftp.consrv.ca.gov/pub/dmg/csmip/GeotechnicalArrayData/											

Wildlife Refuge Array (Holzer *et al.* 1989)

The Wildlife Refuge site is located on the west side of the Alamo River in Imperial County, southern California. Evidence of liquefaction was observed at or near the site following the 1930, 1950, 1957, 1979, and 1981 Imperial Valley earthquakes (Youd and Wieczorek 1984). These observations triggered an interest in Wildlife which in an insightful effort, was instrumented in 1982 by the United States Geological Survey (Holzer *et al.* 1989). The instrumentation included a surface and a downhole accelerometer (at 7*m* depth, below the liquefiable layer), and a number of pore-pressure transducers. Two earthquakes were recorded in 1987. A mild tremor (causing no liquefaction) was followed by the Superstition Hills earthquake that resulted in liquefaction with recorded pore-pressure measurement. This data set remains among the most significant records for conducting liquefaction analyses.

Hualien Arrays, Taiwan (Tang *et al.* 1991, Yang *et al.* 1995a, b)

Hualien is located on the east coast of Taiwan, in a highly active seismic zone near the Philippine Sea Plate boundary. Extensive instrumentation was deployed to record seismic structural and ground responses, and to monitor soil pore-water pressure buildup (Tang *et al.* 1991, Yang *et al.* 1995a, b). The ground instrumentation included 15 triaxial accelerometer stations along ARM1, ARM2 and ARM3; and three downhole triaxial accelerometers that extended to a depth of 52.6*m* below ground surface (Fig. 1). The first downhole array (DH1) was located at the end of ARM1, and the other two arrays were located at the beginning and end of ARM2. Downhole triaxial accelerometers were installed at depths of 5.3, 15.8, 26.3 and 52.6*m*; oriented in the (NS) north-south (longitudinal), (EW) east-west (transverse) and (UP) vertical directions (Yang *et al.* 1995a, b). Table 6 lists 8 events recorded through 1995.

Table 6: Earthquakes recorded by the Hualien Array through 1995 (after Yang *et al.* 1995a,b).

No.	Date yr/mo/dy	Time(UTC) hh:mm:ss	M_L	Lat	Long	Depth (*km*)	Epic dist. (*km*)	PGA, (*g*)			Acc. Recorded at Depth, *m*
								NS	EW	UP	
1	93//09/16	12:18:45.36	4.2	23.58	121.40	21.1	7.65				
2	94/01/20	05:50:18.57	5.6	24.03	121.51	49.5	24.42				
3	94/05/30	07:50:51.80	4.5	24.05	121.34	18.5	9.60				
4	94/06/05	01:09:30.10	6.2	24.27	121.50	5.3	54.00				
5	94/10/05	01:13:24.47	5.8	23.09	121.43	31.3	95.8				
6	95/02/23	05:19:02.78	5.8	24.12	121.41	21.7	21.83	0.047	0.044	0.015	0, 5.3, 15.8, 26.3, 52.6
7	95/05/01	14:50:45.67	4.9	24.02	121.39	8.4	4.58	0.126	0.074	0.023	
8	95/05/02	06:17:25.21						0.087	0.035	0.015	
Epic dist. (Epicenter distance)											

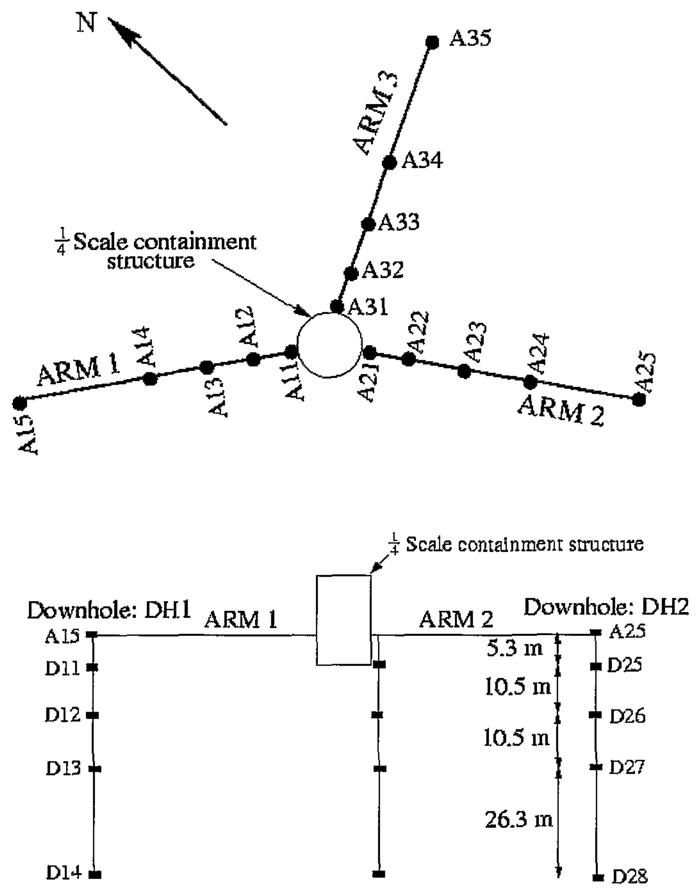

Figure 1: Hualien Downhole Array Sensor Arrangements (Yang et al. 1995a, b).

Lotung Arrays, Taiwan (Tang 1987)

The Lotung site included constructions of ¼ and 1/12 scale models of a nuclear plant containment structure. The site was situated on a flat plain in a basin of triangular shape that is 15*km* wide and 8*km* long. Geological material at the site generally consists of recent alluvium Pleistocene material over a Miocene basement. The alluvium layer is 40-50*m* thick and the Miocene basement rock is located approximately 400*m* below ground surface at the test site (EPRI 1993). Extensive instrumentation was deployed to record seismic structural and ground responses, and to monitor soil pore-water pressure buildup. The ground instrumentation included (Fig. 2) three linear surface arrays and two downhole arrays (DHA and DHB) that extended to a depth of 47*m* below ground surface. Downhole triaxial accelerometers were installed at depths of 6, 11, 17, and 47*m*; oriented in the north-south (NS), east-west (EW), and vertical (UP) directions. Eighteen earthquakes were recorded during the period of 1985--1986 as listed in Table 7 (Tang 1987, Geomatrix Consultants 1990).

Table 7: Earthquakes recorded by Lotung Array (Tang 1987).

No.	Date yr/mo/dy	Time(UTC) hh:mm:ss	Donated as	M_L	Depth (*km*)	Epic dist. (*km*)	PGA, (*g*) NS	PGA, (*g*) EW	PGA, (*g*) UP	Acc. Recorded at Depth, *m*
1	85/09/20	15:01:27	LSST#1				---	---	---	
2	85/10/26		LSST#2	5.3			0.03	0.03	0.01	0, 6, 11, 17, 47
3	85/11/07		LSST#3	5.5			0.01	0.01	0.01	0, 6, 11, 17, 47
4	86/01/16	13:4:37	LSST#4	6.5	10.2	23.7	0.26	0.15	0.11	0, 6, 11, 17, 47
5	86/03/29	07:17:14	LSST#5				0.03	0.04	0.03	0, 6, 11, 17, 47
6	86/04/08	02:15:02	LSST#6	5.4	10.9	31.4	0.03	0.04	0.01	0, 6, 11, 17, 47
7	86/05/20	05:26:00	LSST#7	6.5	15.8	66.2	0.21	0.16	0.04	0, 6, 11, 17, 47
8	86/05/20	05:37:51	LSST#8	6.2	21.8	69.2	0.03	0.03	0.01	0, 6, 11, 17, 47
9	86/07/11	18:25:25	LSST#9	4.5	1.1	5.0	0.05	0.07	0.01	0, 6, 11, 17, 47
10	86/07/16	23:50:32	LSST#10	4.5	0.9	6.1	0.04	0.03	0.02	0, 6, 11, 17, 47
11	86/07/17	00:03:33	LSST#11	5.0	2.0	6.0	0.10	0.07	0.04	0, 6, 11, 17, 47
12	86/07/30	11:31:44	LSST#12	6.2	1.6	5.2	0.19	0.16	0.20	0, 6, 11, 17, 47
13	86/07/30	11:32:40	LSST#13	6.2			0.03	0.05	0.02	0, 6, 11, 17, 47
14	86/07/30	11:38:29	LSST#14				0.05	0.04	0.02	0, 6, 11, 17, 47
15	86/08/05	00:56:20	LSST#15	4.9	2.3	4.7	0.09	0.10	0.03	0, 6, 11, 17, 47
16	86/11/14	21:20:17	LSST#16	7.0	6.9	77.9	0.17	0.13	0.10	0, 6, 11, 17
17	86/11/14	23:04:49	LSST#17				0.04	0.04	0.02	0, 6, 11, 17, 47
18	86/11/15	00:18:10	LSST#18				0.02	0.03	0.01	0, 6, 11, 17, 47
Epic dist. (Epicenter distance)										

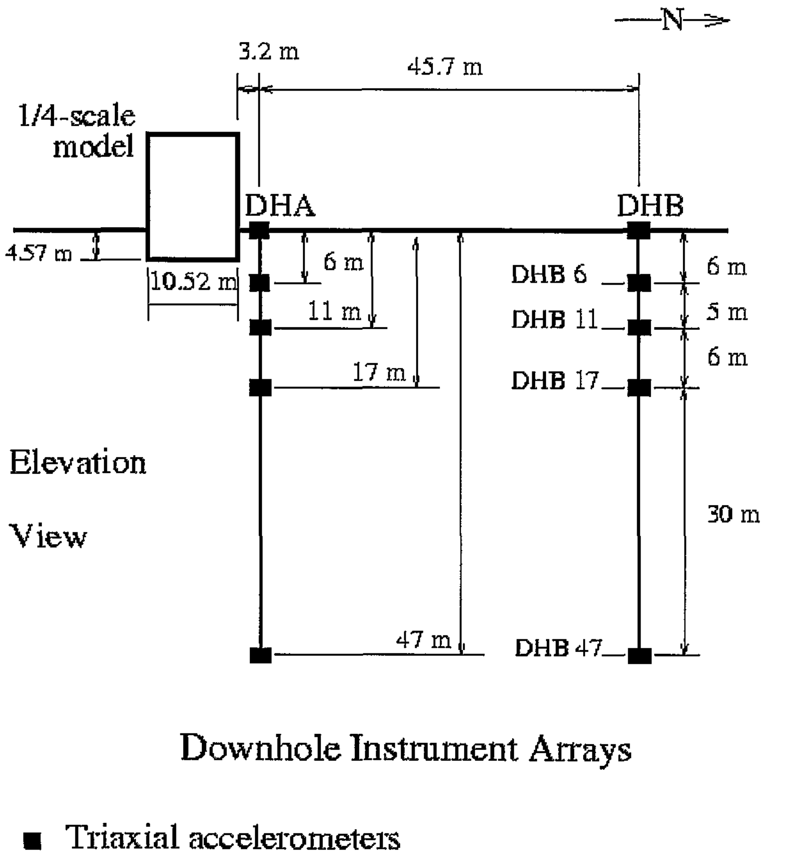

Figure 2: Instrumentation at Lotung Site (Tang 1987, Elgamal et al. 1995).

Soil Response from Centrifuge Testing Downhole Arrays (U.S.)

Rensselaer Liquefaction Research

Since 1992, the centrifuge facility at Rensselaer Polytechnic Institute (http://www.rpi.edu/~dobryr/centrifuge/) has generated many valuable liquefaction data sets (please see next section on literature overview). Contacts include Professor Ricardo Dobry (dobryr@rpi.edu), Director, and Dr. Tarek Abdoun (abdout@rpi.edu), Facility Manager.

UC Davis DKS02 Centrifuge Experimental Arrays

Highly instrumented centrifuge experiments simulating a dense sand stratum were conducted recently at the University of California at Davis (UCD) to study the linear and nonlinear behavior of stiff soil sites during earthquake excitation (http://cgm.engr.ucdavis.edu/research/projects). This effort was initiated as a collaborative USGS funded project between UC Davis and UC San Diego. The experiments employed a Flexible Shear Beam (FSB) container mounted on the 9*m*-radius geotechnical centrifuge at UCD (Kutter *et al.* 1994). The FSB container dimensions are 1.651*m* × 0.787*m* × 0.584*m* in length, width and height respectively. Nevada sand at about 100% relative density was used to represent the stiff soil. Numerous accelerometers were installed to document the horizontal and vertical responses of the model (Fig. 3). The configuration of the FSB container and locations of the installed accelerometers are illustrated in Fig. 3. The recorded input-output accelerations provide an excellent opportunity for numerical model validation. The experiments were conducted at centrifugal acceleration levels of 10*g*, 20*g* and 40*g* respectively representing a prototype site of 5.5, 11, and 22*m* height respectively. At each acceleration level, the input motions included earthquake-like shaking, frequency sweeps and hammer impulse excitation. The peak ground surface acceleration among a total of 31 shaking events in prototype scale ranged from 0.05*g* to 0.99*g* in amplitude covering linear response as well as highly nonlinear response (Stevens *et al.* 1999, Lai *et al.* 1999, Elgamal *et al.* 2001, Stevens *et al.* 2001). Table 8 lists all earthquake events.

At UC Davis, 3 additional test (Stevens *et al.* 2001) configurations were modeled (rectangular rigid box, a saturated model, and an elliptic basin shaped model). This data is available at the UC Davis centrifuge website. At this website, a number of other valuable data sets are also available (please see http://cgm.engr.ucdavis.edu/)

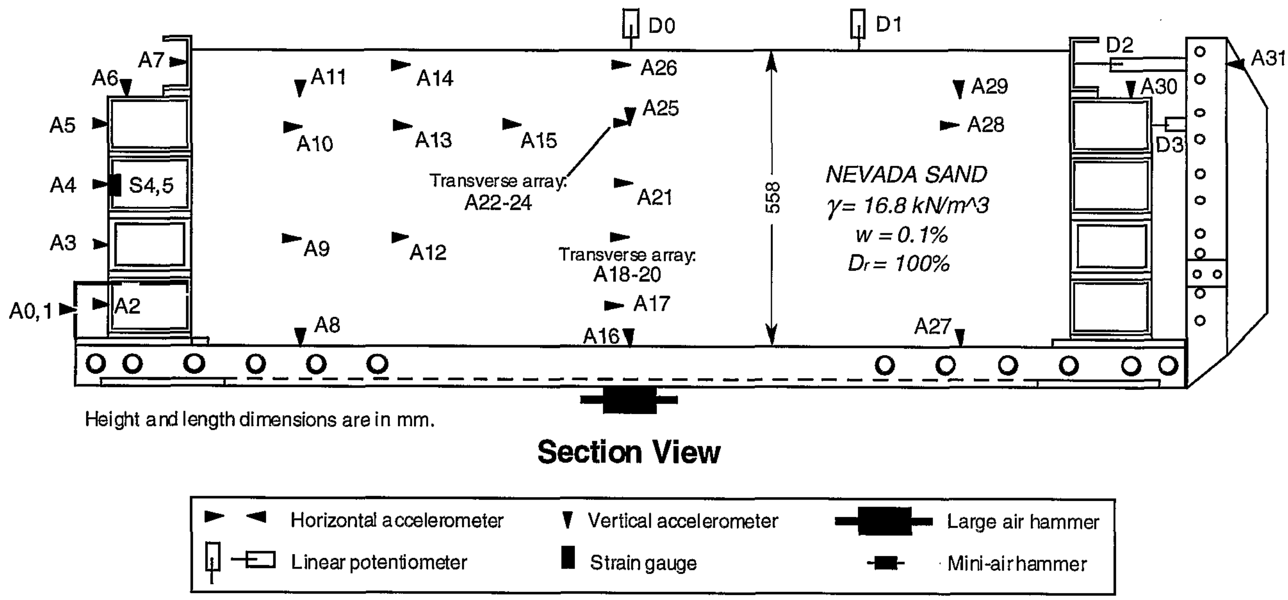

Figure 3: Model Configuration of the DKS02 FSB Container (after Stevens et al. 1999).

Table 8: USD DKS02 Centrifugal experiment central vertical array (Bruce Kutter, Center Director).

No.	Event ID	Centrifuge Acceleration *g* Level	PGA in Long., (*g*)	Acc. Recorded at Depth, *m*
1	DKS02_c	10	0.073	0.25, 1.25, 2.5, 3.5, 4.75, 5.5
2	DKS02_d		0.239	
3	DKS02_e		0.071	
4	DKS02_f		0.200	
5	DKS02_ad		0.251	
6	DKS02_ae		0.173	
7	DKS02_ag		0.991	
8	DKS02_ah		0.630	
9	DKS02_ai		0.430	
10	DKS02_aj		0.350	
11	DKS02_ak		0.506	
12	DKS02_al		0.817	
13	DKS02_l	20	0.078	0.5, 2.5, 5, 7, 9.5, 11
14	DKS02_m		0.117	
15	DKS02_n		0.093	
16	DKS02_z		0.160	
17	DKS02_aa		0.107	
18	DKS02_au		0.308	
19	DKS02_av		0.334	
20	DKS02_az		0.487	
21	DKS02_bb		0.598	
22	DKS02_bd		0.575	
23	DKS02_be		0.757	
24	DKS02_u	40	0.051	1.0, 5, 10, 14, 19, 22
25	DKS02_v		0.052	
26	DKS02_bk		0.117	
27	DKS02_bl		0.277	
28	DKS02_bt		0.411	
29	DKS02_bu		0.431	
30	DKS02_bv		0.196	
31	DKS02_by		0.413	

Data available at http://cgm.engr.ucdavis.edu/research/projects/dks/dks02/index_old.html
Long. (Longitudinal direction)

LITERATURE OVERVIEW

Seismic site response, manifested in the form of dynamic motion and ground failure, often results in costly and disastrous structural damage, e.g., during major earthquakes such as Sept. 19, 1985 Mexico (Seed *et al.* 1987), Oct. 17, 1989 Loma Prieta (Seed *et al.* 1990), Jan. 17, 1995 Kobe (EQE 1995, Sitar 1995, Bardet *et al.* 1995), Sept. 21, 1999 Ji-Ji, Taiwan (Uang *et al.* 1999), and Nov. 12, 1999, Düzce, Turkey (Ansal *et al.* 1999) earthquakes. In order to mitigate these disasters, it is crucial to understand the involved mechanisms of site response.

Soil shear stiffness characteristics at low-strain levels can be conveniently obtained from in-situ tests (e.g., Stokoe and Nazarian 1985, Nazarian and Desai 1993). At larger strain levels, soil dynamic characteristics are often evaluated through laboratory tests (NRC 1985). However, applicability of experimental results is somewhat restricted due to disturbance introduced during soil sampling, and difficulties in reproducing in-situ stress-state, seismic loading histories, site stratification conditions, and appropriate boundary conditions.

Site seismic response records are a valuable complement to the above in-situ and laboratory geotechnical investigation techniques. In particular, analyses of downhole seismic array data can provide unique information on actual soil and overall site dynamic characteristics, over a wide range of loading conditions that are not readily simulated by in-situ or laboratory experimentation procedures (Elgamal *et al.* 1997, Archuleta *et al.* 2000a, Baise and Glaser 2000c).

The earliest downhole arrays were perhaps deployed in Japan and the US. In the United States, an early downhole data set was recorded at Union Bay in Seattle, Washington (Seed and Idriss 1970a). This data was employed to verify site amplification procedures, and analyze the response of peat and clay deposits in Seattle. In Japan, an array of two surface and two downhole seismometers was installed on the premises of Tokyo Station, and recorded a set of seven earthquakes in the late 1950's (Shima 1962). Using these earthquake records, site resonance and damping characteristics were estimated (Shima 1962, Dobry *et al.* 1971). Other related notable efforts were directed towards earth dams in which crest and free-field earthquake records were employed (Abdel-Ghaffar and Scott 1978, 1979).

The above early efforts were followed by more comprehensive array installations worldwide. Using these arrays, soil dynamic characteristics are being increasingly examined through numerous downhole array records obtained from worldwide downhole array sites such as those in the US, Japan, Taiwan, Mexico, Greece, and New Zealand.

Most downhole arrays in the US are deployed in California, (e.g., Garner Valley, the Wildlife Refuge in Imperial County, Borrego Valley, Treasure Island, Hollister Municipal Airport, San Francisco, McGee Creek, Los Angeles, Cholame Valley near Parkfield, and Cajon Pass). Other sites in the US include Paducah in Kentucky (Street *et al.* 1997) and an array at Northeastern University in Boston, Massachusetts (Yegian, M. 2000, personal communication). In Japan, numerous downhole array sites were deployed (e.g., Port Island, Rokko Island, Chiba, Ashigara Valley, Kushiro, Hokkaido, Hiyoshi, TKS, KNK, SGK in Kobe, Shuzenji, Choshi, Tateyama, Higashimatsuyama, Sunamachi, Etchujima, TTRL, Samukawa, Fujisawa, ShinFuji, Sandai, Tomioka, Fuchu, Westa, Shizuoka, Iwaki, Yokohama, Kanto, and Tokyo International Airport). Taiwan is another seismically active region with well-instrumented downhole array sites (e.g., Lotung, Hualien, Wuku, Dahan and other arrays in the Taipei basin). Downhole arrays are also available in many other regions of the world such as Mexico, Mainland China, Greece, and New Zealand.

The following sections present a brief overview of downhole array studies reported by many researchers worldwide. Some of the techniques used in analysis and identification of ground seismic response are highlighted. In view of the extensive available literature, it was impossible to document every published study. With the assistance of many colleagues (please see Acknowledgements), all materials available or brought to the authors attention are compiled below. Future literature review efforts will hopefully be even more comprehensive, with additional details of conducted investigations.

Garner Valley, CA

A number of earlier studies on the Garner Valley downhole array were conducted by Archuleta *et al.* (1992). The Garner Valley downhole seismographic array, sponsored jointly by the US Nuclear Regulatory Commission and the French Institut de Protection et de Surete Nucleaire (Archuleta *et al.* 1992, Archuleta 1998), was designed to improve understanding of the effects of a shallow soil column on ground motion (Steidl *et al.* 1998). This site is in a seismically active area of southern California located 7 km east of the San Jacinto fault. At this location, the upper 18m of soil is followed by weathered granite (up to 45 m), with solid granite bedrock thereafter. The array consists of 5 accelerometer stations that extend to a 220m depth. The observational instrumentation is complemented by geophysical and geotechnical logging and sampling surveys and laboratory dynamic testing of samples. Outcome of weak seismic motion analyses of 218 recorded events was found to be in agreement with in-situ low-strain shear wave velocity measurements (Archuleta *et al.* 1992).

Archuleta *et al.* (1996) found that peak spectral amplification was about 8 over the frequency range 2-20 Hz with resonances around 1.9, 3.1, 6.0 Hz. The general site response was matched using the measured elastic wave velocities and assuming Q factors from 10-30 in the upper 20 m (for damping). They found that (Steidl *et al.* 1998) downhole recordings from as far away as 20 km (Pinon flat) could be used to predict the surface response at the downhole site. A surface rock site record only about 5 km away was not successful. They suggested that a single downhole recording was much better as a reference ground motion than a surface rock site record to predict site amplification (linear). Finally, aftershock recordings were used to predict main shock recordings for surficial peak accelerations less than 0.1 g, and the response was found linear to this level.

Using data from this array, Archuleta and Steidl (1998) investigated the effect of nonlinearity on soil response, amplification and attenuation of seismic waves, effects of smooth versus discontinuous variation of material properties, and water saturated versus dry soil response. In addition, Archuleta *et al.* (2000a) reproduced the observed surface ground motion using the geotechnical site characterization data, the observed downhole motions, and a linear wave propagation technique. They showed the need to be cautious when using surface rock motion as the input motion in site response analysis due to the site effects present at the rock outcrop.

Baise and Glaser (2000a, b) identified the empirical Green's function from depth to the surface at Garner Valley by isolating the systematic effects of the soil profile on the recorded downhole array seismic motions. They showed that the site ground-motion was consistent at Garner Valley. They suggested that consistency of site response over a wide range of shaking levels indicated an "effective" range of linear soil behavior for peak ground acceleration (PGA) up to 0.1 g. They found that the location and magnitude of significant impedance contrasts within the soil profile controlled site response of Garner Valley.

Ching and Glaser (2001) developed an extended-Kalman filter/State Space approach for direct material property estimation. They directly identified shear velocity and viscous damping coefficients for a number of Garner Valley site earthquakes using this Extended Kalman filter/State Space model.

Kelner *et al.* (1999) characterized the fracturing of the anisotropic shallow granite (< 250 m in depth) present at Garner Valley. They concluded that the seismic anisotropy and attenuation observed at Garner Valley was due to the presence of fractures in the granite.

Mohammadioun *et al.* (1992) and Mohammadioun and Gariel (1995) found that the transfer functions computed from downhole array data sets at Garner Valley agreed with those derived from a mono-dimensional model. Mohammadioun and Gariel (1996) validated a number of available seismological and engineering computer codes for modeling earthquake ground motion using data set accumulated at Garner Valley since 1989. Mohammadioun (1998) used the seismic records to analyze soil nonlinearity, horizontal to vertical response ratios, and the potential for microzoning.

Pecker (1995) compared the motions computed from the downhole array records at Garner Valley and found that a carefully conducted geotechnical survey could yield an accurate shear wave velocity profile. It was reported that rate-independent damping might not be appropriate to represent soil behavior in the small strain range.

Additional studies on the Garner Valley downhole array were conducted by Coutant (1996), Theodulidis *et al.* (1996), Tumarkin (1998), Tumarkin and Archuleta (1997), and Volant *et al.* (1998).

Wildlife Refuge, Imperial County, California

Evidence of liquefaction at or near the Wildlife Refuge site was observed following the 1930, 1950, 1957, 1979, and 1981 Imperial Valley earthquakes (Youd and Wieczorek 1984, Holzer *et al.* 1989). The Wildlife Refuge array was specifically designed to simultaneously measure pore pressure and ground motion. It was instrumented in 1982 by the United States Geological Survey with a surface and a downhole accelerometer at 7m depth, below a liquefiable layer, and six piezometers that record seismically induced excess pore-pressures (Holzer *et al.* 1989). The surface records during the November 24, 1987 Superstition Hills earthquake (M_W = 6.6) displayed peculiar acceleration spikes associated with simultaneous instants of excess pore-pressure drop (Holzer *et al.* 1989, Youd and Holzer 1994, Scott and Hushmand 1995).

Data collected at this downhole array provided important information for studies on nonlinear ground motion (Archuleta 1998). Archuleta and Steidl (1998) employed the 1987 seismic records to assess the magnitude and effect of nonlinearity on soil response. Yoshida and Iai (1998) used the downhole data to assess the nonlinear behavior of a soft surface ground stratum during strong earthquakes. They pointed out that effective stress analysis was better than nonlinear total stress analysis, and nonlinear analysis was better than equivalent linear analysis.

Glaser (1996) and Baise and Glaser (2000b) studied the effects of liquefaction using the stationary and recursive versions of a black box system identification (SI) method. The black box SI method was demonstrated to consistently characterize the Wildlife site ground motion. They found the site exhibited linear behavior for the first portion of the record prior to the onset of liquefaction and that once the soil started to liquefy and change state, nonlinear soil behavior dominated site behavior. Ching and Glaser (2001) applied an extended-Kalman filter/State Space approach for direct material property estimation.

Zeghal and Elgamal (1994), Zeghal *et al.* (1996b), and Elgamal *et al.* (1997) used cross-correlation analyses to assess the site stiffness degradation associated with the phase of sharp pore-pressure rise. The seismic shear stress-strain and effective stress path histories were directly evaluated using the recorded downhole accelerations and pore pressures. The dramatic change in site response due to liquefaction was evident in the stress-strain history of the Superstition Hills earthquake. During the strong shaking phase, the site experienced clear and gradual stiffness degradation associated with the sharp increase in recorded pore water pressure. At low effective confining pressures (high excess pore pressures), the effective stress-path clearly exhibited a reversal of behavior from contractive to dilative at large strains (NRC 1985, Zeghal and Elgamal 1994). Thus, this case history clearly showed an in-situ mechanism of shear stress hardening at large strain excursions during liquefaction. Such a mechanism has been observed in a number of experimental studies and is a consequence of soil dilation at large strain excursions, which results in associated instantaneous pore-pressure drops. This observed phenomenon of hardening at large shear strain excursions (during liquefaction) is of paramount importance in restricting the extent of lateral deformation due to seismic excitation (see later section of this paper on Liquefaction and Downhole Arrays).

Zorapapel and Vucetic (1994) used the ground surface and subsurface accelerations and pore water pressures recorded during the 1987 earthquakes to evaluate the effects of gradual buildup of seismic pore water pressure and associated degradation of stiffness on the ground surface motion for shallow saturated liquefiable deposits. Ground surface displacements and accelerations, the Fourier Transforms of the acceleration-time histories and layer gain factors were analyzed.

Borrego Valley, California

The Borrego Valley Downhole Array (BVDA) is located in the northern part of Borrego Valley adjacent to the Coyote Creek branch of the San Jacinto fault in Southern California (Archuleta 1998, Archuleta and Steidl 1998). BVDA consists of three different arrays: (1) a downhole array at the main station in the center of the valley, (2) two pairs of surface/downhole arrays at a rock outcrop and sites in its vicinity, and (3) two linear surface arrays between the main station and the rock station. Observation of strong motions at BVDA was initiated in early 1993, and more than 200 earthquakes with various magnitudes have been recorded. Various types of geophysical and geotechnical methods have been used to characterize the 1-D to 3-D geological structure, providing calibration and verification of site response modeling techniques for stiff Quaternary soil sites (Kato *et al.* 1998, Archuleta 1998).

Archuleta and Steidl (1998) evaluated the nonlinear soil response at Borrego Valley. They found the low strain attenuation (known as $Q = 1/2b$ where b is damping) was 10-20 in all soil layers. By comparing the Borrego Valley Downhole Array (unsaturated) with Garner Valley and Hollister downhole arrays (saturated), they observed the difference in low-strain attenuation between saturated and unsaturated soils.

Nigbor *et al.* (1999) used 1D, 2D, and 3D models to calculate the ground shaking for an earthquake recorded by the array. They showed the strengths and weaknesses of different site response estimation methods.

Olsen *et al.* (2000a, b) simulated 2 Hz wave propagation in a three-dimensional model of the Borrego Valley for an earthquake with epicenter 5 km north of the valley. The simulation reproduced the overall pattern of ground motions and showed a correlation of observed to synthetic waveforms. The 3D simulation reproduced the recorded peak motions, cumulative kinetic energies, and Fourier spectral amplitudes within a factor of 2 for most components at the individual sites. Their prediction required the inclusion of anelastic attenuation in the simulation with Q values for P- and S-waves in the saturated alluvium of about 30.

Treasure Island, California

Treasure Island is a reclaimed island located in the San Francisco bay. It was constructed in the 1930's of hydraulic fill over natural sand and Bay Mud. The fill (about 12 m thick) is in a relatively loose condition, and is susceptible to liquefaction. Geologic formation at Treasure Island (including the upper loose hydraulic fill) is similar to that of the nearby Marina District in San Francisco (Pease and O'Rourke 1995, 1997). At both locations, widespread liquefaction with devastating consequences was documented during the recent 1989 Loma Prieta Earthquake (Hryciw *et al.* 1991, Finn *et al.* 1993, Power *et al.* 1995). The Treasure Island liquefaction case history and associated loss of soil stiffness and strength was documented by Pease and O'Rourke (1997) using surface accelerations recorded at Treasure Island, and representative bedrock accelerations recorded at the nearby outcrop of Yerba Buena.

The Treasure Island downhole array is located between the San Andreas and Hayward faults. The array consists of six accelerometer stations extending to a 104m depth, and 6 piezometers located within the top 12m reclaimed hydraulic fill. The array was installed in 1992 by the California Strong Motion Instrumentation Program, and the National Science foundation (de Alba *et al.* 1992, de Alba *et al.* 1994, de Alba and Faris 1998). This array is intended to provide data that can be used to identify the mechanism of rock-motion amplification by deep soil deposits in the San Francisco area, the mechanisms of site liquefaction in the upper hydraulic fill strata, and to develop more reliable methods for predicting permanent ground deformations and displacements.

Since its installation, the array recorded a number of low amplitude shaking events, and is currently active in anticipation of a future strong earthquake excitation. These low amplitude events provide a source of benchmark information on Treasure Island low strain dynamic response characteristics. Elgamal *et al.* (1996a) employed the 1993 downhole records to evaluate: (1) shear wave velocity profile, (2) site shear stress-strain response, and (3) low-strain soil dynamic properties. The identified stiffness and damping parameters showed a noticeably higher damping ratio in the upper loose hydraulic-fill layer, possibly reflecting the soft nature of the fill, along with other surface wave propagation characteristics that were not modeled by the employed simple 1D shear wave propagation concept (Zeghal and Elgamal 2000). Baise (2000) and Yoshida and Iai (1998) also studied the Treasure Island site behavior using downhole array data.

Hollister Municipal Airport, California

At Hollister, the near-surface sediment consists of clay, sand, and gravel (Archuleta 1998). The downhole arrays were installed in 1991. The site is located in the Salinas Valley where alluvium overlies Tertiary sandstone overlying a granite basement. The array consists of nine accelerometers, six at the main station and three remote rock stations - one on granite, one on Tertiary sandstone and one in a downhole at 53m depth (Archuleta 1998). Archuleta and Steidl (1998) summarized the installation and data analysis of the Hollister downhole arrays. Archuleta *et al.* (1998) studied the records from two downhole arrays and two surface rock sites and found that a single downhole recording was much better as a reference ground motion than a surface rock record to predict site linear amplification. More recent studies were conducted by Glaser and Baise (personal communication 1999).

San Francisco, California

A four-level downhole array of three-component instruments was established on the southwest shore of San Francisco Bay (Borcherdt *et al.* 1999). The deepest instrument is at a depth of 186 m, 2 m below the top of the Franciscan bedrock (Joyner *et al.* 1976). The arrays are designed to address the issue of anelastic and nonlinear soil response at high strain levels (Borcherdt *et al.* 1999). Borcherdt *et al.* (1999) developed anelastic models to account for contrasts in characteristics at boundaries and the resultant inhomogeneity of propagating wave fields. They found that significant amounts of energy might be trapped in soil basins with resultant larger amplifications than those obtained from conventional homogeneous wavefield models.

McGee Creek, California

At the McGee Creek, California, site, three-component strong-motion accelerometers are located at depths of 166 m, 35 m, and 0m. The surface material is glacial moraine, to a depth of 30.5 m, overlying hornfels. Accelerations were recorded from two California earthquakes: Round Valley, M_L 5.8, Nov. 23, 1984, and Chalfant Valley, M_L 6.4, July 21, 1986. Anti-plane shear strains have been determined for the Round Valley and Chalfant Valley events (Seale and Archuleta 1989). Seale and Archuleta (1989) applied a constant phase velocity Haskell-Thomson model to generate synthetic SH seismograms at the surface using the accelerations recorded at 166 m. They found that for low amplitude strain, a downhole time history of acceleration could be linearly propagated to the surface based on geotechnical logs of P and S wave velocities in the vertical column. The synthetic acceleration time history could match the observed response both in phase and amplitude up to 10 Hz. In the frequency band 0.10 to 10.0 Hz, they found that the seismic amplification at the surface was a result of the resonance of the surface layers and the contrast of impedance (shear stiffness) in the near surface materials.

Los Angeles, California

Hauksson *et al.* (1987) described the downhole array operating in the seismically active Newport-Inglewood fault zone of the Los Angeles basin. Results of observations and measurements were given for an M_L 2.8 earthquake that occurred 0.9 km from the array on July 31, 1986, generating rays traveling almost vertically up the downhole. They reported results derived from P- and S-wave pulse shapes, near-surface site response and resulting amplifications of the P and S waves, Q values, wave spectra, corner frequencies (determined from displacement spectra), and the effects on f_{max} on near-surface attenuation.

Cholame Valley near Parkfield, California

A wedging system for coupling downhole accelerometers into cased downholes has been developed and deployed at an Electric Power Research Inst. (EPRI)/U.S. Geological Survey (USGS) instrument array located in the Cholame Valley near Parkfield, California. The wedging system allows downhole accelerometers to be set and retrieved by hand. With this system, accelerometers can be readily retrieved from cased holes for inspection, maintenance, or redeployment (Youd *et al.* 1989).

Cajon Pass, California

Early estimates of Cajon Pass site response were limited to shallower holes, where the surface reflection interferes with the upgoing direct wave, and the deepest sensor was not below the severe near-surface effects, in bedrock (Abercrombie 1997). Following early efforts, deep downhole arrays were deployed, penetrating 500 m of Miocene sandstone and then crystalline, granitic basement rock. Near surface attenuation and site effects have been investigated using the seismograms of 17 local earthquakes recorded at depths of 0, 0.3, 1.5, 2.5, and 2.9 km (Abercrombie 1997).

Paducah, Kentucky

The downhole vertical accelerometer array VSAP near Paducah, Kentucky (Street *et al.* 1997), consists of three-component accelerometers at the surface, the top of the McNairy Formation (41 m depth), and the top of the Paleozoic bedrock (99 m depth). The array is at the northern end of the Mississippi Embayment. The array is intended to verify ground-motion modeling for the site, assuming a significant earthquake in the New Madrid Seismic Zone. Accelerograms from M_b 2.0 and 4.2 earthquakes have been used to check aspects of the modeling pertaining to linear behavior of the soil column. The soil column models derived by drilling and geotechnical methods and through the use of high-resolution P- and SH-wave seismic refraction and reflection techniques have been examined (Street *et al.* 1997).

Port Island, Japan

Port Island is a reclaimed island located on the southwest side of Kobe, Japan. Soil in the reclaimed layer consisted of decomposed weathered granite fill with grain sizes ranging from gravel and cobble-sized particles, to fine sand. A 4-station downhole accelerometer array extending to 83 m depth was installed at Port Island in August 1991 (Iwasaki 1995, Iwasaki and Tai 1996). The array site consists of: (1) a reclaimed, loose surface layer down to about 19 m depth, (2) an alluvial clay layer between 19 m and 27 m depth, (3) sand and sand with gravel strata interlayered with clay between 27 and 61 m depth, (4) a diluvial clay layer between 61 m and 82 m depth, and (5) sand with gravel layers interlayered with clay starting at about 82 m depth. The water table was located at a depth of 4m approximately. The Port Island downhole array data have been the subject of numerous recent studies as described below.

Aguirre and Irikura (1995) showed the strong influence of nonlinear effects in horizontal components, and the linear amplification of vertical components. Thus explained why the vertical motions had disproportionate large amplitudes in comparison to the horizontal ones. Aguirre (1996) used linear and nonlinear simulations to study the nonlinear site effects at Port Island during the 1995 Hyogo-ken Nanbu earthquake. Aguirre and Irikura (1997) used a spectral ratio technique and a nonlinear inversion process for the velocity structure.

Ansary *et al.* (1995) and Yamazaki *et al.* (1995) conducted analyses of the downhole records using a nonlinear dynamic effective stress method taking into account liquefaction under multi-directional shearing. Computed and recorded ground motions and associated response spectra were found to be in good agreement. Coupled effects of the two horizontal motions on the dynamic response and liquefaction of the ground were examined.

Baise and Glaser (2000a, b, c) identified the empirical Green's function at Port Island by isolating the systematic effects of the soil profile on the recorded ground motions. They indicated that strong nonlinear behavior (liquefaction) controlled site response. The stationary and recursive versions of the black box system identification method were used to show that the site exhibited linear behavior for the first portion of the record prior to the onset of liquefaction. Using foreshocks and aftershocks, they showed that the liquefied ground gradually returned to pre-liquefied site response conditions.

Cubrinovski *et al.* (1996) conducted a series of fully coupled effective stress analyses to investigate the ground response associated with the recorded accelerations. They showed a governing influence of the excess pore pressures on the ground response.

Davis and Berrill (1998a) and Davis (2000) presented a scheme for interpolating displacement and acceleration measurements using Port Island downhole array records to provide higher accuracy approximations for subsurface shear strain and stress as continuous functions of time. Davis and Berrill (1998b) analysed the Port Island downhole records from the Hyogo-ken Nanbu earthquake to obtain approximate histories of shear stress, shear strain and dissipated energy at a range of depths. They showed that a rapidly developing zone of liquefaction was initiated at a depth of roughly 15 meters in the Port Island reclaimed soils.

Elgamal *et al.* (1996c, 1997) and Zeghal *et al.* (1996a, b) evaluated shear stress-strain response using the recorded downhole accelerations. They found that two different response patterns were exhibited at the site. Below 32m depth, the shear stress-strain histories showed an essentially linear soil response, with no appreciable reduction in soil stiffness. On the other hand, at shallow depths (near the ground surface) the stress-strain histories indicated an abrupt sharp loss of stiffness and reduction of yield strength, evidently associated with site liquefaction. This liquefaction response mechanism was marked by the virtual absence of very large strains and associated hardening (near ground surface), in contrast to the Wildlife case.

Haddadi and Kawakami (1998a, b, 2000) used the normalized input-output minimization (NIOM) method to model wave propagation and identify dynamic characteristics of subsurface layers at the Port Island downhole array site. Variations of wave amplification and damping were discussed. The stiffness characteristics of the liquefied portion recovered gradually from the time of the main shock of the Hyogoken-Nanbu earthquake to the earthquake of February 18, 1995.

Igarashi (1996) derived an explicit formula to evaluate the factor of safety against liquefaction Fl_e from energy-related parameters of soil and ground motion, namely, the liquefaction energy amplitude, dynamic friction angle, root mean square shear stress, a bandwidth factor, and effective number of cycles. He applied the formula to the liquefaction at Port Island using the measured downhole accelerations.

Iwasaki and Tai (1996) analyzed downhole array records obtained at Kobe Port Island during the Hyogo-ken Nanbu earthquake. The peak horizontal acceleration was minimum at the ground surface and increased with depth, whereas, the peak vertical acceleration, the peak horizontal velocity, and displacement all decreased with depth.

Kamiyama and Matsukawa (1998) and Kamiyama *et al.* (1998, 2000) proposed a method for estimating the dynamic variation of stiffness and damping of soils related closely to the nonlinear ground earthquake response. The downhole array records obtained at Port Island during the 1995 Kobe earthquake were used to investigate the capability of the method. They concluded that the method was effective for estimating the nonstationary variation of soil stiffness and damping and could be applied to various phenomena associated with nonlinear seismic behavior.

Kawase *et al.* (1995, 1996) studied the strong motion records of the Hyogo-ken Nanbu earthquake observed by the downhole array at Port Island. They simulated the observed accelerograms by using 1-D linear, equivalent linear, and effective stress analyses with reasonable soil constants derived from the boring survey.

Kokusho *et al.* (1994) studied seismic response of deep soil by means of downhole array data with special focus on soil damping evaluated in-situ and in the laboratory. Kokusho *et al.* (1995) estimated S-wave velocity and damping ratio corresponding to the main shock as well as a small aftershock by an inversion technique. Their study revealed the effect of soil liquefaction and nonlinear soil characteristics on the strong motion amplification mechanism at the site.

Mok *et al.* (1998) utilized the ground motion recordings at Port Island downhole array to back-calculate the compression-wave velocities (V_p) during strong seismic events and to examine the effects of soil damping on vertical site response. They suggested that dynamic soil behavior was related to the degree of saturation.

Nozu and Uwabe (2000) applied the empirical Green's function (EGF) method to the records obtained at Port Island during the 1995 Hyogo-ken Nanbu earthquake and its aftershocks, to evaluate the nonlinear effect on the mainshock records. Nonlinear ground response analysis showed that amplitude reduction during reverberation could exist under certain conditions.

Numata *et al.* (1998, 2000) estimated ground motion behavior of an improved site and an unimproved site during the 1995 Kobe earthquake using downhole array data. A simplified liquefaction evaluation approach was used.

Oka *et al.* (1996, 2000) studied the nonlinear ground motion amplification, focusing on its time-dependent characteristics due to the decrease of excess pore water pressure after the large event. They applied a frequency-dependent equi-linearized technique, and an effective stress-based liquefaction analysis method. Oka *et al.* (1997) carried out a three-dimensional effective-stress liquefaction analysis in order to understand the basic behavior of the reclaimed island subjected to liquefaction. The analytical results were found to be in good agreement with the array records.

Sato *et al.* (1996), Kokusho *et al.* (1996), Kokusho and Matsumoto (1997, 1998), and Kokusho (1999) analyzed downhole array records corresponding to the 1995 Hyogoken-Nambu earthquake including Port Island with an inversion technique (to estimate S-wave velocity and damping ratio corresponding to the main shock as well as small aftershocks). They showed the effects of soil liquefaction and nonlinear soil characteristics on the peculiar seismic amplification mechanism at this site.

Shiono (1978, 1979) analyzed early downhole array records to identify wave types. They found that the vertical component was composed of vertical incident standing P-waves while the horizontal component was composed of S-waves with the same behavior. The wave types did not change throughout the length of the records although the frequency contents varied significantly with time.

Soeda *et al.* (1999) studied the nonlinearity and irregularity on strong seismic motions using equivalent linear models. The stiffness degradation due to strong motions was evaluated based on considerations of irregularity of the recorded motions.

Sugito (1995), Furumoto *et al.* (1999), and Sugito *et al.* (2000) investigated the nonlinear ground motion amplification using a frequency-dependent equivalent linearization technique. An effective stress-based liquefaction analysis was also conducted.

Tanaka (1996, 2000) discussed the liquefaction damage at Port Island based on the downhole array seismic records. Tanaka (1997) showed how the stiffness of the Port Island ground dropped and recovered during and after the Great Hanshin earthquake of 17 January 1995.

Uetake and Satoh (1998) showed that Port Island downhole array records directly revealed the nonlinearity of soil sediments, and that the effects of nonlinearity on strong motions were not negligible with or without liquefaction. They indicated that downhole array records were useful for estimating underground topography, S-wave velocities, and damping factors.

Using the downhole array records obtained from the 1995 Kobe earthquake, Yanagisawa and Kazama (1996) estimated average stress-strain relationships in the ground at Kobe Port Island. The stress was directly evaluated from earthquake acceleration records. The strain was evaluated from the relative displacement divided by the distance between adjacent observation points. The hysteretic deformation characteristics were analyzed from the following points of view: (1) Softening of the ground stiffness during the earthquake, (2) Liquefaction process of the reclaimed ground during the main shock, and (3) Nonlinear characteristics during the main shock and the aftershocks.

Yang and Sato (1999, 2000a) and Yang *et al.* (2000a, b) studied the response of the liquefiable Port Island site. They suggested that the stress-strain response and the build-up of pore pressure were well correlated to the variation of the characteristics of ground motion during the shaking history. Yang and Sato (2000b) presented a mechanism to explain the observed vertical amplification at Port Island in order to understand why the horizontal peak accelerations were reduced, but motions in the vertical direction were significantly amplified at the surface. They showed a mechanism of large amplification caused by incomplete saturation of near-surface layers and suggested that the condition of saturation in the study of vertical site amplification might need to be carefully examined.

Yoshida (2000) conducted effective stress dynamic analysis to evaluate the effect of liquefaction of improved ground at Port Island using the downhole array records. He reported that the existence of the improved ground did not significantly affect the downhole array records. Yoshida *et al.* (1996) studied the nonlinear behavior of Port Island ground using downhole arrays. It was reported that severe nonlinear behavior occurred in two materials, the Holocene clay and the fill material which was shown to affect the response of the ground by the effective stress analysis. Their back analysis of the vertical array records indicated that nonlinear behavior with shear strain larger than 1% occurred.

Additional studies at Port Island were carried out by Fukushima and Irikura (1997), Kamiyama and Matsukawa (1998), Kazama (1996), Miwa *et al.* (2000), and Sugito *et al.* (1996a, b), Taguchi *et al.* (1996), Wang *et al.* (2001), and Yoshida and Iai (1998).

Chiba, Japan

The prospect for conducting 3-dimensional (3D) studies using downhole array data is illustrated by the Chiba downhole array (Katayama *et al.* 1990). This array is located at Chiba Experiment Station of the University of Tokyo, Japan. Ground surface at the array location is essentially flat and the site is dry. Geological material consists of a top loam layer 4-5m in thickness, followed by a 4m thick clayey layer. A sand layer lies under this clayey stratum. Site instrumentation included a dense network of downhole accelerometers, that constitute a system of 9 downhole arrays extending to a 40m depth. Extensive data was recorded by the Chiba array (Nagata *et al.* 1990). Most of these events produced low shaking levels with amplitudes below 0.05g. However, peak ground accelerations of about 0.1g were recorded during one event, and 0.3 g during another. The recorded data was used to conduct numerous valuable studies including back-calculation of the 3D seismic strain field (e.g., Farjoodi *et al.* 1983, Katayama *et al.* 1990), site amplification analyses, and orientation error (also known as azimuthal error) analyses of the buried accelerometers.

Farjoodi *et al.* (1983) used finite element interpolations to estimate 3D seismic strains at Chiba. They evaluated the Chiba site seismic strain field using linear finite element shape functions and found the calculated strains were in good agreement with those measured in-situ by displacement and strain instruments.

Ghayamghamian and Kawakami (1996) investigated nonlinear response of the soil by comparing the spectral ratios (uphole/downhole) using weak and strong motions from the Chiba downhole array. Reduction in the predominant frequency of the transfer function with increase in excitation level reflected the nonlinear response of the soil. Ghayamghamian and Kawakami (2000a, b) used strong motion records from the Chiba downhole array to examine soil shear modulus and material damping as a function of shear strain during large earthquakes. Acceleration data from the site were processed directly for evaluation of site shear stress-strain hysteresis curves for different time windows of the record. They illustrated the significance of the site nonlinearity during strong ground motions as well as the accuracy of the dynamic soil characteristics obtained from laboratory tests.

Ikemoto *et al.* (1999, 2000) performed an inverse analysis of records from the Chiba downhole array. The dynamic soil parameters were identified using horizontal and vertical ground motions in the downhole array records. Applications of the method to actual vertical acceleration records as well as horizontal ones were discussed.

Kurita and Matsui (1997) proposed a formula to estimate the confidence region of identified parameters in Chiba. Their technique was based on the propagation law of errors and the sensitivity of the identified parameters with respect to the model parameter errors.

Sawada *et al.* (1995) developed a localized identification method to calculate dynamic soil characteristics such as shear wave velocity and quality factor of the specified subsurface layers, using the Chiba downhole array records. Sawada *et al.* (1998) investigated the frequency dependency of Q-value in subsurface layers, and found that the frequency dependency of the Q-value for Chiba was clearly identified with stable results of shear wave velocity.

Sykora and Bastani (1998) evaluated the influence of soil stiffness and its distribution with depth at Chiba. For this analysis, they used peak horizontal acceleration (PHA) and peak horizontal particle velocity (PHPV) obtained from acceleration time histories measured in the free-field Chiba downhole strong motion array.

Yoshida and Iai (1998) assessed the recorded nonlinear behavior at Chiba. They showed the importance of taking nonlinear behavior into account in predicting site response. They found that equivalent linear analysis was a good approximation when the maximum strain is less than about 0.5%.

Many other researchers also studied the downhole array data at Chiba including Baise and Glaser (2000a, b, c), Haddadi and Kawakami(1998b), Miura *et al.* (2000), and Tsujihara *et al.* (1990).

<u>Rokko Island, Japan</u>

The Rokko Island downhole array instruments were installed at depths of 0.0 m, 35.0 m, 98.0 m, and 154.5 m (Oka *et al.* 2000).

Baise and Glaser (2000c) examined the variability of site response using parametric autoregressive moving-average (ARMA) models between the geologically similar Port Island and the Rokko Island sites, which are separated by approximately 5 km and are both man-made islands in the same sedimentary basin. They found that site response estimated using the downhole array recordings at the two islands were similar. The Port Island site response amplified the ground motion slightly more than observed at Rokko Island, but the Port Island filter could be used to adequately predict the Rokko Island site response.

Sugito *et al.* (1996a, b) evaluated the orientation error of accelerographs using the data obtained during the South Hyogo earthquake. An error of 22 degrees in the horizontal plane was detected for the sensor installed at 83m depth. The peak acceleration of each time history was found to be significantly affected by the correction of the error (of the order of 60 % larger or smaller than the original peak value). Based on correcting the downhole array records, Furumoto *et al.* (1999), Sugito *et al.* (1996b, 2000), and Oka *et al.* (2000) investigated the nonlinear ground motion amplification using a frequency-dependent equivalent linearization technique for frequency domain analysis, and an effective stress approach for liquefaction analysis. They discussed the time-dependent amplification characteristics of the reclaimed Rokko Island depending on reclamation history.

<u>Ashigara Valley, Japan</u>

The Ashigara Valley downhole instruments were installed at depths of 0, 10, 30, 100, and 467m in Odawara, Japan, by the Earthquake Research Institute, University of Tokyo (Yao 1999).

Sato *et al.* (1998a, b) investigated Ashigara Valley site amplification using downhole array records corresponding to the 1995 Hyogoken-Nambu earthquake with the inversion technique to estimate S-wave velocity and damping ratio. They found the effects of source radiation, geotechnical structure, and nonlinear and anisotropic soil characteristics on the seismic amplification mechanism at the site.

Satoh *et al.* (1993) pointed out based on an inversion method that the main part of the strong motion had the potential of making the surface soil nonlinear, but that the soil returned to the linear range just after the main part. Satoh and Kawase (1995) and Satoh *et al.* (1999) studied the amplification characteristics of soil sediments by using strong and weak motion downhole records in the Ashigara Valley. They found that the amplification factors for the main part of the weak and strong motions could be simulated by nonlinear one-dimensional site analysis for the alluvial surface layers and the diluvial layers. They also performed two-dimensional finite element soil analysis to simulate the amplification factors. Spectral ratio analysis revealed the nonlinearity of soil during the strong ground shaking. In order to quantify the nonlinear behavior of soil sediments, they identified their S-wave velocities and damping factors by minimizing the residual between the observed spectral ratio and the theoretical amplification factor (calculated from a one-dimensional wave propagation theory).

Yao (1999) investigated near-surface attenuation and site effects using the strong motion downhole array records. He showed that accelerograms near the ground surface have peak amplitudes 3 to 4 times larger than those at the deep downhole areas. Q values for S-waves in sedimentary layers obtained by fitting the theoretical transfer functions (1-D multiple reflection theory of SH-wave) to the observed spectral ratios were very low for the near-surface layers, but showed strong frequency dependence.

Kushiro, Japan

Different acceleration records of the surface motion were observed at two adjacent observation stations during the Kushiro-oki earthquake on January 15, 1993, one of which was set up on the building foundation of the Kushiro Meteorological Observatory (JMA) and the other was on the ground. In order to investigate an amplitude discrepancy between two nearby observation stations, two downhole array stations were set up after the earthquake (Yahata *et al.* 2000). Analyses of the downhole array data revealed that the Kushiro site behaved nonlinearly during strong earthquakes (Yahata *et al.* 2000, Yoshida and Iai 1998, Kanda and Motosaka 1997, Uetake and Satoh 1998).

Yahata *et al.* (2000) carried out analyses by applying one and two-dimensional models considering nonlinear soil behavior for the downhole strong motions during the Hokkaido-Toho-oki earthquake of October 4, 1994. They showed that the different surface motions at two sites were generated by the influence of a topographic cliff during strong seismic excitation.

Iai *et al.* (1995) reported data from a downhole array at Kushiro Port. The data was employed for calibration of a state-of-the-art computational code.

Hokkaido, Japan

Hayashi *et al.* (2000) studied liquefaction array observations to measure ground acceleration and pore water pressure during earthquakes simultaneously (on soft ground on the south side of Lake Utonai, Hokkaido, Japan). It was found that the dynamic characteristics of the ground were not affected by the existence of an adjacent road embankment through 1D and 2D equivalent linear analyses.

Hiyoshi, Japan

Kawakami and Haddadi (1998) employed the method of normalized input-output minimization (NIOM) to analyze the ground motion records of three earthquakes detected at the Hiyoshi downhole array in Japan. They presented the amplification characteristics of soil layers at the site.

TKS, KNK, and SGK, Kobe, Japan

Sato *et al.* (1996), Kokusho *et al.* (1996), Kokusho and Matsumoto (1997, 1998), and Kokusho (1999) analyzed TKS, KNK, and SGK downhole array records with the inversion technique to estimate S-wave velocity and damping ratio corresponding to the main shock as well as a small aftershock (Kobe, Hyogo-ken Nanbu earthquake). They showed the effects of nonlinear soil characteristics on the peculiar seismic amplification mechanism at these sites. Strain dependent changes in the shear modulus and the damping ratio were back-calculated from the downhole array records.

Shuzenji, Choshi, Tateyama, and Higashimatsuyama, Japan

The four downhole array sites, Shuzenji, Choshi, Tateyama, and Higashimatsuyama at suitable rock sites surrounding Tokyo were equipped with strong-motion instruments (Omote *et al.* 1980). A large overall array is composed of four local arrays. Each local array comprises a single sub-array in a triangle with 500-m side length and a downhole array. Three-component sensor units were employed. A control and monitoring center located in Tokyo was connected to the sub-arrays via telephone lines. Recorded accelerograms have been analyzed (Omote *et al.* 1980).

Sunamachi, Japan

Davis and Berrill (2001) studied the dynamic pore pressure recordings obtained from downhole arrays at Sunamachi. The calculated stress and strain wavefields were integrated to produce time histories of dissipated energy density for comparison with measured values. Good agreement between measured and calculated pore pressures was reported.

Etchujima, TTRL, Samukawa, Fujisawa, and Shinfuji, Japan

Ghayamghamian and Kawakami (1996) investigated nonlinear response of the soil by comparing the spectral ratio (uphole/downhole) using weak and strong motions from Etchujima, TTRL, Samukawa, Fujisawa, and Shinfuji downhole arrays. The reduction in predominant frequency in the transfer function with the increase in excitation level reflected nonlinear soil response.

Ghayamghamian and Kawakami (2000a, b) used strong motion records from Etchujima, TTRL, Samukawa, Fujisawa, and Shinfuji downhole arrays to examine soil shear modulus and material damping as a function of shear strain during large earthquakes. Acceleration data from the sites were processed directly for evaluation of site shear stress-strain hysteresis curves for different time windows of the records. Additional studies on Etchujima, TTRL, and Shinfuji downhole arrays were carried out by Haddadi and Kawakami (1998a, b) and Yoshida and Iai (1998).

Sendai, Japan

Satoh *et al.* (1995) evaluated local site effects due to surface layers overlying bedrock using one-dimensional soil models. They identified S-wave velocities and frequency-dependent quality factors Q from amplification factors between surface records and downhole records observed at 10 sites at depths of several tens of meters. They estimated the so-called engineering bedrock waves from downhole records by using 1D models with identified soil constants. Uetake and Satoh (1998) showed that Sendai downhole array records directly revealed the nonlinearity of soil sediments.

Tomioka, Japan

The downhole arrays at a site in Tomioka city were installed in the vertical direction from bedrock to ground surface in Fukushima Prefecture, Japan. Ghayamghamian and Kawakami (1996, 2000b) investigated nonlinear response of the soil by comparing the spectral ratios (uphole/downhole) using weak and strong motions from the Tomioka downhole arrays in Japan. Reduction in the predominant frequency with the increase in excitation level was noted as evidence of nonlinear soil response.

Iwata *et al.* (1992) compared the downhole array records obtained from 0 m to about 1 km in depth at Tomioka. Synthetic seismograms were computed using the full-wave theory for a multilayered structural model with a deterministic source. Uetake and Satoh (1998) studied the Tomioka downhole array records as well.

Fuchu, Japan

Kinoshita (1999) studied the Fuchu site effects using a stochastic method for investigations by means of downhole array observation. The wave transfer function for SH waves, the separation of upcoming and downgoing waves and the effect of fundamental mode Love waves on a surface seismogram were investigated without any knowledge of the velocity structure beneath the site.

Westa, Japan

Power *et al.* (1986) studied the downhole array data from free-field ground motion in Westa and found that both peak accelerations and response spectra of ground motions decrease significantly with depth in the range of typical embedment of nuclear power plant structures and other buildings. They concluded that appropriate variations of ground motion with depth should be included in carrying out soil-structure interaction analyses and characterizing foundation input motions for embedded structures.

Yamada (1990) suggested that generation of local surface waves with multiple horizontal reflection between underground boundaries might account for periodic seismic pulses in the coda part of seismic waves by studying the records from the Wesda downhole array, Tokyo. The effect of repetition of seismic pulses on artificial structures was examined.

Shizuoka, Japan

Nozawa *et al.* (1989) investigated the strain dependence of soil characteristics by interpolating the strong-motion accelerograms recorded at the Shizuoka downhole array. They indicated that the accelerograms recorded by the downhole array with peak horizontal ground acceleration exceeding 400 gal were affected by saturation.

Iwaki, Japan

The downhole arrays at a site in Iwaki city are installed from bedrock to the ground surface in Fukushima Prefecture, Japan. Sugawara *et al.* (1991) investigated the characteristics of vertical earthquake ground motions. The relationships between wave motions of vertical and horizontal (radial) components, wave propagation aspects of vertical components from bedrock to ground surface, and amplification functions of vertical components through soil deposits were examined.

Yokohama, Japan

The Yokohama downhole array stations are located in and around Yokohama, the southwestern part of Tokyo metropolitan area. Stations are located within 20×20 km^2. All stations have P- and S-wave profiles by elastic wave explorations. The deepest accelerographs were installed in soft rock with S-wave velocity of about 600 m/s at depth between 75 and 100m. Efforts were carried out to identify S-wave and Qs profiles. With the identified profiles, site amplification characteristics can be removed and incident spectra from bedrock can be evaluated (Toshinawa *et al.* 2000).

Kanto, Japan

The Kanto downhole array sites are located around the Tokyo gulf in the Kanto district, Japan. Kurita *et al.* (2000) used the downhole array records to evaluate local site effects. Local site effect was calculated as the geometric average of the acceleration response spectral ratios between the estimated values from an attenuation relation and observed seismic ground motions. The amplification characteristics of surface geology were considered as the theoretical transfer function. A theoretical transfer function between the wave at ground surface and incident wave at the base layer was calculated from the optimum ground structure model. The optimum ground structure models were identified from vertical array observation records.

Tokyo International Airport, Japan

A horizontal seismometer array having six observation points along a straight line of 2500m length has been established at the

Tokyo International Airport. Each observation point is equipped with two horizontal seismometers. Downhole seismometer arrays have also been established at two points, one at an end of the observation line and the other at a point 500m inside the other end of the line. The observations started in April 1974 and 28 earthquakes had been recorded as of June 1975. Correlations among the ground motions at the points on the ground surface and the two points in the ground where the downhole seismometers were installed have been studied (Tsuchida and Kurata 1975, Tsuchida and Kurata 1976, Tsuchida *et al.* 1977, Hayashi *et al.* 1977, Tsuchida and Iai 1978).

In 1988, a three-dimensional seismic array was deployed at the Tokyo International Airport, Japan. The array extends 2550 meters along a runway in one wing accommodating six observation stations, with another wing extending normal to the runway about 500 meters and accommodating three observation stations. Each observation station has four downhole seismometers down to a depth of about 80 meters with three pore water pressure meters. Phase velocities and directions of incidence to the base of the ground at a depth of 80 meters were obtained from the seismic array records (Iai *et al.* 1994).

Lotung, Taiwan

The U.S. Electric Power Research Institute in cooperation with the Taiwan Power Company conducted a Large-Scale Seismic Test (LSST) at a site near Lotung (Tang 1987). Two models (1/4-scale and 1/12-scale) of a nuclear-plant containment structure were constructed on a flat and vast alluvium basin (in the vicinity of seismically active faults). Soil at this site consists predominantly of interlayered silty-sand and sandy-silt, and ground-water level was at or within 1m of ground surface. Extensive instrumentation was deployed to record both structural and ground seismic responses. The ground instrumentation included three linear surface arrays (arms 1, 2, and 3), and two downhole arrays (DHA and DHB) that extended to a depth of 47m below ground surface (Tang 1987). Eighteen earthquakes were recorded during the period 1985-1986 (Tang 1987). This wealth of data constituted a basis for a number of valuable research efforts. Numerous analysis techniques and ground response models have been developed to identify the soil dynamic parameters and evaluate the Lotung site seismic performance.

Baise and Glaser (2000a) identified the empirical Green's function from depth to the surface at Lotung. They suggested that consistency of site response over a wide range of shaking levels indicated an "effective" range of linear soil behavior for PGA up to 0.21 g at Lotung. Baise and Glaser (2000c) compared the Lotung site responses with Chiba and found that they were dissimilar although the geologic profile showed consistencies.

Beresnev and Wen (1995) examined the nonlinearity in P-wave amplification using the strong-motion data from a downhole array at the Lotung site where a significant nonlinear response to S waves had been found. They analyzed soil transfer functions and found that that the response remained linear in the shear strain range of 7×10^{-5}. Beresnev and Wen (1996a) examined the relationship of spectral ratios between soft soil and reference rock sites. They suggested that the soil-to-rock spectral ratios could be considered reliable estimates of the real site response. Beresnev and Wen (1996b) indicated that nonlinear site effects were more common than previously recognized in strong-motion seismology.

Borja *et al.* (1999a) showed that soil structure interaction effects were partly responsible for the reduced peak north-south ground surface acceleration recorded by a downhole array near the containment structure. Lin and Borja (2000) noticed the pore pressure records in Lotung were erratic and suggested the presence of artesian conditions during the LSST12 and LSST16 seismic events. They proposed the possibility of double drainage (i.e., water was draining not only to the top but also to a sand layer at a depth between 8-9 meters, just above the clayey silt layer). A coupled analysis using a u-w-p finite element formulation was employed. They argued that the moduli and damping ratio curves developed by Zeghal *et al.* (1995) tended to underpredict the Arias intensities of the ground motion.

Borja *et al.* (1999b, 2000) used a nonlinear FE model (accounting for soil column effects) to examine the nonlinear ground response at the LSST site in Lotung. They showed that the recorded downhole motion was dominated by nonlinear response. They suggested that it was not necessary to have a complete damping ratio-shear strain curve to model nonlinear ground response (the zero shear-strain damping ratio asymptote was sufficient to obtain a measure of true viscous damping, and the remainder of the damping ratio curve was redundant information).

Chang *et al.* (1989) found evidence of significant nonlinear soil response for peak accelerations greater than about 0.15g at the ground surface using the downhole ground motion data. Effective shear moduli or shear-wave velocities were found to decrease as the level of shaking increased. Chang *et al.* (1990) evaluated the equivalent linear and nonlinear analysis techniques for modelling nonlinear soil behavior using downhole ground motion data from Lotung. They compared computed motions with recorded motions. Both deconvolution and upward wave propagation analyses were performed using equivalent linear techniques (only upward wave propagation analyses were performed for the nonlinear analysis technique). Chang *et al.* (1994) analyzed vertical motions recorded at the Lotung downhole array in Taiwan during three large events having magnitudes ranging from 6.2 to 7.0. The recorded motions were first used to examine any change in locations of peak Fourier spectral ratios between motions at the ground surface and at depth for different events having various levels of excitation. Using the frequencies of the peak Fourier spectral ratios, values of P wave velocity for the soil profile were estimated and compared with the geophysical measurements.

Chang *et al.* (1996) evaluated equivalent-linear dynamic shear moduli from the recorded downhole earthquake accelerations. The identified reduction in shear modulus, as a function of effective shear strain, was shown to be in agreement with laboratory test data, and provided evidence of nonlinear soil behavior during earthquake excitation. They evaluated the accuracy of dynamic characteristics obtained from geophysical measurements and laboratory tests.

Chen and Chen (1989) presented seismic wave velocity analysis using the acceleration time-histories recorded at the Lotung downhole array. The frequencies of maximum amplification of soil layers were identified using the spectral ratios between the surface and downhole accelerograms. They proposed an elastic 1-D wave propagation model to estimate the ground seismic wave velocities. They indicated that significant reduction of shear wave velocity as well as soil modulus was induced by earthquake excitation as compared to the values obtained from low strain level soil tests.

Davis and Berrill (2001) studied the dynamic response and pore pressure recordings obtained from downhole arrays at Lotung. The calculated stress and strain wave fields were integrated to produce time histories of dissipated energy density for comparison with measured values. Good agreement between measured and calculated pore pressures was reported. Shen *et al.* (1991) also evaluated excess pore pressures during three different LSST earthquakes.

Glaser (1995), Glaser and Baise (2000), and Ching and Glaser (2001) estimated soil characteristics at the Lotung downhole array site with a mapping to a lumped mass model using both time-invariant and time-variant parametric modeling methods (system identification). They found that the estimated shear stiffness ranged between 0.5 and 6 MN/m, inversely proportional to PGA, and the estimated equivalent viscous damping ratio varied from 2% to 30% of critical damping (in proportion to PGA). They noticed the degradation of soil behavior, while less pronounced with increasing depth, consistently occurred above a peak input acceleration of 0.07g.

Huang *et al.* (2000) studied the linear and nonlinear behavior of soft soil layers. Spectral analyses showed that the strong motion caused peaks in spectral ratios to shift to lower predominant frequencies. Compared to the weak motions, the strong motions also decreased the amplification factor. The maximum reduction in amplification reached 50%. A waveform simulation showed that the linear model based on the Haskell method could predict well the weak motions (PGA < 60 gals) at various depths. This model was not good for the strong motion data (PGA > 150 gals). They showed that the nonlinear numerical scheme could significantly improve the simulation results although PGA at the surface station was still underestimated.

Li *et al.* (1998) used two major earthquakes at Lotung within a 4-month period to perform numerical analyses with a fully coupled, multidirectional dynamic procedure incorporating a bounding surface hypo-plasticity model. The calculated responses for the two different events showed equally reasonable agreements with the field records in both 3D acceleration and pore-pressure time histories.

Wen *et al.* (1994, 1995b) studied the nonlinear seismic response at Lotung by comparing the spectral ratios of surface to downhole horizontal accelerations during weak and strong motion. The dependence of soil amplification on the amplitude of input excitation was established. Wen (1994) investigated the issues of linear versus nonlinear soil response and isotropy versus anisotropy at the Lotung site.

Mok *et al.* (1998) utilized the ground motion recordings at Lotung to back-calculate the compression-wave velocities (V_p) during strong seismic events and to examine the effects of soil damping on vertical site response. They suggested that dynamic soil behavior was related to the degree of saturation.

Shen *et al.* (1991), Elgamal *et al.* (1996a) and Zeghal *et al.* (1996b) employed the Lotung downhole seismic records to calibrate linear and nonlinear computational site response models and showed downhole records to be a valuable means of advancing the state-of-the-art in site amplification computations.

Zeghal and Elgamal (1993), Zeghal *et al.* (1995), Elgamal *et al.* (1995), Elgamal *et al.* (1996a), and Elgamal *et al.* (1997) performed cross correlation and spectral analyses of the recorded Lotung downhole accelerations to evaluate shear wave propagation characteristics, variation of shear wave velocity with depth, and site resonant frequencies and modal configurations. They found that a shear-beam model, calibrated by the identified site characteristics can represent the site dynamic response characteristics over a wide frequency range. They utilized strong-motion earthquake records to investigate the Lotung site large-strain soil response characteristics. A shear stress strain imaging technique was developed to evaluate soil shear stress-strain histories directly from the free-field downhole accelerations. From these histories, they found two salient response features: (1) stiffness reduction due to the increase in shear strain amplitude and (2) stiffness reduction due to pore pressure buildup. The identified stiffness and damping characteristics provided quantitative evidence of nonlinear site amplification during strong-motion earthquakes.

Many other researchers also conducted studies on the Lotung downhole array including Lin (1994), Loh and Yeh (1992), Sykora and Bastani (1998), and Yoshida and Iai (1998).

Hualien, Taiwan

Hualien is located south of Lotung on the east coast of Taiwan within a highly active seismic zone. The Hualien LSST was initiated in 1993 by an international consortium of industrial and research enterprises from five countries (Japan, USA, China, France and Korea). In contrast to the Lotung soft soil conditions, the Hualien experiment was located at a relatively stiff site (Tang *et al.* 1991, Graves *et al.* 1996). Extensive instrumentation was deployed to record seismic structural and ground responses, and to monitor soil pore-water pressure buildup. The ground instrumentation (installed around a one-quarter scale nuclear-plant containment structure) included fifteen surface accelerometer stations, and three downhole accelerometer arrays. Each downhole array consisted of 5 accelerometers and extended to a 52.6m depth. During the period July 1993 to May 1995, seven earthquakes were recorded at the Hualien site (Yang *et al.*

1995a, b). The largest peak lateral acceleration of these events is about 0.1 g. However, the instrumentation is still active and available to record anticipated future stronger earthquake excitation. Actually, motions from the recent 1999 Ji-Ji Taiwan earthquake were recorded by this array (C. Chen and H. Graves, personal communication 2000).

The earthquake records at this site revealed a unique mechanism of azimuthal anisotropic soil response (Ueshima and Okano 1996, Chen and Chiu 1998, Gunturi *et al.* 1998, and Pires and Higgins 1998).

Based on correlation analyses and identified seismic stress-strain histories, Chen and Chiu (1998) employed the free-field motions of six earthquakes to identify the predominant frequencies of soil layers and estimate the shear wave velocities. They found that the soils at the Hualien LSST site were anisotropic such that the earthquake responses exhibited different characteristics in two horizontal principal directions. Chen and Chiu (1999) presented the results of ground response analyses by using the free-field motions recorded at the site during the earthquake of May 1, 1995.

Gunturi *et al.* (1998) found the shear wave velocity profile estimated in the EW direction to be lower than in the NS direction. They showed that this anisotropic soil response had been manifested during earlier in-situ experimental studies of foundation impedance functions (de Barros and Luco 1995). The identified linear soil characteristics adequately represented the recorded seismic site response at small strains.

Pires and Higgins (1998) found that the site exhibited cross-anisotropy while studying the soil-structure interaction response observed under dynamic lateral load testing. Similar conclusions were reported by de Barros and Luco (1995).

Wuku, Taiwan

This downhole array was installed in a sewage disposal plant in the Wuku Industrial Area at the end of 1993. It is a sub-project of "An Integrated Survey of the Subsurface Geology and Engineering Environment of the Taipei basin" initiated in 1991. The array is located at the western part of the Taipei Basin. It consists of accelerometers, a GPS timing system and a digital recording system. The main purpose of this downhole array project is to study the basin effects on seismic waves (Wen *et al.* 1995a, Wen and Peng 1998). Wen *et al.* (1995a) conducted travel time analysis of seismic waves and calculated V_p and V_s for the soil layer from surface to the depth of 352 meters using weak motions records. By comparing the peak ground motions at different depths with ground surface motions they found that the main amplification existed in the top 60 meters of the soft soil layer and that no nonlinear amplification effect occurred in the weak motion data set. They obtained an equation representing the variation of horizontal peak ground acceleration with respect to depth using regression analysis. They also performed ground response analysis in the frequency domain.

Dahan, Taiwan

The Dahan downhole array was installed at depths of 0, 50, 100 and 200 m. Chiu *et al.* (1994) showed that the polarization of later arrivals could be used to estimate the orientation error and the tilt of the downhole accelerometers in the Dahan downhole strong-motion array. Huang and Chiu (1996) used Four-level Dahan downhole recordings to investigate site amplification due to the near-surface structure. They selected eight sets of data presenting well-separated incident and reflected waves (from the free surface) to study site amplification. They also tested five techniques of spectral ratios to determine the most reliable way to estimate site response.

Mexico City, Mexico

The Central de Abasto Oficinas (CAO) downhole arrays in Mexico and related analyses have been reported by Taboada *et al.* (1999a, b, 2000).

The valley of Mexico City is frequently affected by strong ground motions due to a combination of high rate subduction-related seismicity at regional distances, and unique soft clay site material conditions. The CAO site is located within the central lacustrine deposit zone of the valley, close to the downtown of Mexico City. Geological material of the site consists of quaternary soft clayey and silty soil over a partially cemented gravel and sandy alluvial stratum. The clayey deposit is 40-50m thick and it contains not only important fractions of silt, but also some thin layers of fine sand and volcanic glass at various depths. It may be observed that water content varies from 50 to 200% within the top 10 meters; and reaches 350 to 450% between 10m and 40m. The CAO downhole acceleration array is located near the central part of the valley. The downhole array of the site includes one superficial accelerometer and three more located at 12m, 30m and 60m below ground surface (Taboada *et al.* 2000).

Faccioli *et al.* (1996) used data from the Jalapa building in the soft clay zone of Mexico City, equipped with a local array of 14 digital accelerographs (including one free-field and two downhole instruments at 20 m and 45 m depth), to study salient aspects of site response and soil-structure interaction (SSI) at PGA levels in free-field up to about 0.05 g. The analyses were focused on the interpretation of the peak amplitude reduction of spectral ratios between surface and intermediate depth downhole recordings and on the influence of surface waves on ground motion.

Taboada *et al.* (1999a, b, 2000) used the CAO downhole array records from the 3/31/93, 24/10/93, 23/05/94, 10/12/94 and 09/10/95 seismic events to investigate the soil stiffness and damping ratio as a function of shear strain amplitude. The shear stress-strain histories were evaluated directly from the downhole array records, employing a technique of system identification. These histories were used to obtain the variation of shear modulus and damping ratio with shear strain amplitude. A shear-beam model, calibrated by the identified properties, was found to represent the site dynamic response characteristics.

Tangshan, Mainland China

The Tangshan downhole array is located at Xiangtang town in Tangshan city where a destructive earthquake of $M_L = 7.8$ occurred in 1976 (Xie *et al.* 1999). This is a three dimensional strong-motion array instrumented in 1994. It consists of five digital strong-motion accelerographs with two on a surface rock site and the other three on a soil site with different depths in the downholes. The array was designed to study local soil effects on seismic ground motion. A number of strong motion accelerograms have been recorded from 60 earthquakes of magnitudes M_L 1.5 to M_L 5.9 and the maximum peak ground acceleration reached up to 60 cm/sec^2 (Xie *et al.* 1999).

Thessaloniki, Greece

Raptakis *et al.* (1998a, b) employed an accelerogram data set recorded at the Euroseistest array in the Mygdonia graben (Lake Volvi area) near Thessaloniki, Greece, during the period April 1994 to June 1996 to study the effectiveness of the standard spectral ratio and the horizontal-to-vertical spectral ratio techniques in investigating and quantifying the influence of geological conditions on strong ground motion. They showed that the horizontal-to-vertical spectral ratio technique could reveal the fundamental resonant frequency of alluvial deposits by using only a single strong motion station. Raptakis *et al.* (1998a, b) also examined the probable influence of the dominant soil formation, composed of stiff red clay, on the wavefield produced by either weak or strong earthquakes. They noted that this soil formation, having surprisingly high shear wave velocity and a low-quality factor, acts like a protection shield.

Centrifuge-Testing Downhole Arrays

Centrifuge modeling is a very useful technique for simulation of the effects of earthquakes on geotechnical structures (Kutter *et al.* 1994, Kutter 1995). The basic principle is to produce stresses, strength, and stiffness in a small-scale model that are similar to those in a prototype. A number of centrifuge model tests instrumented with downhole arrays and corresponding analyses have been carried out to study seismic ground response, seismic soil-structure interaction, and liquefaction, among other problems (e.g., Balakrishnan and Kutter 1999, Dobry and Abdoun 1998, Elgamal *et al.* 1996b, Elgamal and Yang 2000, Fiegel and Kutter 1992, Kutter and Balakrishnan 2000, Taboada and Dobry 1998, and Wang *et al.* 1998).

At the Rensselaer Polytechnic Institute (RPI) Centrifuge Facility, downhole acceleration arrays, embedded pore-pressure transducers, and LVDTs along the model height (to measure lateral displacements in laminar container experiments) have provided a wealth of information on liquefaction, associated lateral deformations, and related soil-pile interaction phenomena. This work is detailed in a number of Ph.D. theses (R. Dobry, academic advisor) including those of Liu (1992), Taboada (1995), and Abdoun (1997).

Elgamal *et al.* (1996b) used centrifuge downhole arrays to study dynamically induced liquefaction of a saturated loose sand stratum. The experiments were conducted at Rensselaer Polytechnic Institute (Taboada and Dobry 1998) and California Institute of Technology (Scott *et al.* 1993). The observed acceleration, pore pressure and lateral displacement responses showed a high level of consistency, and were used to estimate the corresponding dynamic shear stress-strain histories. Elgamal and Yang (2000) used centrifuge downhole arrays to calibrate a liquefaction constitutive model. They found that there was significant difference in soil response between level-ground and sloping sites, due to the strong influence of soil dilatancy, an important mechanism in possibly limiting soil lateral spreading during liquefaction. Such dilatancy effects were also documented by many other centrifuge experiments instrumented with downhole arrays (Fiegel and Kutter 1992, Taboada and Dobry 1998, Dobry and Abdoun 1998, and Balakrishnan and Kutter 1999).

Fiegel and Kutter (1994a) presented centrifuge model tests with downhole arrays for studying the mechanism of liquefaction in layered soils. Fiegel and Kutter (1994b) used centrifuge downhole arrays to evaluate liquefaction induced lateral spreading of mildly sloping ground.

In centrifuge model tests and field case histories, the soil stiffening due to dilatancy has been observed to be accompanied by large magnitude, short duration spikes in acceleration time histories (Kutter and Wilson 1999). Kutter and Wilson (1999) proposed de-liquefaction as a term to describe the solidification due to dilatancy. By studying data from dense downhole accelerometer arrays in their model tests, slow traveling (about 5 to 30 m/s) but spatially sharp (0.1m wavelength or less) de-liquefaction wave-fronts were observed.

Wang *et al.* (1998) analyzed downhole array centrifuge test data to evaluate the beam on nonlinear Winkler foundation (BNWF) model (soil-pile analysis). Placing the linear viscous dashpots (representing radiation damping in the far-field) in series with the hysteretic component of p-y elements (representing nonlinear soil-pile response in the near-field), was found to be technically preferable to a parallel arrangement of the viscous and hysteretic damping components.

In a pile-soil interaction investigation, Wilson *et al.* (1998) described the signal processing procedures when conducting centrifuge model tests instrumented with downhole arrays. Boulanger *et al.* (1999) also used centrifuge downhole arrays to study seismic soil-pile structure interaction. In addition, Wilson *et al.* (2000) used centrifuge downhole arrays to study seismic lateral resistance of liquefying sand.

The above is only a brief summary of related research efforts at RPI and UC Davis. Obviously, many other seismic/dynamic centrifuge data sets have been generated worldwide (with much data lately from Japan). The intent of this section is only to draw attention to the large role of centrifuge-testing downhole arrays, particularly in liquefaction studies.

SOIL PROPERTIES IDENTIFIED FROM DOWNHOLE RECORDINGS

In this section, the following studies will be discussed:
1) Lateral and vertical response at Hualien,
2) Lateral and vertical response at Lotung, and
3) Lateral vibration of dense sand in a UC Davis centrifuge experiment.

Site Response Analysis and System Identification Technique

The employed procedure is based on the following steps (Gunturi 1996):
1. All site response analyses were conducted using the computer program SHAKE (Schnabel *et al.* 1972). In the conducted investigations, the effective strain was taken as 0.5 of the maximum strain.
2. Total motion was prescribed at the shear beam base as the accelerations actually recorded at this location.
3. Linear soil stiffness properties were defined by the following relationship: $v = v_0 + v_H(\frac{z}{H})^b$ in which v_0 is wave velocity at ground surface, $(v_0 + v_H)$ is wave velocity at the base, z is depth coordinate, H is beam height, and $0 \leq b \leq 1.0$ dictates a smooth variation of v with depth.
4. A hyperbolic relationship (Kondner 1963) with a reference strain parameter γ_{rm} was used to define the modulus reduction with strain amplitude.
5. Damping ratio was composed of a constant strain-independent term and a strain-dependent term derived from another hyperbolic relation (with a reference strain parameter γ_{rd}).
6. SNOPT, a numerical optimization code (Gill *et al.* 1997) was employed (Zeghal 1990) to minimize the difference between the acceleration response spectra (ARS, with 5% damping) of the SHAKE results and the ARS of downhole records.
7. For each case, a weighted ensemble of available recorded motions was used simultaneously in the minimization process. Soil modeling parameters were defined such that an optimal match was achieved for the entire ensemble.
8. Once the optimal soil properties were defined, a so-called indifference interval (Bard 1974) for a given modeling parameter may be sought. In this section, variability in a parameter was defined such that additional incurred difference (between computed and recorded acceleration response spectra) was within 10% of the minimized difference, for each individual earthquake in the ensemble.

The general goal of the following sections is to:
1. Define ranges (rather than specific values) for modeling parameters that achieve a level of success in matching the recorded site response.
2. Get a rough idea about sensitivity of the modeling procedure to variations in the defined optimal parameters.

Generally, the reported results may be considered as a first attempt in defining modeling parameters (rather than actual soil properties). More refined system identification techniques (and the availability of additional earthquake records) will continue to improve the quality of the calculated results.

Results for stiff as well as soft soil sites are reported below. In addition, lateral as well as vertical vibration is addressed each separately using the one-dimensional code SHAKE as explained above. In some cases, SHAKE was used to conduct a linear elastic analysis (when only small tremors are available), in which damping ratio and shear modulus were both strain-level independent.

Model Properties from Lateral Excitation Records

Hualien Site

The Hualien site has demonstrated an azimuthal anisotropy as reported earlier by a large number of investigators. This section highlights this phenomenon and defines a range of optimal damping values for the site.

The Hualien site was modeled as a 52.6*m* shear beam, and the total motion at the 52.6*m* deep was defined as the actual recorded acceleration at this depth. Data of the DH2 free-field vertical array was used for the events of Feb 23, 95, May 1, 95 and May 2, 95 (Fig. 1, Table 6). The original data were corrected with a high pass filter (0.1*Hz*) and a low pass filter (20*Hz*) to remove any noise in the signal. The horizontal peak ground surface accelerations among the three events ranged from 0.035*g* to 0.126*g* in amplitude, representing predominately linear response (for the purpose of our study). As such, only a linear material model was used for this identification process.

The analysis strongly suggested an azimuthal anisotropy at this site. Figure 4 illustrates the difference of the optimized shear wave velocity profiles in the longitudinal and transverse directions and the associated 10% indifference interval. However, no marked difference in damping and its 10% indifference was observed between the two horizontal directions (Fig. 5). For the effective strain range shown in the damping figure, it is seen that the optimized damping is rather high in comparison to earlier reported laboratory test results. In this figure, the range of optimized damping ratios was between 7% and 10%. As mentioned earlier, peak recorded accelerations were in the range of 0.035*g* to 0.126*g*.

The optimized properties were used to reproduce the site response of each earthquake by exciting the 52.6*m* shear beam at the base. Figures 6-13 show representative results comparing recorded and computed acceleration time histories and ARS (with 5% damping).

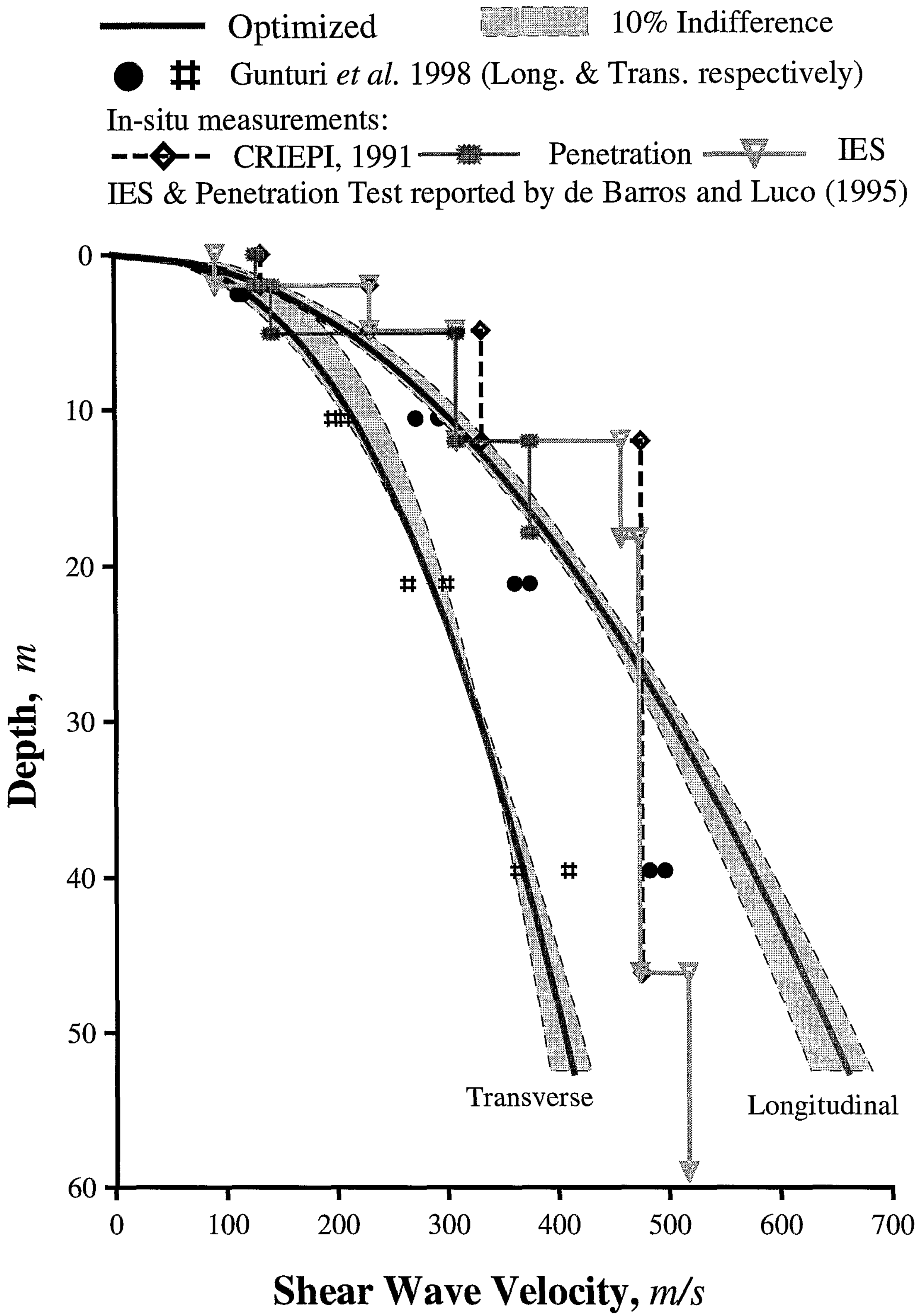

Figure 4: Optimized Shear Wave Velocity Profiles and 10% Indifference at the Hualien DH2 Array.

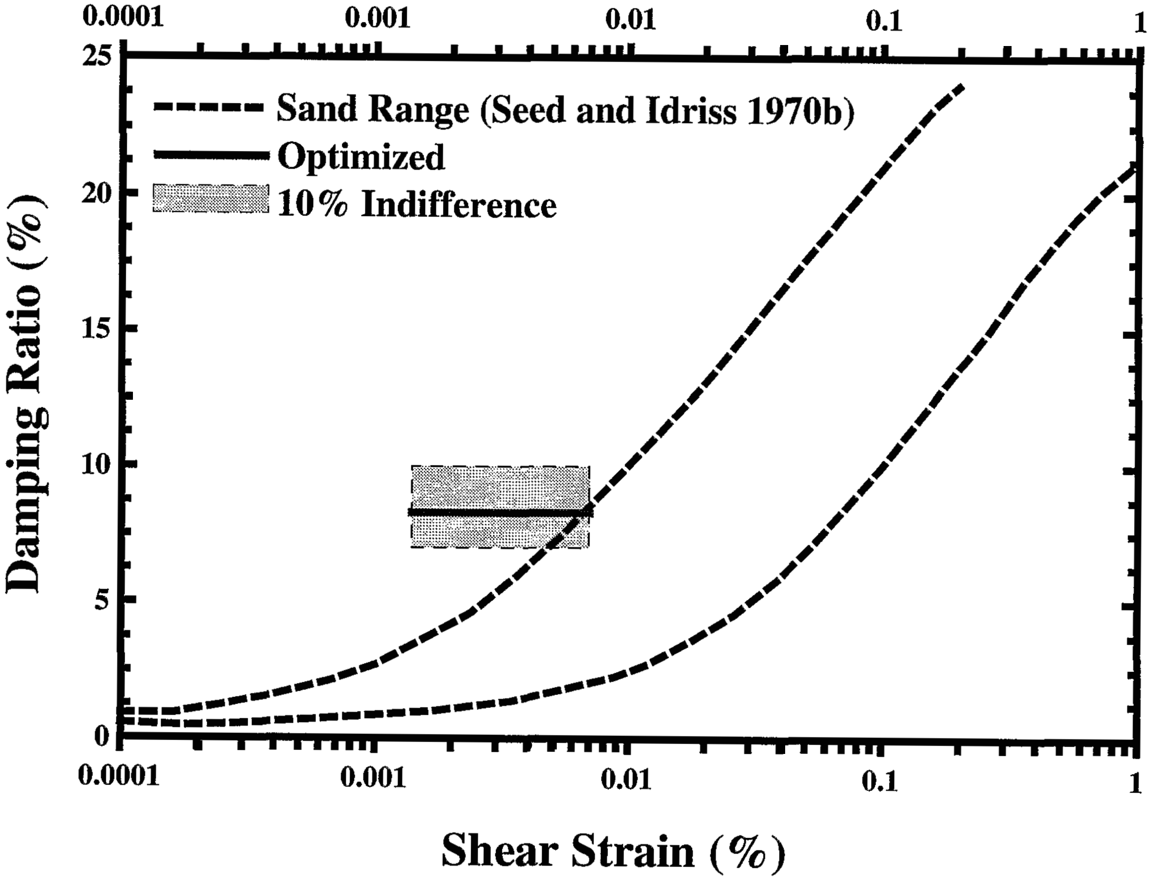

Figure 5: Optimized Damping and 10% Indifference Region at Hualien.

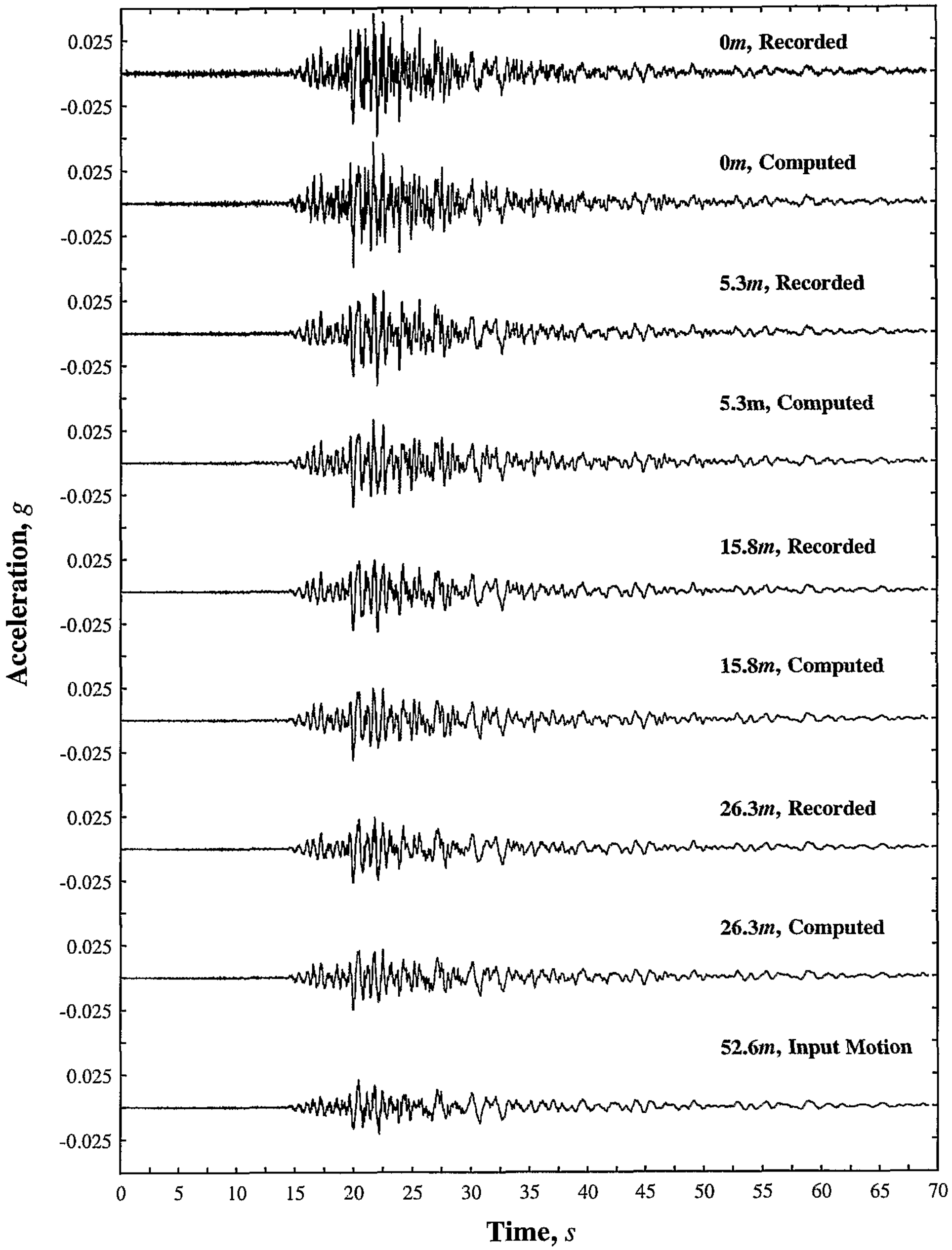

Figure 6: Recorded and Computed Longitudinal Accelerations during Hualien Feb. 23, 95.

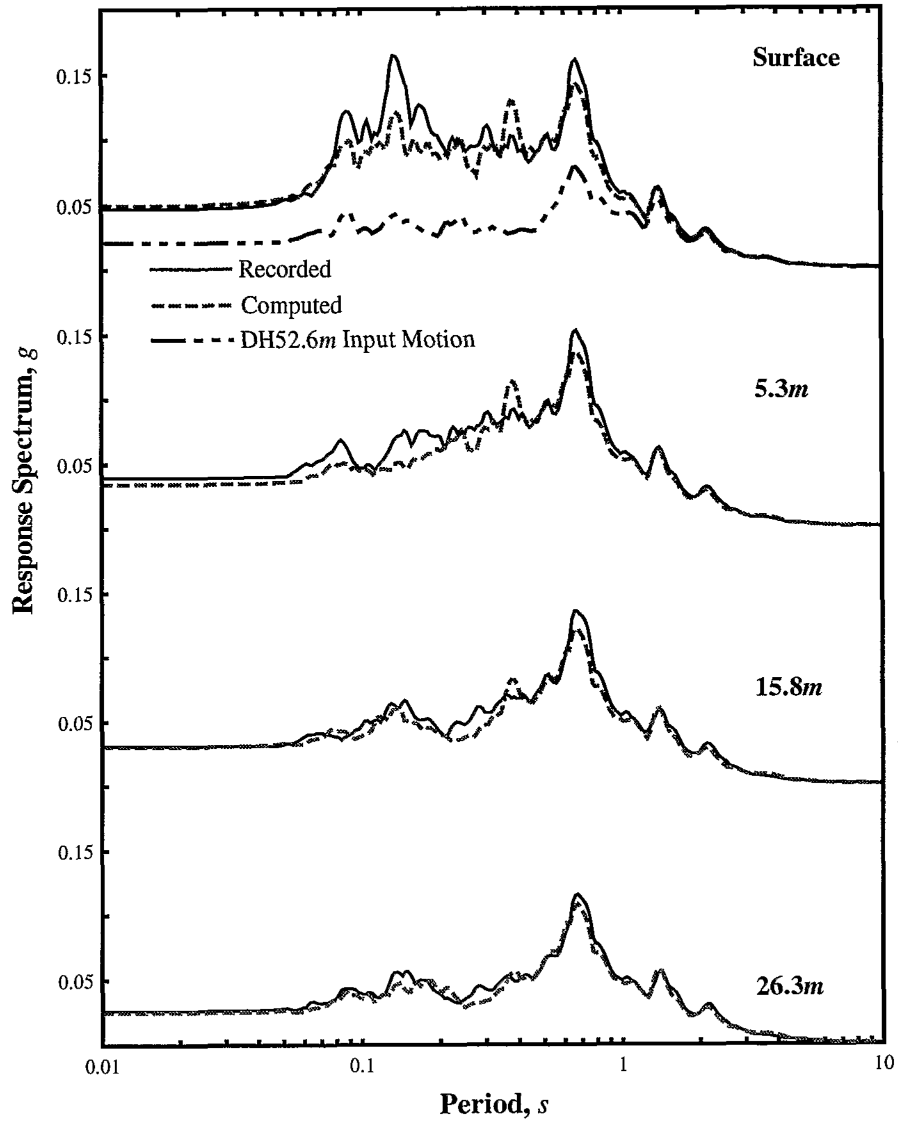

Figure 7: Recorded and Computed Longitudinal ARS during Hualien Feb. 23, 95.

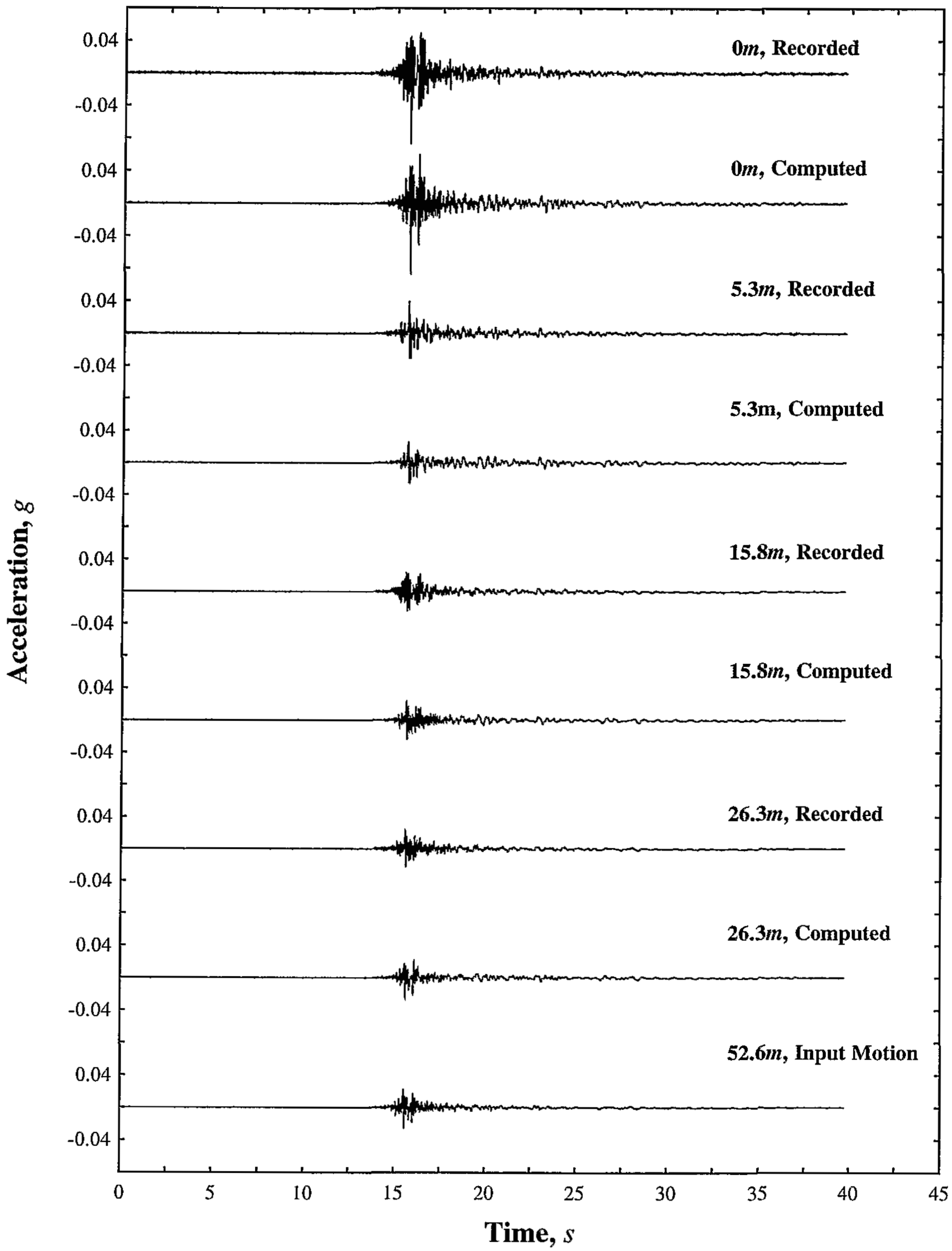

Figure 8: Recorded and Computed Longitudinal Accelerations during Hualien May 02, 95.

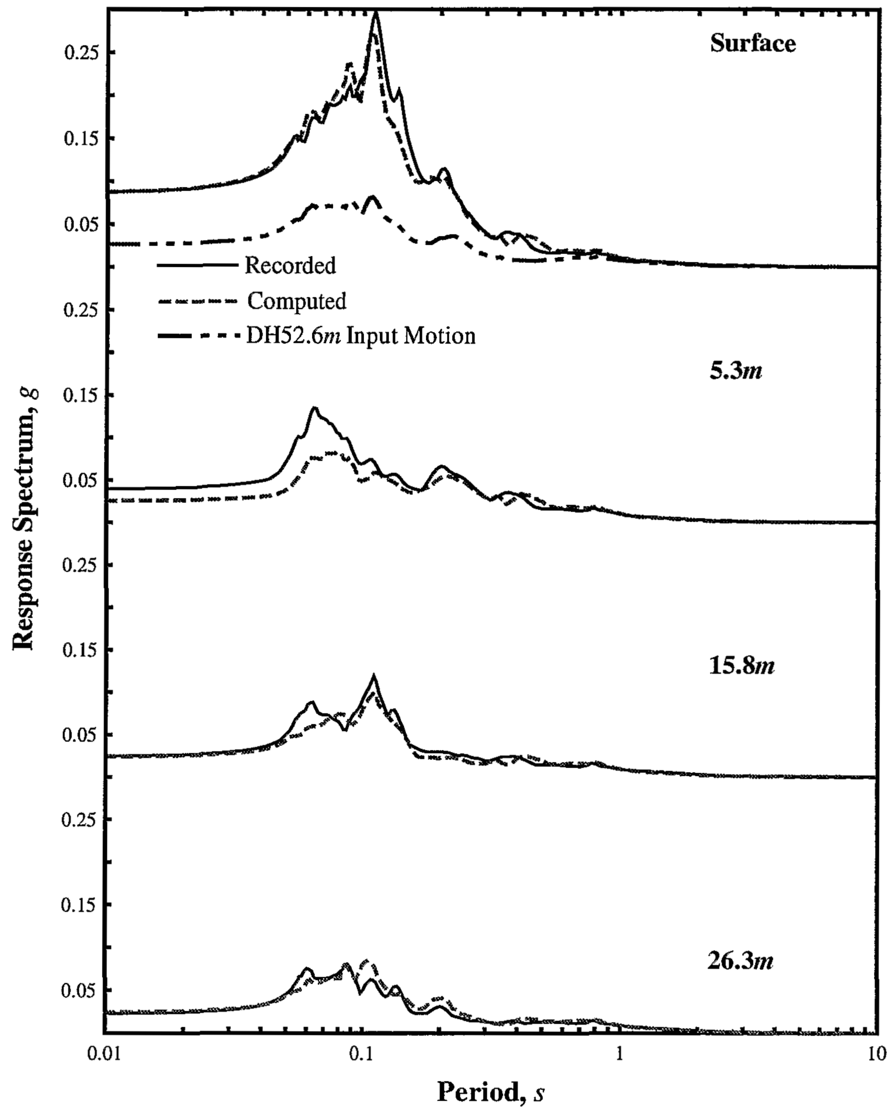

Figure 9: Recorded and Computed Longitudinal ARS during Hualien May 02, 95.

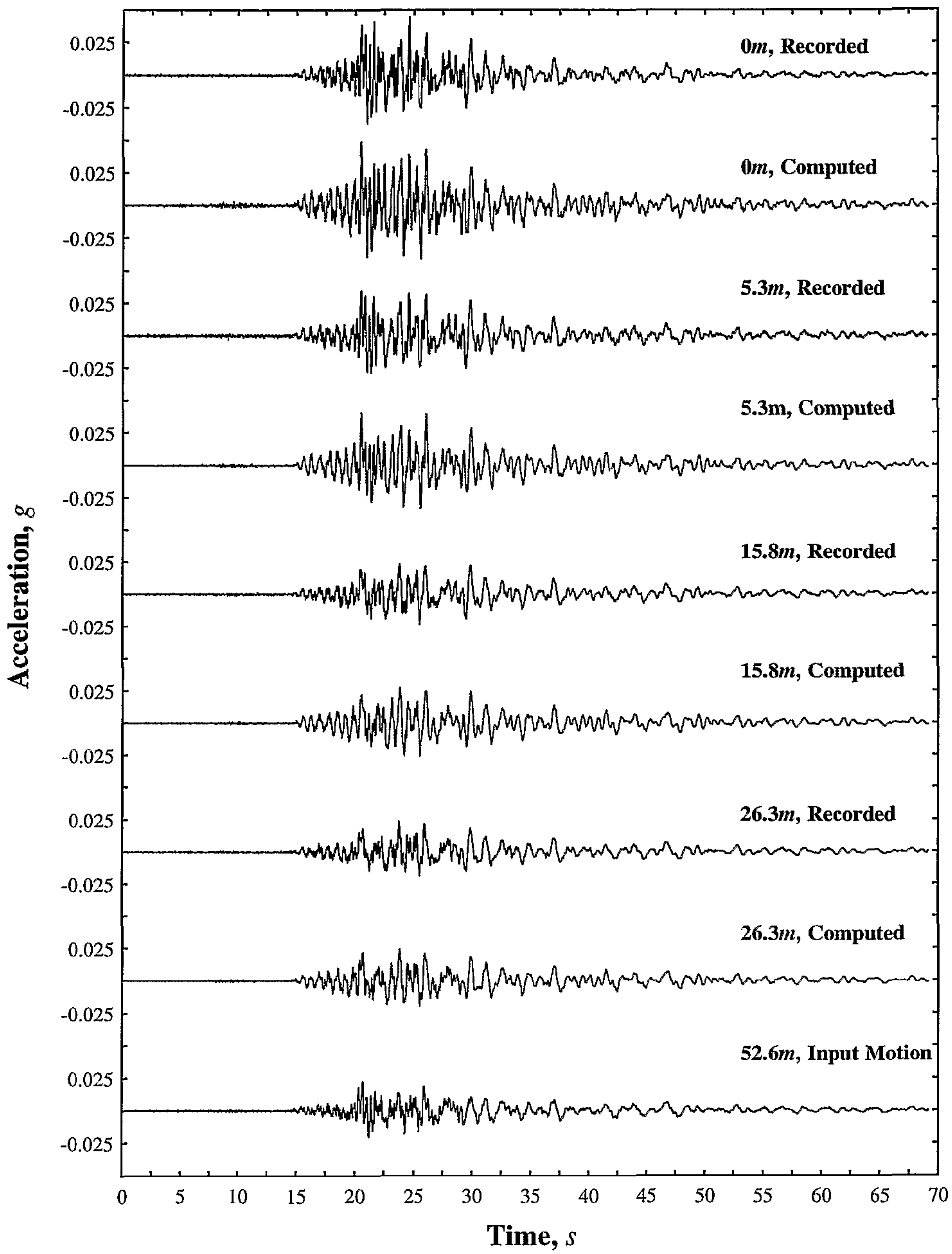

Figure 10: Recorded and Computed Transverse Accelerations during Hualien Feb. 23, 95.

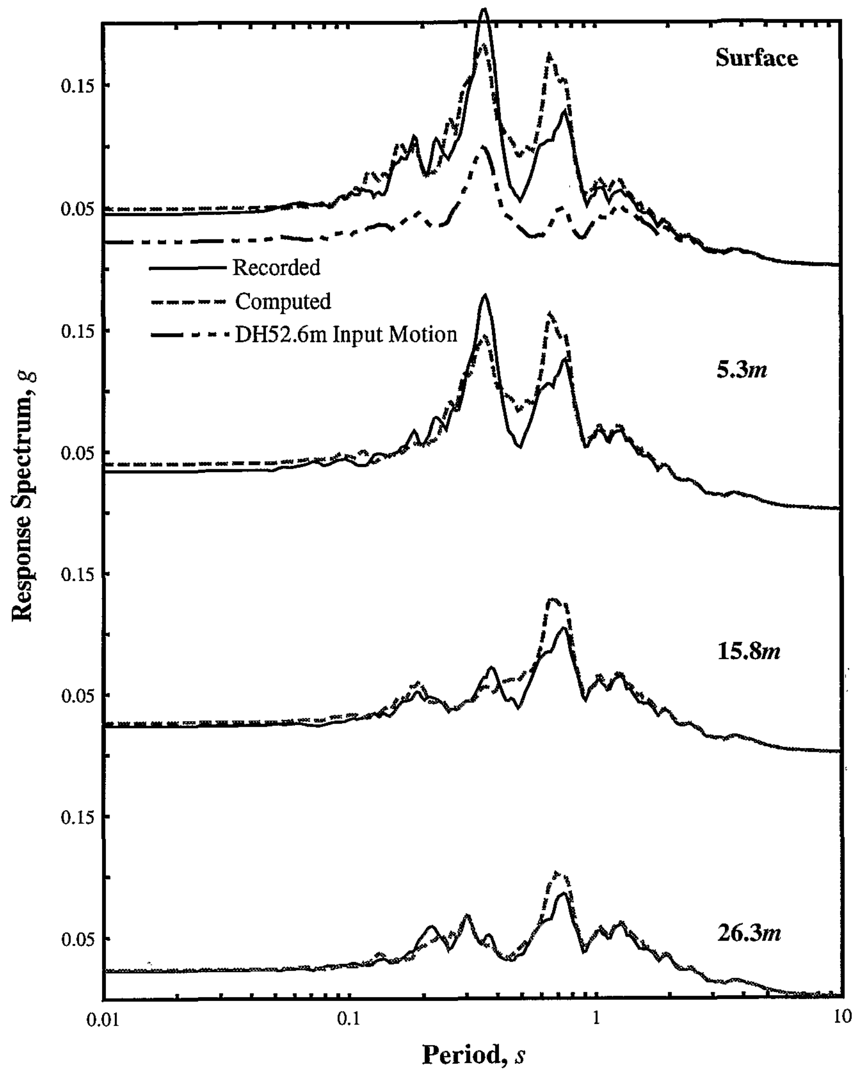

Figure 11: Recorded and Computed Transverse ARS during Hualien Feb. 23, 95.

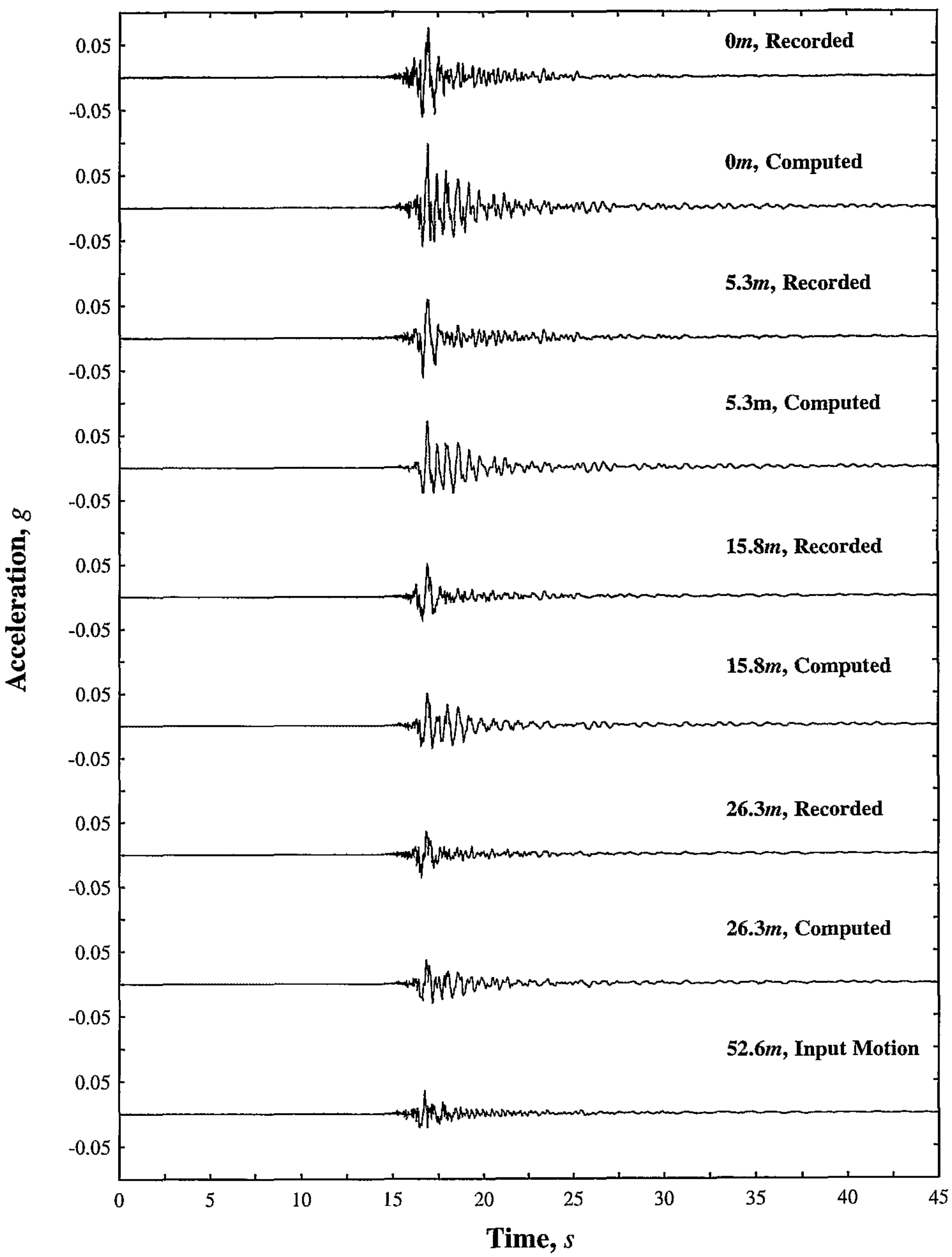

Figure 12: Recorded and Computed Transverse Accelerations during Hualien May 01, 95.

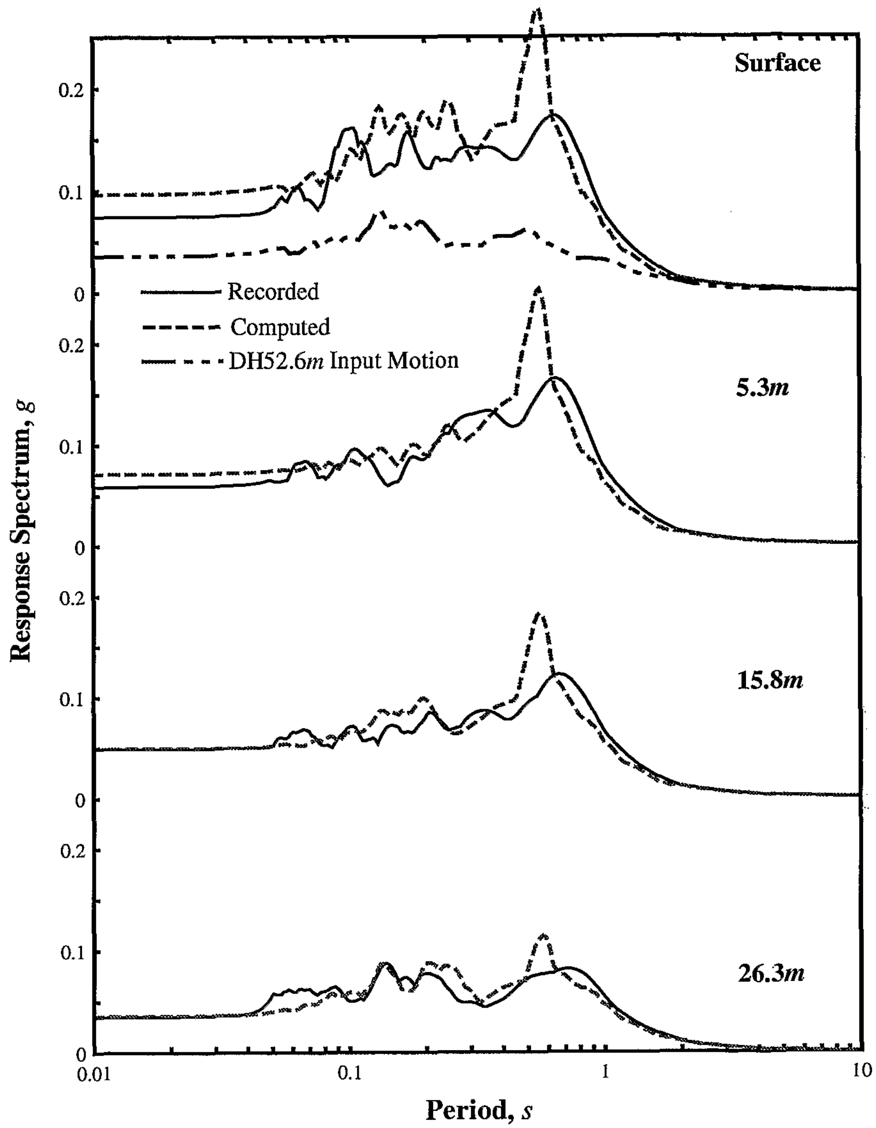

Figure 13: Recorded and Computed Transverse ARS during Hualien May 01, 95.

Lotung Site

The Lotung site (Fig. 2) was modeled as a $17m$ one-dimensional shear beam, with the total motion at the $17m$ depth defined as the actual recorded acceleration at this depth. Out of the 18 earthquakes listed in Table 7, acceleration recordings at DHB of six events (LSST 6, 7, 8, 13, 16, 17) in two horizontal directions were selected for identification of soil shear wave properties. The horizontal peak ground surface accelerations among the selected six events ranged from $0.03g$ to $0.21g$ in amplitude covering linear response as well as moderate nonlinear response. Figures 14-16 show the optimized properties for shear wave velocity profile, shear modulus and damping versus shear strain level applicable to all six events. In the Lotung case, the stiffness profile is in agreement with geophysical measurements. In addition, the EW and NS properties showed no appreciable difference (no azimuthal anisotropy). Shear modulus variation with strain amplitude is also in good agreement with laboratory testing results. However, the lowest optimized damping ratio was about 5%. At higher strains, damping follows and exceeds published upper-bound estimates. It is noted here that the lowest damping ratio of 5% produced a satisfactory match for minor shaking events (of as little as 0.03g in peak acceleration).
The optimized properties were used to reproduce the site response of each earthquake by exciting the $17m$ shear beam at the base. Figures 17-28 show some representative results comparing recorded and computed acceleration time histories and ARS (with 5% damping). As shown in Figs. 23 and 27, only the first 23 seconds of LSST16 excitation were studied (in order to avoid the effect of pore-pressure buildup during the remainder of this event which lasted for about 56 seconds, Elgamal *et al.* 1997).

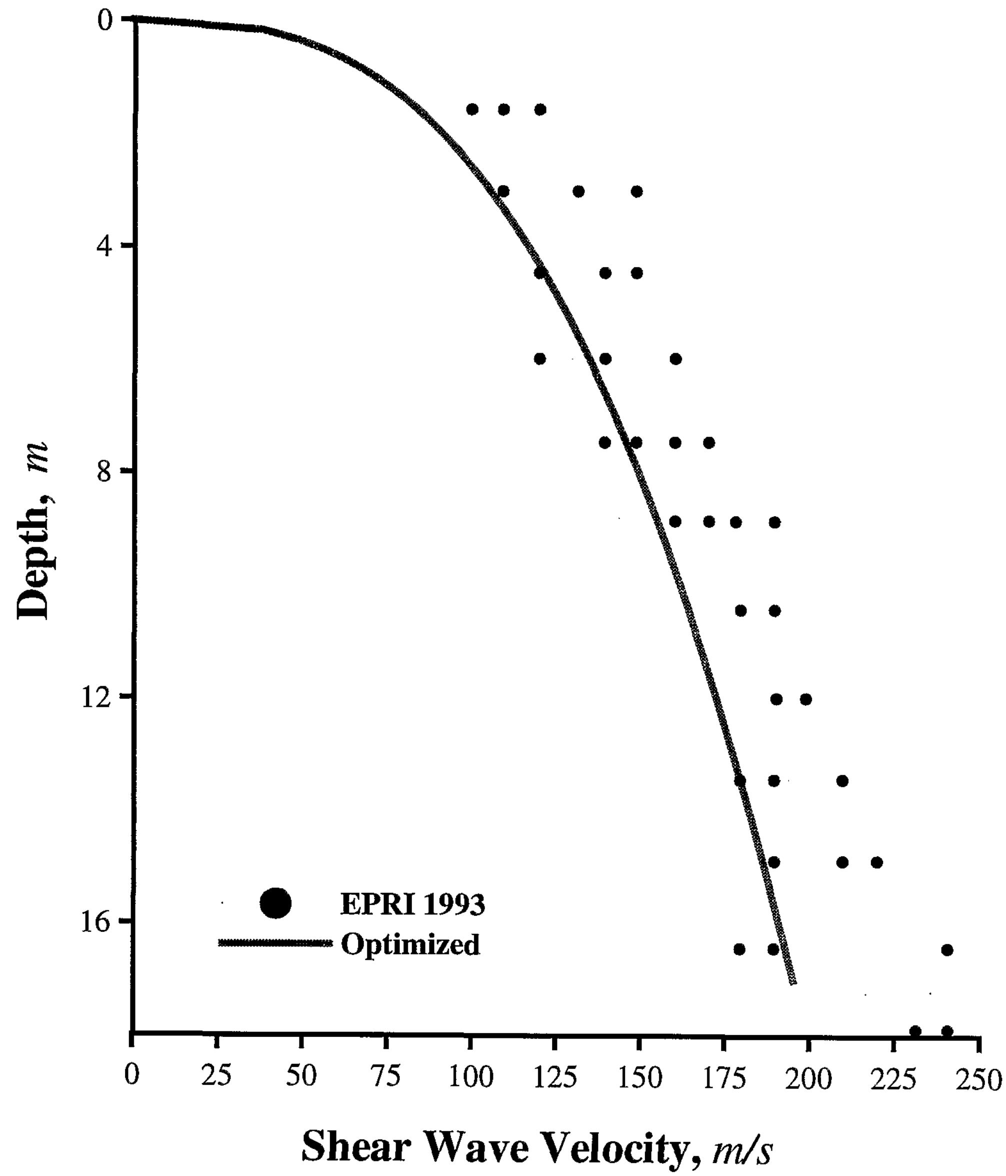

Figure 14: Optimized Shear Wave Velocity Profile at Lotung.

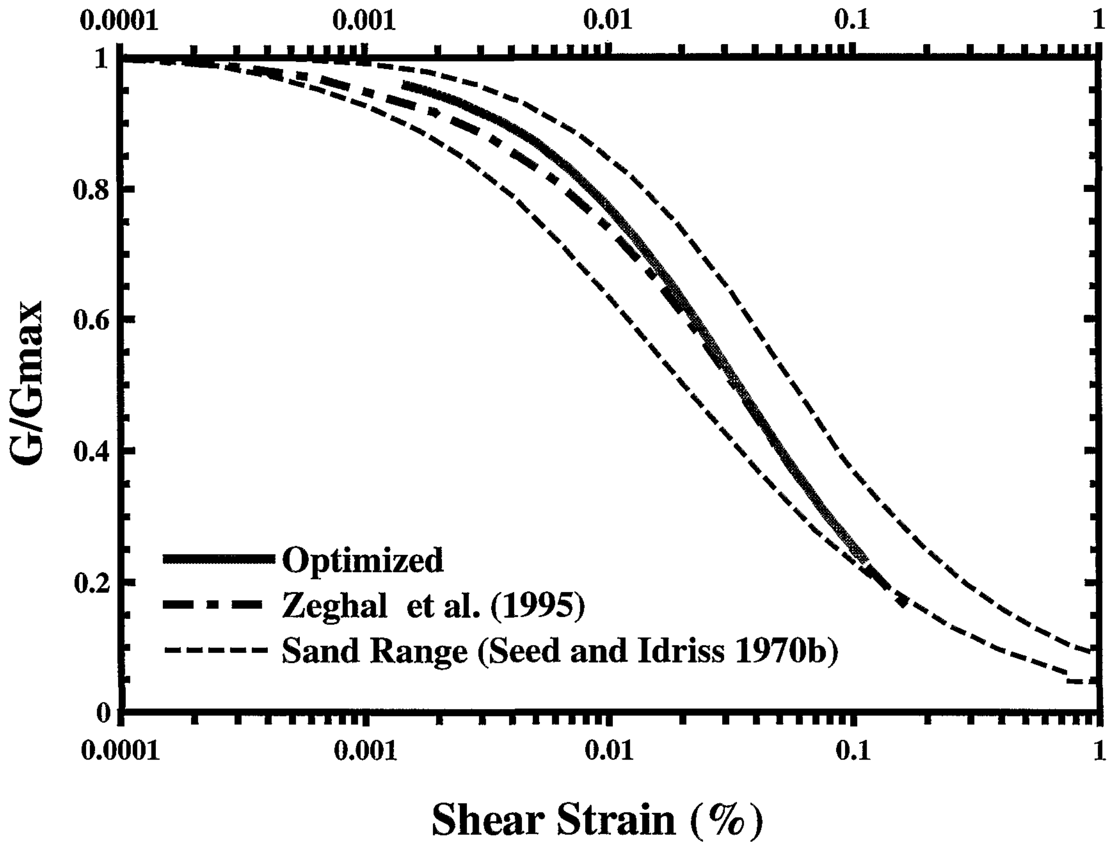

Figure 15: Optimized Shear Modulus Reduction at Lotung.

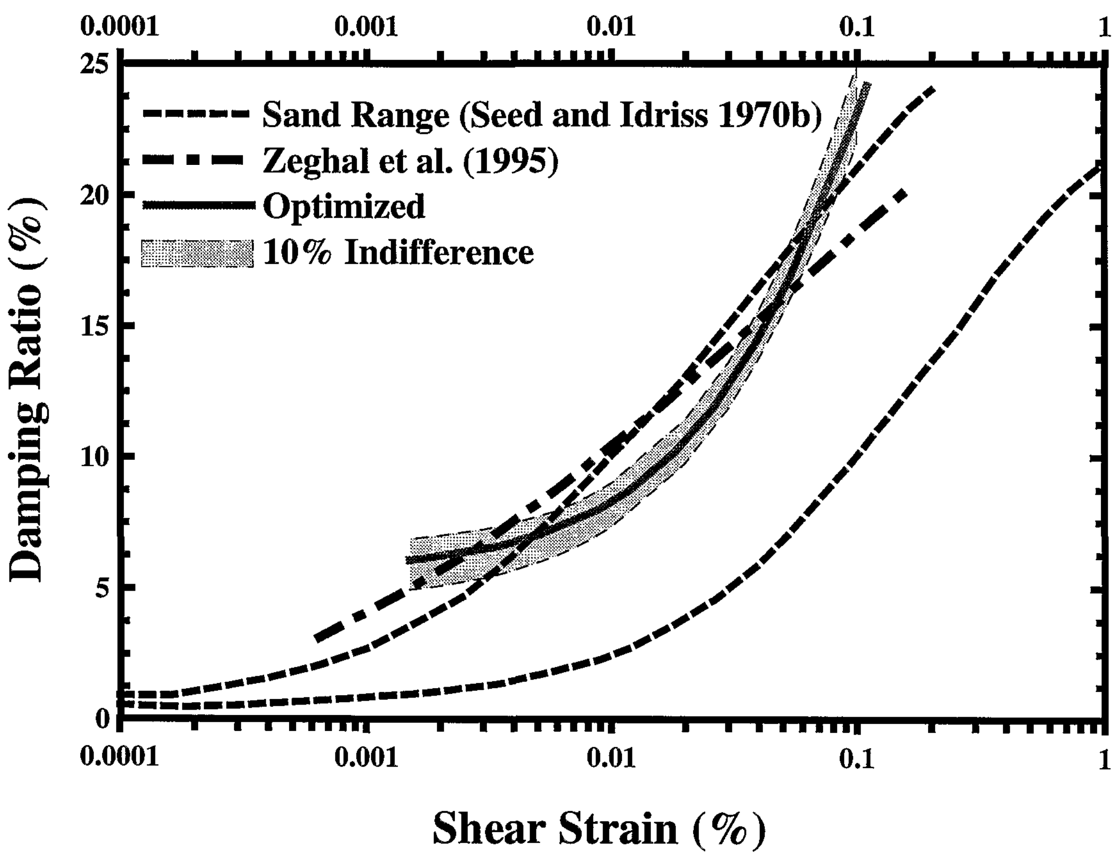

Figure 16: Optimized Shear Wave Related Damping and 10% Indifference Region at Lotung.

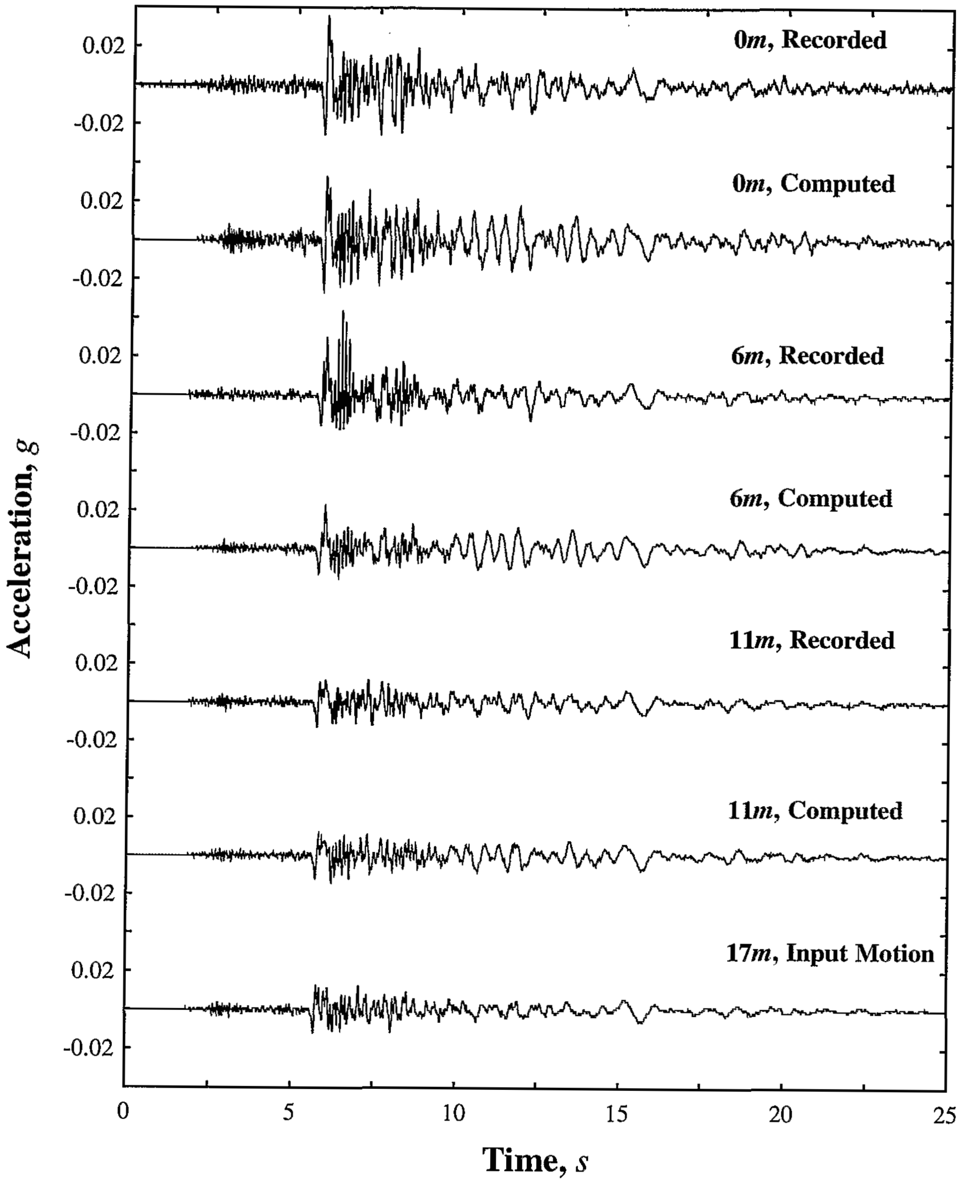

Figure 17: Recorded and Computed EW Accelerations during LSST6.

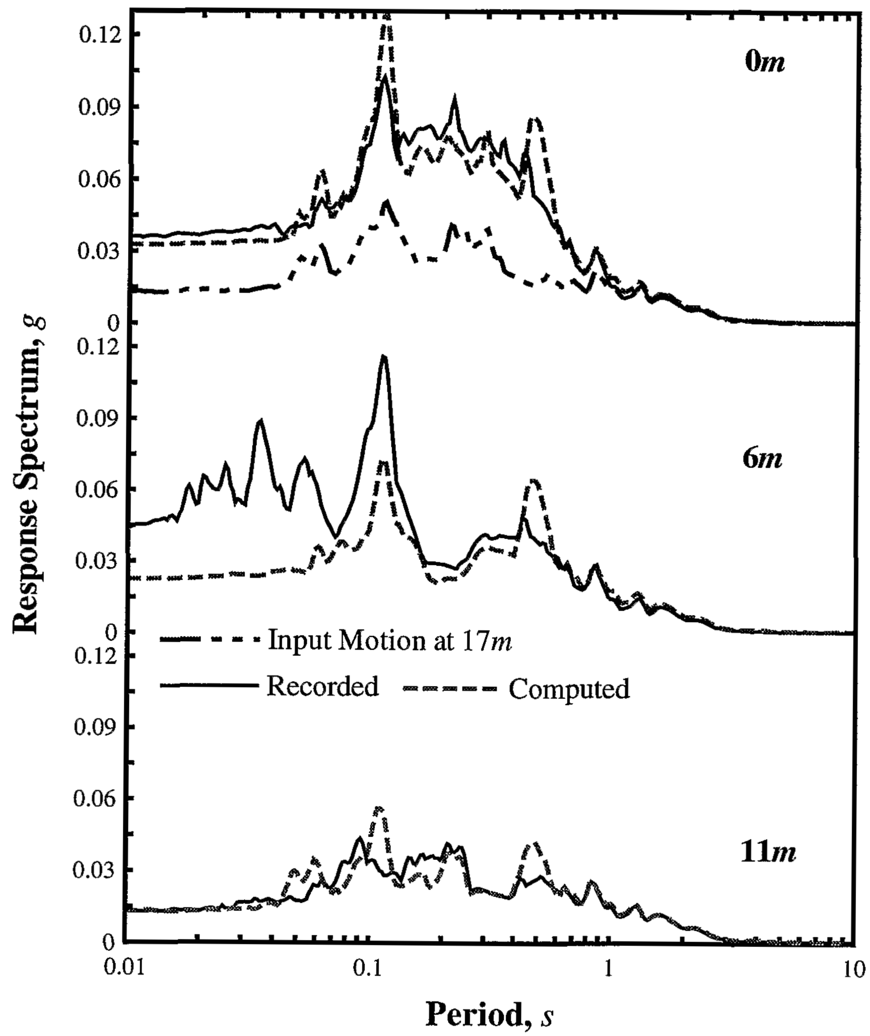

Figure 18: Recorded and Computed EW ARS during LSST6.

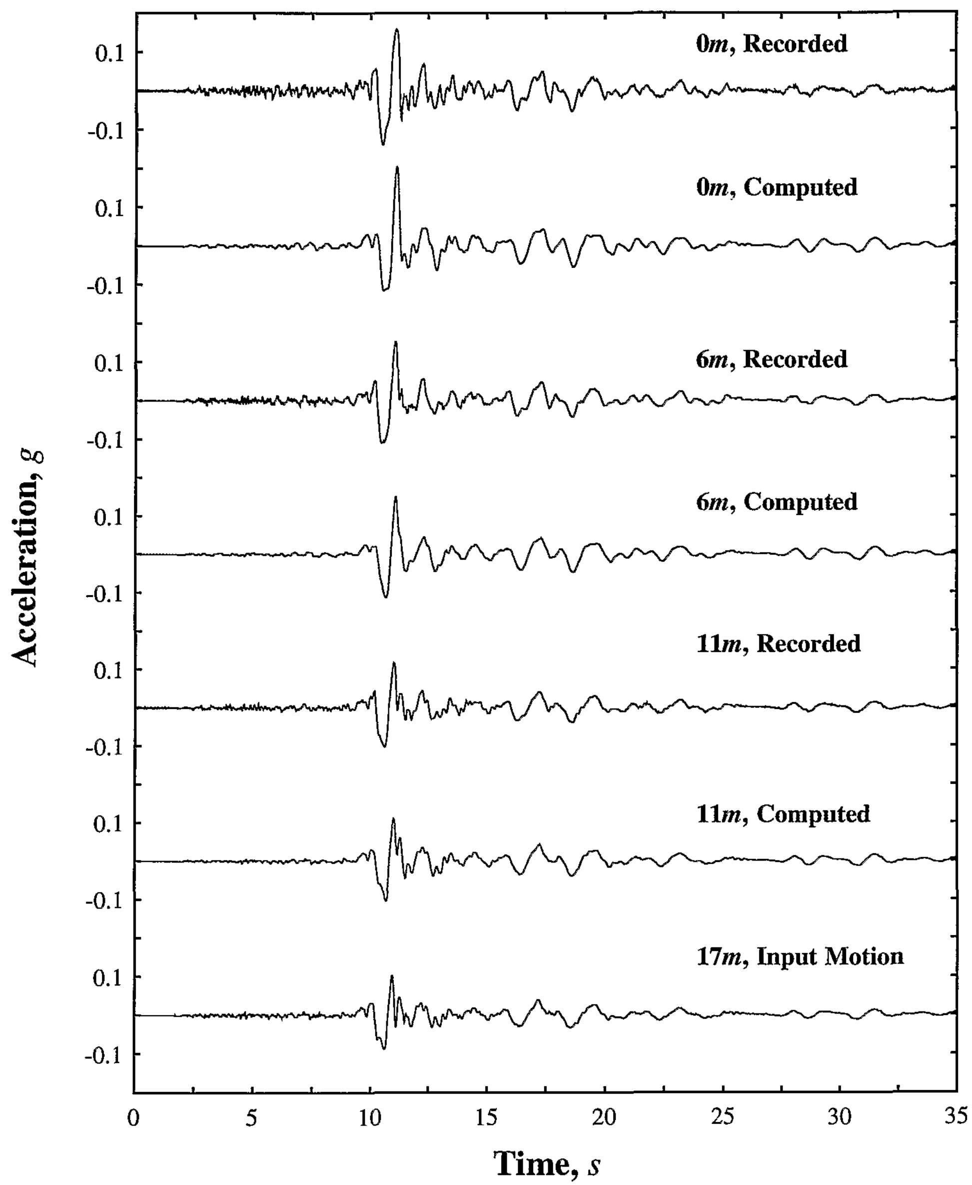

Figure 19: Recorded and Computed EW Accelerations during LSST7.

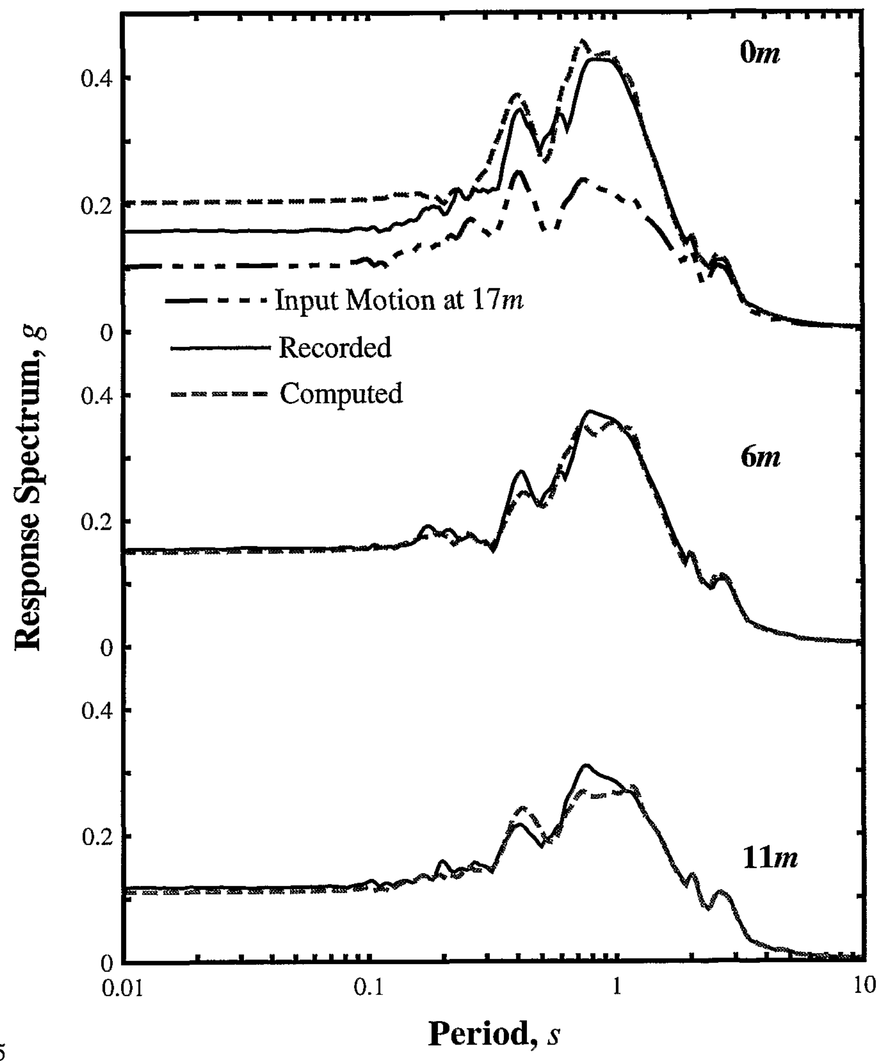

Figure 20: Recorded and Computed EW ARS during LSST7.

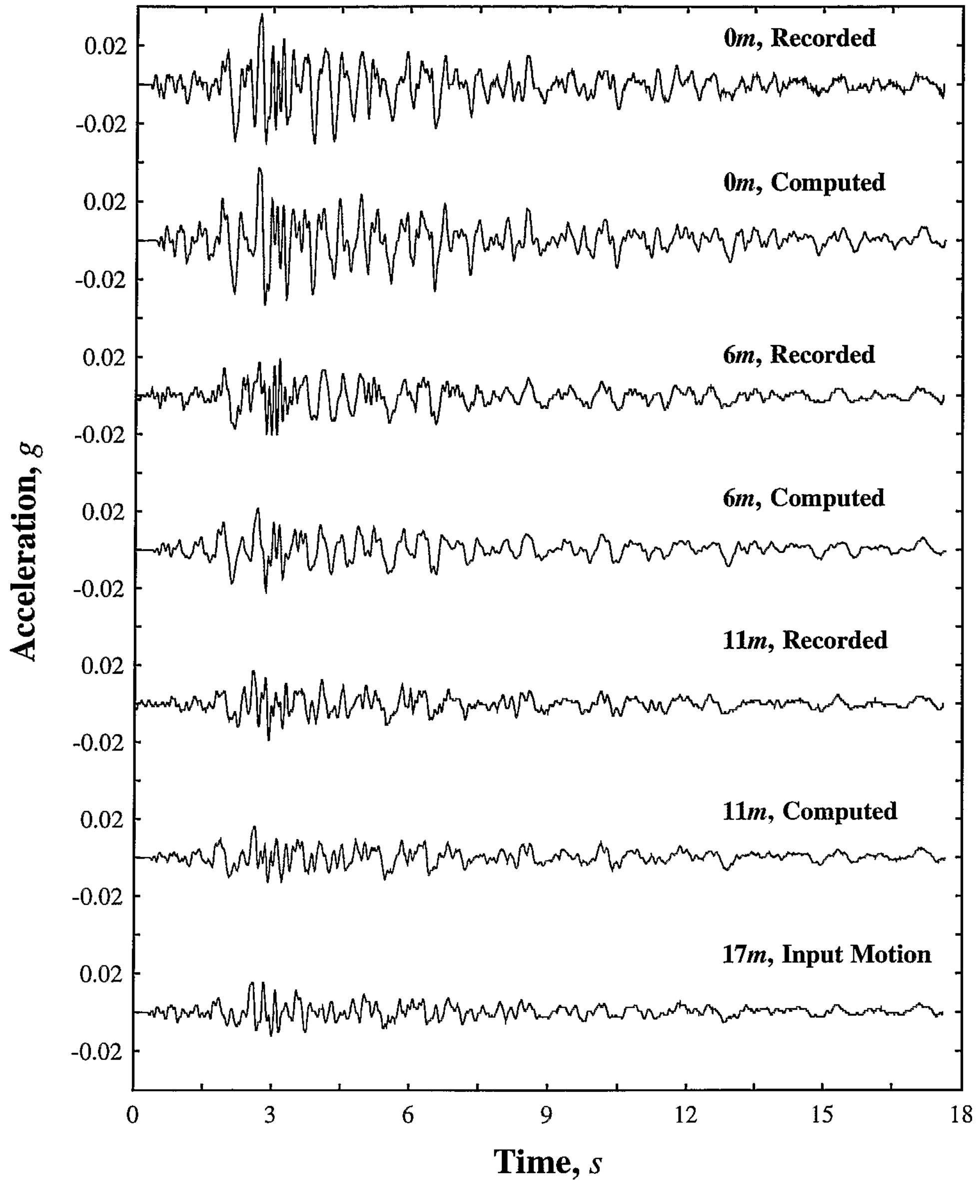

Figure 21: Recorded and Computed EW Accelerations during LSST8.

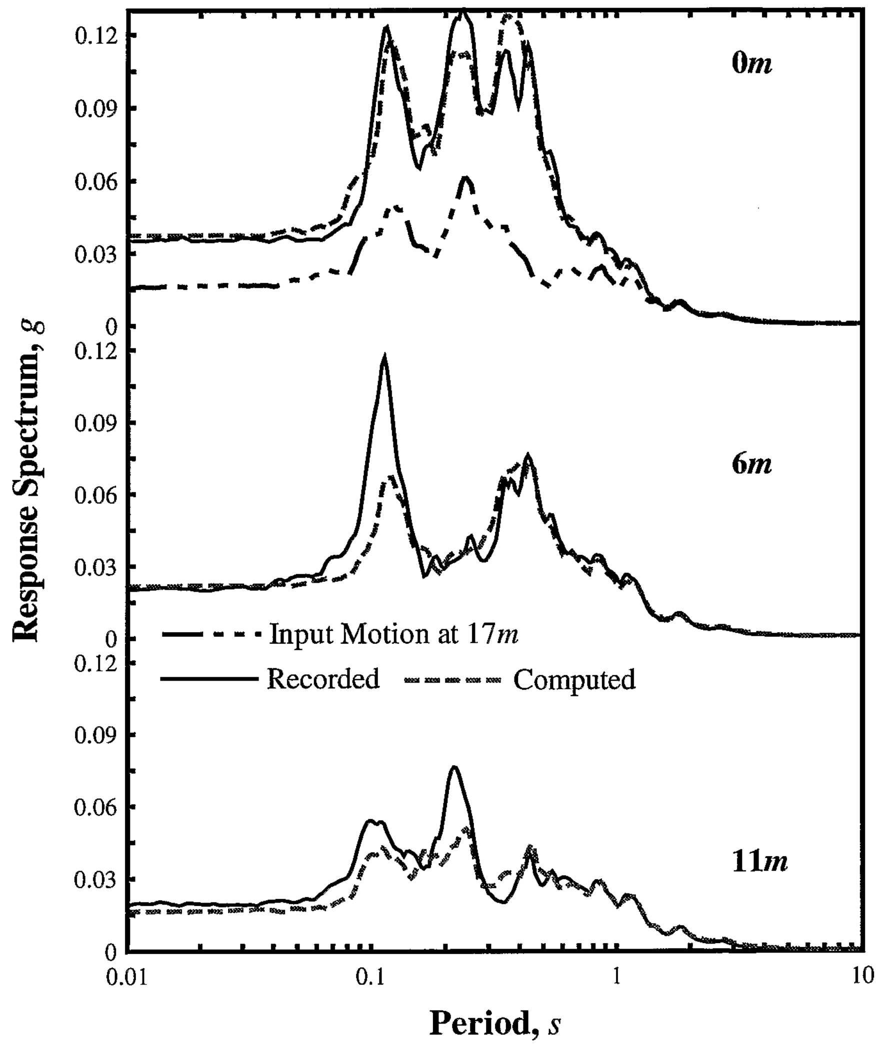

Figure 22: Recorded and Computed EW ARS during LSST8.

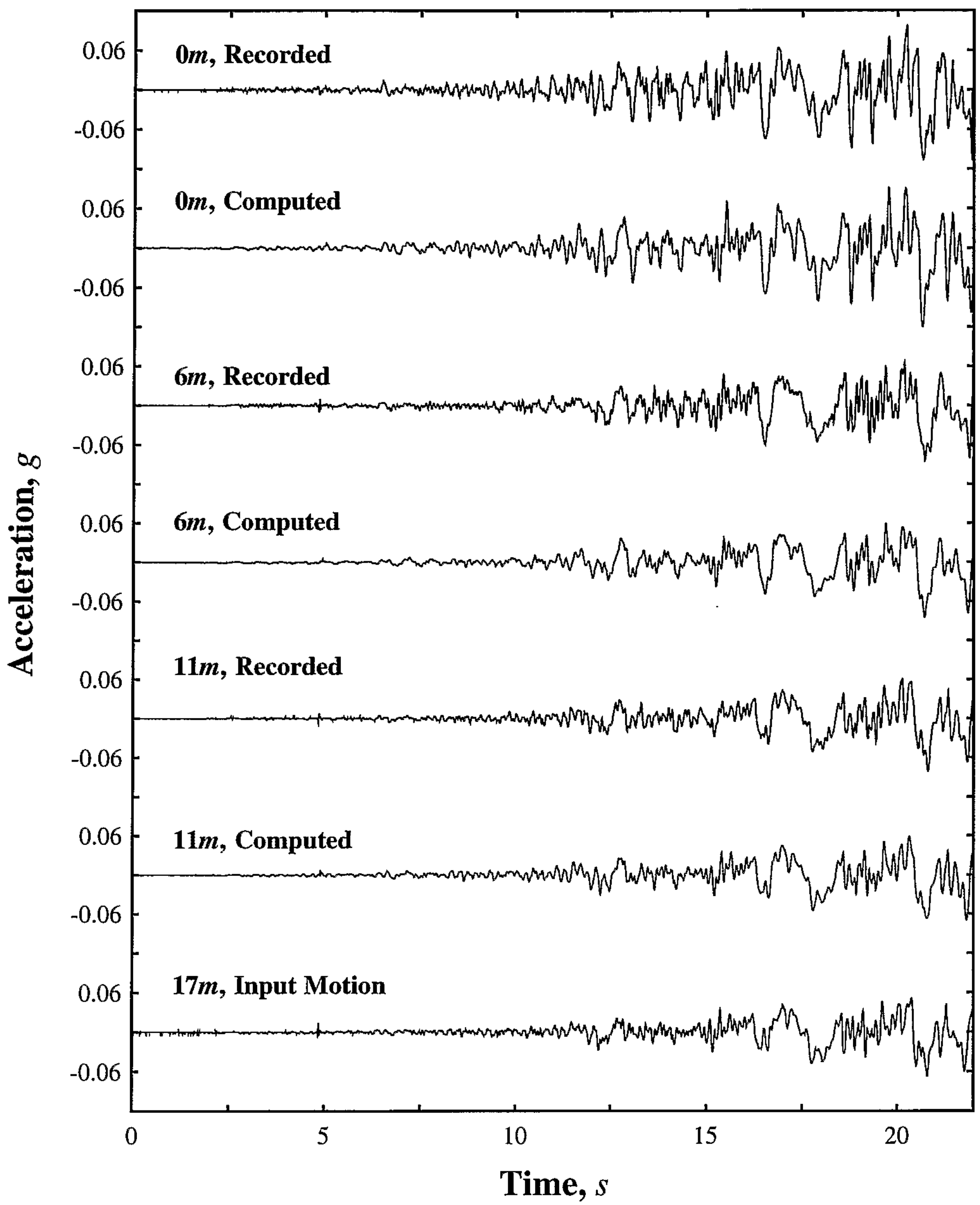

Figure 23: Recorded and Computed EW Accelerations during LSST16.

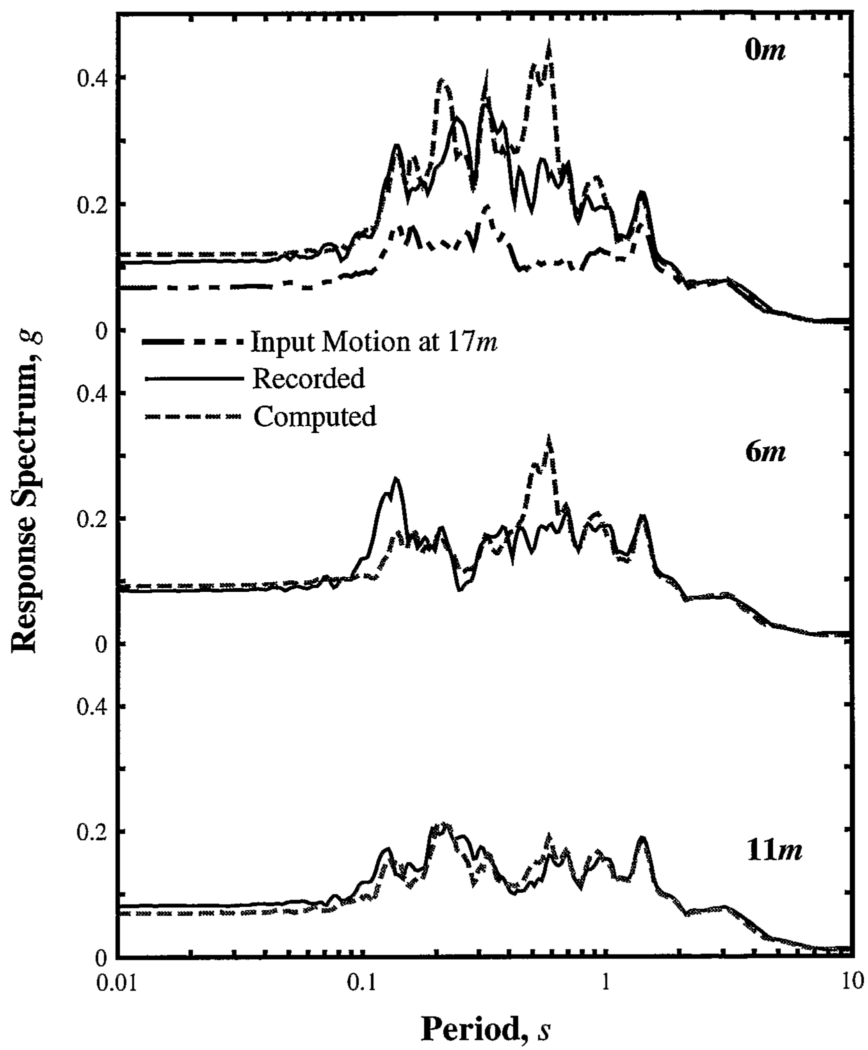

Figure 24: Recorded and Computed EW ARS during LSST16.

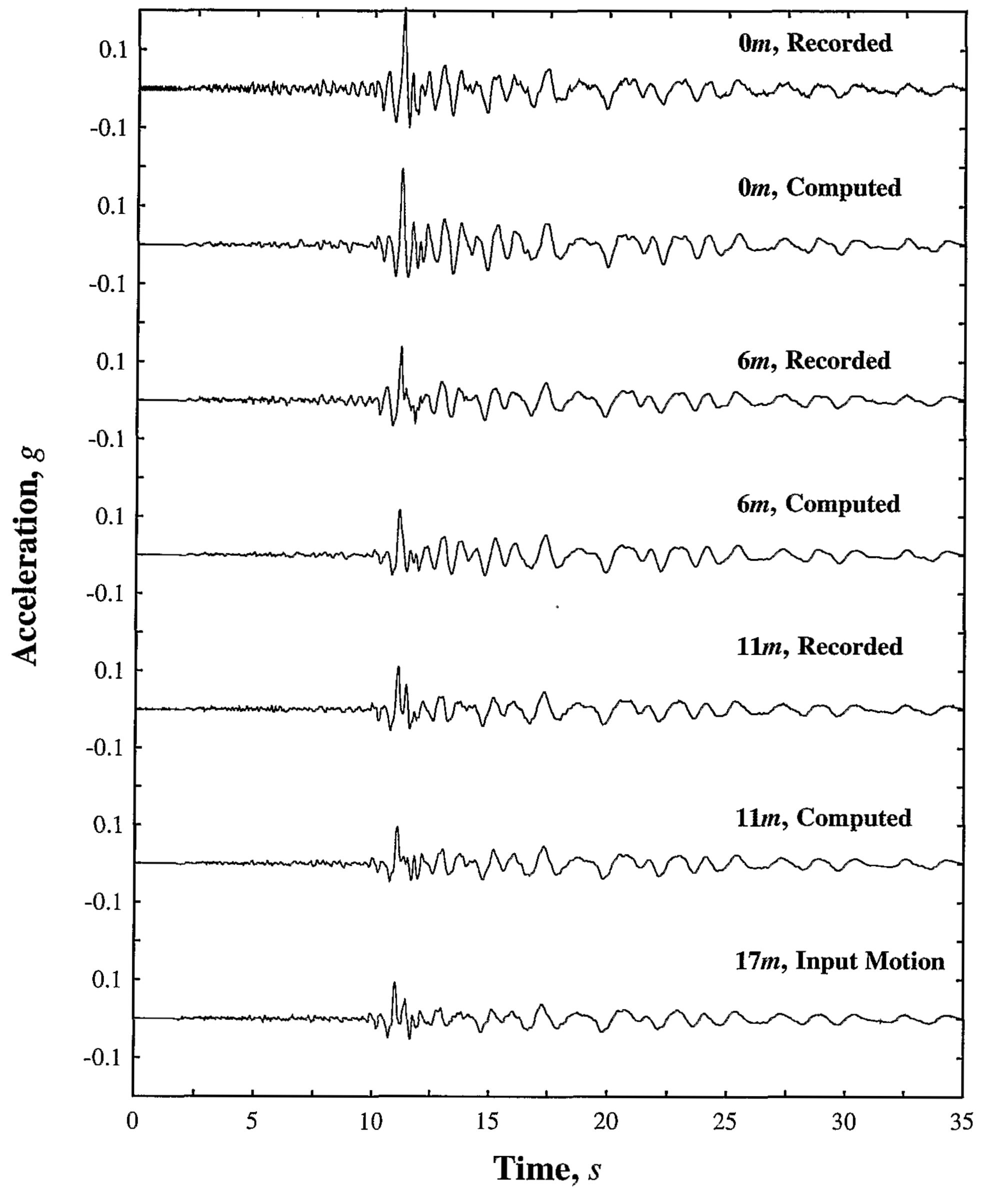

Figure 25: Recorded and Computed NS Accelerations during LSST7.

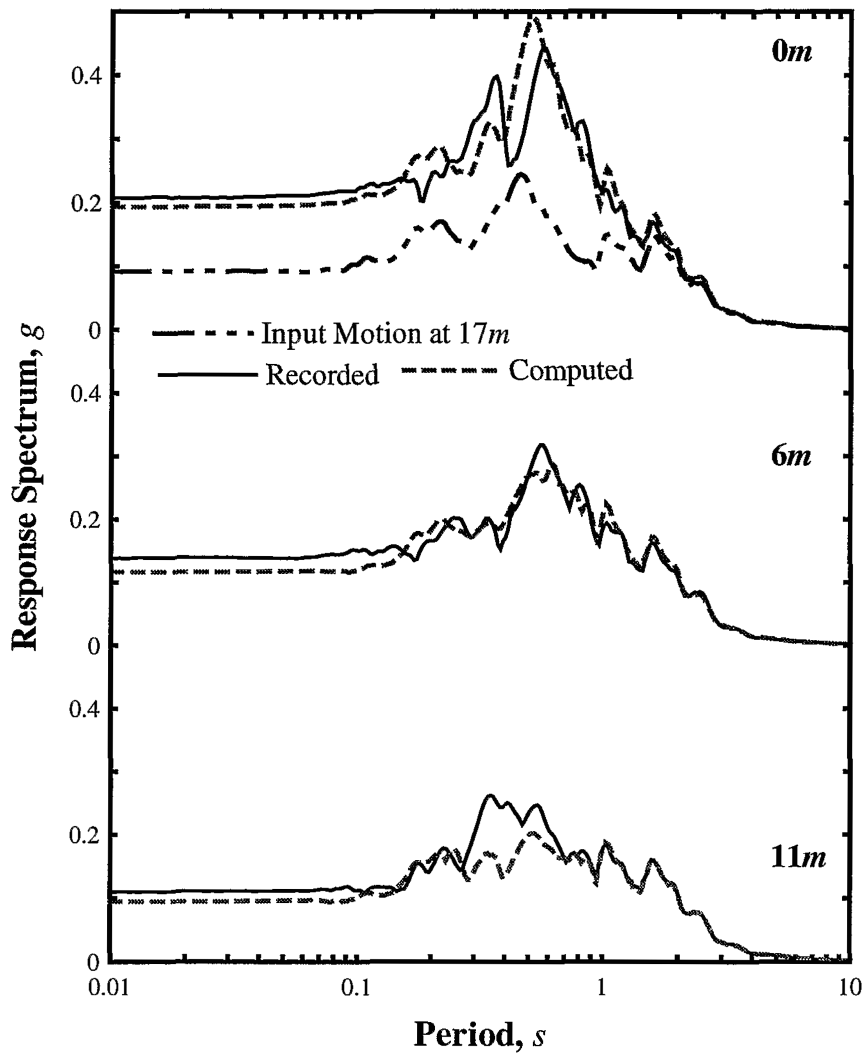

Figure 26: Recorded and Computed NS ARS during LSST7.

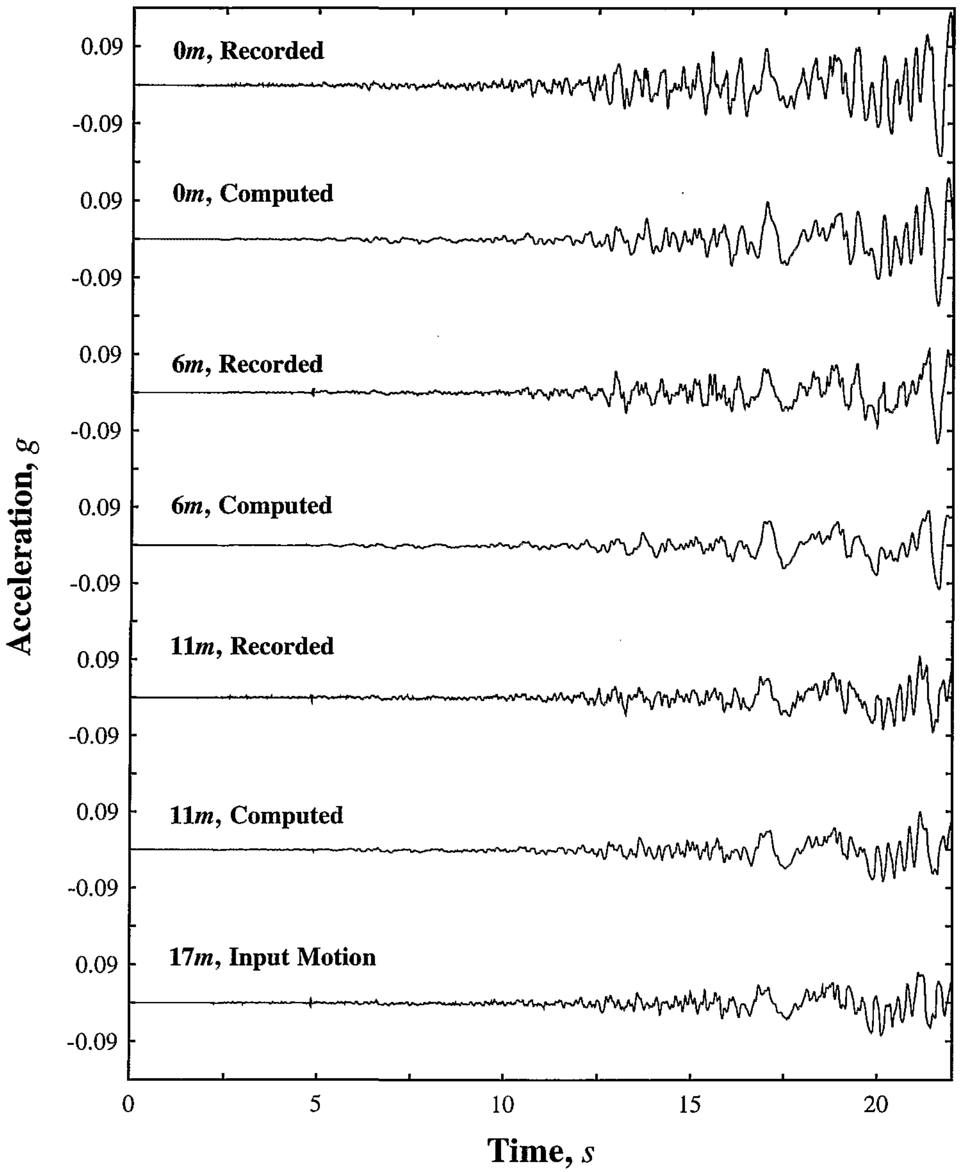

Figure 27: Recorded and Computed NS Accelerations during LSST16.

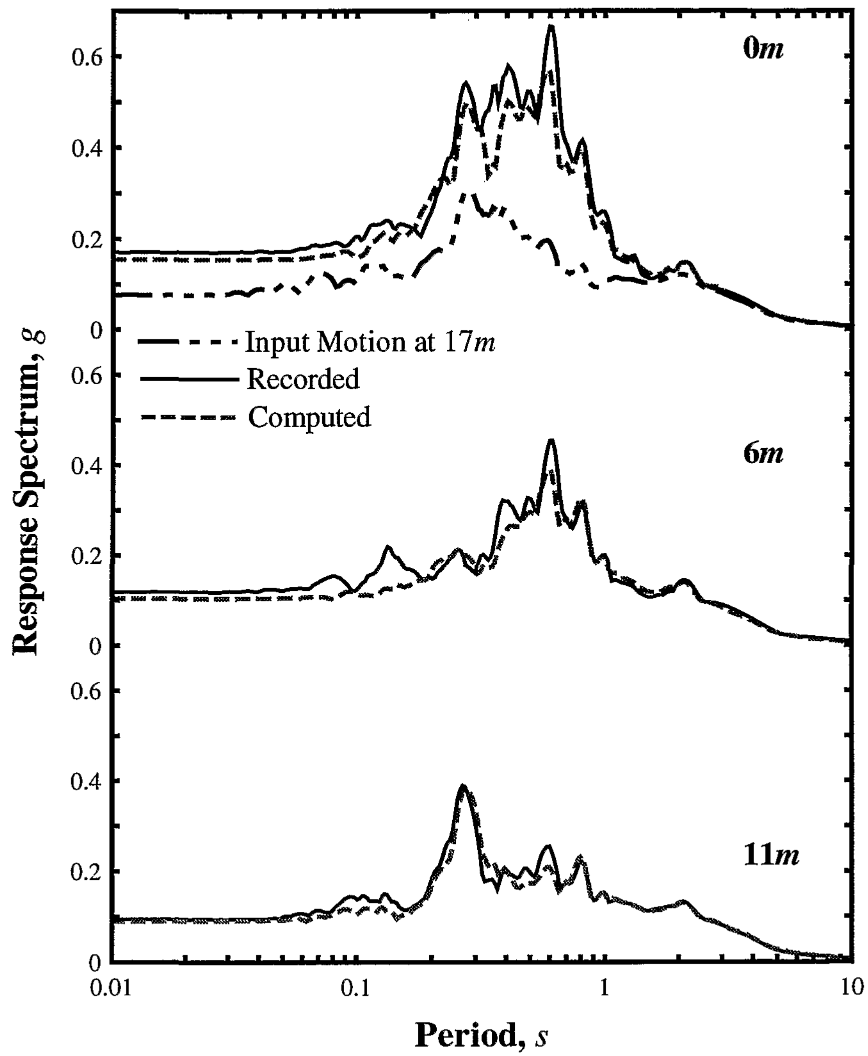

Figure 28: Recorded and Computed NS ARS during LSST16.

Model Properties identified from UCD DKS02 Centrifuge Experiment (Stevens et al. 1999, 2001)

The DKS02 Flexible Shear Beam (FSB) container in the longitudinal direction was modeled as a one-dimensional shear beam down to accelerometer location **A17** instead of the actual aluminium container base (Fig. 3). This modification was made in order to avoid potential relative slip movement between the container base (accelerometer) and the overlying soil. As such, the experiments conducted at centrifugal acceleration levels of $10g$, $20g$ and $40g$ represent a prototype site of $4.75m$-, $9.5m$- and $19m$-depth respectively (Lai *et al.* 1999). All the earthquake-like shaking events listed in Table 8, covering linear response as well as highly nonlinear response, were utilized for the identification of the dense sand properties (http://cgm.engr.ucdavis.edu/research/projects/dks/). Evidence of 3D effects was noted at higher frequencies, and frequency windows (*Hz*) of [0, 11], [0, 6.5] and [0, 4] were applied to all recorded motions under centrifugal accelerations of $10g$, $20g$ and $40g$ respectively (to minimize those effects on the conducted analyses). Figures 29-31 show the optimized properties for the dense sand (Nevada sand with Dr of about 100%) shear wave velocity profile, shear modulus and damping ratio versus shear strain level (using all shaking events simultaneously). It is noted that the optimized stiffness profile is somewhat lower than expected. However, modulus variation is found to track the upper bound of published data. The unexpected surprise appears in the optimized damping, which exceeds upper bound values. Damping in this case did not fall below 7% even for the smallest recorded tremors. Professor Ken Stokoe of the University of Texas has indicated (Personal Communication 2000) that damping ratio might show some increase with increase in excitation frequency. This frequency dependence of damping ratio might be partially responsible for the larger optimized damping values in the current study, since the centrifuge soil system resonances occurred at very high frequencies (>70*Hz*).

The optimized properties were used to reproduce the site response during each shaking experiment by exciting the shear beam at **A17** with its recorded motion. Figures 32-43 show selected comparisons of recorded and computed acceleration time histories and ARS (with 5% damping), one small and one large shaking event at each of the employed centrifugal acceleration levels. In general, good agreement is noted between recorded and optimized response.

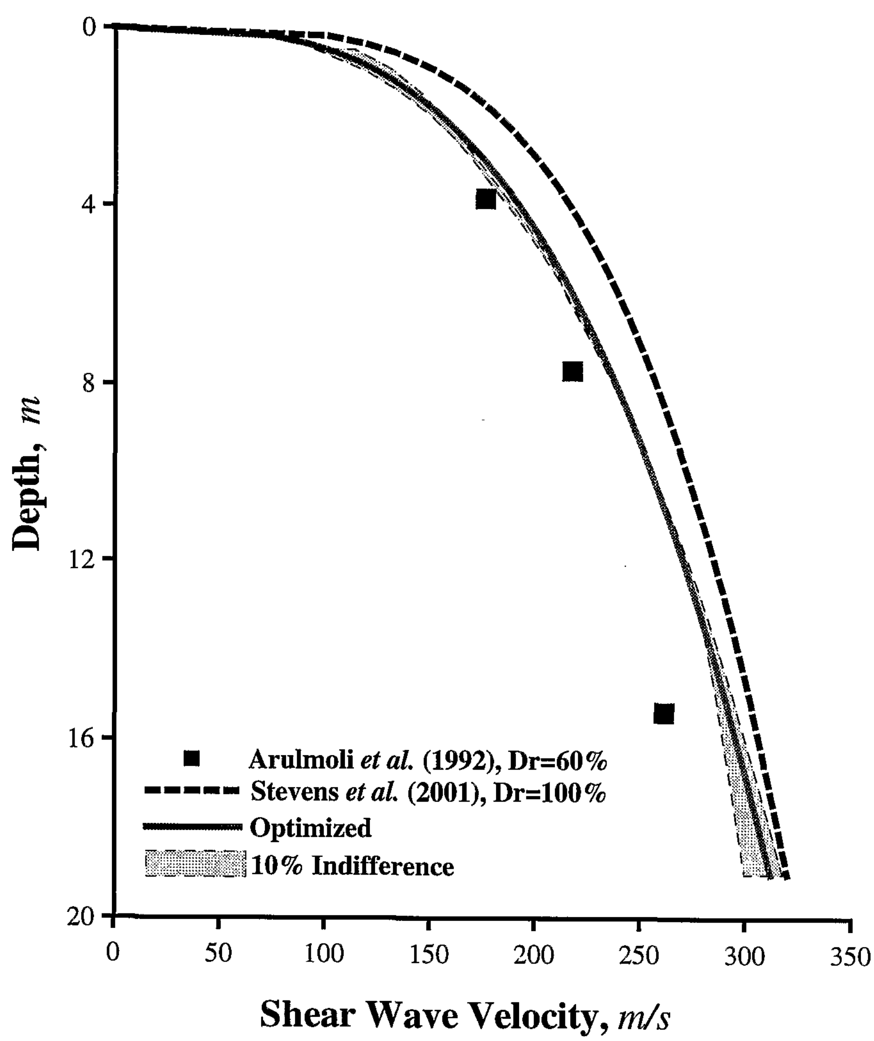

Figure 29: Optimized Velocity Profile and 10% Indifference for Stiff Sand (DKS02).

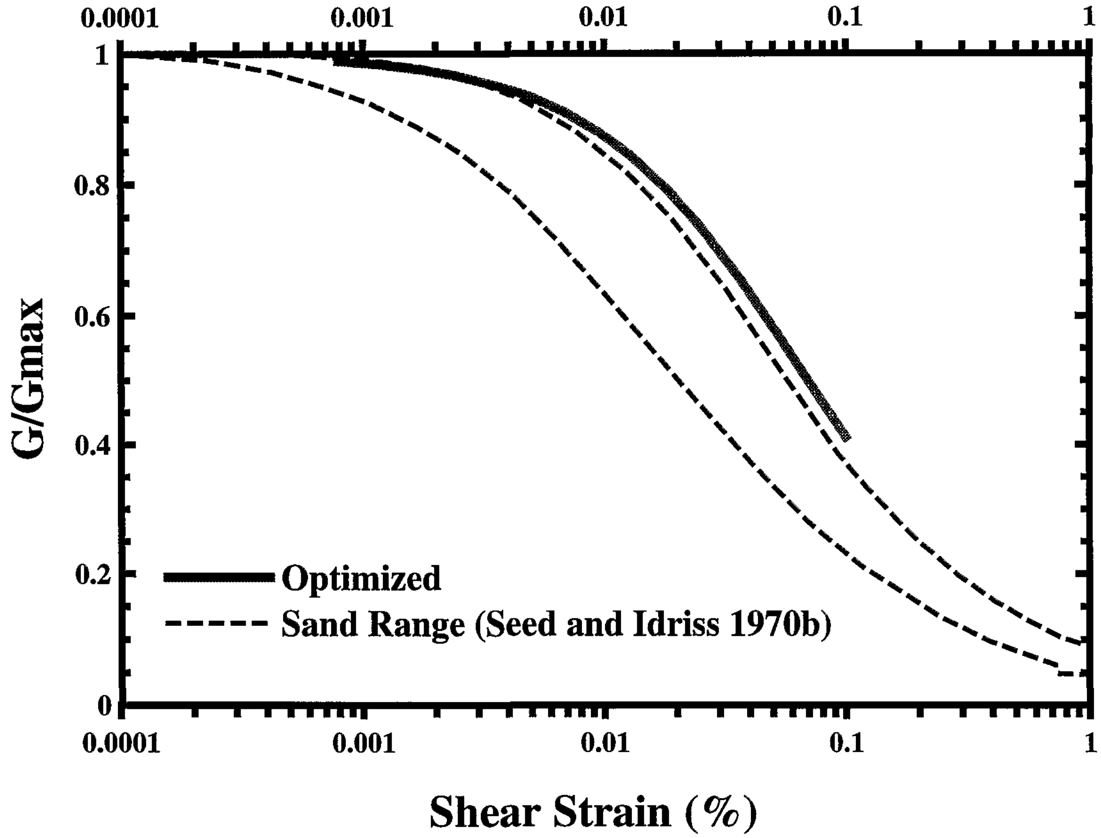

Figure 30: Optimized Shear Modulus Reduction for Stiff Sand (DKS02).

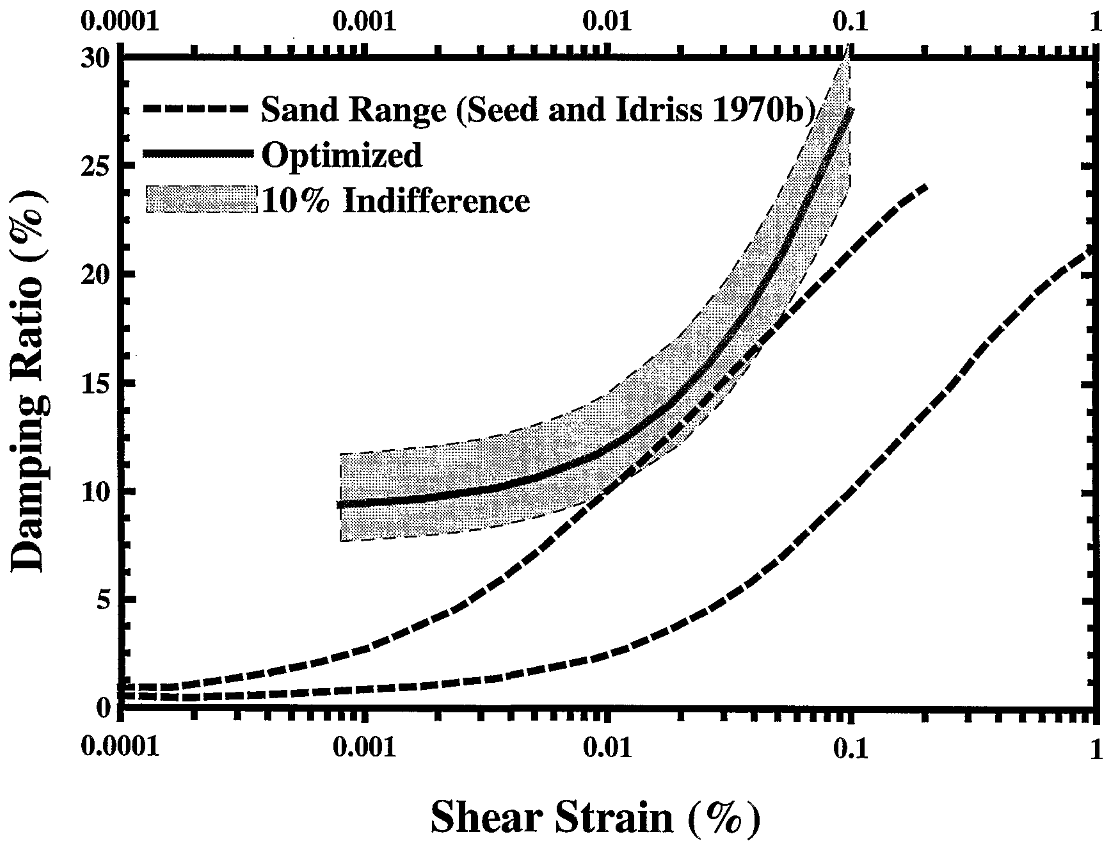

Figure 31: Optimized Shear Damping Value and 10% Indifference for Stiff Sand (DKS02).

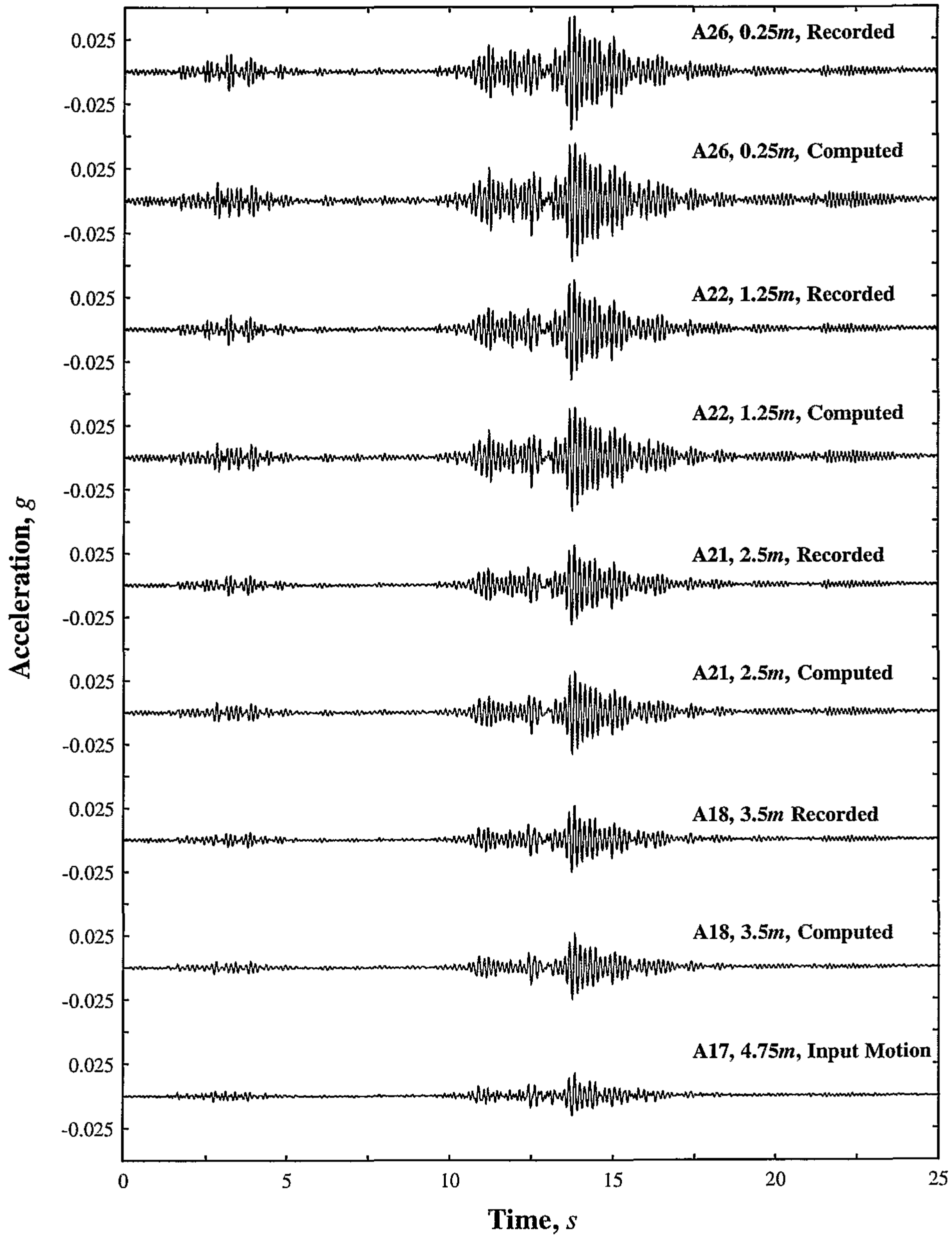

Figure 32: Filtered Recorded and Computed Accelerations of DKS02_c (10g).

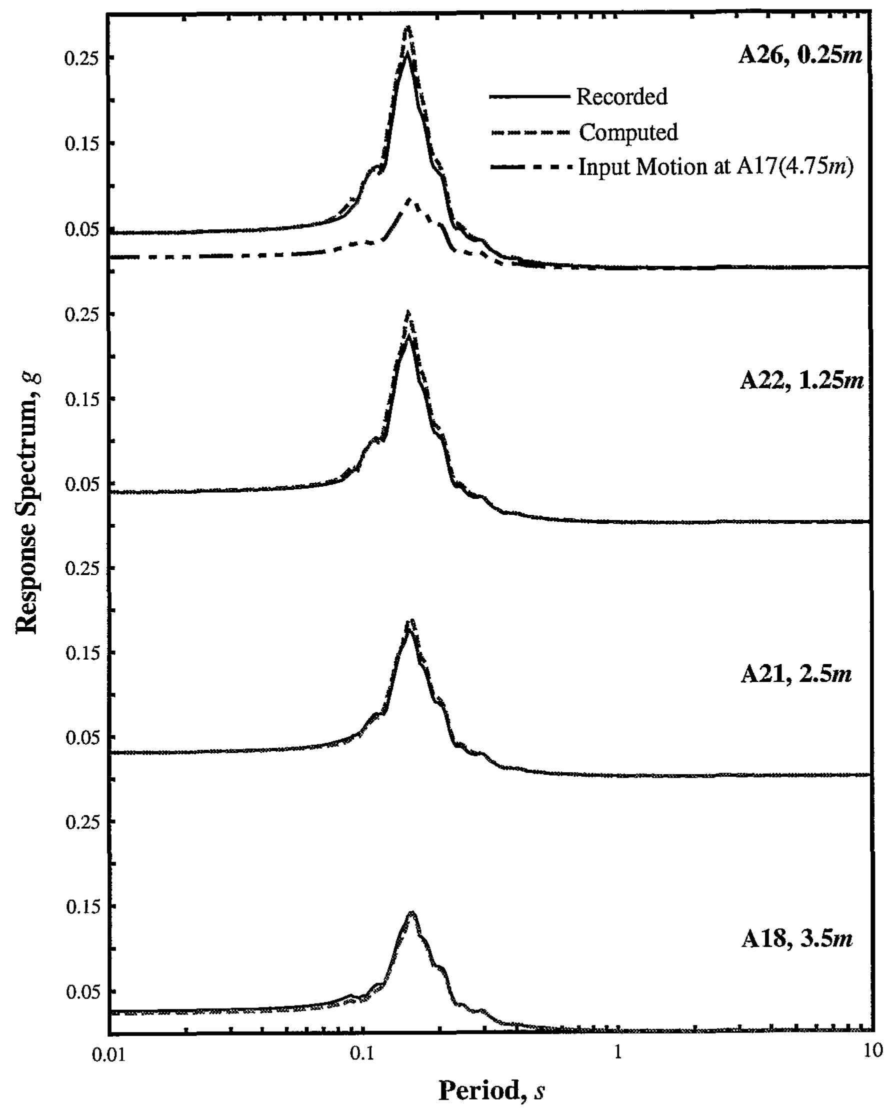

Figure 33: Filtered Recorded and Computed ARS of DKS02_c (10g).

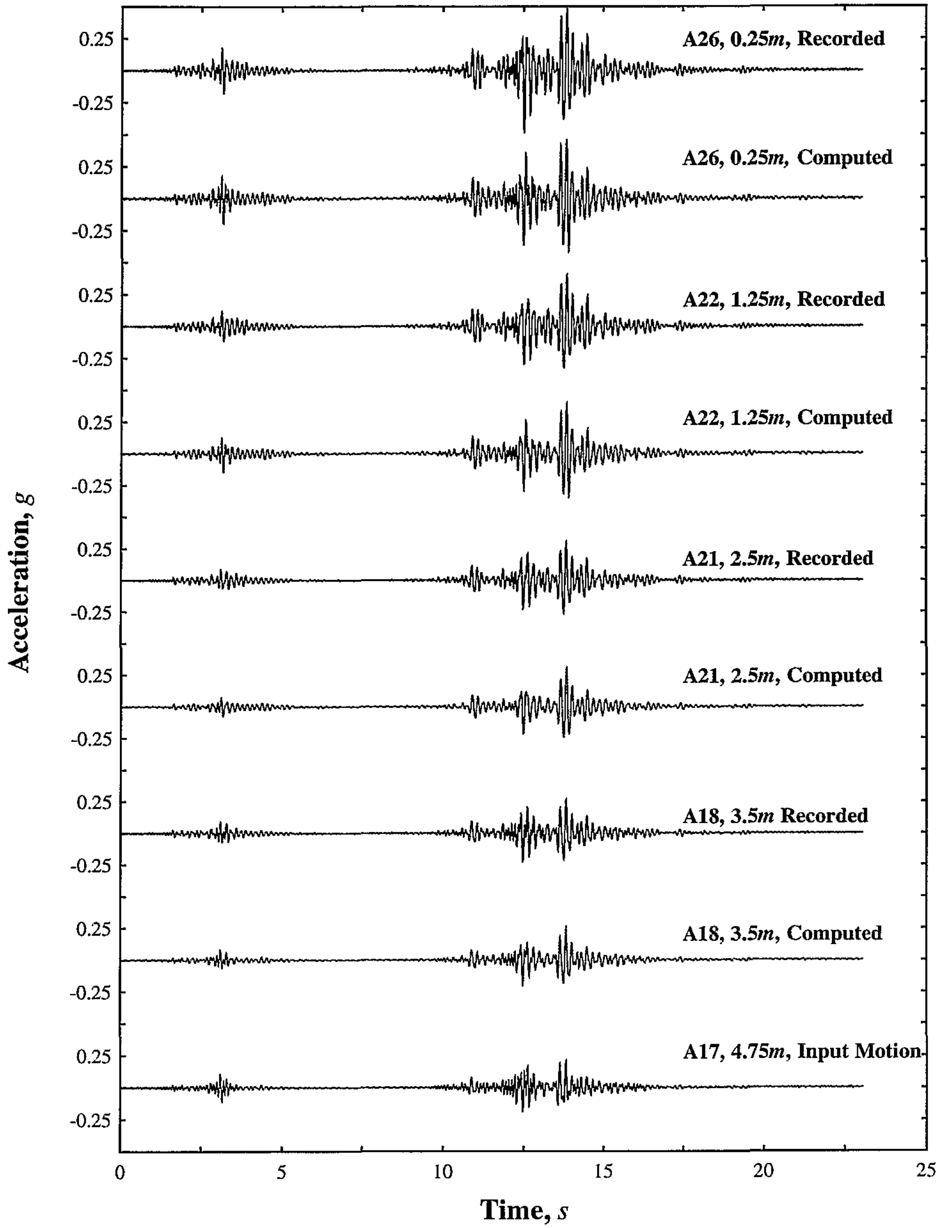

Figure 34: Filtered Recorded and Computed Accelerations of DKS02_ah (10g).

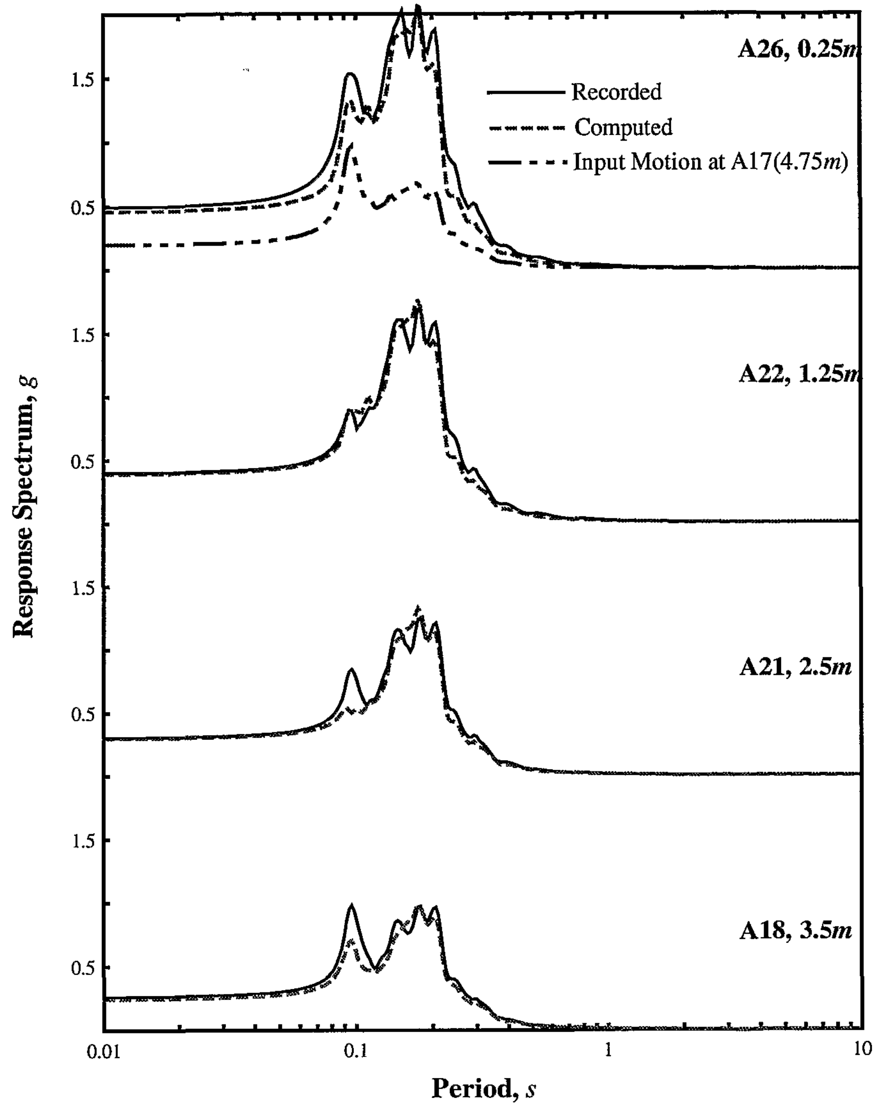

Figure 35: Filtered Recorded and Computed ARS of DKS02_ah (10g).

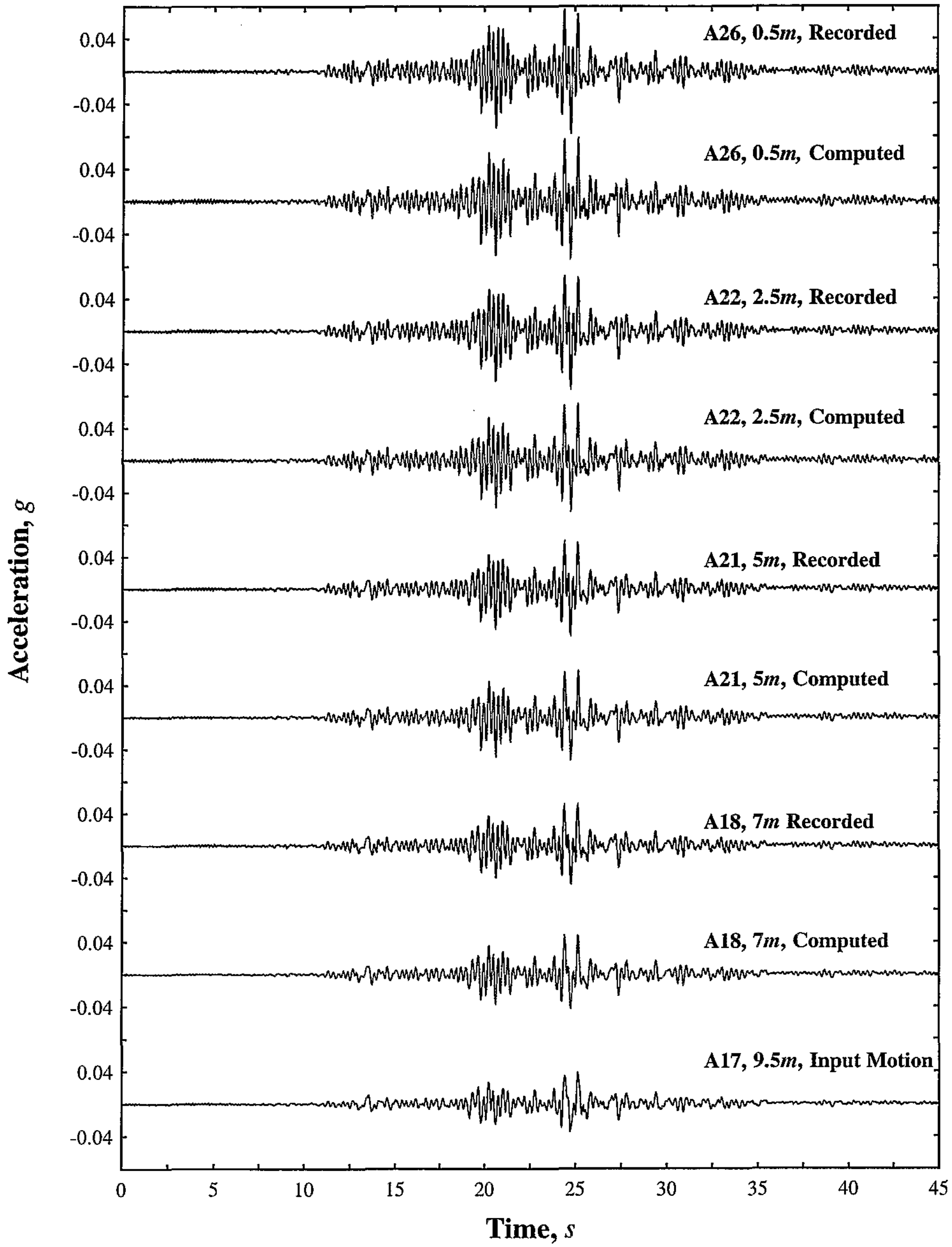

Figure 36: Filtered Recorded and Computed Accelerations of DKS02_n (20g).

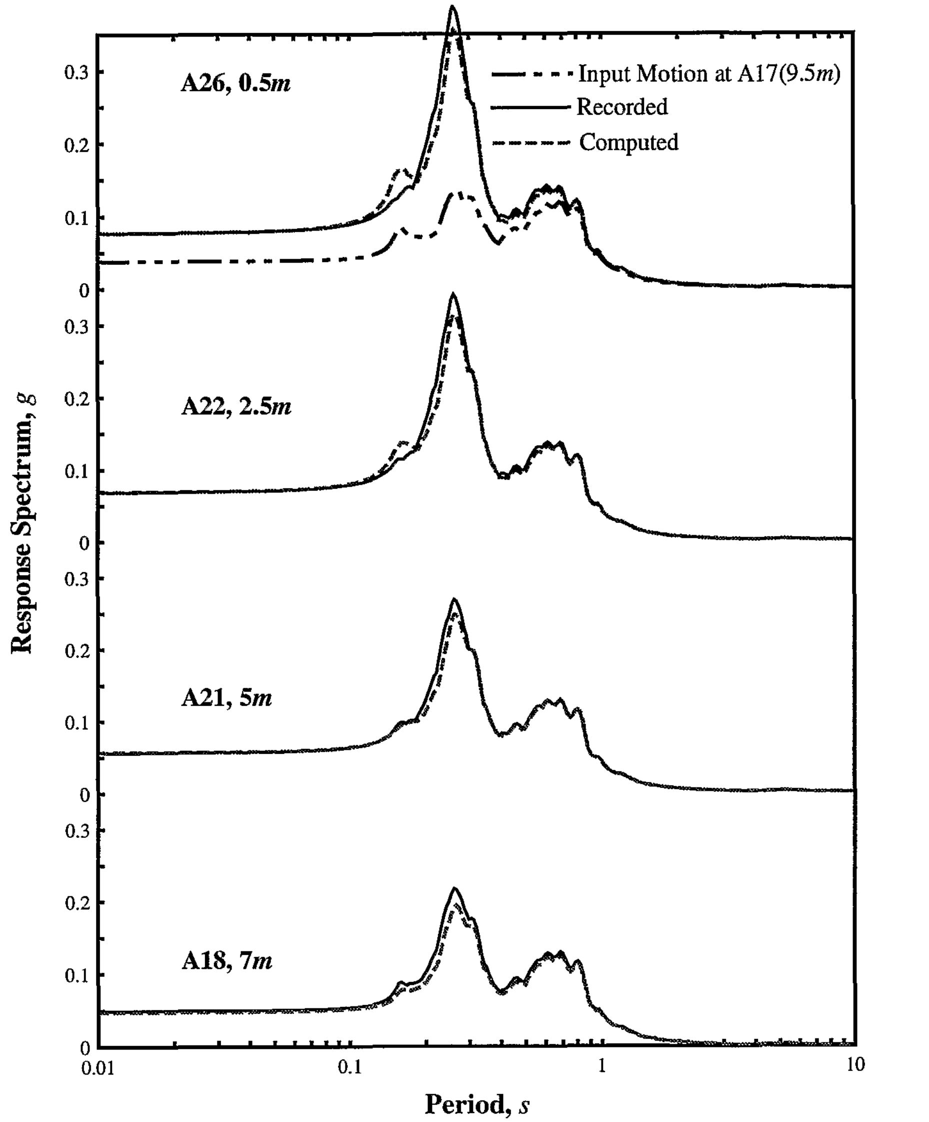

Figure 37: Filtered Recorded and Computed ARS of DKS02_n (20g).

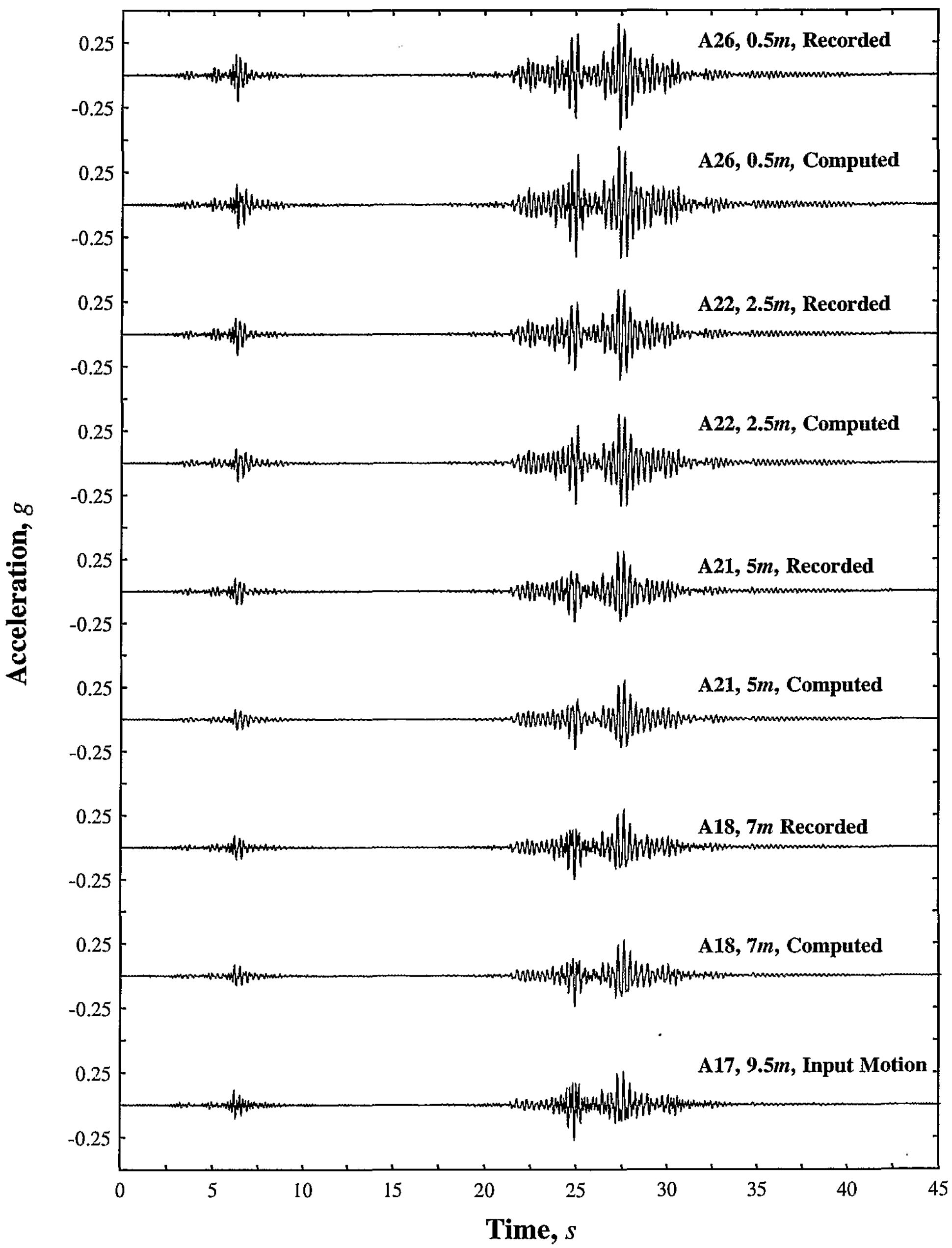

Figure 38: Filtered Recorded and Computed Accelerations of DKS02_bb (20g).

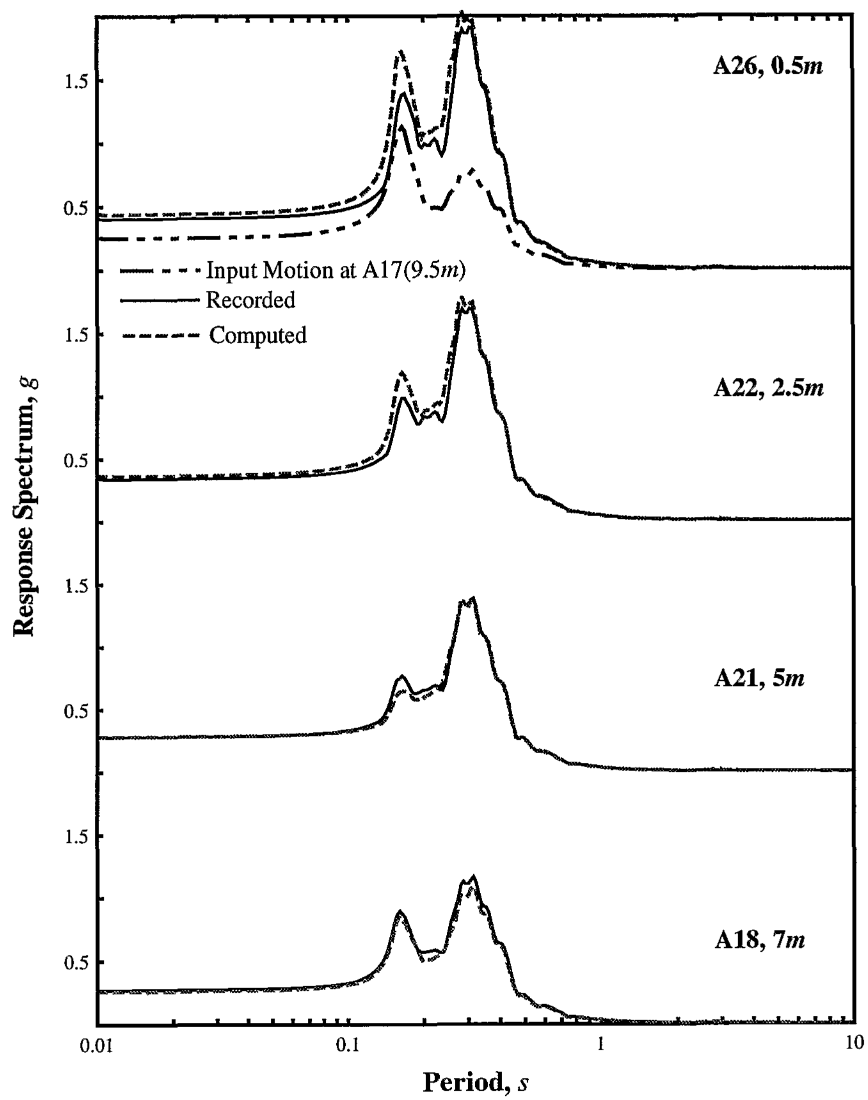

Figure 39: Filtered Recorded and Computed ARS of DKS02_bb (20g).

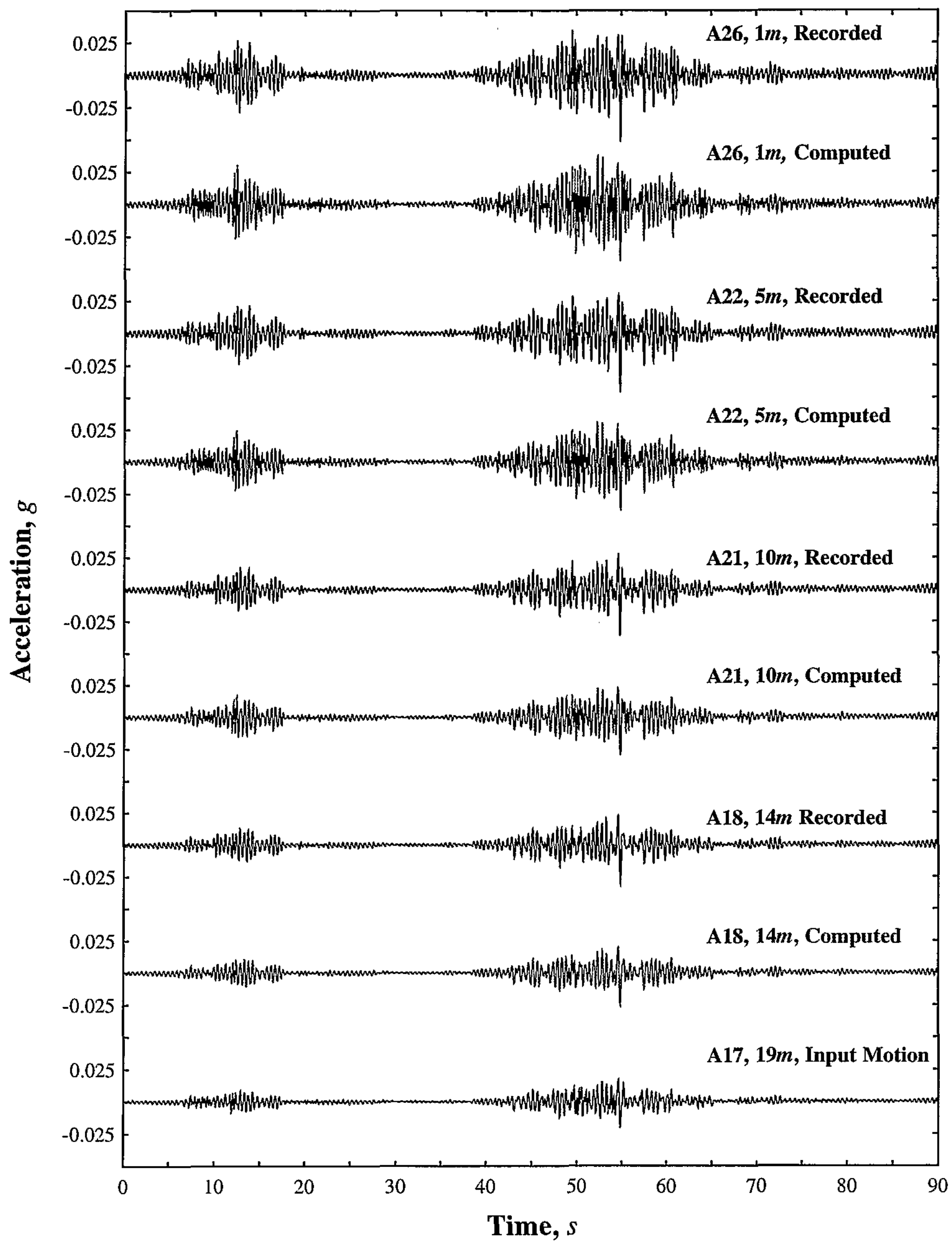

Figure 40: Filtered Recorded and Computed Accelerations of DKS02_u (40g).

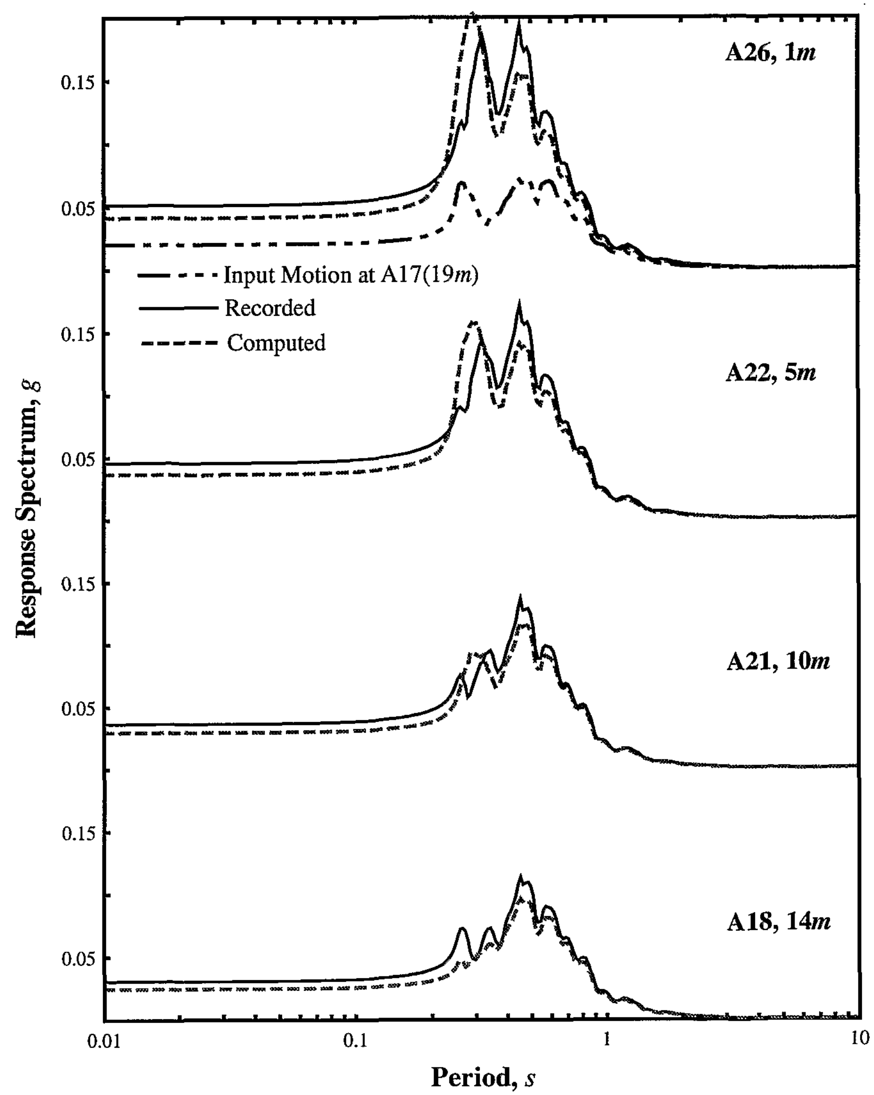

Figure 41: Filtered Recorded and Computed ARS of DKS02_u (40g).

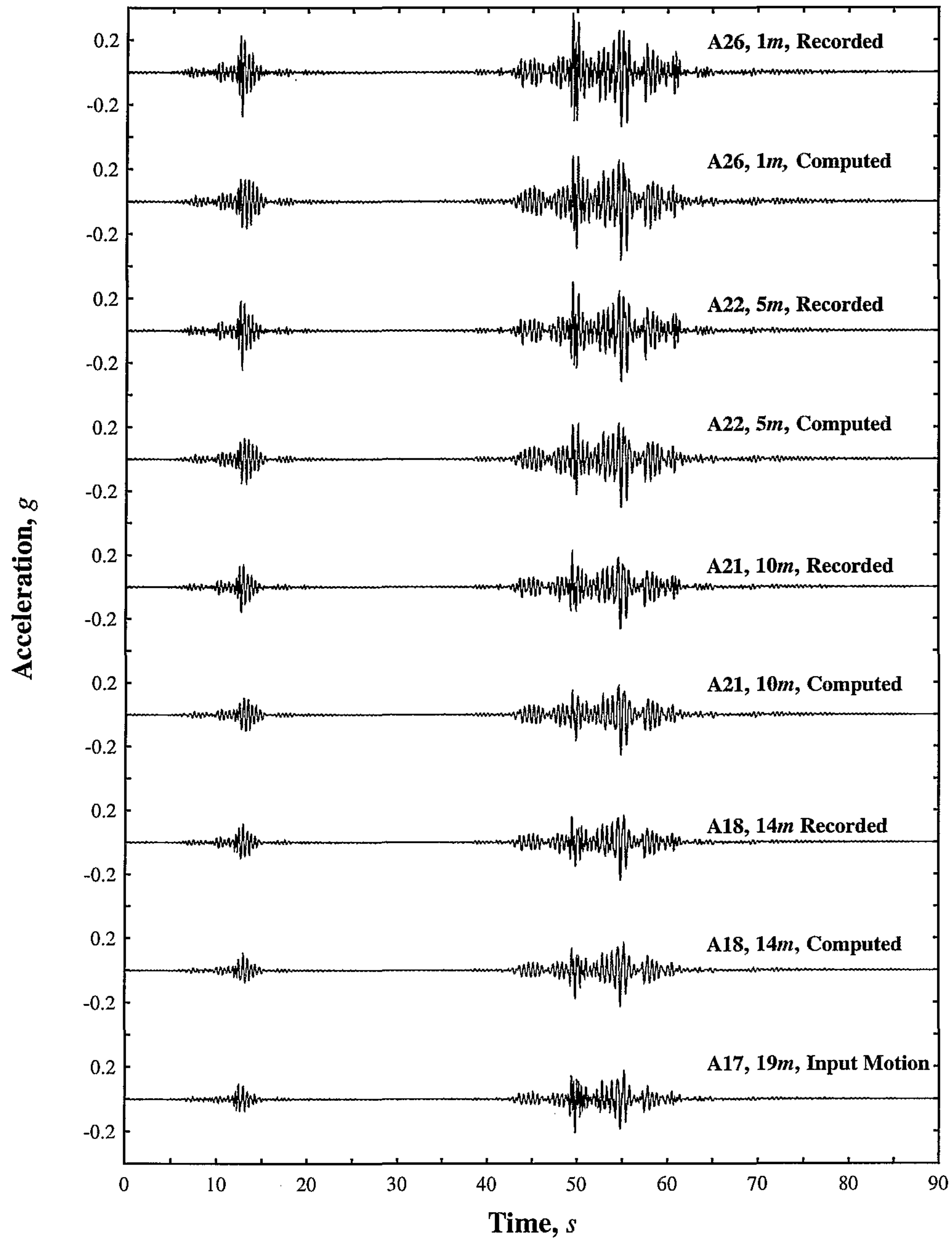

Figure 42: Filtered Recorded and Computed Accelerations of DKS02_by (40g).

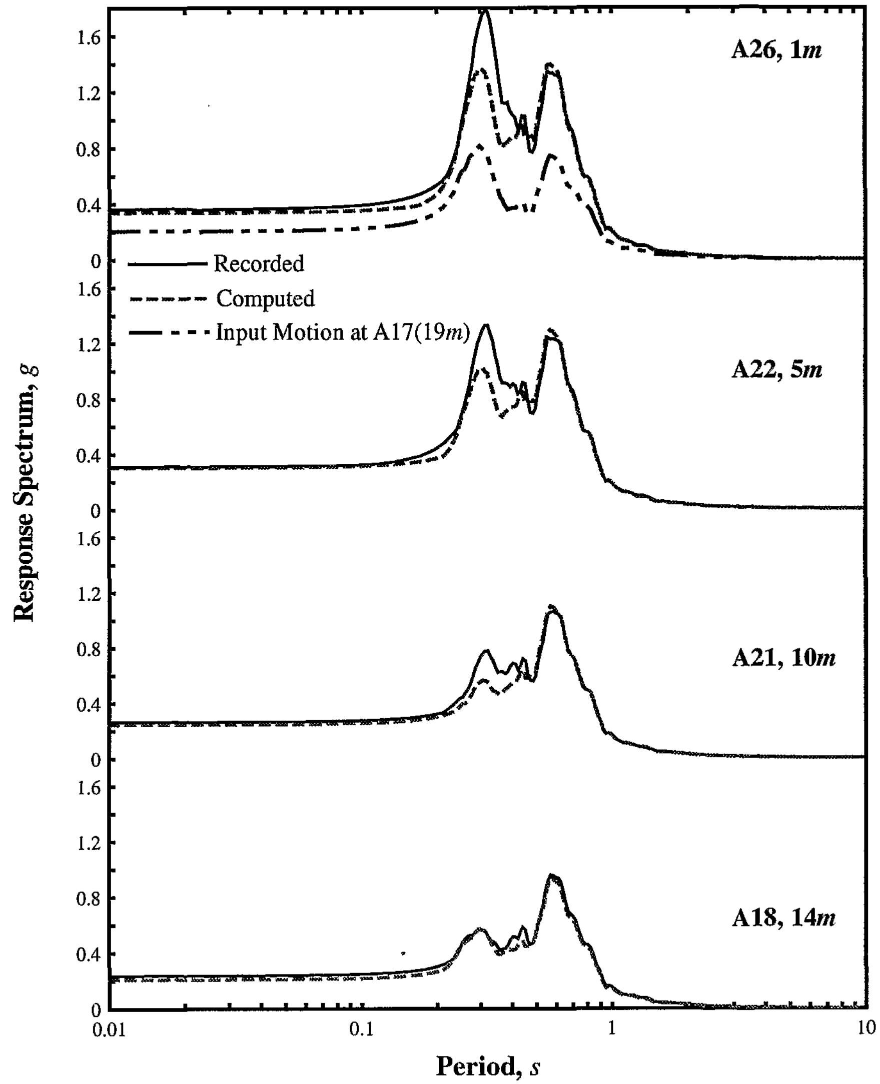

Figure 43: Filtered Recorded and Computed ARS of DKS02_by (40g).

Model Properties for Vertical Seismic Excitation

Hualien Site

Recordings of DH2 during three events (Feb. 23, 95, May 1, 95 and May 2, 95) (Fig. 1 and Table 6) were selected for identification of model properties under vertical excitation conditions. The vertical peak ground surface accelerations are less than 0.023*g* in amplitude, indicating a predominately linear response. The site was modeled as a 52.6*m* one-dimensional (1D) column as described earlier. Figure 44 shows the optimized properties for vertical motion in terms of stiffness profile. In this case, the optimization process was inconclusive. Two different stiffness profiles were found to yield nearly equal minimal error. Quality of the data may be questioned since the peak accelerations are quite small (among other reasons). However, in both cases, the optimized damping ratio was extremely large. Damping in this case was in the range of 14% to 25%. This outcome suggests that the underlying physical mechanisms are not well understood, and calls the validity of the employed 1D modeling procedure in questions.

Nevertheless, the optimized properties were used to reproduce the site response of each earthquake. Figures 45 and 46 show a comparison of recorded and computed acceleration time histories and ARS (with 5% damping). Similar quality matches were observed for the other two shaking events as well. In summary, further studies are needed before conclusion can be drawn.

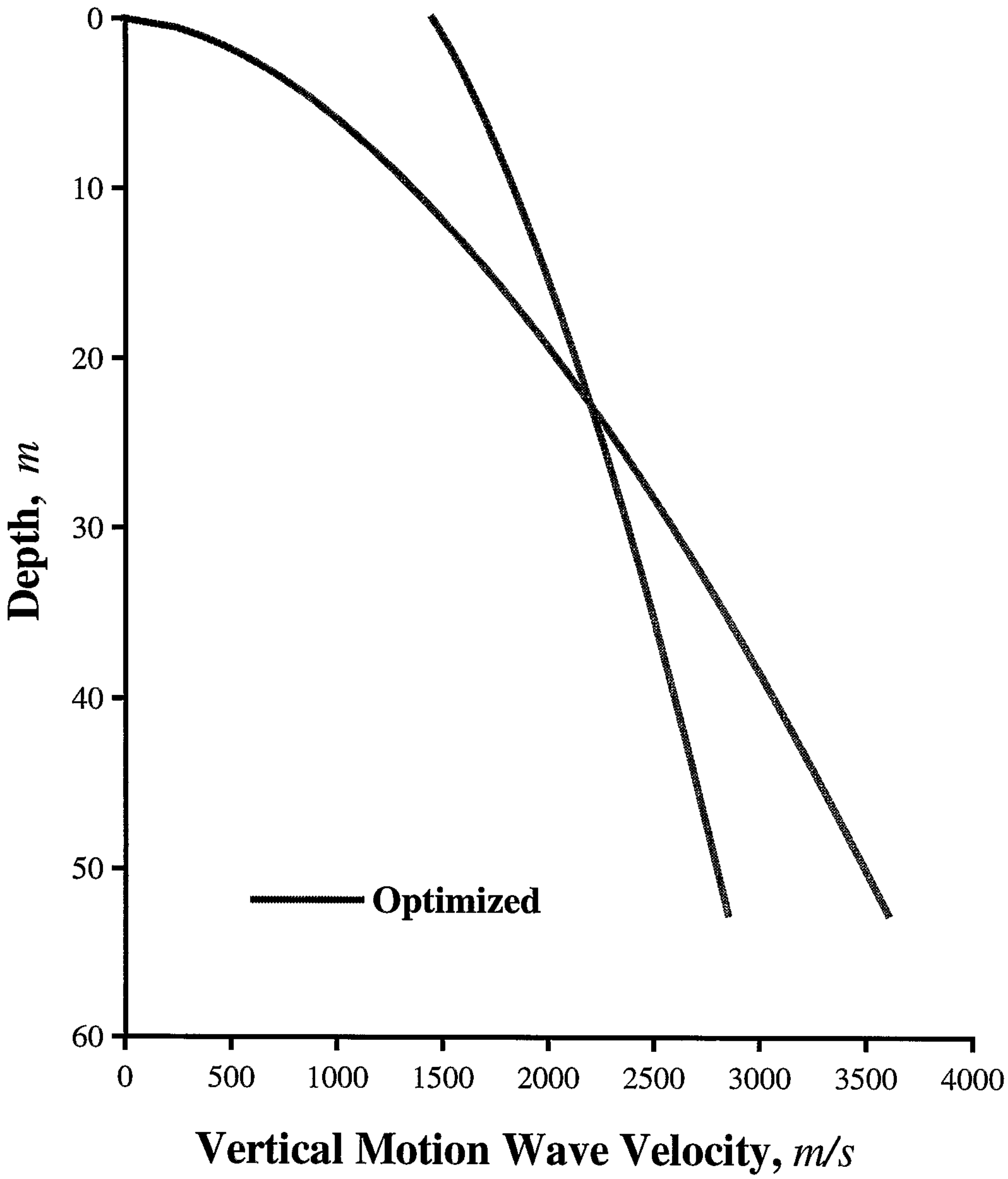

Figure 44: Optimized Vertical Motion Velocity Profile at Hualien.

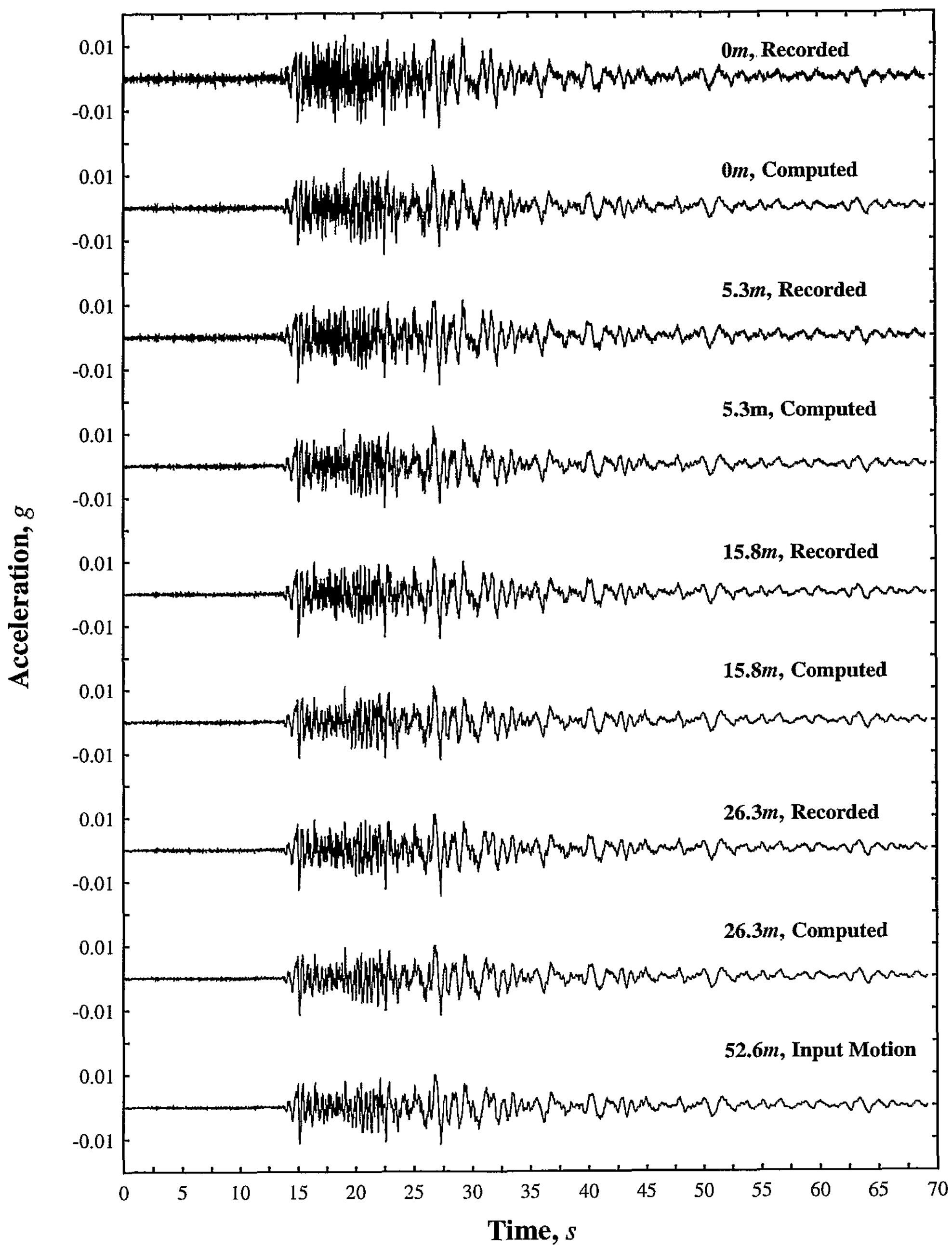

Figure 45: Recorded and Computed Vertical Accelerations of Hualien Feb. 23, 95.

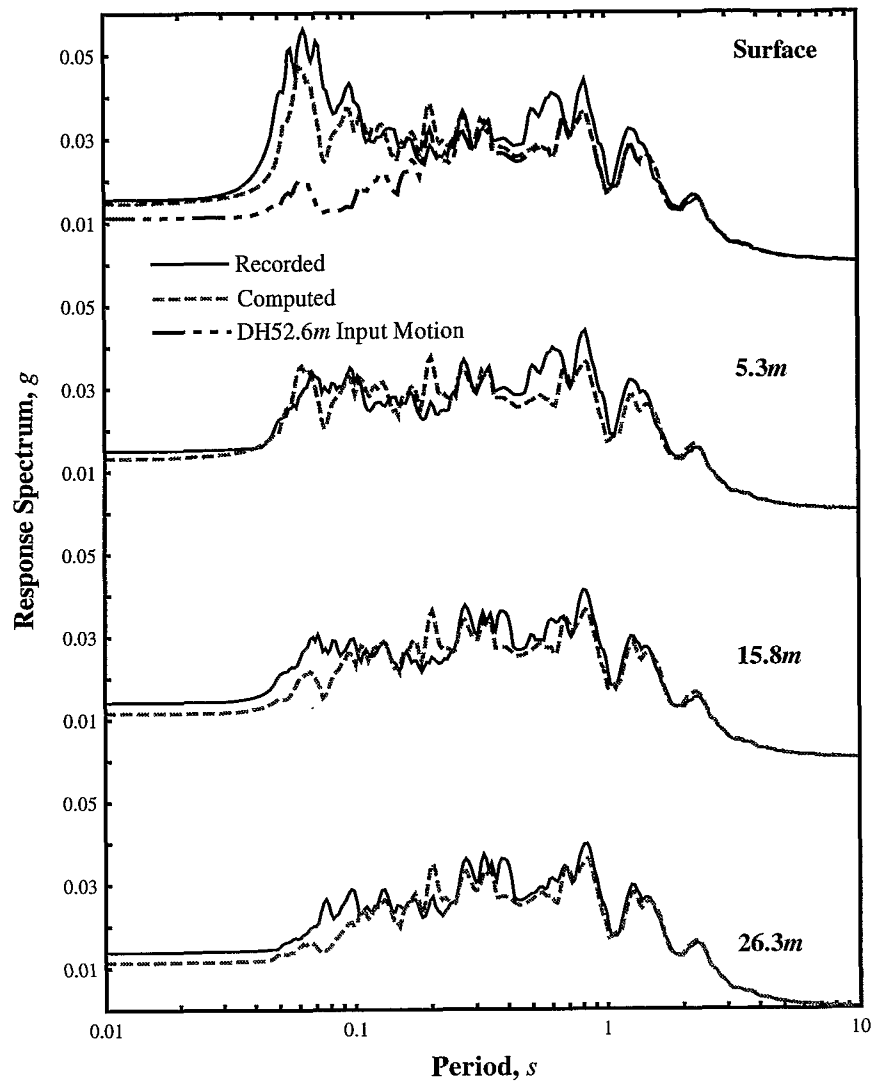

Figure 46: Recorded and Computed Vertical ARS during Hualien Feb. 23, 95.

Lotung Site

Recordings of DHB (Fig. 2 and Table 7) of the same six events (LSST 6, 7, 8, 13, 16, 17) were selected for identification of model properties for vertical excitation. The vertical peak ground surface accelerations are less than 0.10g in amplitude, suggesting a predominately linear response. The site was modeled as a 17m 1D column as described earlier. The site response was simulated with the recorded total vertical motion at 17m depth specified at this location. Figure 47 shows the optimized stiffness profile for vertical excitation. In this case, the optimization process consistently produced a stiffness profile that increased gradually with depth. However, the upper bound of this profile is about 25% lower than reported from in-situ measurements (Tang 1987). At Lotung, damping for vertical excitation was also high (optimal value of 18% with an indifference range of 14% - 19%). Overall, the combined findings about damping from Hualien and Lotung suggest that large damping ratios are needed when a 1D model is to be used for vertical vibration analyses (14% as a lower limit).

The optimized model properties were used to reproduce the site response for each earthquake. Figures 48-53 show comparisons of recorded and computed acceleration time histories and ARS (with 5% damping). Good agreement is noted. Similar match quality was observed for all other investigated events. As mentioned before only the first 23 seconds of event LSST16 were used (Fig. 49).

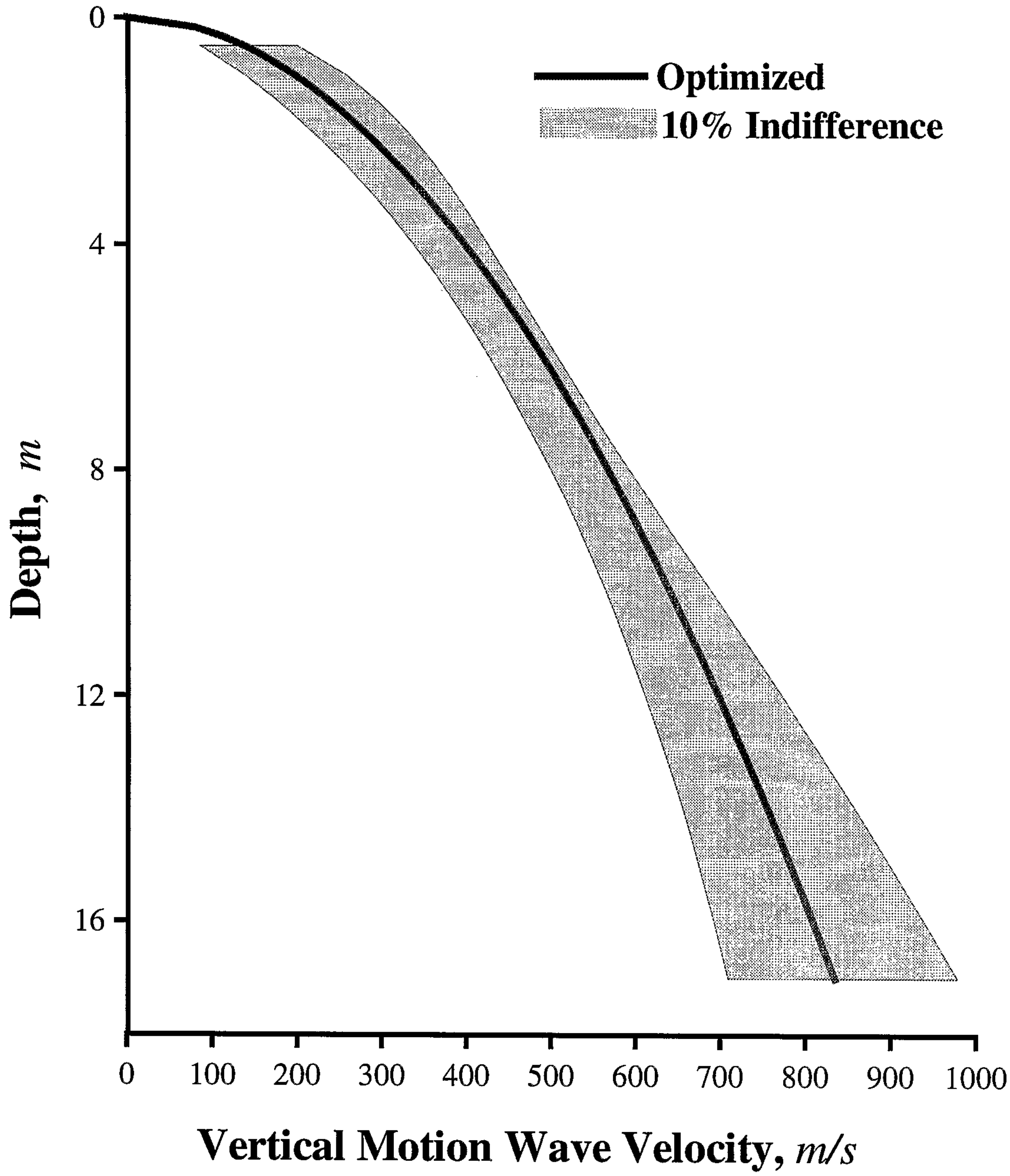

Figure 47: Optimized Vertical Motion Velocity Profile and its 10% Indifference at Lotung.

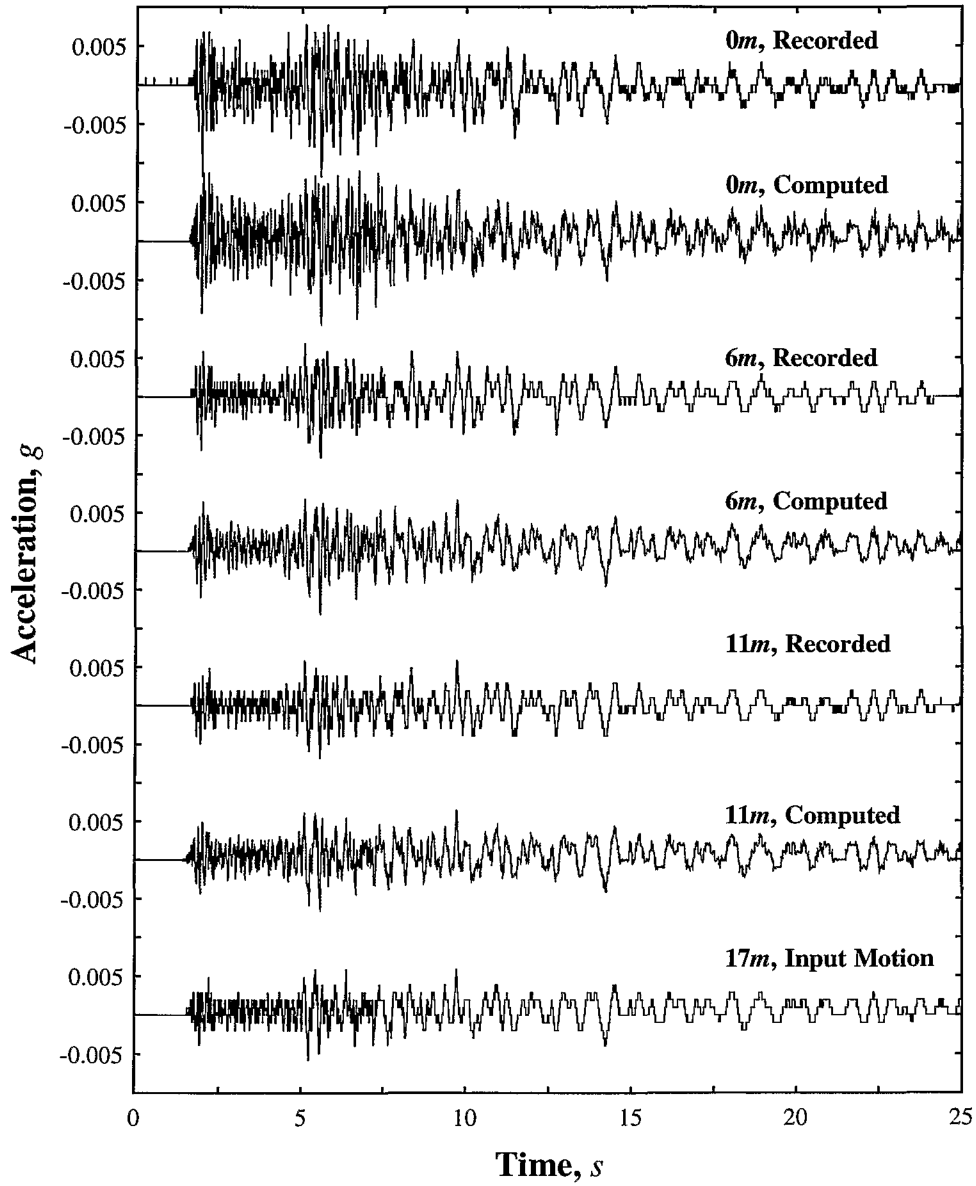

Figure 48: Recorded and Computed Vertical Accelerations during LSST6.

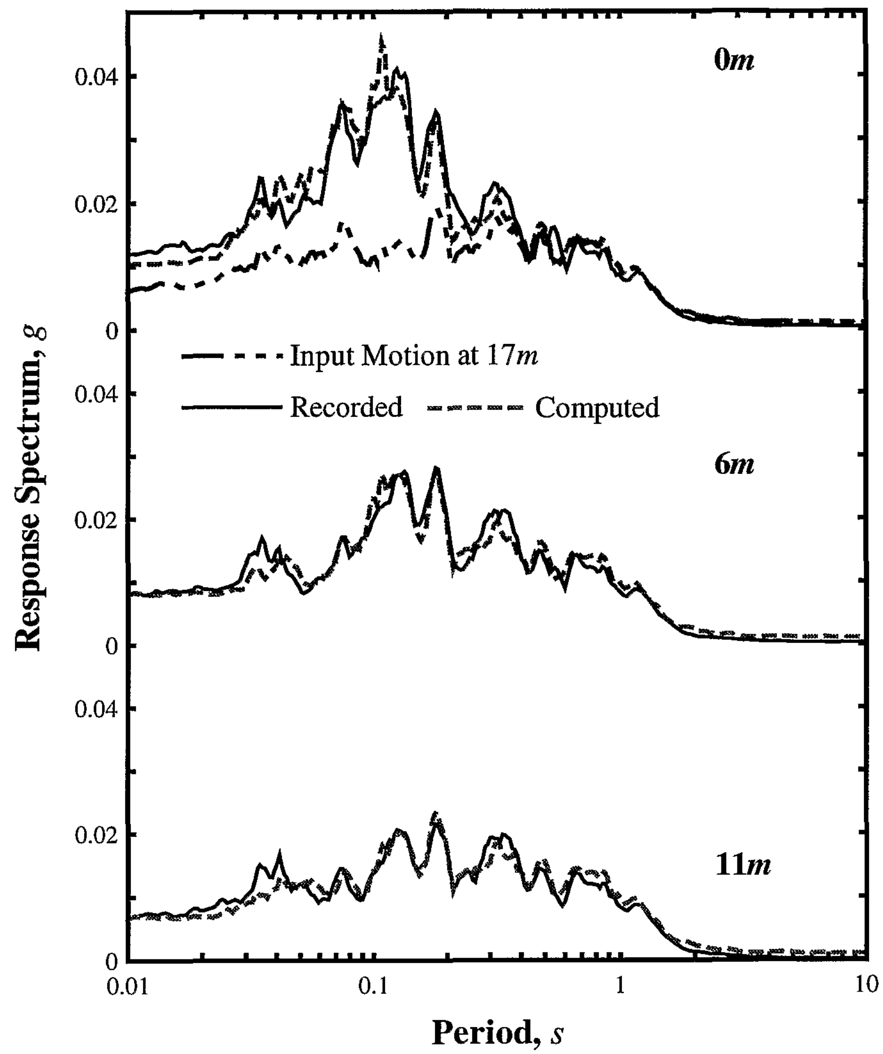

Figure 49: Recorded and Computed Vertical ARS during LSST6.

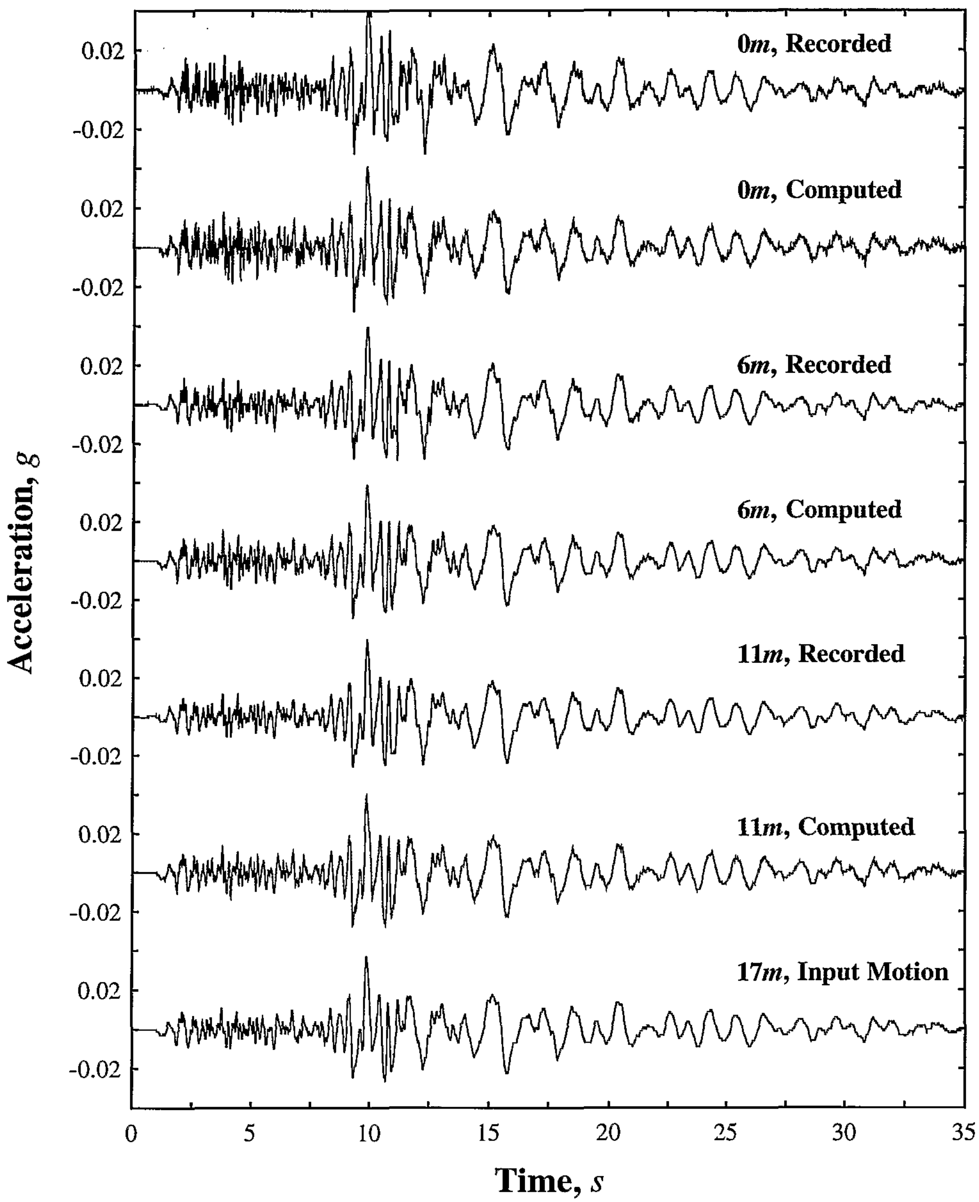

Figure 50: Recorded and Computed Vertical Accelerations during LSST7.

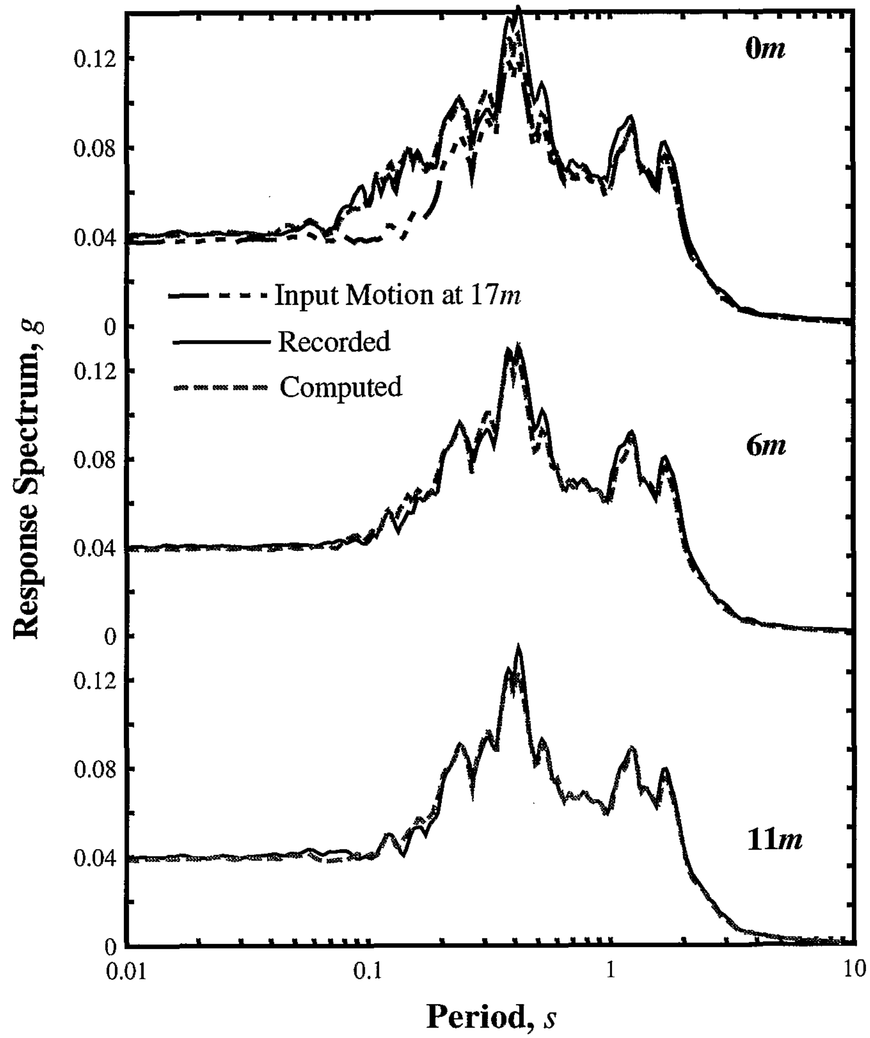

Figure 51: Recorded and Computed Vertical ARS during LSST7.

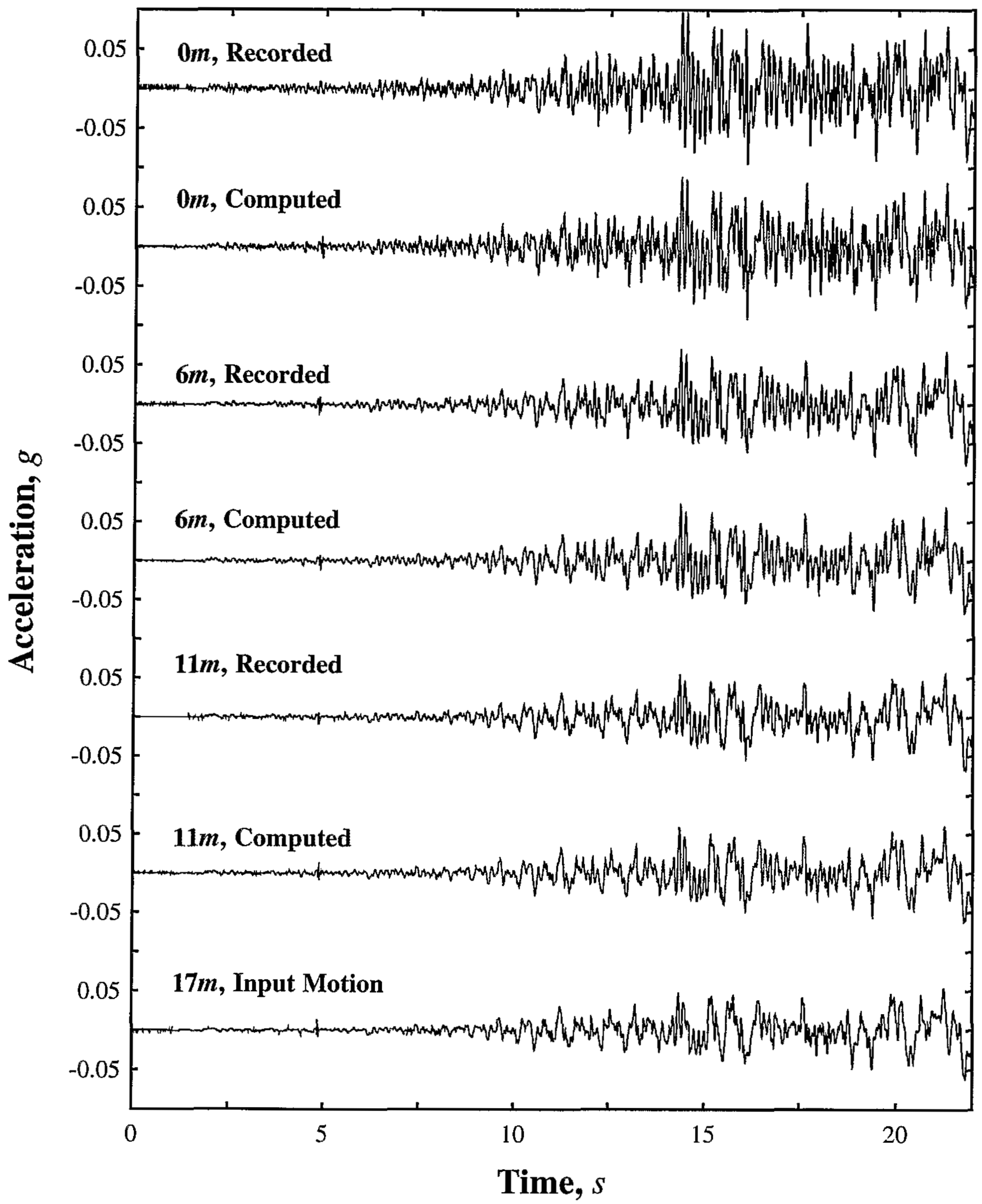

Figure 52: Recorded and Computed Vertical Accelerations during LSST16

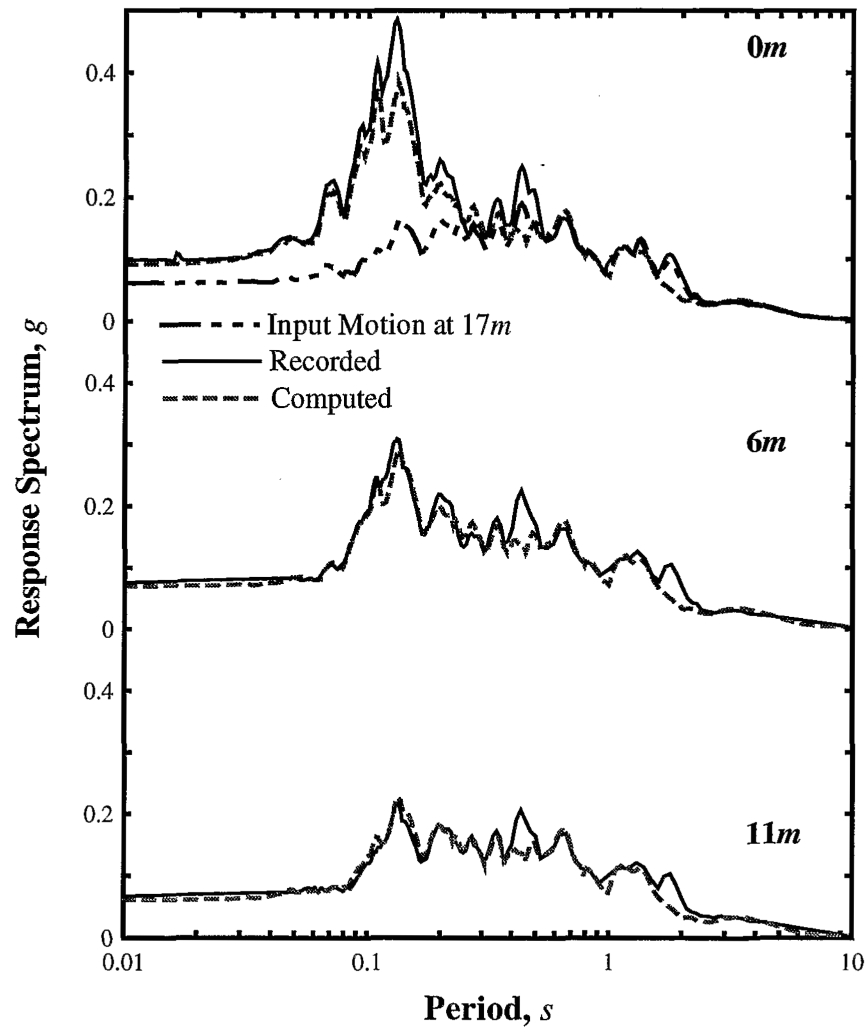

Figure 53: Recorded and Computed Vertical ARS during LSST16

LIQUEFACTION AND DOWNHOLE ARRAYS

Liquefaction (excess pore pressure ratio $r_u = u_e / \sigma'_v$ approaching and reaching 1.0, where u_e = excess pore pressure and σ'_v is effective vertical stress) and associated deformations remain among the main causes of damage during earthquakes (Seed *et al.* 1990, Bardet *et al.* 1995, Sitar 1995, Japanese Geotechnical Society 1996, Ansal *et al.* 1999). Indeed, dramatic unbounded (flow failure) deformations due to liquefaction in dams and other structures (Seed *et al.* 1975, 1989, Davis and Bardet 1996) have highlighted the significance of this problem in earthquake engineering research.

In this section, samples of downhole acceleration data in which liquefaction response is involved are presented. Many of these records point to the significance of an associated cyclic mobility phenomenon (described briefly below). Computational modeling of this important phenomenon is addressed thereafter. Finally, an available website for conducting live online site amplification and liquefaction computational modeling is presented (http://cyclic.ucsd.edu).

Soil Liquefaction from Field Downhole Arrays

***The Wildlife Refuge** (California, USA):* This site is located on the West Side of the Alamo River in Imperial County, southern California. Evidence of liquefaction was observed at or near the site following the 1930, 1950, 1957, 1979, and 1981 Imperial Valley earthquakes (Youd and Wieczorek 1984). These observations triggered an interest in the site, which was instrumented in 1982, in an insightful effort (Youd and Wieczorek 1984) by the United States Geological Survey (USGS). In 1987, the site was shaken by two main earthquakes (Holzer *et al.* 1989), including the Superstition Hills earthquake (M_W = 6.6), which caused a sharp increase in recorded pore-water pressure. In addition, subsequent field investigations showed evidence of site liquefaction and ground fissures. The surface records displayed peculiar acceleration spikes (Holzer *et al.* 1989) associated with simultaneous instants of excess pore-pressure drop (Fig. 54).

Using the simple approach of Koga and Matsuo (1990), the site lateral seismic response during liquefaction was inferred from the stress-strain and effective-path histories (Figs. 55 and 56) of the Superstition Hills earthquake (Zeghal and Elgamal 1994). At low effective confining pressures (high excess pore pressures), the effective stress-path clearly exhibited a reversal of behavior from contractive to dilative (Fig. 55), as the line of phase transformation (see below for further discussion) was approached (National Research Council, NRC 1985). Such a mechanism is a consequence of soil dilation at large strain excursions, resulting in associated instants of pore-pressure drop.

***Aomori Harbor** (Japan):* Towhata *et al.* (1996) presented (Fig. 57) a ground surface lateral acceleration history recorded at Aomori Harbor during the 1968 Tokatchi-Oki earthquake. This history was recorded at a location where liquefaction of subsoil was observed. It may be noted that the Wildlife site acceleration record (Fig. 54) shows a pattern of spikes, which is quite similar to that of this Aomori Harbor record (Fig. 57). Thus, a shear stress-strain response of similar characteristics to that at Wildlife might have occurred at Aomori Harbor during this earthquake.

***Port Island** (Kobe, Japan):* Port Island is an artificial (reclaimed) island located on the west-south side of Kobe, Japan. In the phase completed by 1981, 436 ha were reclaimed by bottom dumping from barges (Nakakita and Watanabe 1981). Soil in the artificial reclaimed layer (O'Rourke 1995, Sitar 1995, Japanese Geotechnical Society 1996) consisted of decomposed weathered granite fill (Masado soil mined from the nearby Rokko mountains) with grain sizes ranging from gravel and cobble-sized particles, to fine sand (2 mm mean particle size, with silt-sized particles or smaller of less than 10% by weight).

A downhole accelerometer array was installed at the Northwest corner of Port Island in August 1991(Iwasaki 1995). The array consisted of triaxial accelerometers located at the surface, 16 m, 32 m, and 83 m depths. This array documented the observed widespread liquefaction of reclaimed ground during the 1995 Hyogoken-Nambu earthquake. Using the recorded downhole accelerations, the corresponding one-dimensional shear stress-strain response was evaluated (Elgamal *et al.* 1996c, 1997). At shallow depths, the stress-strain histories indicated (Fig. 58): (1) a noticeable reduction in stiffness with slight but visible signs of shear strain hardening at elevation 24m, and (2) an abrupt sharp loss of stiffness and reduction of yield strength near the surface at 8m depth. It is noted here that no clear signs of permanent lateral deformations were observed at the array site.

***Kushiro Port** (Japan):* Iai *et al.* (1995) presented downhole accelerations recorded during the 1993 Kushiro-oki earthquake. The downhole array is located in Kushiro port. Upper layers at this site included saturated sand with shear wave velocities of 250 m/sec. The recorded accelerations showed clear spikes at ground surface and at 2 m depth (Fig. 59). These spikes were attributed to sand dilation (during the lateral seismic shear process), and were successfully simulated by a noteworthy computational model (Fig. 60) as will be discussed below. In this case, acceleration spikes do not necessarily denote r_u values approaching or equal to 1.0, but may nevertheless be associated with a phase of significant increase in excess pore-water pressure (and relatively high dynamic shear stress).

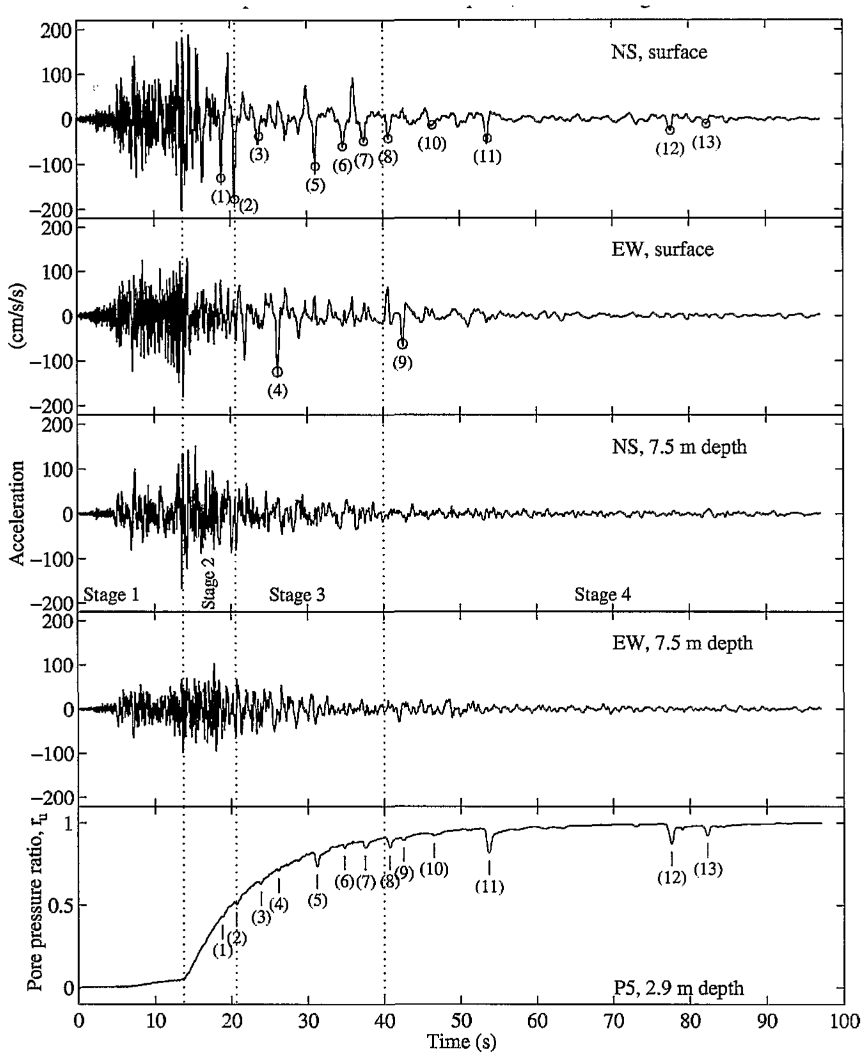

Figure 54: Recorded response at the Wildlife refuge site, Superstition Hills earthquake (Holzer et al. 1989, Zeghal and Elgamal 1994).

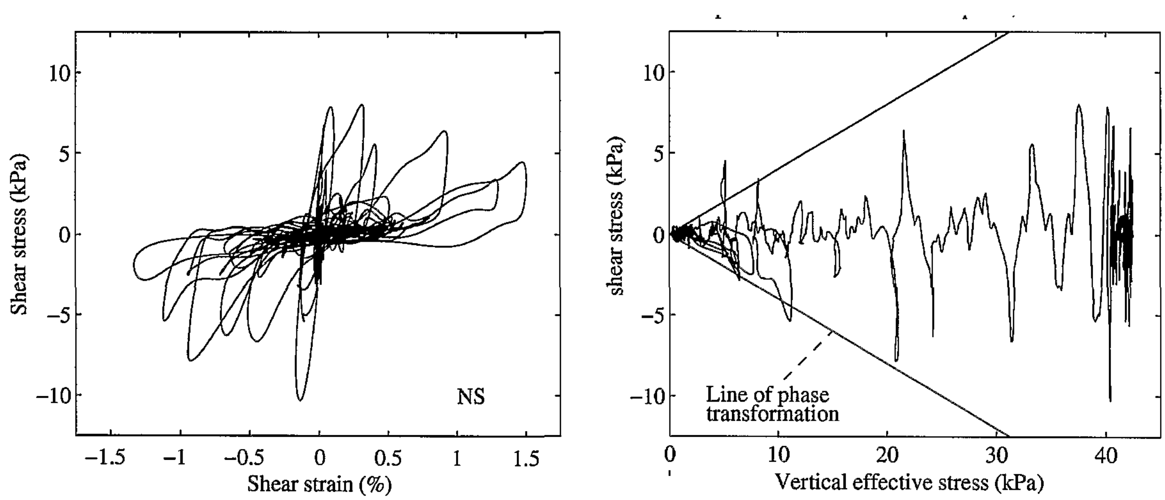

Figure 55: Wildlife-refuge NS shear stress-strain and effective-stress histories during the Superstition Hills 1987 earthquake (evaluated from acceleration histories, Zeghal and Elgamal 1994).

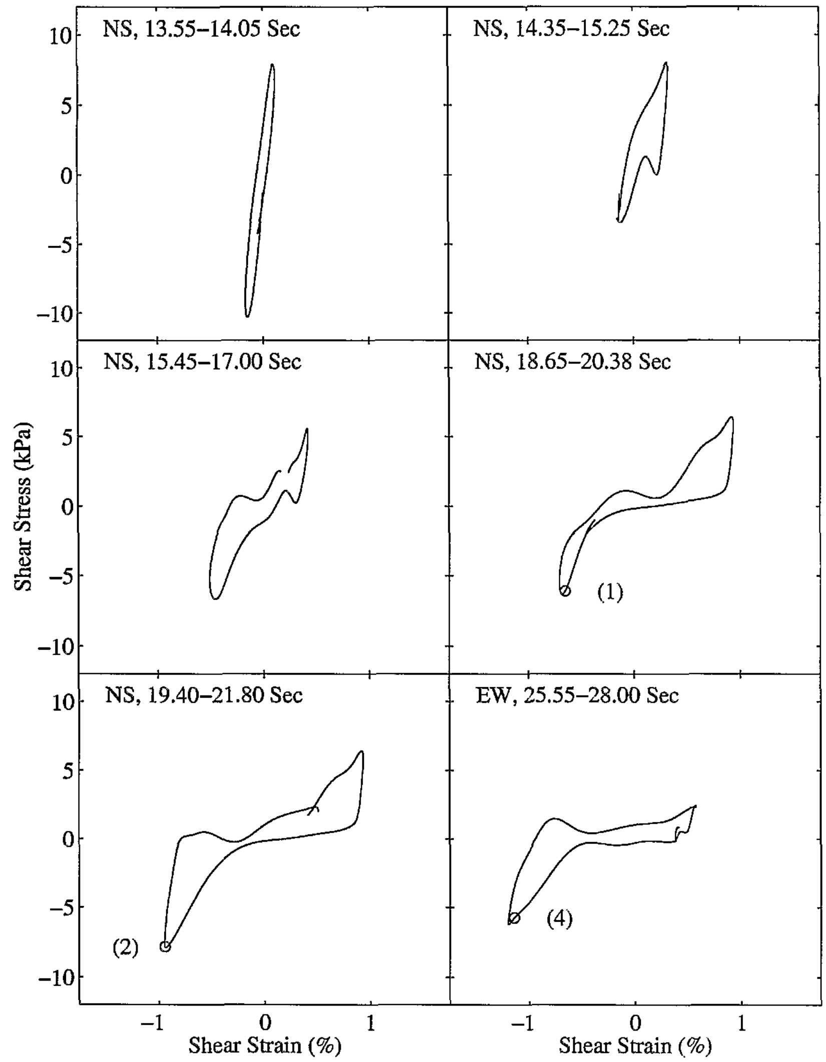

Figure 56: Selected stress-strain loops of Wildlife-refuge response during Superstition Hills earthquake (Zeghal and Elgamal 1994).

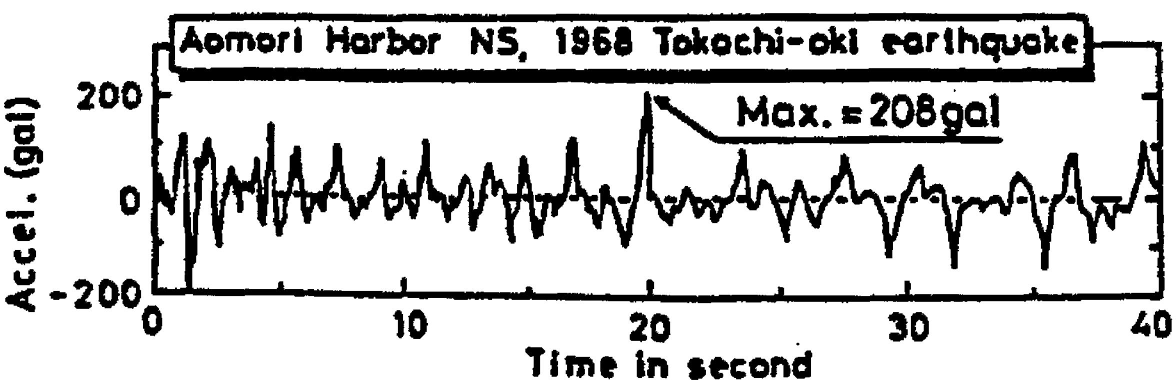

Figure 57: Aomori Harbor NS, 1968 Tokachi-oki earthquake (Towhata et al. 1996).

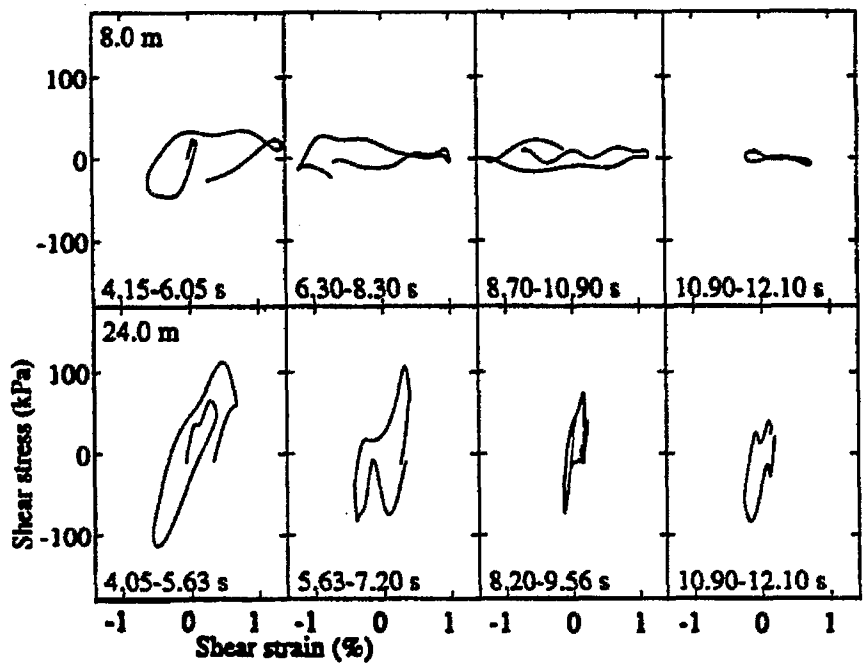

Figure 58: Selected stress-strain loops, Port Island, Hyogoken Nambu earthquake (Elgamal et al. 1996c).

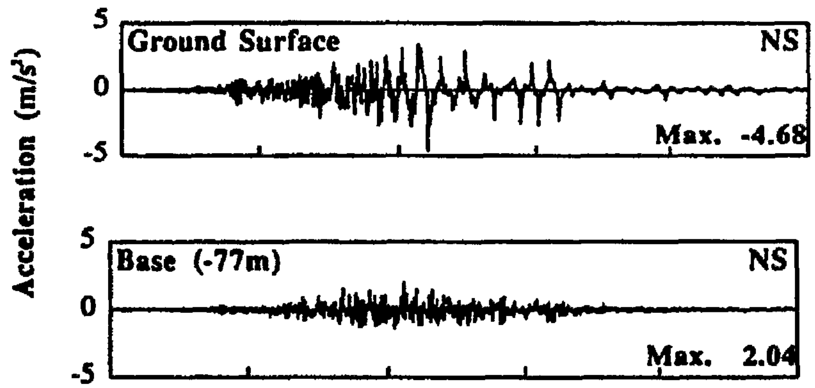

Figure 59: Recorded acceleration, Kushiro-oki earthquake 1993 (Iai et al. 1995).

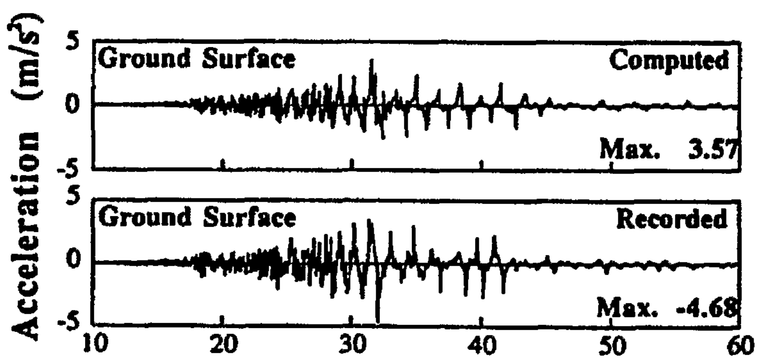

Figure. 60: Kushiro-oki 1993, recorded and computed earthquake accelerations at the ground surface (Iai et al. 1995).

Soil Liquefaction from Centrifuge Downhole Arrays

A large body of centrifuge experiments using Nevada Sand (Arulmoli *et al.* 1992, Taboada and Dobry 1992) has also shown clear evidence of cyclic dilative soil response effects. Many of these experiments are described in (Arulanandan and Scott 1993, 1994) as part of the VELACS project (Taboada and Dobry 1993, Scott *et al.* 1993, Wilson and Kutter 1993, Dobry and Taboada 1994, Whitman and Ting 1994). Relative density of the Nevada sand varied within the range of about 40% to 75% in these tests. A representative set of recorded accelerations is shown in Figs. 61-63. In addition to VELACS, a number of RPI Ph.D. theses contain extensive evidence of this response (e.g., Liu 1992, Taboada 1995, Adalier 1996, Abdoun 1997). A large number of studies (mostly using Nevada Sand) conducted at the University of California, Davis (e.g., Divis *et al.* 1996, Arulanandan *et al.* 1977, Balakrishnan *et al.* 1997, Wilson *et al.* 1997) also show a similar response (e.g., Fig. 64).

The basic nature of associated shear stress-strain response is clearly manifested by back-calculated shear stress-strain lateral-deformation histories as reported by Dobry *et al.* (1995) and Elgamal *et al.* (1996b). These histories (Fig. 65) are based on the recorded acceleration and displacement responses of infinite mild-slope dynamic simulations (Fig. 61) in a set of pioneering tests conducted by Taboada (1995), and duplicated by Scott *et al.* (1993).

Cyclic Liquefaction

Summarizing the above observations from field and centrifuge downhole array data, it may be concluded that liquefaction frequently results in limited but objectionable levels of deformation (Bartlett and Youd 1995, Youd *et al.* 1999). Such response has been well documented in the pioneering work of Seed and Lee (1966), and Castro (1975). In such situations (Fig. 66), the deformation process may be characterized mainly as cyclic straining with limited amplitudes (Seed 1979), commonly known as cyclic mobility (Castro and Poulos 1977) or cyclic liquefaction (Casagrande 1975).

Much other laboratory experimental data sets also suggest the importance of the cyclic liquefaction mechanism. A valuable comprehensive survey of experimental research (triaxial, shear, and shake-table tests), documenting the significance of cyclic mobility during liquefaction (Fig. 66) was compiled by Seed (1979). Based on this survey, clean sands with a relative density D_r of 45% or more, appear to exhibit the mechanism of limited strain cyclic mobility during liquefaction. At and above D_r = 45%, the tendency for soil-skeleton dilation at large shear strain excursions instantaneously reduces r_u, allowing for significant regain in soil stiffness and strength, and eventually arresting further deformations.

In addition to the above, a survey compiled by Elgamal *et al.* (1998) indicates that a large body of laboratory experiments (e.g., Ishihara 1985, Arulmoli *et al.* 1992, Boulanger and Seed 1995), shake-table, and centrifuge tests (Dobry *et al.* 1995, Taboada 1995, Dobry and Abdoun 1998, Fiegel and Kutter 1992, Kutter and Balakrishnan 1998, Balakrishnan and Kutter 1999) all point to the same pattern of deformation (clean sands and non-plastic silts). In these experimental observations, clean uniform cohesionless soils with a reported D_r of as low as 37%, may accumulate large liquefaction-induced cyclic shear strains, but do not exhibit flow-type failures (in laboratory sample, shake-table, and centrifuge tests).

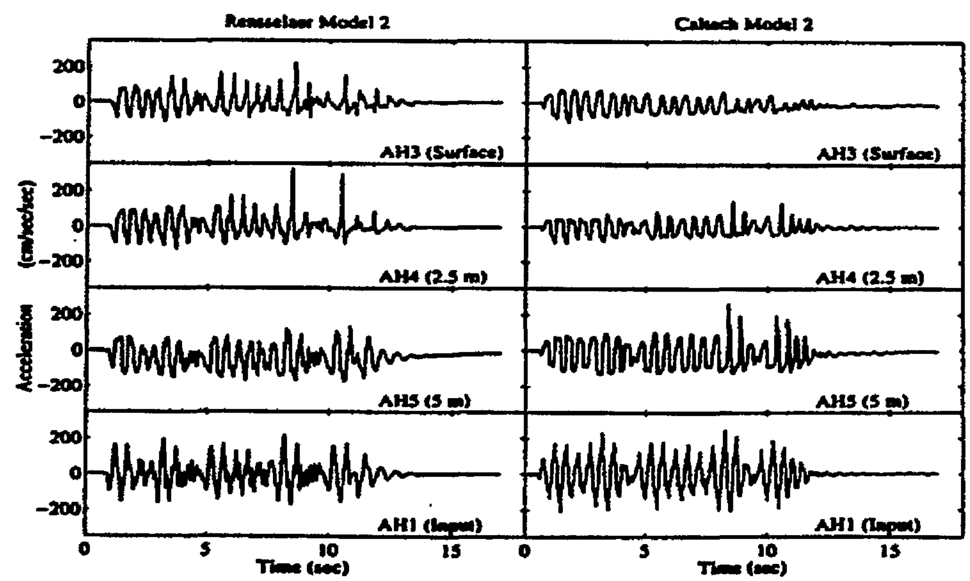

Figure 61: RPI and CalTech Model 2 acceleration histories at free surface (AH3), 2.5m depth (AH4), and 5m depth (AH5), and input acceleration (AH1) at 10m depth (Taboada and Dobry 1993, Scott et al. 1993).

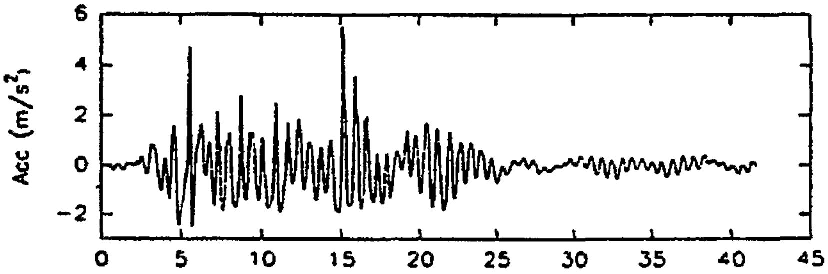

Figure 62: Recorded horizontal acceleration in UCD Model 7 (Wilson and Kutter 1993).

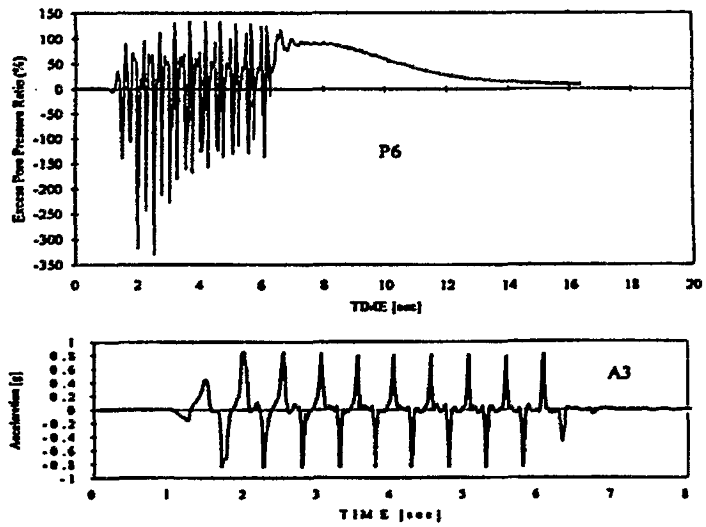

Figure 63: Pore-pressure and acceleration near surface of backfill, test 2e (Whitman and Ting 1994).

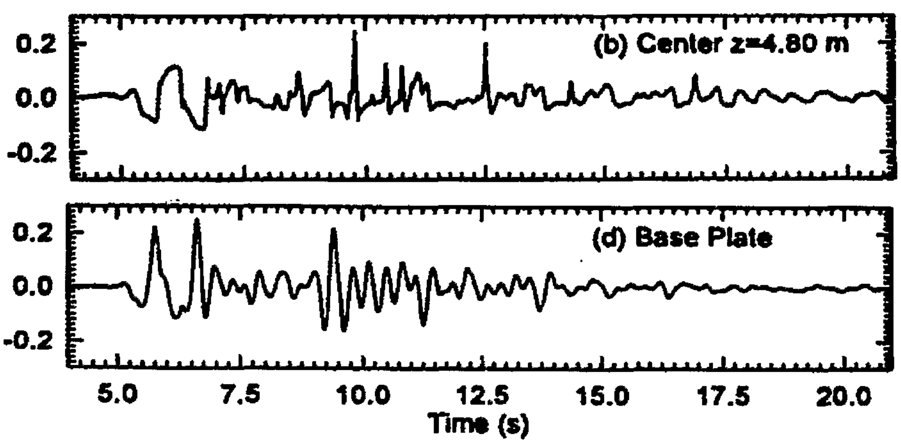

Figure 64a: Recorded lateral accelerations at UCD (Divis et al. 1996).

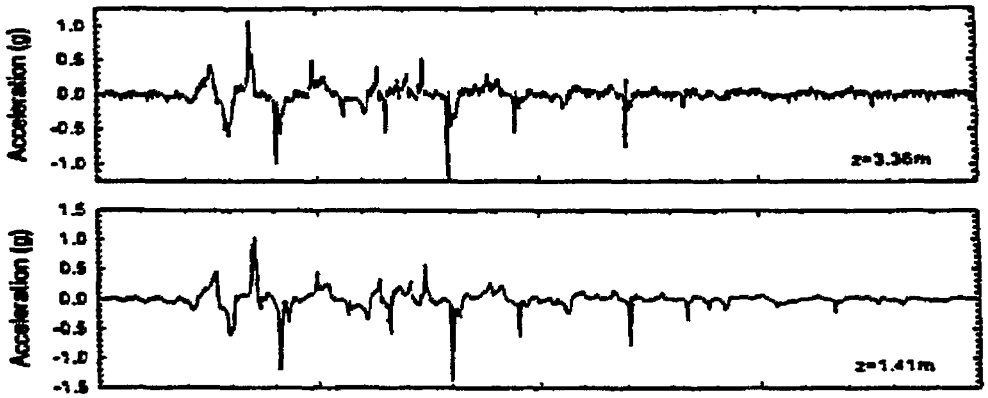

Figure 64b: Recorded lateral accelerations at UCD (Balakrishnan et al. 1997).

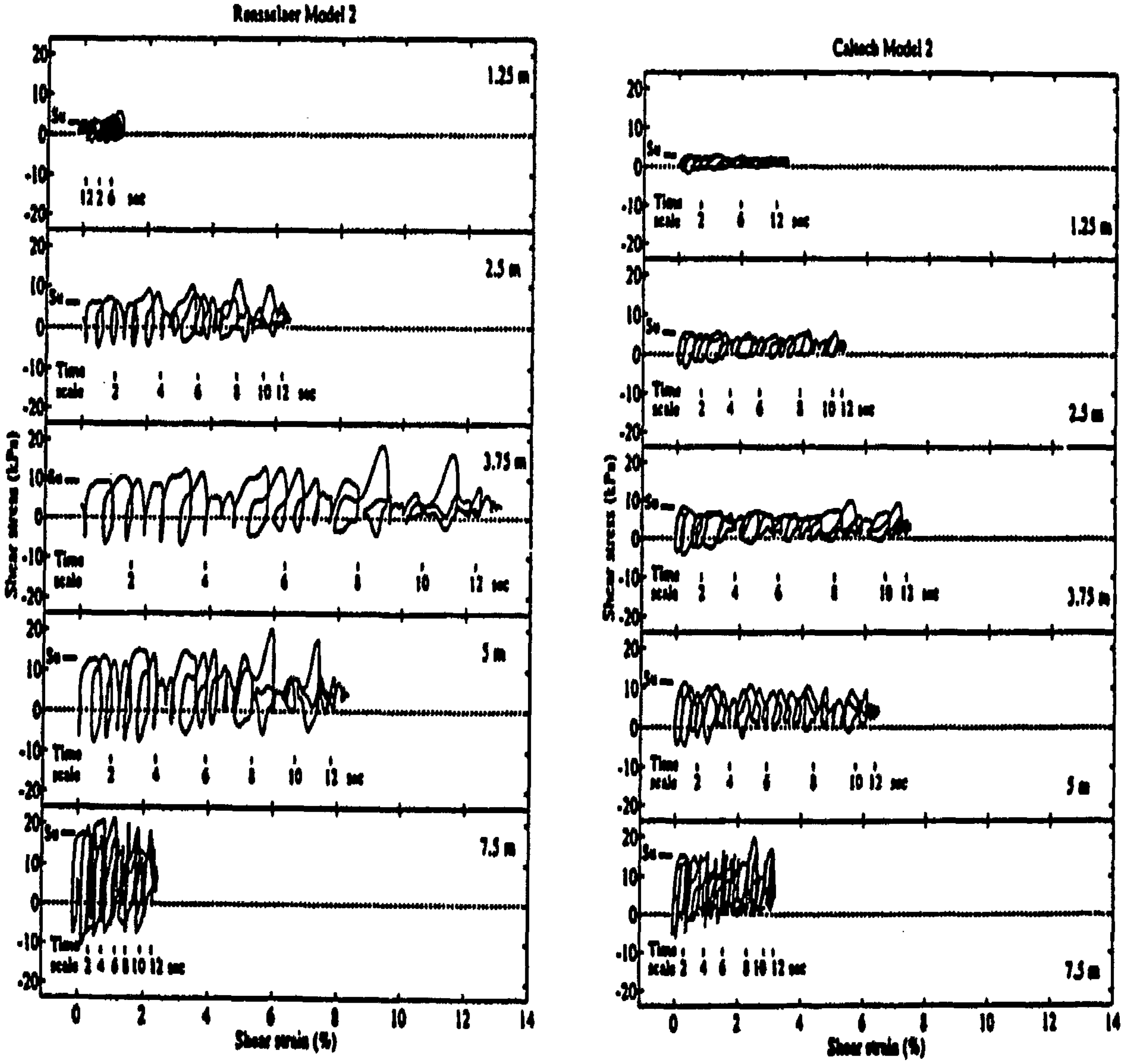

Figure 65: RPI (Dobry and Taboada 1994) and CalTech Model 2 (Scott et al. 1993) shear stress-strain histories (Elgamal et al. 1996b).

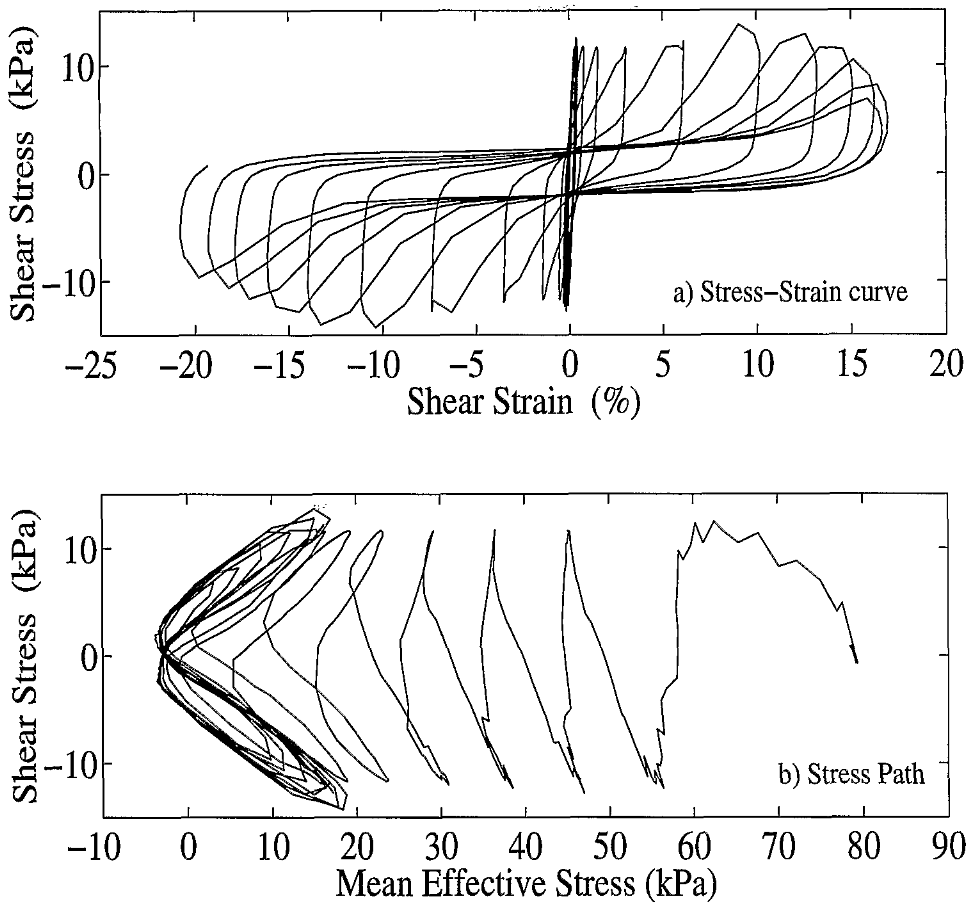

Figure 66: Stress-strain and stress path response for Nevada Sand (Dr=60%) in a stress-controlled, undrained cyclic simple shear test (Arulmoli et al. 1992).

Computational Modeling for Liquefaction Analysis

Available Constitutive Models

A number of computational models have become available recently to simulate the processes associated with sand dilation during liquefaction (Prevost 1985, 1998, Pastor and Zienkiewicz 1986, Matsuoka and Sakakibara (1987), Muraleetharan *et al.* (1988), Nishi and Kanatani 1990, Iai 1991, Anandarajah 1993, Aubry *et al.* 1993, Bardet *et al.* 1993, Byrne and McIntyre 1994, Proubet 1991, Li 1990, 1993, 1997, Kimura *et al.* 1993, Tobita and Yoshida 1995). Many of the essential features of cyclic mobility have been successfully modeled by Iai (1991, Fig. 67), under undrained loading conditions as shown by the computed acceleration during the 1993 Kushiro-oki earthquake (Fig. 60).

At this point, few results have been published to show the performance of most constitutive models for the important case of an acting driving shear stress (e.g., lateral spreading situations, near and below slopes, the retaining wall problem). Such situations demand a high degree of control over accumulated cycle by cycle deformations as depicted in Fig. 68 (Tateishi *et al.* 1995).

Modeling the Phase Transformation Phenomenon

As described earlier, during a shear loading process, a saturated undrained cohesionless soil initially exhibits a tendency for contraction (phase 0-1 in Fig. 69), leading to development of excess pore-pressure and reduction in effective confinement (Lambe and Whitman 1969). As the shear strain increases and the shear stress approaches the failure envelope (or more precisely the so-called phase transformation (PT) envelope, Ishihara 1985, 1996, Vaid and Thomas 1995, Vaid and Sivathayalan 1999, Iai 1991, 1998, Dobry and Abdoun 1998, Kramer and Arduino 1999, Fig. 69), the contractive tendency changes to a dilative tendency that increases effective confinement (Vaid and Thomas1995, Vaid and Sivathayalan 1999) and allows the soil to resist increased levels of shear stress (by moving upwards along the failure envelope, e.g., phase 2-3 in Fig. 69). For the purpose of liquefaction-induced shear deformations, medium-dense clean granular soils are found to exhibit this type of response (Elgamal *et al.* 1998). During a dilative phase (phase 2-3 in Fig. 69), the increased confinement may generate significant shear stiffness and strength in the soil, which progressively prevents further shear deformation.

Dilation can result in significant increases in shear stress and mean effective confining stress (Fig. 69). This increase will be limited by (Casagrande 1936, 1975):

(1) Fluid Cavitation: If soil response is essentially undrained (fluid migration is relatively slow), the tendency for dilation can eventually drop pore-pressure to the minimum value of −1.0 atmospheric pressure (i.e., cavitation). Cavitation will prevent the effective confining pressure from further increase (Iai 1998).

(2) Critical void-ratio or constant volume soil response: If the soil is partially or fully drained (relatively rapid flow of pore-fluid), dilation-induced expansion of the soil skeleton will occur. To this end, the soil will eventually reach a critical void-ratio or "constant volume state", whereupon further shear deformation continues to develop without additional volume change. At this state, effective confinement will remain constant (due to shear loading).

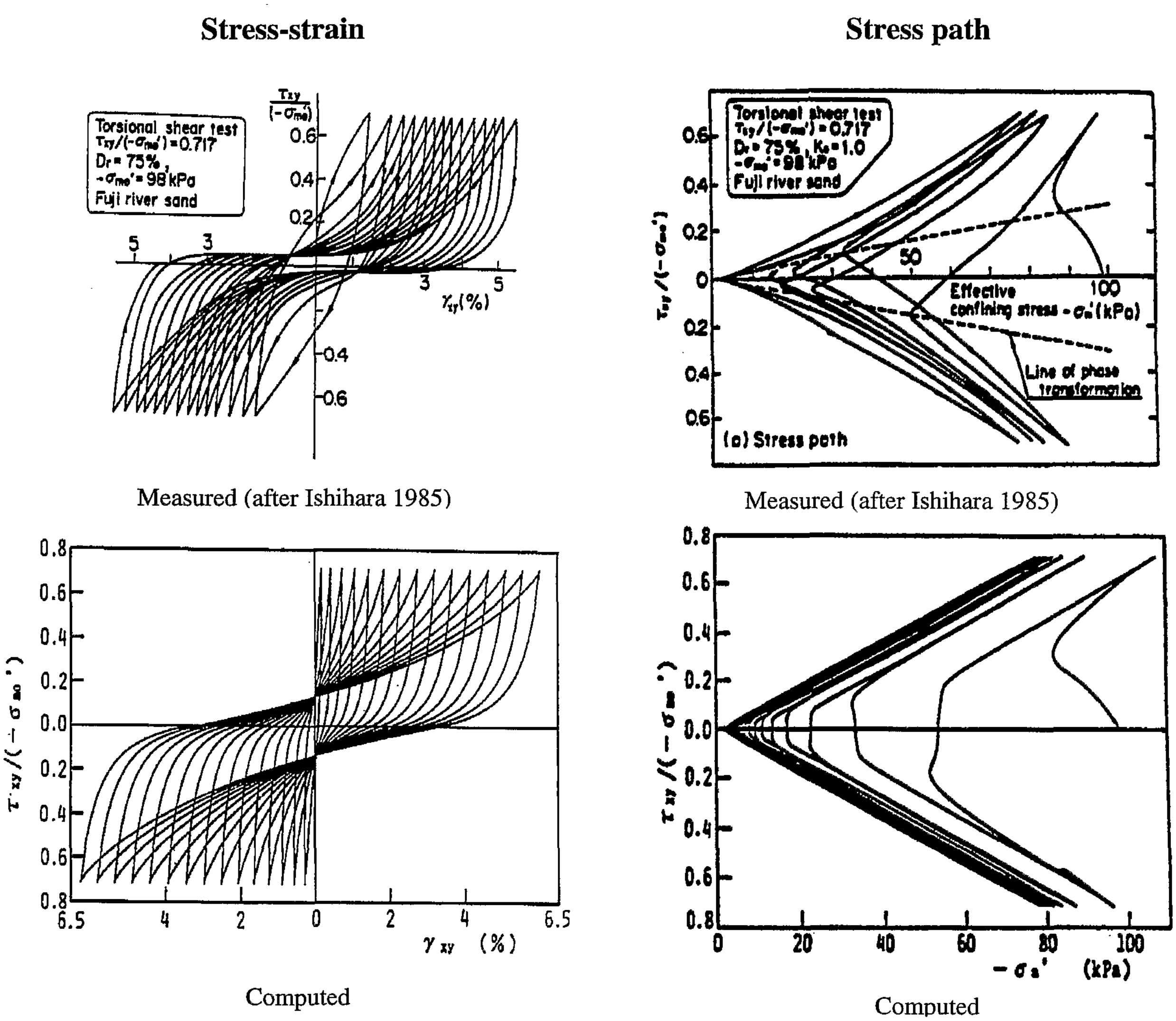

Figure 67: Measured and numerically simulated shear behavior of Fuji River Sand (Ishihara 1985, Iai 1991).

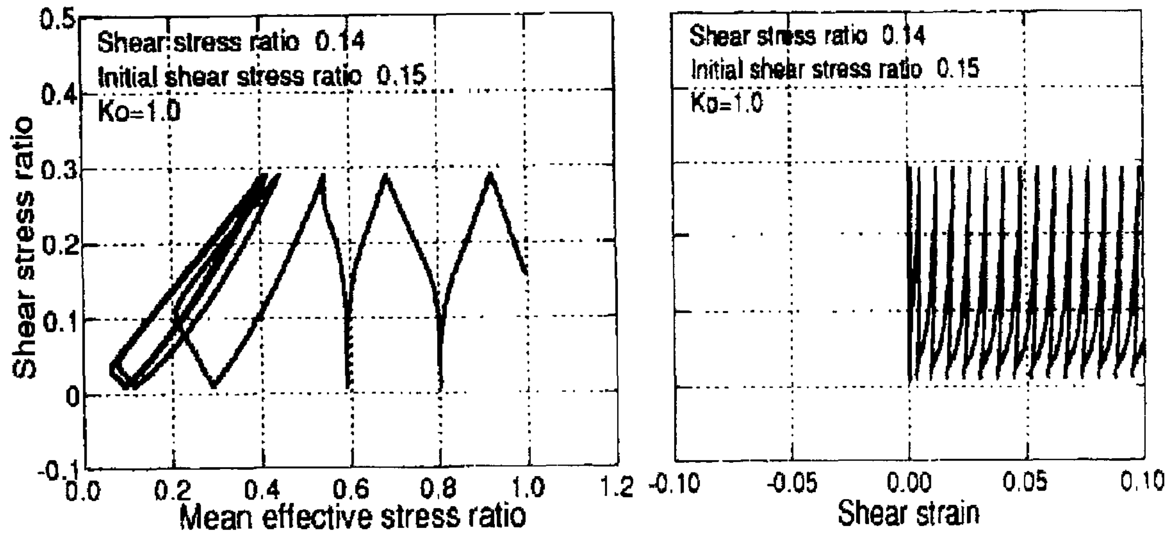

Figure. 68: Computed undrained torsional shear test response (Tateishi et al. 1995).

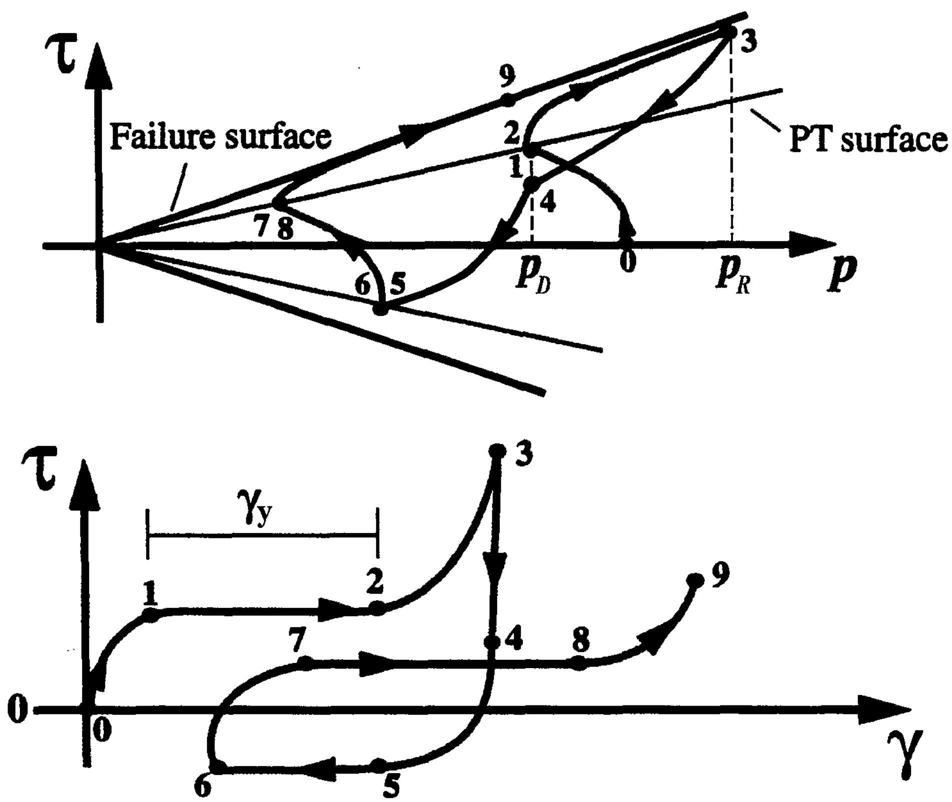

Figure 69: Schematic of constitutive model response showing the octahedral stress τ, the effective confinement p, and the octahedral strain γ relationship (after Parra 1996).

UCSD Liquefaction Model

A liquefaction soil constitutive model has been developed recently (Parra 1996, Yang 2000). In this model, emphasis is placed on controlling the magnitude of cycle-by-cycle permanent shear strain accumulation in clean medium-dense sands (Parra 1996, Yang 2000). Specifically, the experimentally observed accumulation of permanent shear strain (e.g., Arulmoli *et al.*

1992, Fig. 66) was modeled by using strain-space parameters (Yang 2000), within a multi-yield surface stress-space model (Prevost 1985). Furthermore, appropriate loading-unloading flow rules were devised to reproduce the observed strong dilation tendency (Arulmoli *et al.* 1992, Fig. 66), and resulting increase in cyclic shear stiffness and strength. The main components of this model are summarized below.

Yield function

Following the classical plasticity convention (Hill 1950), it is assumed that material elasticity is linear and isotropic, and that nonlinearity and anisotropy result from plasticity. The selected yield function (Prevost 1985, Lacy 1986) forms a conical surface in stress space with its apex at p_0 along the hydrostatic axis (Fig. 70). In the context of multi-yield-surface plasticity (Iwan 1967, Mroz 1967, Prevost 1985), a number of similar yield surfaces with the common apex p_0 and different sizes form the hardening zone (Fig. 70). The outmost surface is designated as the failure surface. Each surface is associated with a constant stiffness (elasto-plastic modulus), and the stiffness value typically decreases with the surface size (Fig. 71).

Hardening rule

A purely deviatoric kinematic hardening rule (Prevost 1985) is employed to account for the Bauschinger effect exhibited by soil under cyclic loading. All yield surfaces but the outermost may translate in stress space (Prevost 1985, Parra 1996, Yang 2000).

When subjected to a drained monotonic shear loading, this hardening rule generates a piecewise-linear, gradually softening shear stress-strain curve (Fig. 71), the so-called back-bone curve (Kramer 1996). Therefore, the elasto-plastic moduli associated with the yield surfaces can be calibrated by matching a computed back-bone curve to that from experimental data. Furthermore, when subjected to a drained cyclic shear loading, this hardening rule generates a piecewise-linear shear stress-strain loop with hysteretic damping.

Flow rule

During shear loading, the soil contractive/dilative behavior is handled by a non-associative flow rule (Parra 1996, Yang 2000) so as to achieve appropriate interaction between shear and volumetric response. In particular, nonassociativity is restricted to the volumetric component P'' of the plastic flow tensor (outer normal to the plastic potential surface in stress-space). Therefore, depending on the relative location of the stress state (Fig. 69) with respect to the *phase transformation* (PT) surface, different expressions for P'' were specified for (Parra 1996):

1) The contractive phase, when the stress-state lies inside the PT surface (Fig. 69, phase 0-1),
2) The dilative phase during loading, if the stress-state lies outside the PT surface (Fig. 69, phase 2-3), and
3) The contractive phase during unloading, with the stress-state starting outside the PT surface (Fig. 69, phase 3-4).

At low effective confining pressure, when the stress state reaches the PT surface while loading, permanent shear strain may accumulate rapidly with essentially no change in shear stress (Fig. 69, phase 1-2). This is achieved by activating a *perfectly plastic zone* (PPZ, Fig. 69, phase 1-2) before the initiation of dilation outside the PT surface (Fig. 69, phase 2-3). The PPZ is defined in deviatoric strain space as a circular, initially isotropic surface (Yang *et al.* 2000). Depending on the current strain state and plastic loading history, the PPZ may enlarge and/or translate in deviatoric strain space to model the accumulation of permanent shear deformations (Yang 2000).

Model Calibration

The developed model has been extensively calibrated for No. 120 Nevada sand at a relative density Dr of about 40% (Parra 1996, Yang 2000). The calibration procedure for medium Nevada sand (Dr=40%) was carried out in the following stages. First, the data of a monotonic Consolidated Isotropically Drained Compression triaxial test (Arulmoli *et al.* 1992) was employed to define elastoplastic moduli and sizes of the multi-yield surfaces. Next, the data from a monotonic Consolidated Isotropically Undrained Compression triaxial test (Arulmoli *et al.* 1992) was used to define constitutive model parameters that control contraction and dilation behavior. Thereafter, the remaining model parameters (especially the parameters that control the extent of cyclic accumulation of liquefaction-induced large yield strain) were calibrated based on matching recorded responses from a Consolidated Anisotropically Undrained Cyclic loading test (Arulmoli *et al.* 1992) and two (Taboada and Dobry 1993, Dobry and Taboada 1994) dynamic centrifuge tests (dealing with liquefied site response and lateral spreading).

Model Performance

Figures 72 and 73 illustrate the mechanism of model response. These figures depict a simulation of a biased simple shear stress - strain history. A static driving "locked-in" deviatoric stress was simulated by applying load cycles in the range of 0.0 kPa to 60 kPa (Figure 72). Under this loading history, gradual pore pressure buildup and liquefaction occurs (i.e., effective confinement approaches zero, Figure 73). During liquefaction, the model reproduces a stable cycle-by-cycle accumulation of shear deformation. For engineering applications, three performance scenarios were selected (Elgamal *et al.* 1999) to represent clean medium, medium-dense and dense sand (or non-plastic silt) situations (relative density in the range of about 40% to 90%). In Figure 72, maximum accumulated cycle-by-cycle shear deformations are about 1.3% (medium), 0.5% (medium-dense) and 0.3% (dense).

The medium sand response was calibrated according to the procedure described above. At this point, the deformation characteristics for the medium-dense and dense sand situations are based on engineering judgment (motivated by the literature review in Elgamal *et al.* (1998). Further data is needed to refine the estimates of the proposed model (Figs. 72 and 73), particularly for the medium-dense and dense sand situations.

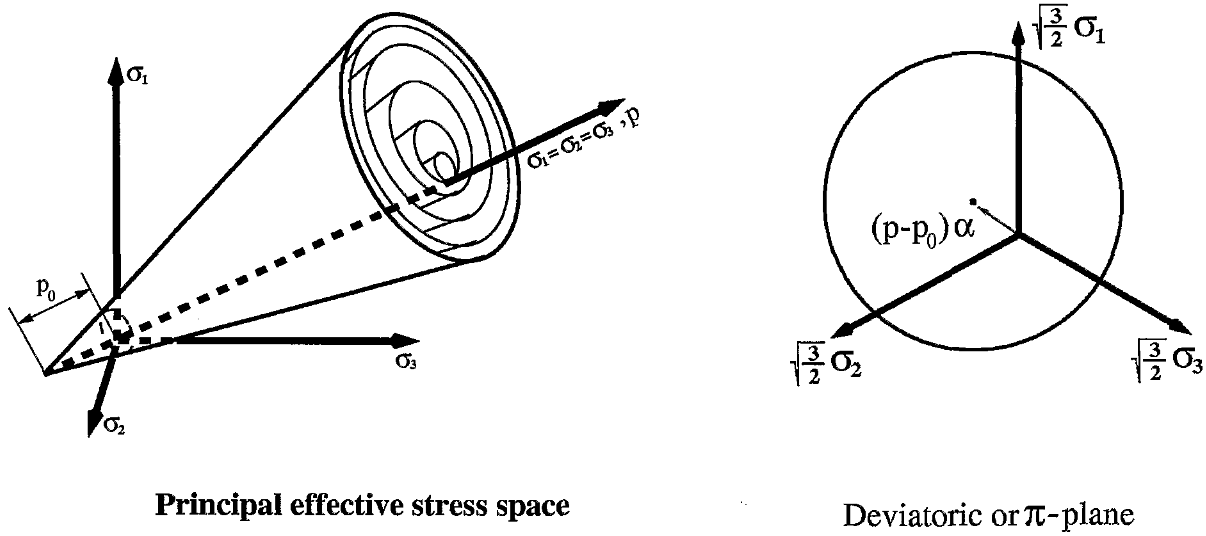

Figure 70: Conical yield surface in principal stress space and deviatoric plan (after Prevost 1985, Lacy 1986, Parra 1996, and Yang 2000).

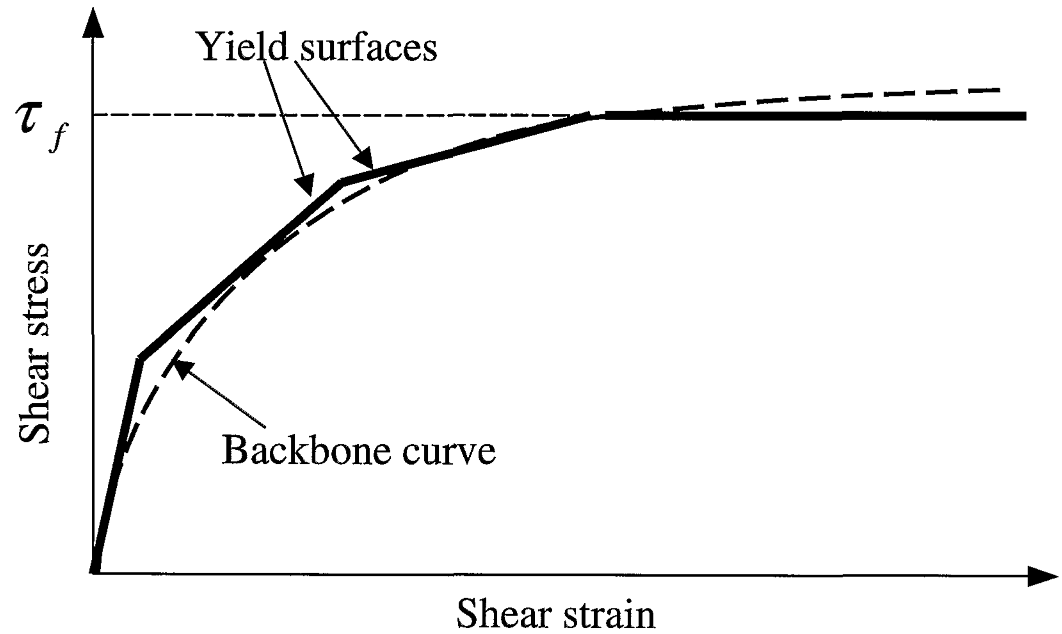

Figure 71: Hyperbolic representation of soil nonlinear shear stress-strain response.

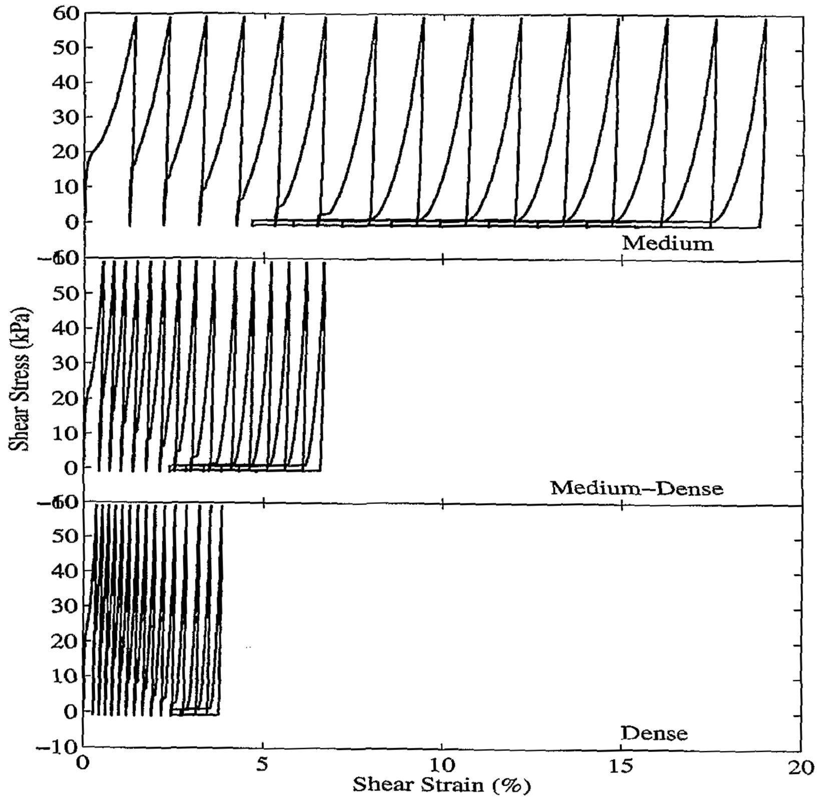

Figure 72: Simulation of undrained biased cyclic simple shear tests (Elgamal et al. 1999, Yang et al. 1999).

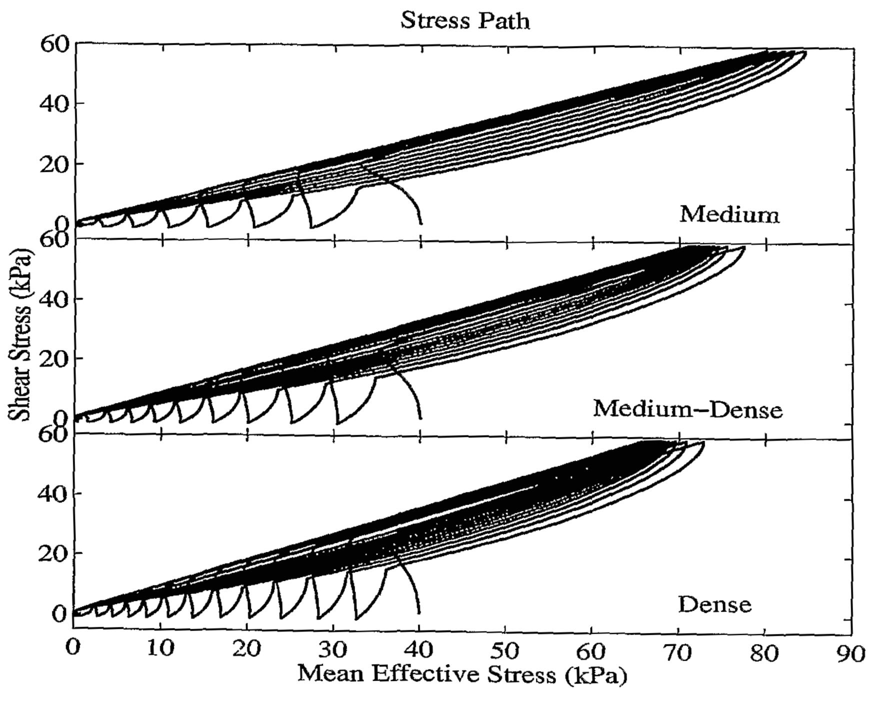

Figure. 73: Computed stress path during undrained biased cyclic simple shear (Elgamal et al. 1999, Yang et al. 1999).

Website for Site Amplification/Liquefaction

Introduction

A large number of computational programs have been and continue to be developed for assessing seismic ground response and liquefaction effects (e.g., DYNAFLOW (Prevost 1998), DYSAC2 (Muraleetharan *et al.* 1988), and other notable codes (see Arulanandan and Scott 1993, 1994). Ease of use of such programs is among the most important concerns. One efficient solution is being increasingly facilitated by the Internet in the form of an *interactive web page*. An interactive web page for a computer code CYCLIC 1D (http://cyclic.ucsd.edu) allows remote users via a web browser to select the desired model parameters and excitation signal, run the computational code CYCLIC, and view/retrieve the computation results. Thus, regardless of the specifics of a particular computational program, all interested users can gain access around the clock.

Website

The website (http://cyclic.ucsd.edu) allows remote users to operate a nonlinear finite element program CYCLIC that is specially developed for numerical simulation of earthquake ground response and liquefaction effects. CYCLIC is a two-phase (solid and fluid) fully coupled, two-dimensional Finite Element program. Fig. 74 depicts a typical element employed in CYCLIC. This program has been evolving over the past 10 years with extensive calibration through numerous sources including field downhole array records, laboratory tests, and centrifuge experiments (some of which are mentioned above).

Currently Available Options

(1) Soil profile height (any value up to100 m).
(2) Number of elements (10 - 100 elements).
(3) Depth of water table.
(4) Inclination angle of the soil profile (any value from 0.0 to 10.0 degrees can be chosen, with 0.0 degree representing level ground). This option allow for mild infinite slope simulations.
(5) Bedrock stiffness. If "Rigid", the input motion is treated as a total motion; otherwise, the input motion is handled as an incident motion.
(6) There are 15 materials available (3 cohesive and 12 cohesionless soils), covering a wide range of densities and permeabilities. A different material may be assigned to individual elements.
(7) Base excitation can be chosen from an input motion library.
(8) The amplitude of input motion can be scaled by a factor ranging from 0.01 to 1.0.

Sample Web-Site Results

Figures 75 - 77 show the numerical simulation results of a 10m saturated medium sand stratum with an inclination angle of 6.0 degrees, subjected to 10 cycles of 0.2g sinusoidal base excitation. The results (Figs. 76 and 77) show the involved cyclic-mobility lateral spreading response characteristics.

In Figure 76, acceleration near ground surface is seen to display asymmetric response with spikes that are directly related to the instants of excess pore-pressure drop during liquefaction. Associated lateral spreading is also seen to accumulate on a cycle-by-cycle basis. In Figure 77, the cyclic mobility characteristics are displayed in terms of: i) high stiffness and strength in the shear stress-strain response during liquefaction, and ii) phases of increase in shear strength (and increase in effective stress) as the stress path travels above the phase transformation line during cyclic loading.

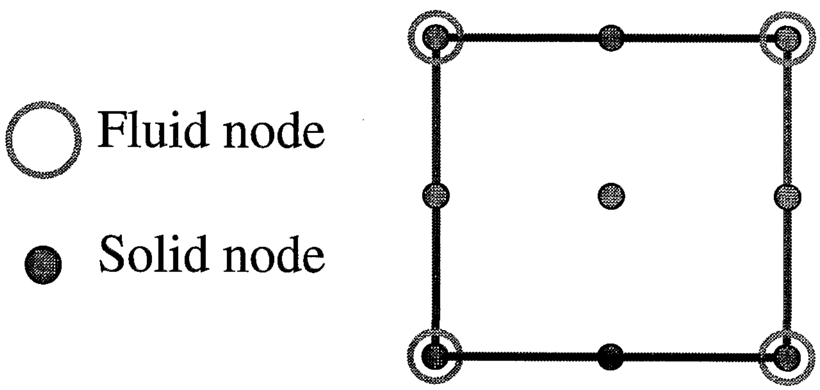

Figure 74: Typical 9-4-node element employed in CYCLIC (effective stress u-p coupled formulation).

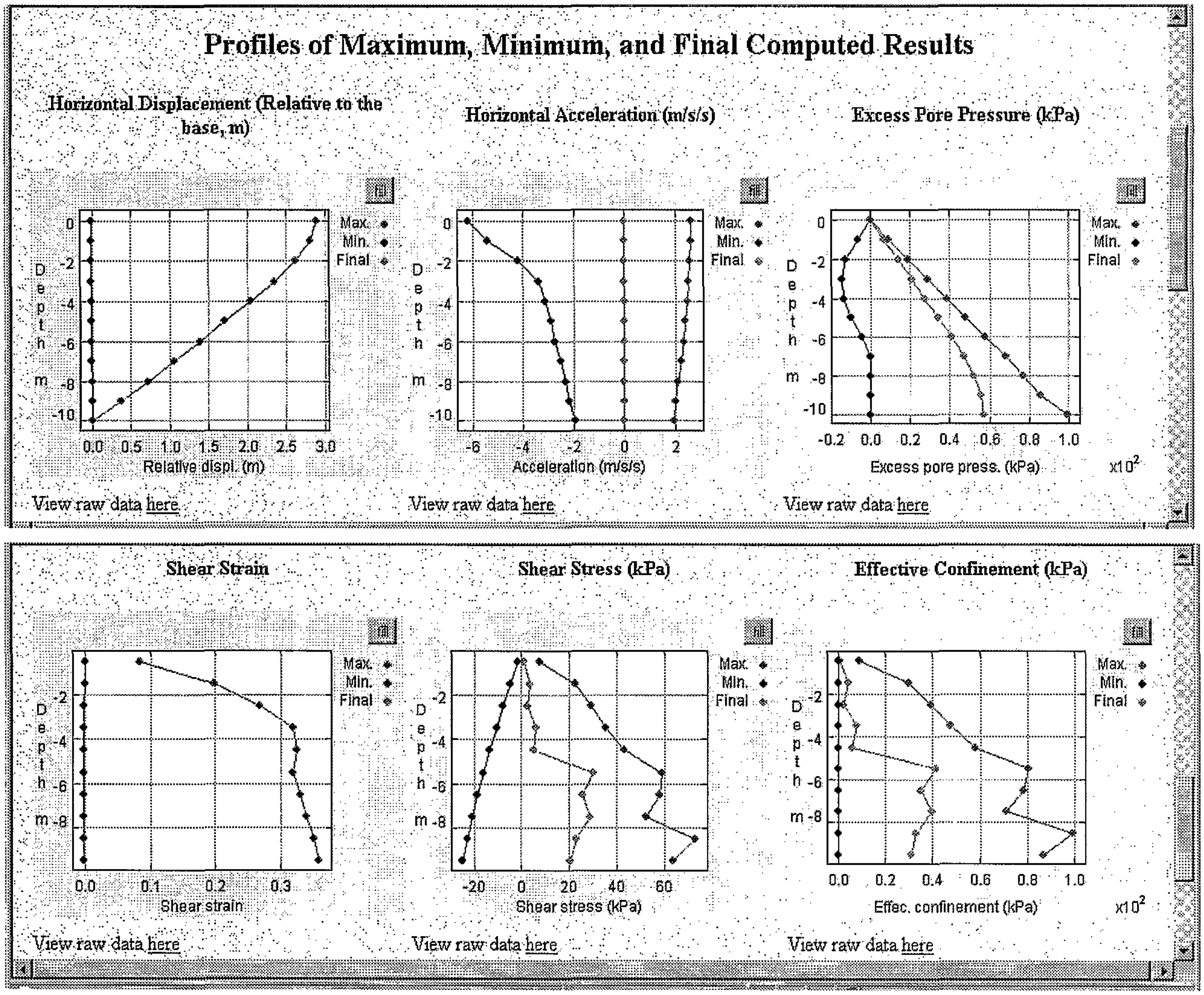

Figure 75 Profiles of maximum, minimum, and final computed results (http://cyclic.ucsd.edu).

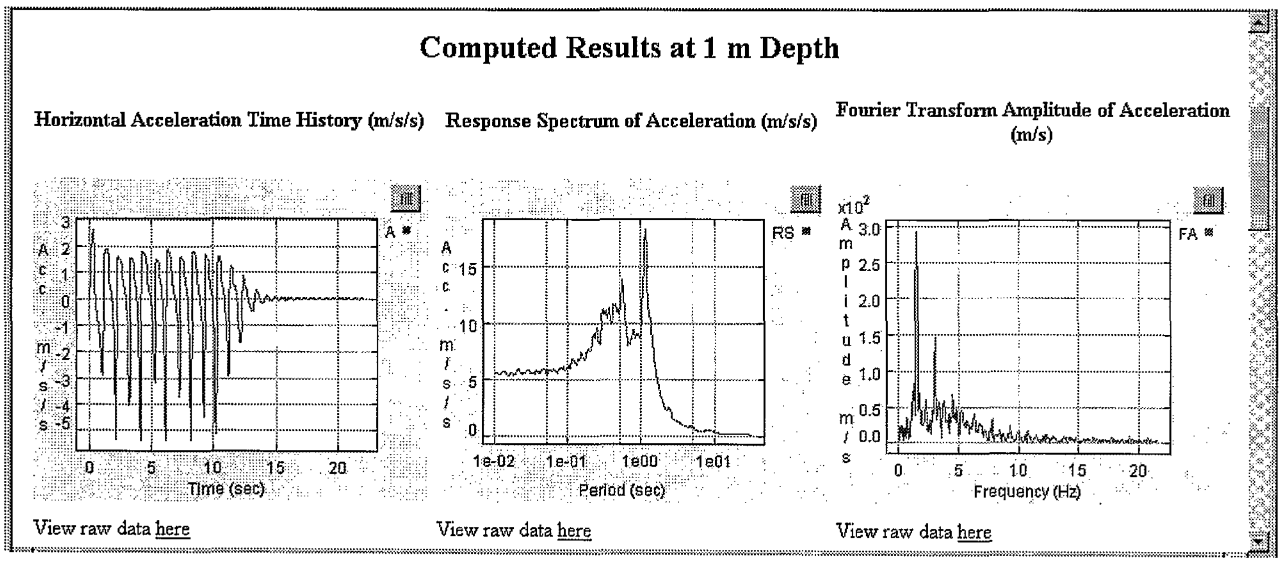

Figure 76a: Computed acceleration, lateral displacement and excess pore-pressure histories at 1m depth (http://cyclic.ucsd.edu).

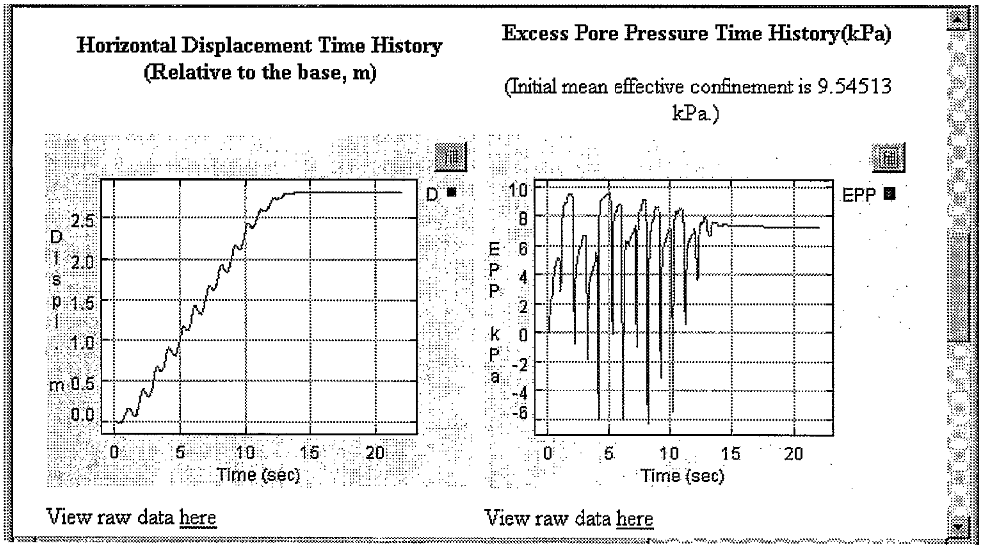

Figure 76b: Computed acceleration, lateral displacement and excess pore-pressure histories at 1m depth (http://cyclic.ucsd.edu).

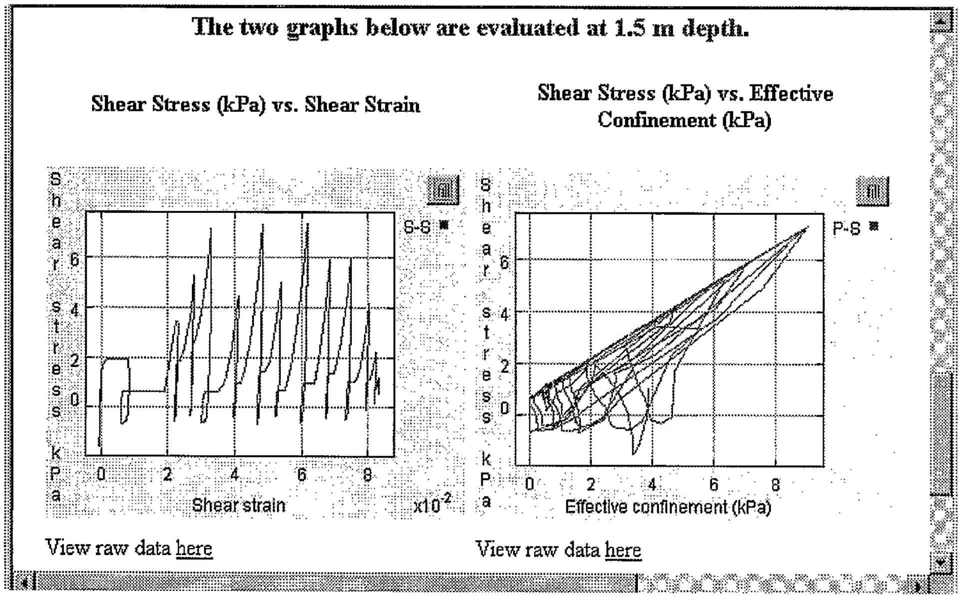

Figure 77: Computed shear stress-strain and stress path at 1.5m depth (http://cyclic.ucsd.edu).

SUMMARY AND DISCUSSION OF FUTURE NEEDS AND APPLICATIONS

In the earlier sections, downhole array data have shed light on the following main site response characteristics:

1. Definition of damping ratio ranges that result in satisfactory computational response of lateral and vertical 1D seismic site response.
2. The possible presence of azimuthal site anisotropy, in the form of different stiffness characteristics in different horizontal directions (at Hualien, Taiwan stiff soil site).
3. The significance of cyclic mobility in liquefaction response with possible consequence such as:
   - Appearance of high amplitude acceleration spikes in the recorded surface motions.
   - Possible asymmetry in recorded accelerations with the spikes appearing in a direction that corresponds to evolution of cyclic lateral deformation (down-slope cyclic deformation).
   - Ability of soil (clean sands and non-plastic silts) to restrain the magnitude of shear deformation as a consequence of this phenomenon (i.e., undergo a number of limited deformation cycles before possible evolution of a flow-failure).

Much remains to be explored based on downhole array deployments. The involved high expenses of installation and maintenance are still a major challenge. In this regard, it is hoped that advances in sensor technology will eventually result in economical solutions and allow for wide deployment.

Additional issues of current relevance to the quality and value of recorded motions include:

1. Development of standards for installation techniques of downhole instruments into the ground (nature of connection between instruments and borehole casing, and construction procedures of boreholes in different soils).
2. Accuracy in definition of sensor depth and accounting for sensor package size (some 3-accelerometer downhole units are of the order of 0.5m in length).
3. Relative orientation between downhole sensor instruments. This problem is known as azimuthal error (e.g., a downhole sensor assumed to be aligned in the NS-EW directions is actually significantly off).
4. Accuracy in deployment in terms of maintaining correct polarity for all recorded data (e.g., positive amplitudes are North and negative are South for all sensors).
5. Need for more closely-spaced downhole instruments. In many cases today, instruments are sparse covering depths of 100m or more with 2 or 3 sensor locations. This lack of sufficient instrumentation is especially detrimental when the soil profile is of significant variability.
6. Increased accuracy by employing a sufficiently small digitization time step (e.g., 0.005 second or smaller). In addition, accuracy in time synchronization between all instruments in the array is of utmost importance. This accuracy allows for tracking propagating waves, among other time domain analysis applications.
7. Need for more accuracy in measuring seismic ground displacement. Currently, integration of recorded accelerations necessitates the removal of useful long-period signals. This has always been a tough problem to overcome and Geographical Positioning System (GPS) or similar techniques might eventually offer a viable solution.
8. In situations related to liquefaction, additional concerns related to occurrence of relative motion between sensor and surrounding soil (both vertically and laterally) and proper saturation of piezometers must be addressed carefully. When excess pore-pressure remains after dynamic excitation, piezometer data should be collected (at a slow rate) to document the important dissipation phase (which might be accompanied by significant liquefaction-induced deformations).
9. Finally, the data-processing phase is currently a major chore. Much effort is currently expended in attempts to acquire available recorded data. Often, many questions arise thereafter and must be answered before the data is ready for use. Meticulous book-keeping is needed in handling the data files, and new versions of the data files must be prepared for use in analysis packages (e.g., MATLAB) or home-made codes. Simplification of the above process is of utmost importance. In this regard, a web-based environment equipped with data processing and visualization tools can be of much value. In this environment, duplication of work between researchers can be minimized, and all users can consistently and conveniently have access to the same data. This extra investment of resources is well worth it.

Looking into the future, synchronized and more elaborate 1D, 2D and 3D downhole arrays (e.g., the Chiba Array in Japan, Katayama 1990) will eventually contribute much increased knowledge about:

1. 3D wave propagation mechanisms and analyses related to surface and body waves.
2. Increased understanding of lateral and vertical vibration including considerations related to inhomogenity, anisotropy and topography.
3. Major advances in soil-structure interaction when a super-structure (including foundation) and underlying ground are instrumented as one integrated entity. Examples of ongoing applications currently include bridges, buildings and dams. Deployment for other critical facilities (e.g., Power Plants, Ports and Harbor facilities, and water-front structures) will be of great value.

Advances in technology may also allow speculation about:

1. Massive (compared to the situation today) deployment of downhole sensors allowing fine resolution for highly stratified or inhomogeneous sites and for assessment of liquefaction countermeasure techniques.
2. Real-time or near real-time data availability and automated levels of data processing for early warning, decision-making purposes, and emergency response applications.
3. Possibility of more global synchronization of sensor data which may become a basis for larger scale studies such as seismic response of basins underlying a city, and other similar applications.

Finally, many downhole arrays are active today and are ready to record earthquake excitations. In most cases, strong shaking of engineering significance is yet to be recorded. In the heavily instrumented areas, our database will increase substantially with each new earthquake. In the meantime, efforts are underway (e.g., at the University of Texas, Prof. Ken Stokoe) to develop in-situ dynamic excitation sources that can be used to trigger downhole installations and generate additional (man-made) tailored data sets (to augment our currently available database).

ACKNOWLEDGMENTS

The authors are grateful to Drs. R. J. Archuleta (UCSB), L. Baise (Tufts Univ.), I. Beresnev (Iowa State Univ.), J. Berrill (U. of Canterbury, New Zealand), R.D. Borcherdt (USGS), R.I. Borja (Stanford), C.Y. Chang (Geomatrix Consultants), C. H. Chen (National Taiwan Univ.), R. Davis (U. of Canterbury, New Zealand), S.D. Glaser (UC Berkeley), V. Grazier (CSMIP), H. Graves (NRC), F. Heuze (LLNL), T. Kokusho (Chuo Univ., Japan), B. L. Kutter (UC Davis), C. Miller (City Univ. of New York), A. Shakal (CSMIP), C. Roblee (Caltrans), T. Shantz (Caltrans), V. Taboada (UNAM, Mexico), D. Wilson (UC Davis), and M. Zeghal (RPI). Their contributions were a major boost to our efforts (generously providing numerous references and necessary data sets). These contributions are sincerely appreciated. The authors are also grateful for the research funding provided by the Pacific Earthquake Engineering Research Center (PEER), under the Earthquake Engineering Research Centers Program of the National Science Foundation (Award Number EEC-9701568), and by the United States Geological Survey (grant No. 99HQGR0020), with Dr. John D. Unger as Program Manager.

LIST OF REFERENCES

Abdel-Ghaffar, A.M. and Scott, R.F. (1978), Investigation of the Dynamic Characteristics of an Earth Dam, *Report No. EERL 78-02*, Earthquake Engineering Laboratory, California Institute of Technology, Pasadena, California.

Abdel-Ghaffar, A.M. and Scott, R.F. (1979), Shear Moduli and Damping Factors of Earth Dam, *Journal of the Geotechnical Engineering*, ASCE Vol. 105, No. GT12.

Abdoun, T. (1997), *Modeling of Seismically Induced Lateral Spreading of Multi-Layered Soil and Its Effect on Pile Foundations*, Ph.D. Thesis, Department of Civil Engineering, Rensselaer Polytechnic Institute, Troy, NY.

Abercrombie, R.E. (1997), Near-Surface Attenuation and Site Effects From Comparison of Surface and Deep Borehole Recordings, *Bulletin of the Seismological Society of America*, Vol. 87, pp.731-744.

Adalier, K. (1996), *Mitigation of Earthquake Induced Liquefaction Hazards*, Ph.D. Thesis, Department of Civil Engineering, Rensselaer Polytechnic Institute, Troy, NY.

Aguirre, J. (1996), Non-Linear Site Effects at Port Island Vertical Array During 1995 Hyogoken-Nambu Earthquake, *Proceedings of the Eleventh World Conference on Earthquake Engineering*, Pergamon, Elsevier Science Ltd., Oxford, England, Disc 2, Paper No. 725.

Aguirre, J. and Irikura, K. (1995), Preliminary Analysis of Non-Linear Site Effects at Port Island Vertical Array Station During the 1995 Hyogoken-Nambu Earthquake, *Journal of Natural Disaster Science*, Vol. 16, No. 2, pp. 49-58.

Aguirre, J. and Irikura, K. (1997), Nonlinearity, Liquefaction, and Velocity Variation of Soft Soil Layers in Port Island, Kobe, During the Hyogoken-Nambu Earthquake, *Bulletin of the Seismological Society of America*, Vol. 87, pp. 1244-1258.

Anandarajah, A. (1993), VELACS project: Elasto-Plastic Finite Element Predictions of the Liquefaction Behavior of Centrifuge Models No. 1, 3 and 4a, *Proc. of the Intl. Conference on the Verification of Numerical Procedures for the Analysis of Soil Liquefaction Problems*, Arulanandan, K. and Scott, R. F., Eds. Vol. 1, Davis, CA, pp. 45-66, Balkema.

Ansal, A., Bardet, J.P., Barka, A., Baturay, M.B., Berilgen, M., Bray, J., Cetin, O., Cluff, L., Durgunoglu, T., Erten, D., Erdik, M., Idriss, I.M., Karadayilar, T., Kaya, A., Lettis, W., Olgun, G., Paige, W., Rathje, E., Roblee, C., Stewart, J., and Ural, D. (1999), Initial Geotechnical Observations of the November 12, 1999, Düzce Earthquake, *A report of the Turkey-US geotechnical earthquake engineering reconnaissance team.* Nov. 26.

Ansary, M.A., Yamazaki, F., and Katayama, T. (1995), Analysis of Ground Motions at Kobe Port Island During the 1995 Great Hanshin Earthquake, *Pacific Conference on Earthquake Engineering*, Melbourne, Australia, 20-22 November 1995: Proceedings, Australian Earthquake Engineering Society, Parkville, Victoria, Australia, Vol. 1, pp. 81-90.

Archuleta, R.J., Seale, S.H., Sangas, P.V., Baker, L.M., and Swain, S.T. (1992), Garner Valley Downhole Array of Accelerometers: Instrumentation and Preliminary Data Analysis, *Bulletin of the Seismological Society of America*, Vol. 82, pp. 1592-1621.

Archuleta, R.J., Steidl, J.H., and Tumarkin, A.C. (1996), Garner Valley Downhole Array: A Case Study of Site Effects, *Proceedings of the Eleventh World Conference on Earthquake Engineering*, Pergamon, Elsevier Science Ltd., Oxford, England, Disc 4, Paper No. 2041.

Archuleta, R.J. (1998), Direct Observation of Nonlinearity in Accelerograms, *The Effects of Surface Geology on Seismic Motion: Recent Progress and New Horizon on ESG Study: Proceedings of the Second International Symposium on the Effects of Surface Geology on Seismic Motion*, Yokohama, Japan, 1-3 December, edited by Kojiro Irikura, Kazuyoshi Kudo, Hiroshi Okada, and Tsutomu Sasatani, pp. 787-792.

Archuleta, R.J. and Steidl, J.H. (1998), ESG Studies in the United States: Results from Borehole Arrays, *The Effects of Surface Geology on Seismic Motion: Recent Progress and New Horizon on ESG study: Proceedings of the Second International Symposium on Effects of Surface Geology on Seismic Motion*, Yokohama, Japan, 1-3 December, edited by Kojiro Irikura, Kazuyoshi Kudo, Hiroshi Okada, and Tsutomu Sasatani, Vol. 1, pp. 3-14.

Archuleta, R.J., Steidl, J.H., Tumarkin, A.G., Bonilla, L.F., and Nigbor, R. (1998), Analysis of Downhole and Surface Recordings in the Epicentral Area of the Mw. 5.1 San Juan Bautista Earthquake on 08/12/98, *Amer. Geophy. Union*, Fall Meeting, Published as a supplement to Eos, 79, F577.

Archuleta, R.J., Steidl, J.H., and Bonilla, L.F. (2000a), Engineering Insights From Data Recorded on Vertical Arrays, *Proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 2681.

Archuleta, R.J., Elgamal, A.W., Heuze, F., Lai, T., Lavallee, D., Lawrence, B., Liu, P.C., Matesic, L., Park, S., Riemer, M., Steidl, J., Vucetic, M., Wagoner, J. and Yang, Z. (2000b), Strong Earthquake Motion Estimates for Three Sites on the U.C. Riverside Campus, Lawrence Livermore Nationa Laboratory Report, *UCRL-ID-140522*, California.

Arulanandan, K. and Scott, R.F., Eds. (1993), *Verification of Numerical Procedures for the Analysis of Soil Liquefaction Problems*, Conference Proceedings, Davis, CA, Vol. 1, Balkema.

Arulanandan, K. and Scott, R.F., Eds. (1994), *Verification of Numerical Procedures for the Analysis of Soil Liquefaction Problems*, Conference Proceedings, Davis, CA, Vol. 2, Balkema.

Arulanandan, K., Muraleetharan, K.K., Yogachandran, C., (1997), Seismic Response Of Soil Deposits In San Francisco Marina District, *Journal of Geotechnical and Geoenvironmental Eng.*, ASCE, 123, 10, Oct., pp. 965-974.

Arulmoli, K., Muraleetharan, K.K., Hossain, M.M., and Fruth, L.S. (1992), *VELACS: Verification of Liquefaction Analyses by Centrifuge Studies, Laboratory Testing Program, Soil Data Report*, Report, The Earth Technology Corporation, Project No. 90-0562, Irvine, California.

Aubry, D., Benzenati, I. and Modaressi, A. (1993), Numerical Predictions for Model No. 1, *Proc. of the Intl. Conference on the Verification of Numerical Procedures for the Analysis of Soil Liquefaction Problems*, Arulanandan, K. and Scott, R. F., Eds. Vol. 1, Davis, CA, pp. 45-66, Balkema.

Baise, L.G. (2000), *Investigations in Earthquake Site Response Using System Identification and ARMA Modeling*, PhD. Dissertation, University of California, Berkeley.

Baise, L.G. and Glaser, S.D. (2000a), Consistency of Ground-Motion Estimates Made Using System Identification, *Bulletin of the Seismological Society of America*, Vol. 90, No. 4, Aug., pp. 993-1009.

Baise, L.G. and Glaser, S.D. (2000b), Consistency of Dynamic Site Response at Port Island, *Earthquake Engineering and Structural Dynamics*, in press.

Baise, L.G. and Glaser, S.D. (2000c), Fundamental Aspects of Site Response Determined From Inversion of Vertical Array Data, *Proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 0572.

Balakrishnan, A., Kutter, B.L. and Idriss, I.M. (1997), Liquefaction Remediation at Bridge Sites-Centrifuge Data Report For BAM05, *Report No. UCD/CGMDR-97/10*, Center for Geotechnical Modeling, Department of Civil and Environmental Engrg., University of California, Davis, May.

Balakrishnan, A. and Kutter, B.L. (1999), Settlement, Sliding, and Liquefaction Remediation of Layered Soil, ASCE *Journal of Geotech and Geoenvir. Engrg.*, Vol. 125, No. 11, November, pp. 968-978.

Bard, Y. (1974), *Nonlinear parameter estimation*, Academic Press, Now York.

Bardet, J.P., Huang, Q. and Chi, S.W. (1993), Numerical Prediction for Model No. 1, *Proc. of the Intl. Conference on the Verification of Numerical Procedures for the Analysis of Soil Liquefaction Problems*, Arulanandan, K. and Scott, R. F., Eds. Vol. 1, Davis, CA, pp. 67-86, Balkema.

Bardet, J.P., Oka, F., Sugito, M., and Yashima, A. (1995), *The Great Hanshin Earthquake Disaster*, Preliminary Investigation Report, Dept. of Civil Engrg., University of Southern California, Los Angeles, CA.

Benoit, J. and de Alba, eds. (1988), Designated Sites for Geotechnical Experimentation in the United States, *Proc. of Workshop at the University of New Hampshire.*

Bartlett, S.F. and Youd, T.L. (1995), Empirical Prediction of Liquefaction-Induced Lateral Spread, *Journal of Geotechnical Engineering*, Vol. 121, No. 4, pp. 316-329.

Beresnev, I.A. and Wen, K.L. (1995), P Wave Amplification by Near Surface Deposits at Different Excitation Levels, *Bulletin of the Seismological Society of America*, Vol. 85, Oct. pp. 1490-1494.

Beresnev, I.A. and Wen, K.L. (1996a), The Accuracy of Soil Response Estimates Using Soil-to-Rock Spectral Ratios, *Bulletin of the Seismological Society of America*, Vol. 86, pp. 519-523.

Beresnev, I.A. and Wen, K.L. (1996b), Nonlinear Soil Response – a Reality? *Bulletin of the Seismological Society of America*, Vol. 86, pp. 1964-1978.

Borcherdt, R.D., Liu, H.P., Warrick, R.E., Westerlund, R.E., and Gibbs, J.F. (1999), Integrated Surface and Borehole Strong-Motion, Soil-Response Arrays in San Francisco, California, *Technical Memorandum of PWRI 3653, Proceedings of the 31st Joint Meeting of U.S.-Japan Panel on Wind and Seismic Effects*, UJNR, Japan Public Works Research Institute, pp. 179-190.

Borcherdt, R.D., Liu, H.P., Westerlund, R.E., Dietel, C., Glassmoyer, G., Gibbs, J.F. and Warrick, R.E. (2000), Integrated Surface and Borehole Strong-Motion, Soil Response Arrays in San Francisco, California, *SCEC/ROSRINE Borehole Data Utilization Workshop*, Nov. 16, Palm Springs, California, USA.

Borja, R.I., Chao, H.Y., Montáns, F.J., and Lin, C.H. (1999a), SSI Effects on Ground Motion at Lotung LSST Site, *Journal of Geotechnical and Geoenvironmental Engineering,* ASCE, Vol. 125, pp. 760-770.

Borja, R.I., Chao, H.Y., Montáns, F.J., and Lin, C.H. (1999b), Nonlinear Ground Response at Lotung LSST Site, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 125, No. 3, Mar., pp. 187-197.

Borja, R.I., Lin, C.H., Sama, K.M. and Masada, G.M. (2000), Modeling Non-Linear Ground Response of Non-Liquefiable Soils, *Earthquake Engineering and Structural Dynamics*, Vol. 29, No. 1, Jan., pp. 63-83.

Boulanger, R.W. and Seed, R.B. (1995), Liquefaction of Sand Under Bidirectional Monotonic and Cyclic Loading, *Journal of Geotechnical Engineering*, ASCE, Vol. 121, No. 12, Dec., pp. 870-878.

Boulanger, R.W., Curras, C.J., Kutter, B.L., Wilson, D.W., and Abghari A. (1999), Seismic Soil-Pile Structure Interaction Experiments and Analysis, *Journal of Geotechnical and Geoenvironmental Engineering,* ASCE, Vol. 125, No. 9, Sept., pp. 750-759.

Byrne, P.M. and McIntyre, J. (1994), Deformations in Granular Soils due to Cyclic Loading, *Proceedings of Settlement 94*, ASCE Geotechnical Special Publication No. 40, Texas, June, pp. 1864-1896.

Casagrande, A. (1936), Characteristics of cohesionless soils affecting the stability of earth fills, *J. of the Boston Society of Civil Engineers*, January, pp. 13-33.

Casagrande, A. (1975), Liquefaction and Cyclic Deformation of Sands - A critical Review, Proceedings, *5th Pan-American Conference on Soil Mechanics and Foundation Engineering*, Buenos Aires, Argentina, also published as Harvard Soil Mechanics Series No. 88, January 1976, Cambridge, Mass.

Castro, G. (1975), Liquefaction and Cyclic Mobility of Saturated Sands, *Journal of the Geotechnical Engineering Division*, ASCE, 101, GT6, pp. 551-569.

Castro, G and Poulos, S.J. (1977), Factors Affecting Liquefaction and Cyclic Mobility, *Journal of the Geotechnical Engineering Division*, ASCE, Vol. 103, No. GT6, June, pp. 501-516.

Chang, C.Y., Power, M.S., Tang, Y.K., and Mok, C.M. (1989), Evidence of Nonlinear Soil Response During a Moderate Earthquake, *Proceedings of Twelfth International Conference on Soil Mechanics and Foundation Engineering*, Rio de Janeiro, Brazil, August 13-18, Vol. 3, Publ. by A. A. Balkema, Rotterdam, Neth., pp. 1927–1930.

Chang C.Y., Mok, C.M., Power, M.S., Tang, Y.K., Tang, H.T., and Stepp, J.C. (1990), Equivalent Linear Versus Nonlinear Ground Response Analyses at Lotung Seismic Experiment Site, *Proceedings of the Fourth U.S. National Conference on Earthquake Engineering*, Vol. 1, Palm Springs, California, May 20-24.

Chang, C.Y., Mok, C.M., Tang, Y.K., and Tang, H.T. (1994), Analysis of Seismic Vertical Motion Using Lotung Downhole Array Data, *The Fifth U.S. Conference on Earthquake Engineering*, Chicago, Illinois, July 10-14.

Chang, C.Y., Mok, C.M., and Tang, H.T (1996), Inference of Dynamic Shear Modulus from Lotung Downhole Data, *Journal of Geotechnical Engineering*, Vol. 122, Aug., pp. 657-665.

Chen, C.H. and Chen, L.Y. (1989), Analysis for Vertical Velocity of Seismic Waves, *Zhongguo Gongchen Xuekan*, Vol. 12, No. 2, Mar., pp. 165-177.

Chen, C.H. and Chiu, H.J. (1998), Anisotropic Seismic Ground Responses Identified from the Hualien Vertical Array, *International Journal of Soil Dynamics and Earthquake Engineering*, Vol. 17, No. 6, August, pp. 371-395.

Chen, C.H. and Chiu, H.J. (1999), Identification of Shear Wave Velocity from Earthquake Ground Motions, *The Second Int. Conference on Earthquake Geotechnical Engineering*, June 21-25, Lisbon, Portugal, Vol. 1, pp. 205-210.

Ching, J.Y., and Glaser, S.D. (2001), Time Domain Solution of 1-D Shear Wave Propagation in Layered Media, ASCE *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 127, No. 1, Jan., pp. 36-47.

Chiu, H.C., Huang, H.C, Leu, C.L. and Ni, S.D. (1994), Application of Polarization Analysis in Correcting the Orientation Error of a Downhole Seismometer, *Earthquake Engineering and Structural Dynamics*, Vol. 23, No.10, Oct., pp. 1069-1078.

Coutant, O. (1996), Observation of Shallow Anisotropy on Local Earthquake Records at the Garner Valley, Southern California, Downhole Array, *Bulletin of the Seismological Society of America*. Vol. 86, Apr., pp. 477-488.

CRIEPI (1991), *Interim report on geotechnical investigation (Oct. to Dec., 1990) of Hualien site*, CRIEPI, August.

Cubrinovski, M., Ishihara, K., Tanizawa, F. (1996), Numerical Simulation of the Kobe Port Island Liquefaction, *Proceedings of the Eleventh World Conference on Earthquake Engineering*, Pergamon, Elsevier Science Ltd., Oxford, England, Disc 1, Paper No. 330.

Darragh, R., Huang, M. and Shakal, A. (1993), Processed Strong-Motion Records from the CSMIP/NSF Treasure Island Geotechnical Array for the Gilroy Earthquake of January 16, 1993, *Report No. OSMS 93-09*, California Division of Mines and Geology.

Darragh, R., Graizer, V. and Shakal, A. (1997), Site Characterization and Site Response Effects at CSMIP Stations: Tarzana and La Cienega Near the Santa Monica Freeway (I-10), *Report No. OSMS 96-07*, California Division of Mines and Geology, pp. 262.

Davis, C.A. and Bardet, J.P. (1996), Performance of Two Reservoirs During the 1994 Northridge Earthquake, *J. Geotech. Engrg*., Vol. 122, No. 8.

Davis, R.O. and Berrill, J.B. (1998a), Rational Approximation of Stress and Strain Based on Downhole Acceleration Measurements, *International Journal for Numerical and Analytical Methods in Geomechanics*. Vol. 22, No. 8, Aug., pp. 603-619.

Davis, R.O. and Berrill, J.B. (1998b), Energy Dissipation and Liquefaction at Port Island, Kobe, *Bulletin of the New Zealand National Society for Earthquake Engineering*, Vol. 31, No. 1, Mar., pp. 33-50.

Davis, R.O. (2000), Estimation of Soil Shear Modulus Softening During Strong Ground Shaking Using Ground Surface and Downhole Acceleration Recordings, *Earthq. Engrg. And Struct. Dyns.*, Vol. 29, pp. 359-376.

Davis, R.O. and Berrill, J.B. (2001), Correlation of Pore Pressure and Dissipated Energy in Earthquakes – Field Verification, *ASCE Jour. Geotech. and Geoenviron. Engrg.*, in press.

de Alba, P., *et al.* (1992), Deep Instrumentation Array at Treasure Island Naval Station, California, *New Trends in Earthquake Engineering*: Earthquake Engineering Research Institute 44th Annual Meeting.

de Alba, P., Benoît, J., Pass, D.G., Carter, J.J., Youd, T.L. and Shakal, A.F. (1994), Deep Instrumentation Array at the Treasure Island Naval Station, in The Loma Prieta, California, Earthquake of October 17, 1989: *Strong Ground Motion and Ground Failure*, U. S. Geol. Surv. Prof. Pap. 1551-A, R. D. Borcherdt, Ed., U.S. Geological Survey, Washington D.C., A155-A168.

de Alba, P. and Faris, J.R. (1998), Treasure Island, California, Deep Instrumentation Array, *The Effects of Surface Geology on Seismic Motion: Recent Progress and New Horizon on ESG Study, Proceedings of the Second International Symposium*, A.A. Balkema, Rotterdam, Vol. 1, pp. 201-208.

de Barros, F.C.P. and Luco, J.E. (1995), Identification of Foundation Impedance Functions and Soil Properties from Vibration Tests of the Hualien Containment Model, *Soil Dynamics and Earthquake Engineering*, Elsevier, Vol. 14, pp. 229-248.

Divis, C.J., Kutter, B.L., and Idriss, I.M. (1996), Uniformity of Specimen and Response of Liquefiable Sand Model In A Large Centrifuge Shaker, *Proc. 6th U.S.-Japan Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Liquefaction*, June 11-13, Waseda University, NCEER Report, Buffalo, NY.

Dobry, R., Whitman, R.V., and Roesset, J.M. (1971), Soil Properties and the One-Dimensional Theory of Earthquake Amplification, *Research Report, R71-18*, School of Engineering, Massachusetts Institute of Technology.

Dobry, R. and Taboada, V.M. (1994), Possible Lessons from VELACS Model No. 2 Results, *Proc. of the International Conference on the Verification of Numerical Procedures for the Analysis of Soil Liquefaction Problems*, Arulanandan, K. and Scott, R. F., Eds. Vol. 2, Davis, CA, pp. 1341-1352, Balkema.

Dobry, R., Taboada, V. and Liu, L. (1995), Centrifuge Modeling of Liquefaction Effects During Earthquakes, *Proc. 1st Intl. Conf. On Earthquake Geotechnical Engineering* (IS-Tokyo), Keynote Lecture, Ishihara, K. Ed., 3, Balkema, Nov. 14-16, Tokyo, Japan, pp. 1291-1324.

Dobry, R. and Abdoun, T. (1998), Post-Triggering Response of Liquefied Sand in the Free Field and Near Foundations," *Proc. Geot. Eq. Engrg. and Soil Dynamics III*, Vol. 1, Dakoulas, P., Yegian, M. and Holtz., R. D., Eds., Geot. Special Publication No. 75, ASCE, Seattle, Washington, Aug 3-6, keynote lecture, pp. 270-300.

Elgamal, A.W., Zeghal, M, Tang, H.T., and Stepp, J.C. (1995), Lotung Downhole Array. I: Evaluation of Site Dynamic Properties, *Journal of Geotechnical Engineering*, Vol. 121, No.4, Apr., pp. 350-362.

Elgamal A.W., Zeghal, M., Parra, E., Gunturi, R., Tang, H.T., and Stepp, J.C. (1996a), Identification and Modeling of Earthquake Ground Response I. Site Amplification, *Soil Dynamics and Earthquake Engineering*, Vol. 15, No. 8, Dec., pp. 499-522.

Elgamal, A.W., Zeghal, M., Taboada, V.M., and Dobry, R. (1996b), Analysis of Site Liquefaction and Lateral Spreading Using Centrifuge Testing Records, *Soils and Foundations*, Vol. 36, No.2, June, pp. 111-121.

Elgamal, A.W., Zeghal, M., and Parra, E. (1996c), Liquefaction of Reclaimed Island in Kobe, Japan, *Journal of Geotechnical Engineering*, Vol. 122, Jan., pp. 39-49.

Elgamal, A.W., Zeghal, M., and Parra, E. (1997), Identification and Modeling of Earthquake Ground Response, *Proc. 1st Intl. Conf. on Earthquake Geotechnical Engineering* (IS-Tokyo 1995), Theme Lecture, Nov. 14-16, 1995, Tokyo, Japan, A.A. Balkema, Rotterdam, Vol. 3, pp. 1369-1466.

Elgamal, A.W., Dobry, R., Parra, E. and Yang, Z. (1998), Soil Dilation and Shear Deformations During Liquefaction, *Proc. 4th Intl. Conf. on Case Histories in Geotechnical Engineering*, S. Prakash, Ed., St. Louis, MO, March 8-15.

Elgamal, A.W., Yang, Z, Parra, E. and Dobry, R. (1999), Modeling of Liquefaction-Induced Shear Deformations, *Second International Conference on Earthquake Geotechnical Engineering*, Lisbon, Portugal, 21-25 June, Balkema, pp. 895-900.

Elgamal, A.W. and Yang, Z. (2000), Numerical Modeling of Liquefaction-Induced Lateral Spreading, *Proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 2817.

Elgamal, A.W., Lai, T., Wilson, D.W., and Kutter B.L. (2001), Identification of Small Strain Dynamic Properties of Dense Sand, *4th International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, March 26-31, 2001, San Diego, CA.

EPRI (1993), Guidelines for Determining Design Basis Ground Motions, Volumn 1: Method and Guidelines for Estimating Earthquake Ground Motion in Eastern North America, *Report No. TR-102293*, Electric Power Research Institute, Palo Alto, California.

EQE (1995), *The January 17, 1995 Kobe Earthquake*, an EQE Summary Report, April.

Faccioli, E., Paolucci, R., and Vanini, M. (1996), Studies of Site Response and Soil-Structure Interaction Effects in a Tall Building in Mexico City, *Proceedings of the Eleventh World Conference on Earthquake Engineering*, Pergamon, Elsevier Science Ltd., Oxford, England, Disc 1, Paper No. 569.

Farjoodi, J., Katayama, T., and Sato, N. (1983), Estimation of Seismic-Induced Ground Strains by Dense Seismometer Array Observation, *Proceedings of the 17th JSCE Conference on Earthquake Engineering*, pp. 69-72, Tokyo, Japan.

Fiegel, G.L. and Kutter, B.L. (1992), Liquefaction Mechanism for Layered Soil, *Journal of Geotechnical Engineering*, ASCE, Vol. 120, No. 4, pp.737-755.

Fiegel, G.L. and Kutter, B.L. (1994a), A Mechanism of Liquefaction for Layered Soils, *Journal of Geotechnical Engineering*, ASCE, Vol. 120, No. 4, pp.733-755.

Fiegel, G.L. and Kutter, B.L. (1994b), Liquefaction Induced Lateral Spreading of Mildly Sloping Ground, *Journal of Geotechnical Engineering*, Vol. 120, No. 12, December.

Finn, W.D.L., Ventura, C.C. and Wu, G. (1993), Analysis of Ground Motions at Treasure Island Site During 1989 Loma Prieta Earthquake, *Soil Dynamics and Earthquake Engineering*, Vol. 12, No. 7, pp. 383-390.

Fukushima, Y. and Irikura, K. (1997), Attenuation Characteristics of Peak Ground Motions in the 1995 Hyogo-ken Nanbu Earthquake, *Journal of Physics of the Earth*, Vol. 45, No. 2, pp. 135-146.

Furumoto, Y., Oka, E., Sugito, M., Yashima, A., and Fukagawa, Y. (1999), Time Dependent Ground Motion Amplification Due to Liquefaction on Man-Made Island, MCEER-99-0019, *Proceedings of the Seventh U.S.-Japan Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Soil Liquefaction*, MCEER, SUNY, Buffalo, New York, Nov. 19, pp. 345-360.

Geomatirx Consultants Inc. (1990), Earthquake Data Recorded by the Large Scale Seismic Test (LSST) Array in Lotung, Taiwan. *Res. Proj. 225-29 Databook*, San Francisco, California.

Ghayamghamian, M.R. and Kawakami, H. (1996), On the Characteristics of Non-Linear Soil Response and Dynamic Soil Properties Using Vertical Array Data in Japan, *Earthquake Engineering and Structural Dynamics*, Vol. 25, Aug., pp. 857-870.

Ghayamghamian, M.R., and Kawakami, H. (2000a), On-Site Nonlinear Hysteresis Curves and Dynamic Soil Properties, *Journal of Geotechnical and Geoenvironmental Engineering*. Vol. 126, No. 6, pp. 543-555.

Ghayamghamian, M.R., and Kawakami, H, (2000b), Estimation of Non-Linear Site Amplification Using Downhole Recordings, *Proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 0440.

Gibbs, J.F., Fumal, T.E., Boore, M.D. and Joyner, W.B. (1992), Seismic Velocities and Geologic Logs from Borehole Measurments at Seven Strong-Motion Stations that Recorded the Loma Prieta Earthquake, *U.S. Geol. Surv. Open-File Rept. 92-287.*

Gill, P.E., Murray, W. and Saunders, M.A. (1997), *SNOPT: An SQP Algorithm for Large-scale Constrained Optimization*, Numerical Analysis Report 97-2, Department of Mathematics, University of California at San Diego, California.

Glaser, S.D. (1995), System Identification and its Application to Estimating Soil Properties, *ASCE Journal of Geotechnical Engineering*, Vol. 121, No.7, pp. 553-560.

Glaser, S.D. (1996), Insight into Liquefaction by System Identification, *Geotechnique*, Vol. 46, No. 4, pp. 641-655.

Glaser, S.D. and Baise, L.G. (2000), System Identification Estimation of Damping and Modal Frequencies at the Lotung Site, *Soil Dynamics and Earthquake Engineering*, Vol. 19, No.10, pp. 521-531.

Graizer, V., Shakal, A. and Hipley, P. (2000), Recent Data Recorded from Downhole Geotechnical Arrays, *SMIP2000 Seminar on Utilization of Strong-Motion Data*, Sept. 14, Sacramento, California, USA.

Graves, H.L., Tang, H.T., and Liao, Y.C. (1996), Large-Scale Seismic Test Program at Hualien Taiwan, *Nuclear Engineering and Design*. Vol. 163, No. 3, Jul., pp. 323-332.

Gunturi, V.R. (1996), *Identification and Modeling of Seismic Response of Landfills*, PhD thesis, Department of Civil Engineering, Rensselaer Polytechnic Institute, Troy, NY.

Gunturi, V.R., Elgamal, A. W., and Tang, H. T. (1998), Hualien Seismic Downhole Data Analysis, *Engineering Geology*. Vol. 50, No. 1-2, Sep., pp. 9-29.

Haddadi, H.R. and Kawakami, H. (1998a), Effect of Liquefaction on Ground Motion During the Hyogoken Nanbu Earthquake, 1995, in Japan by Using the NIOM Method, *The Effects of Surface Geology on Seismic Motion: Recent Progress and New Horizon on ESG Study, Proceedings of the Second International Symposium*, A.A. Balkema, Rotterdam, Vol. 2, pp. 1015-1022.

Haddadi, H.R. and Kawakami, H. (1998b), Characteristics of Vertical Component Strong Ground Motions by NIOM (Normalized Input-Output Minimization) Method, *The 10th Earthquake Engineering Symposium, Proceedings*, Vol. 1, pp. 1187-1192, Paper No. C6-18.

Haddadi, H.R. and Kawakami, H. (2000), Analysis of Soil Nonlinear Properties at Port Island by NIOM Method During 1995 Hyogo-ken-Nanbu Earthquake in Japan, *Proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, 2000, Paper No. 1729.

Hauksson, E., Teng, T.L., and Henyey, T.L. (1987), Result from a 1500 m Deep, Three-Level Downhole Seismometer Array: Site Response, Low Q Values, and f max, *Bulletin of the Seismological Society of America*, Vol. 77, No.6, Dec., pp. 1883-1904.

Hayashi, S., Tsuchida, H., and Kurata, E. (1977), Observation of Earthquake Response of Ground with Horizontal and Vertical Seismometer Arrays, *NBS Special Publication 477, Wind and Seismic Effects*, U.S. National Bureau of Standards, Washington, D.C., May, III16-III25.

Hayashi, H., Nishikawa, J., Egawa, T., Miwa S., and Ikeda, T. (2000), Ground Seismic Behavior From Liquefaction Array Observation, *Proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 0517.

Hill, R. (1950), *The Mathematical Theory of Plasticity*, Oxford Univ. Press, London.

Holzer, T.L., Youd, T.L. and Hanks, T.C. (1989), Dynamics of Liquefaction During the 1987 Superstition Hills, California, Earthquake, *Science,* Vol. 244, pp. 56-59.

Hryciw, R.D., Rollins, K.M., Homolka, M., Shewbridge, S.E. and McHood, M. (1991), Soil Amplification at Treasure Island During the Loma Prieta Earthquake, *Proceedings, 2nd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, St. Louis, MO, pp. 1679-1695.

Huang, H.C. and Chiu, H.C. (1996), Estimation of Site Amplification from Dahan Downhole Recordings, *Earthquake Engineering and Structural Dynamics*. Vol. 25, No. 4, April, pp.319-332.

Huang, H.C., Shieh, C.S., and Chiu, H.C. (2000), Linear and Nonlinear Behaviors on a Soil Site Using Lotung Downhole Array in Taiwan, *Proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 1705.

Hutchings, L., Kasameyer, P., Foxall, W., McEvilly, T., Clymer, R., Urhammer, R., Hipley, P., Mualchin, L., Bowman, J., Palmer, M., Jarpe, S. and Bakun, W. (1998), Deep Borehole Instrumentation along San Francisco Bay Bridges, *UCRLID 121085*, Lawrence Livermore National Laboratory.

Iai, S. (1991), A Strain Space Multiple Mechanism Model for Cyclic Behavior of Sand and its Application, *Earthquake Engineering Research Note No. 43*, Port and Harbor Research Institute, Ministry of Transport, Japan.

Iai, S., Matsunaga, Y., Morita, T., Sakarai, H., and Hitachi, S. (1994), Seismic Array Observation of S Wave Propagation -- Phase Velocity and Direction, *Proceedings of the Fifth U.S. National Conference on Earthquake Engineering*, Earthquake Engineering Research Inst., Oakland, California, Vol. III, pp. 141-148.

Iai, S., Morita, T., Kameoka, T., Matsunaga, Y. and Abiko, K. (1995), Response of a Dense Sand Deposit During 1993 Kushiro-Oki Earthquake, *Soils and Foundations*, 35, 1, March, pp. 115-131.

Iai, S. (1998), Seismic Analysis And Performance Of Retaining Structures, *Proc. Geotechnical Earthquake Engineering and Soil Dynamics III*, ASCE, Seattle, Washington, pp. 1020-1044.

Igarashi, S. (1996), Liquefaction Prediction with Energy-Related Parameters of Soil and Ground Motion, *Proceedings of the Eleventh World Conference on Earthquake Engineering*, Pergamon, Elsevier Science Ltd., Oxford, England, Disc 3, Paper No. 1615.

Ikemoto, T., Miyajima, M., Kitaura, M., and Kitada, Y. (1999), Inverse Analyses of Dynamic Soil Parameters Using Horizontal and Vertical Acceleration Records, *Proceedings of the Second International Conference on Earthquake Geotechnical Engineering*, A. A. Balkema, Rotterdam, Vol. 1, pp. 199-204.

Ikemoto, T., Miyajima, M. and Kitaura, M. (2000), Inverse Analysis of Dynamic Soil Parameters Using Acceleration Records, *Proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 1794.

Ishihara, K. (1985), Stability of Natural Deposits During Earthquakes, Theme Lecture, Proceedings, *11th International Conference on Soil Mechanics and Foundation Engineering*, San Francisco, Vol. 2, pp. 321-376.

Ishihara, K. (1996), *Soil behavior in earthquake geotechnics*, Clarendon Press, Oxford.

Iwan, W.D. (1967), On a class of Models for the Yielding Behavior of Continuous and Composite Systems, *Journal of Applied Mechanics*, ASME, Vol. 34, pp. 612-617.

Iwasaki, Y. (1995), *Geological and Geotechnical Characteristics of Kobe Area and Strong Ground Motion Records by 1995 Kobe Earthquake*, Tsuchi-to-Kiso, Japanese Society of Soil Mechanics and Foundation Engineering, Vol. 43, No. 6, pp. 15-20 (in Japanese).

Iwasaki, Y. and Tai, M. (1996), Geotechnical Aspects of the January 17, 1995 Hyogoken-Nambu Earthquake: Strong Motion Records at Kobe Port Island, *Soils and Foundations*, Special Issue, Jan., pp. 29-40.

Iwata, T., Irikura, K., and Gariel, J.C. (1992), Estimation of Effects of Subsurface Structure on Ground Motions Using 3-D Array Data, *Proceedings of the Tenth World Conference on Earthquake Engineering*, A. A. Balkema, Rotterdam, Vol. 1, pp. 247-252.

Japanese Geotechnical Society (1996), *Soils and Foundations Journal*. Special Issue on Geotechnical Aspects of the January 17 1995 Hyogoken-Nambu Earthquake. January, Tokyo, pp. 359.

Joyner, W.B., Warrick, R.E., Oliver, and Adolph, A., III (1976), Analysis of Seismograms from a Downhole Array in Sediments Near San Francisco Bay, *Bulletin of the Seismological Society of America*, Vol. 66, No. 3, June, pp. 937-958.

Kamiyama, M. and Matsukawa, T. (1998), Non-Linear Response in the Downhole Strong-Motion Records at Port Island During the 1995 Kobe Earthquake, Japan, *Proceedings of the Eleventh European Conference on Earthquake Engineering*, A. A. Balkema, Rotterdam.

Kamiyama, M., Matsukawa, T. and Yoshida, M. (1998), Non-Stationary Variation of Soil Rigidity Observed During the 1995 Hyogoken Nanbu Earthquake, *The 10th Earthquake Engineering Symposium, Proceedings*, 1998, pp. 1193-1198, Vol.1, Paper No. C6-19.

Kamiyama, M., Matsukawa, T., and Yoshida, M. (2000), Dynamic Variation of Soil Rigidity Based on Down-Hole Array Observation, *Proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 1099.

Kanda, K. and Motosaka, M. (1997), Analysis on Amplification Characteristics of Ground Motion in Topographic Irregular Site Subjected to Spatially Varying Incident Wave (in Japanese), *Journal of Structural and Construction Engineering* (Transactions of AIJ), 495, pp. 79-86.

Katayama, T., Yamazaki, F., Nagata, S., Lu L. and Turker, T. (1990), A Strong Motion Data Base For the Chiba Seismometer Array and Its Engineering Analysis, *Earthquake Engineering and Structural Dynamics*, Vol. 19, pp. 1089-1106.

Kato, K., Takemura, M., Konno, T., Uchiyama, S., Iizuka, S., and Nigbor, R.L. (1998), Borrego Valley Downhole Array in Southern California: Instrumentation and Preliminary Site Effect Study, *The Effects of Surface Geology on Seismic Motion: Recent Progress and New Horizon on ESG Study, Proceedings of the Second International Symposium*, Yokohama, Japan, 1-3 December, edited by Kojiro Irikura, Kazuyoshi Kudo, Hiroshi Okada, and Tsutomu Sasatani, A.A. Balkema, Rotterdam, Vol. 1, pp. 209-217.

Kawakami, H. and Haddadi, H.R. (1998), Simplified Model of Wave Propagation by Normalized Input-Output Minimization (NIOM) and Its Application to Strong Motion Records of Hiyoshi Vertical Array, *Proceedings of the Eleventh European Conference on Earthquake Engineering*, A. A. Balkema, Rotterdam.

Kawase, H., Sato, T., Fukutake, T., and Irikura, K. (1995), Borehole Records Observed at the Port Island in Kobe During the Hyogo-ken Nanbu Earthquake of 1995 and Its Simulation (in Japanese), *Journal of Structural and Construction Engineering* (Transactions of AIJ), 475, pp. 83-92.

Kawase, H., Satoh, T. and Fukutake, K. (1996), Simulation of the Borehole Records Observed at the Port Island in Kobe, Japan, During the Hyogo-ken Nanbu Earthquake of 1995, *Proceedings of the Eleventh World Conference on Earthquake Engineering*, Pergamon, Elsevier Science Ltd., Oxford, England, Disc 1, Paper No. 140.

Kazama, M. (1996), Nonlinear Dynamic Behavior of the Ground Inferred from Strong Motion Array Records at Kobe Port Island During the 1995 Hyogo-ken Nanbu Earthquake, *Proceedings of the International Workshop on Site Response Subjected to Strong Earthquake Motions*, Yokosuka, Japan, January 16-17, Japan Port and Harbor Research Inst., Yokosuka, Japan, Vol. 2, pp. 185-200.

Kelner, S., Bouchon, M., and Coutant, O. (1999), Characterization of Fractures in Shallow Granite from the Modeling of the Anisotropy and Attenuation of Seismic Waves, *Bulletin of the Seismological Society of America*, Vol. 89, No. 3, June, pp. 706 –717.

Kimura, T., Takemura, J. and Hirooka, A. (1993), Numerical Prediction for Model No. 1, *Proc. of the Intl. Conference on the Verification of Numerical Procedures for the Analysis of Soil Liquefaction Problems, Arulanandan*, K. and Scott, R. F., Eds. Vol. 1, Davis, CA, pp. 141-152, Balkema.

Kinoshita, S. (1999), A Stochastic Method for Investigating Site Effects by Means of a Borehole Array SH and Love Waves, *Bulletin of the Seismological Society of America*. Vol. 89, No. 2 Apr., pp. 484-500.

Koga, Y. and Matsuo, O. (1990), Shaking Table Tests of Embankments Resting on Liquefiable Sandy Ground, *Soils and Foundations*, pp. 30, 4, 162-174.

Kokusho, T., Tohma, J., Yajima, H., Tanaka, Y., and Kanatani, M. (1994), Seismic Response of Soil Layer and its Dynamic Properties, *Proceedings of the Tenth World Conference on Earthquake Engineering*, A. A. Balkema, Rotterdam, Vol. 11, pp. 6671-6680.

Kokusho, T., Sato, K., and Matsumoto, M. (1995), Nonlinear Seismic Amplification of Soil Ground During 1995 Hyogoken-Nanbu Earthquake, *Proceedings of the Fifth International Conference on Seismic Zonation*, October 17-19, 1995, Nice, France, Ouest Editions, Nantes, France, Vol. II, pp. 1603-1610.

Kokusho, T., Sato, K., and Matsumoto, M. (1996), Nonlinear Dynamic Soil Properties Back-Calculated from Strong Seismic Motions During Hyogoken-Nanbu Earthquake, *Proceedings of the Eleventh World Conference on Earthquake Engineering*, Pergamon, Elsevier Science Ltd., Oxford, England, Disc 4, Paper No. 2080.

Kokusho, T. and Matsumoto, M. (1997), Nonlinear Site Response During the Hyogoken-Nanbu Earthquake Recorded by Vertical Arrays in View of Seismic Zonation Methodology, *Seismic Behavior of Ground and Geotechnical Structures*, A. A. Balkema, Rotterdam and Brookfield, Vermont, pp. 61-69.

Kokusho, T. and Matsumoto, M., (1998), Nonlinearity in Site Amplification and Soil Properties During the 1995 Hyogoken-Nambu Earthquake, *Soils and Foundations: Geotechnical Aspects of the January 17, 1995 Hyogoken-Nambu Earthquake*, Special Issue 2, Sept. pp. 1-9.

Kokusho, T. (1999), Effect of Nonlinear Soil Properties on Seismic Amplification in Surface Layers, *Proceedings of the Second International Conference on Earthquake Geotechnical Engineering*, A. A. Balkema, Rotterdam, Vol. 3, pp. 913-918.

Kondner, R.L. (1963), Hyperbolic Stress-Strain Response: Cohesive Soils, *J. of the Soil Mechanics and Foundations Division*, ASCE, Vol. 89, No. SM1, pp. 115-143.

Kramer, S.L. (1996), *Geotechnical Earthquake Engineering*, Prentice Hall.

Kramer, S.L and Arduino, P. (1999), Constitutive Modeling of Cyclic Mobility and Implications for Site Response, Earthquake Geotechnical Engineering, *Proc. 2nd Intl. Conf. On Earthquake Geotechnical Engineering*, Lisboa, Portugal, June 21-25, Seco e Pinto, Ed., Balkema, Vol. 3, pp. 1029-1034.

Kurita, T. and Matsui, K. (1997), Sensitivity Analysis on Measurement Noise in the Identification of Soil Properties from Vertical Array Observation Data, *Earthquake Engineering and Structural Dynamics*, Vol. 26, No. 9, Sept., pp. 951-965.

Kurita T., Kawahara, M., Annaka, T., and Takahashi, S. (2000), Evaluation of Local Site Effects in the Kanto District Based on Observation Records, *Proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 0224.

Kutter, B.L., Idriss, I.M., Khonke, T., Lakeland, J., Li, X.S., Sluis, W., Zeng, X., Tauscher, R.C., Goto, Y., and I. Kubodera (1994), Design of a Large Earthquake Simulator at UC Davis, *Proceedings, International Conference, Centrifuge 94*, Singapore, August, pp. 169-175.

Kutter, B.L. (1995), Recent Advances in Centrifuge Modeling of Seismic Shaking, State-of-the-Art Report, *Proc. Third Int. Conf. on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, St. Louis, MO, Vol. 2, April, pp. 927-942.

Kutter, B.L. and Wilson, D.W. (1999), De-Liquefaction Shock Waves, *Proceedings of the 7th U.S.-Japan Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Soil Liquefaction*, Seattle, August, 1999, Technical Report MCEER-99-0019 (O'Rourke, Bardet, and Hamada eds.), pp. 295-310, November.

Kutter, B.L. and Balakrishnan, A. (2000), Dynamic Model Test Data from Electronics to Knowledge, Keynote Lecture, *Proceedings, Centrifuge 98*, A. A. Balkema, Rotterdam, Vol. 2. Kumura, Kusakabe, and Takemura, Eds. Balkema, Rotterdam.

Lacy, S. (1986), *Numerical Procedures for Nonlinear Transient Analysis of Two-phase Soil System*, Ph.D. dissertation, Princeton University, NJ, USA.

Lai, T., Elgamal, A.W. and Yang, Z.H. (1999), *Comprehensive Investigation of Nonlinear Site Response – Preliminary System Identification Study of Test DKS02 Data*, Department of Structural Engineering, University of California at San Diego, CA.

Lambe, T.W. and Whitman, R.V. (1969), *Soil Mechanics,* John Wiley & Sons, New York.

Li, X.S. (1990), *Free Field Response under Multi-Directional Earthquake Loading,* Ph.D. Dissertation, Dept. of Civil Engrg, University of California, Davis.

Li, X.S. (1993), Numerical Prediction for Model No. 1, *Proc. of the Intl. Conf on the Verification of Numerical Proc for the Analysis of Soil Liquefaction Problems*, Arulanandan, K. and Scott, R. F., Eds.1, Davis, CA, Balkema, pp.169-178.

Li, X.S. (1997), Modeling of Dilative Shear Failure, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 123, No. 7, July, pp. 609-616.

Li, X.S., Shen, C.K. and Wang, Z.L. (1998), Fully Coupled Inelastic Site Response Analysis for 1986 Lotung Earthquake, *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 124, No. 7, July, pp. 560-573.

Lin, C.H. and Borja, R.I. (2000), Dynamic Theory of Mixtures and Its Finite Element Implementation for Nonlinear Analysis of Ground Motion Induced by Seismic Shaking, *John A. Blume Earthquake Engineering Research* Report No. 137.

Lin, J.S. (1994), Extraction of Dynamic Soil Properties Using Extended Kalman Filter, *Journal of Geotechnical Engineering*, Vol. 120, No. 12, Dec., pp. 2100-2117.

Liu, L. (1992), *Centrifuge Earthquake Modeling of Liquefaction and Its Effects on Shallow Foundations*, Ph.D. Thesis, Dept of Civil Engineering, Rensselaer Polytechnic Institute, Troy, NY.

Loh, C.H. and Yeh, C.S. (1992), Identification of Site Response Using 3-D Array Records, *Proceedings of the 10th Conference on Earthquake Engineering*, Madrid, July 19-24, A. A. Balkema, Rotterdam, Vol. 1, pp. 259-263.

Matsuoka H. and Sakakibara A. (1987), A Constitutive Model for Sands and Clays Evaluating Principal Stress Rotation, *Soils and Foundations*, Vol. 27, No. 4, pp. 73-88.

Minster, B., Wagoner, J., Mellors, R., Day, S., Park, S., Elrick, S., Vernon, F. and Heuze, F. (1999), Initial Source and Site Characterization Studies for the U.C. San Diego Campus, Lawrence Livermore Nationa Laboratory Report, *UCRL-ID-134785*, California.

Miura, K., Kobayashi, S. and Yoshida, N. (2000), Equivalent Linear Analysis Considering Large Strains and Frequency Dependent Characteristics, *Proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 1832.

Miwa, S., Ikeda, T. and Hiroshi, O. (2000), A Study on Seismic Behavior of Liquefied Ground Using Strong motion Array Records of the 1995 Hyogoken-Nambu Earthquake, *Proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 1325.

Mohammadioun, B., Mohammadioun, G. and Gariel, J.C. (1992), Preliminary Results from a Vertical Array in Garner Valley, California, *Proceedings of the Tenth World Conference on Earthquake Engineering*, A. A. Balkema, Rotterdam, Vol. 2, pp. 1025-1030.

Mohammadioun, B. and Pecker, A. (1994), Low Frequency Transfer of Energy by Superficial Soil Deposits and Soft Rocks, *Soil Dynamics and Earthquake Engineering*, Vol. 12, pp. 537-564.

Mohammadioun, B. and Gariel, J.C. (1995), An Analysis of Soil Effect Observed on Near-Source Ground Motion Records: Examples from the Garner Valley, California, Downhole Array and Elsewhere, *Proceedings of the 10th European Conference on Earthquake Engineering*, A. A. Balkema, Rotterdam, Vol. 4, pp. 2613-2616.

Mohammadioun, B. and Gariel, J.C. (1996), An Analysis of Soil Effects on Earthquake Bedrock Motion: a Cooperative NRC/IPSN Downhole Experiment at Garner Valley (California), *Proceedings of the Eleventh World Conference on Earthquake Engineering*, Pergamon, Elsevier Science Ltd., Oxford, England, Disc 2, Paper No. 903.

Mohammadioun, B. (1998), Seismic Ground Motion Parameters: An Overview, *Seismic Design Practice into the Next Century: Research and Application, Proceedings of the Sixth SECED Conference*, A. A. Balkema, Rotterdam, pp. 25-33.

Mok, C.M., Chang, C.Y. and Legaspi, D.E. Jr. (1998), Site Response Analyses of Vertical Excitation, *Geotechnical Special Publication*, ASCE, Vol. 1, Reston, VA, USA, pp. 739-753.

Mroz, Z. (1967), On the Description of Anisotropic Work Hardening, *Journal of the Mechanics and Physics of Solids*, Vol. 15, pp. 163-175.

Muraleetharan, K.K., Mish, K.D., Yogachandran, C. and Arulanandan, K. (1988), DYSAC2: Dynamic Soil analysis Code for 2-Dimensional Problems, Computer Code, Dept. of Civil Engineering, Univ. of California, Davis, California.

Nagata, S., Katayama, T., Yamazaki, F., Lu, L., and Türker, T. (1990), A Dense Seismograph Array in Chiba, Japan and Its Strong Motion Database, *Proceedings of the Fourth U.S. National Conference on Earthquake Engineering*, Earthquake Engineering Research Inst., El Cerrito, California, Vol. 1, pp. 357-366.

Nakakita, Y. and Watanabe, Y. (1981), Soil Stabilization by Preloading in Kobe Port Island, *Proceedings of the 9th International Conference on Soil Mechanics and Foundation Engineering*, Tokyo, Japan, pp. 611-622.

National Research Council (1985), *Liquefaction of Soils During Earthquakes,* Committee on Earthquake Engineering, National Academy Press, Washington, D. C.

Nazarian, S. and Desai, M. (1993), Automated Surface Wave Method: Field Testing, *Journal of Geotechnical Engineering*, ASCE, Vol. 119, No. 7, pp. 1094-1111.

Nigbor, R., *et al.* (1999), Comparison of Site Response Estimation Methods at BVDA, *Transactions of the 15th International Conference on Structural Mechanics in Reactor Technology*, International Association for Structural Mechanics in Reactor Technology and Korean Nuclear Society, Seoul, Korea, Vol. VIII, Paper K01/1, pp. VIII-1 to VIII-11.

Nishi, K. and Kanatani, M. (1990), Constitutive Relations for Sand Under Cyclic Loading based On Elasto-Plasticity Theory, *Soils and Foundations*, Vol. 30, No. 2, pp. 43-59.

Norris, G.M. (1988), Liquefaction at the Meloland Overcrossing During the Imperial Valley Earthquake of 1979. *Bull. Assoc. Engrg. Geologists.* V.XXV(2), pp. 235-247.

Nozawa, Y., Ohki, H. and Annaka, T. (1989), Strain Dependence of Soil Properties Inferred from the Strong Motion Accelerograms Recorded by a Vertical Array, Proceedings, *Ninth World Conference on Earthquake Engineering*, 9WCEE Organizing Committee, Japan Assn. for Earthquake Disaster Prevention, Tokyo, Vol. II, Paper No. 3-3-13, pp. 471-476.

Nozu, A. and Uwabe, T. (2000), Applicability of Empirical Green's Function Method to Strong Motion Records on Man-Made Island in Kobe, *Proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 0538.

NRC (1985), *Liquefaction of Soils during Earthquakes*, National Research Council Committee on Earthquake Engineering, National Academy press, Washington D. C.

Numata, A., Mori, S. and Guan, B. (1998), Seismic Response Analysis and Simplified Liquefaction Evaluation at Kobe Port Island (in Japanese), *Proceedings of The 10th Earthquake Engineering Symposium*, Vol. 2, No. D2-12, pp. 1481-1486.

Numata, A., Guan, B. and Mori, S. (2000), Investigation of Liquefaction at Reclaimed Land in Japan During the 1995 Hyogoken-Nambu Earthquake, *Proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 1135.

Oka, F., Sugito, M., Yashima, A., Taguchi, Y. and Sekiguchi, K. (1996), Analysis of Strong Motion Records from the South Hyogo Earthquake of January 17, 1995, *Engineering Geology*. Vol. 43, Sep., pp. 85-106.

Oka, F., Yashima, A., Sugito, M., and Taguchi, Y. (1997), Three Dimensional Liquefaction Analysis of Reclaimed Island, *Proceedings of the International Offshore and Polar Engineering Conference*, Vol.1, Int. Soc. of Offshore and Polar Engineers (ISOPE), Golden, CO, USA, pp. 665-670.

Oka, F., Sugito, M., Yashima, A., Furumota, Y. and Yamada, K. (2000), Time Dependent Ground Motion Amplification at Reclaimed Land After the 1995 Hyogo-ken-Nanbu Earthquake, *Proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 2046.

Olsen, K.B., Nigbor, R.L. and Konno, T. (2000a), 3D Viscoelastic Wave Propagation in the Upper Borrego Valley, California, Constrained by Borehole and Surface Data, *Bulletin of the Seismological Society of America*, Vol. 90, No.1, Feb., pp. 134-150.

Olsen, K.B., Nigbor, R.L. and Konno, T. (2000b), 3D Viscoelastic Wave Propagation in the Borrego Valley, California, *proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 0676.

Omote, S., Ohmatsuzawa, K. and Ohta, T. (1980), Recently Developed Strong Motion Earthquake Instruments array in Japan, *Proceedings of the Seventh World Conference on Earthquake Engineering*, Turkish National Committee on Earthquake Engineering, Istanbul, Vol. 2, pp. 41-48.

O'Rourke, T.D. (1995), Geotechnical Effects, Preliminary Report from the Hyogoken-Nanbu Earthquake of January 17, National Center for Earthquake Engineering Research *Bulletin*, SUNY, Buffalo, Vol. 9, No. 1.

Parra, E. (1996), *Numerical Modeling of Liquefaction and Lateral Ground Deformation Including Cyclic Mobility and Dilation Response in Soil System*, Ph.D. Thesis, Dept. of Civil Engineering, Rensselaer Polytechnic Institute, Troy, NY.

Pastor, M. and Zienkiewicz, O.C. (1986), A Generalized Plasticity Hierarchical Model for Sand under Monotonic and Cyclic Loading, *Proceedings, 2nd International Conference on Numerical Models in Geomechanics*, Pande G. N., and Van Impe W. F. (Eds.), M. Jackson and Son Publ., pp. 131-150.

Pease, J.W. and O'Rourke, T.D. (1995), Liquefaction Hazards in the San Francisco Bay Region: Site Investigation, Modeling, and Hazard Assessment at Areas Most Seriously Affected by the 1989 Loma Prieta Earthquake, *Final Report*, School of Civil and Environmental Engineering, Cornell University, Ithaca, NY.

Pease, J. W. and O'Rourke, T.D. (1997), Seismic Response of Liquefaction Sites, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol.123, No. 1, pp. 37-45.

Pecker, A. (1995), Validation of Small Strain Properties from Recorded Weak Seismic Motions, *Soil Dynamics and Earthquake Engineering*, Vol. 14, No. 6, pp. 399-408.

Pires J. A. and Higgins C.J. (1998), Soil-Structure Interaction in Cross-Anisotropic Site Conditions, *Geotechnical Special Publication*. Vol. 2, ASCE, Reston, VA, USA, pp. 1271-1282.

Power, M.S., Chang, C.Y. and Idriss, I.M. (1986), Variation of Earthquake Ground Motion with Depth, *Proceedings of the Third U.S. National Conference on Earthquake Engineering*, Charleston, South Carolina, August.

Power, M.S., Egan, J.A., *et al.* (1995), Analysis of Liquefaction-Induced Stress at Treasure Island, *The Loma Prieta, California Earthquake of October 17, 1989 – Liquefaction*, Holzer, T. ed., Professional paper 1551-B, USGS, Washington D.C.

Prevost, J.H. (1985), A Simple Plasticity Theory for Frictional Cohesionless Soils, *Soil Dyn. And Earthquake Engineering*, Vol. 4, No. 1, pp. 9-17.

Prevost, J.H. (1998), *DYNAFLOW User's Manual*, Dept. of Civil Engineering and Operations Research, Princeton University.

Proubet, J. (1991), *Application of Computational Geomechanics to Description of Soil Behavior*, Ph.D. dissertation, U. of Southern California, L A, California.

Raptakis, D.G., Anastasiadis, A.J., and Pitilakis, K.D. (1998a), Preliminary Instrumental and Theoretical Approach of Site Effects in Thessaloniki, *Proceedings of the Eleventh European Conference on Earthquake Engineering*, A. A. Balkema, Rotterdam.

Raptakis, D., Theodulidis, N. and Pitilakis, K. (1998b), Data Analysis of the Euroseistest Strong Motion Array in Volvi (Greece): Standard and Horizontal-to-Vertical Spectral Ratio Techniques, *Earthquake Spectra*, Vol. 14, No.1, Feb., pp. 203-224.

Sato, K., Kokusho, T., Matsumoto, M. and Yamada, E. (1996), Nonlinear Seismic Response and Soil Property During Strong Motion, *Soils and Foundations*, Special Issue, January, pp. 41-52.

Sato, K., Higashi, S., Yajima, H., and Sasaki, S. (1998a), Ashigara Valley Test Site, 1D or 2D-3D? *The Effects of Surface Geology on Seismic Motion: Recent Progress and New Horizon on ESG Study, Proceedings of the* Second International Symposium, Yokohama, Japan, 1-3 December, edited by Kojiro Irikura, Kazuyoshi Kudo, Hiroshi Okada, and Tsutomu Sasatani, A.A. Balkema, Rotterdam, Vol. 1, pp. 319-340.

Sato, K., *et al.* (1998b), Site Amplification of a Local Sedimentary Basin at Kuno Site in Ashigara Valley (in Japanese), *Proceedings of the 10th Earthquake Engineering Symposium*, Vol. 1, Paper No. C5-2, pp. 977-982

Satoh, T., Sato, T. and Kawase, H. (1993), Identification of Shear Wave Propagation and Inversion of Nonlinearity of Soil in Sedimentary Basin: Analysis of Weak Motion and Strong Motion Observed at a Vertical Array at Kuno District in the Ashigara Valley (in Japanese), *Journal of Structural and Construction Engineering* (Transactions of AIJ), Vol. 449, pp. 55-68.

Satoh, T. and Kawase, H. (1995), Simulation of Site Amplification Factors Obtained from Borehole Records Considering Both Two-Dimensional Effect and Nonlinear Behavior of Soil Sediments -- Analysis of Weak Motion and Strong Motion Observed at a Vertical Array at Kuno District in the Ashigara Valley (in Japanese), *Journal of Structural and Construction Engineering* (Transactions of AIJ), Vol. 468, pp. 39-49.

Satoh, T., Kawase, H. and Sato, T. (1995), Evaluation of Local Site Effects and Their Removal from Borehole Records Observed in the Sendai Region, Japan, *Bulletin of the Seismological Society of America*, Vol. 85, No. 6, Dec., pp. 1770-1789.

Satoh, T., Sato, T. and Kawase, H. (1999), Nonlinear Behavior of Soil Sediments Identified by Using Borehole Records Observed at the Ashigara Valley, Japan, *Bulletin of the Seismological Society of America*, Vol. 85, No. 6, Dec., pp. 1821-1834.

Sawada, T., Hirao, K. and Taniguchi, T. (1995), A Localized Identification of Dynamic Soil Properties of Subsurface Layers in Ground by Vertical Array Records, *First International Conference on Earthquake Geotechnical Engineering*, A. A. Balkema, Rotterdam, Vol. 1, pp. 493-498.

Sawada, T., *et al.* (1998), A Study on the Frequency Dependency of Q-Value Identified by Vertical Array Records (in Japanese), *The 10th Earthquake Engineering Symposium, Proceedings,* Vol. 1, Paper No. C1-13, pp. 601-606.

Schnabel, P.B., Lysmer, J. and Seed, H.B. (1972), SHAKE – A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites, *Report EERC-72-12*, Earthquake Engineering Research Center, University of California at Berkeley, CA.

Scott, R.F., Hushmand, B. and Rashidi, H. (1993), Duplicate Test of Model No 2: Sloping Loose Sand layer, *Intl. Conf. on Verification of Num. Proc. for Anal. Of Soil Liquefaction Problems*, Arulanandan, K. and Scott, R. F., Eds., 1, Davis, CA, Balkema, pp. 301-314.

Scott, R.F. and Hushmand, B. (1995), Discussion (of piezometer performance at Wildlife liquefaction site, California, by T. Leslie Youd and Thomas L. Holzer, GT June 94, pp. 975-995) with B. Hushmand, *Journal of Geotechnical Engineering*, ASCE, Dec., pp. 912-919.

Seale, S.H. and Archuleta, R.J. (1989), Site Amplification and Attenuation of Strong Ground Motion, *Bulletin of the Seismological Society of America*, Vol. 79, pp.1673-1696.

Seed, H.B. and Lee, K.L. (1966), Liquefaction of Saturated Sands During Cyclic Loading, *Journal of the Soil Mechanics and Foundations Division*, ASCE, 92, SM6, Nov., 105-134.

Seed, H.B. and Idriss I.M. (1970a), Analyses of Ground Motion at Union Bay, Seattle During Earthquakes and Distant Nuclear Blasts, *Bulletin of the Seismological Society of America*, Vol. 60, No.1, pp.125-136.

Seed, H.B. and Idriss, I.M. (1970b), Soil Moduli and Damping Factors for Dynamic Response Analyses, *Report EERC-70-10*, Earthquake Engineering Research Center, University of California at Berkeley, CA.

Seed, H.B., Lee, K.L., Idriss, I.M. and Makdisi, F.I. (1975), The Slides on the San Fernando Dams During the Earthquake of February 9, 1971, J. Geotech. Engrg. Div., ASCE, Vol. No. 7, pp. 651-688.

Seed, H.B. (1979), Soil Liquefaction and Cyclic Mobility Evaluation for Level Ground During Earthquakes, *J. Geotechnical Engrg. Div.*, ASCE, Vol. 105, No. GT2, Feb., pp. 201-255.

Seed, H.B., Romo, M.P., Sun, J. Jaime, A. and Lysmer, J. (1987), Relationship Between Soil Conditions and Earthquake Ground Motions in Mexico City in Earthquake of Sept. 19, 1985, *Report No. UCB/EERC-87/15,* Earthquake Engineering Research Center, University of California Berkeley.

Seed, H.B., Seed, R.B., Harder, L.F. and Jong, H.L. (1989), Reevaluation of the Slide in the Lower San Fernando Dam in the 1971 San Fernando Earthquake, *Report No. UCB/EERC-88/04*, Univ. of California, Berkeley, CA.

Seed, R.B., Dickenson, S.E., Riemer, M.F., Bray, J.D., Sitar, N., Mitchell, J.K., Idriss, I.M., Kayen, R.E., Kropp, A., Hander, L.F. Jr. and Power, M. (1990), Preliminary Report on the Principal Geotechnical Aspects of the October 17, 1989, Loma Prieta Earthquake, *Report No. UCB/EERC-90/05*, Earthquake Engineering Research Center, University of California Berkeley.

Shakal, A. and Petersen, C.P. (1992), Downhole Strong-Motion Accelerometer: Objectives and Techniques, *Seismological Research Letters*, Vol. 63. No. 30.

Shen, C.K., Wang, Z. and Li, X.S. (1991), Pore Pressure Response During 1986 Lotung Earthquakes, *Proceedings, Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, St. Louis, Missouri.

Shima, E. (1962), Modification of Seismic Waves in Superficial Layers as Verified by Comparative Observations on and Beneath the Surface, *Bulletin of Earthquake Research Institute*, Tokyo, Vol. 40, pp. 187-259.

Shiono, K. (1978), Identification of Wave Types in Strong Motions by Means of Down-Hole Array (in Japanese), *Proceedings of the Fifth Japan Earthquake Engineering Symposium-1978*, Architectural Inst. of Japan, Tokyo, Nov., Paper No. 37, pp. 289-296.

Shiono, K. (1979), Wave Type Identification of a Downhole Array Record (in Japanese), *Transactions of the Architectural Institute of Japan*, Vol. 282, Aug., pp. 65-70.

Sitar, N., Ed. (1995), Geotechnical Reconnaissance of the Effects of the January 17, Hyogoken-Nanbu Earthquake Japan, *Report No. UCB/EERC-95/01*, Earthquake Engineering Research Center, Berkeley, California.

Soeda, Y., Tamai, H. and Nakatsu, N. (1999), Nonlinearity and Irregularity on Strong Seismic Motions by Vertical Arrays During the 1995 Kobe Earthquake, *Proceedings of the Second International Conference on Earthquake Geotechnical Engineering*, A. A. Balkema, Rotterdam, Vol. 1, pp. 225-230.

Steidl, J. H., Tumarkin, A.G. and Archuleta, R. J. (1996), What Is a Reference Site? *Bulletin of the Seismological Society of America,* Vol. 86, pp. 1733-1748.

Steidl, J.H., Archuleta, R.J., Tumarkin, A.G., Bonilla, L.F. and Gariel, J.C. (1998), Observations and Modeling of Ground Motion and Pore Pressure at the Garner Valley, California, Test Site, *The Effects of Surface Geology on Seismic Motion: Recent Progress and New Horizon on ESG Study, Proceedings of the Second International Symposium*, A. A. Balkema, Rotterdam, Vol. 1, pp. 225-232.

Stevens, D.K, Kim, B.I., Wilson, D.W. and Kutter B.L. (1999), Comprehensive Investigation of Nonlinear Site Response – Centrifuge Data Report For DKS02, *UCD/CGMDR-99/02*, Dept. of Civil & Environmental Engineering, University of California at Davis, CA.

Stevens, D.K., Wilson, D.W., Kutter B.L., Kim, B.I. and Elgamal, A. (2001). Centrifuge model tests to identify dynamic properties of dense sand for site response calculations, *4th International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, March 26-31, 2001, San Diego, CA.

Stokoe, K.H. and Nazarian S., (1985), Use of Rayleigh Waves in Liquefaction Studies, *Proceedings, Measurement and Use of Shear Wave Velocity for Evaluating Soil Properties*, Geotechnical Engineering Division, ASCE, pp. 1-14.

Street, R., Wang, Z., Woolery, E., Hunt, J. and Harris, J. (1997), Site Effects at a Vertical Accelerometer Array Near Paducah, Kentucky, *Engineering Geology*, Vol. 46, No. 3-4, July 15, pp. 349-367.

Sugawara, Y., *et al.* (1991), A Study on Characteristics of Vertical Earthquake Ground Motions in Array Observations, *Transactions of the 11th International Conference on Structural Mechanics in Reactor Technology*, Atomic Energy Society of Japan, Tokyo, Vol. K1, Paper K02/6, pp. 39-44.

Sugito, M. (1995), Frequency-dependent Equivalent Strain for Equi-Linearized Technique, *First International Conference on Earthquake Geotechnical Engineering*, A. A. Balkema, Rotterdam, Vol. 1, pp. 655-660.

Sugito, M. *et al.* (1996a), Analysis of Borehole Array Records from the South Hyogo Earthquake of Jan. 17, 1995, *Proceedings of the International Workshop on Site Response Subjected to Strong Earthquake Motions*, Yokosuka, Japan, January 16-17, 1996, Japan Port and Harbor Research Inst., Yokosuka, Japan, Vol. 2, pp. 343-357.

Sugito, M., Sekiguchi, K., Yashima, A., Oka, F., Taguchi, Y. and Kato, Y. (1996b), Correction of Orientation Error of Borehole Strong Motion Array Records Obtained During the South Hyogo Earthquake of Jan. 17, 1995, *Journal of Structural Mechanics and Earthquake Engineering*, Vol. 34, Jan., pp. 51-63.

Sugito, M., Oka, F., Yashima, A., Furumoto, Y. and Yamada, K. (2000), Time-Dependent Ground Motion Amplification Characteristics at Reclaimed Land After the 1995 Hyogoken Nambu Earthquake, *Engineering Geology*, Vol. 56, No. 1, pp. 137-150.

Sykora, D.W. and Bastani, S.A. (1998), Distribution of Peak Horizontal Acceleration and Peak Horizontal Particle Velocity with Depth Measured During Earthquakes, *Proceedings of the Sixth U.S. National Conference on Earthquake Engineering*, Earthquake Engineering Research Inst., Oakland, California.

Taboada, V.M. and Dobry, R. (1992), *Comparison Tests for Earth Technology's Laboratory tests*, Report, Civil Engineering Department, Rensselaer Polytechnic Institute, Troy, NY.

Taboada, V.M. and Dobry, R. (1993), Experimental Results of Model 1 at RPI, *Proc. Intl. Conf. Verification of Num. Proc. for the Analysis of Soil Liquefaction Problems*, Arulanandan, K. and Scott, R. F., Eds., Volume 1, Davis, CA, Balkema, pp. 277-294.

Taboada, V.M. (1995), Centrifuge Modeling of Earthquake-Induced Lateral Spreading in Sand Using a Laminar Box, Ph.D. Thesis, Rensselaer Polytechnic Institute, Troy, NY.

Taboada, V.M. and Dobry, R. (1998), Centrifuge Modeling of Earthquake-Induced Lateral Spreading in Sand, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 124, No. 12, pp. 1195-1206.

Taboada, V.M., Martinez, H. and Romo M.P. (1999a), Evaluation of Dynamic Soil Properties in Mexico City Using Downhole Array Records, *Soils and Foundations*, Vol. 39, No. 5, Oct., pp. 81-92.

Taboada, V.M., Martinez, H, Romo, M.P., Ardila, C. and Hernandez, F.G. (1999b), Evaluation of No-linear behavior shear stress-strain at Mexico Valley Clay at CAO site using downhole arrays (in Spanish). *XII National Congress of seismic Engineering*, Morelia, Mexico 1999, Vol. 2, pp. 859-869.

Taboada, V.M., Martinez, H., Romo, M.P. and Ardila, C.D. (2000), Identification of Mexico City Clay Dynamic Properties, *Proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, 2000, Paper No. 1220.

Taguchi, Y., Tateishi, A., Oka, F. and Yashima, A. (1996), Three-Dimensional Liquefaction Analysis Method and Array Record Simulation in Great Hanshin Earthquake, *Proceedings of the Eleventh World Conference on Earthquake Engineering*, Pergamon, Elsevier Science Ltd., Oxford, England, Disc 2, Paper No. 1042.

Tanaka, Y. (1996), Liquefaction of Reclaimed Lands along Osaka Bay by Great Hanshin Earthquake (1995.1.17), *Proceedings of the International Offshore and Polar Engineering Conference*, Vol. 1, Int. Soc. of Offshore and Polar Engineers (ISOPE), Golden, CO, USA, pp. 20-28.

Tanaka, Y. (1997), The Behavior of a Man-Made Island During the Great Hanshin Earthquake, Japan, *Natural Hazards*, Vol. 16, Nov. 2-3, pp. 267-285.

Tanaka, Y. (2000), 1995 Great Hanshin Earthquake and Liquefaction Damages at Reclaimed Lands in Kobe Port, *International Journal of Offshore and Polar Engineering*, Vol. 10, No. 1, pp.64-72.

Tang, H.T. (1987), Large-Scale Soil Structure Interaction, *Report No. NP-5513-SR*, Electric Power Research Institute, Palo Alto, California.

Tang, H.T., Kokusho, T., Nishi, K., Kataoka, T. and Cheng, Y.H. (1991), The Hualien Large-Scale Seismic Test for Soil-Structure Interaction Research, *SMIRT 11 Transactions*, K04/4, pp. 69-74.

Tateishi, A., Taguchi, Y, Oka, F. and Yashima, A. (1995), A Cyclic Elasto-Plastic Model For Sand and Its Application Under Various Stress Conditions, *Proc. 1st Intl. Conf. on Earthquake Geotech. Engrg.*, Vol. 1, A.A. Balkema, Rotterdam, pp. 399-404.

Theodulidis, N., Bard, P.Y. and Archuleta, R.J. (1996), Horizontal-to-Vertical Spectral Ratio and Geological Conditions: the Case of Garner Valley Downhole Array in Southern California, *Bulletin of the Seismological Society of America*, Vol. 86, No. 2, Apr., pp. 306-319.

Tobita, Y. and Yoshida, N. (1995), Stability of Mechanically Well-Behaved Constitutive Model in Liquefaction Analysis of Saturated Sands, *Proc. 1st Intl. Conf. on Earthquake Geotechnical Engineering*, Tokyo, Japan, 1, pp. 429-434, Balkema.

Toshinawa, T., Watanabe, Y., Kobagashi, T. and Uchiyama, Y. (2000), Prediction of Strong-motion Characteristics of Bedrock Motion in Yokohama, Japan, Based on Source Region Classification, *Proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 0277.

Towhata, I, Park, J.K. and Orense, R.P. (1996), Use of Spectrum Intensity For Immediate Detection of Subsoil Liquefaction, *Soils and Foundations*, Vol. 36, No. 2, June, pp. 29-44.

Tsuchida, H. and Kurata, E (1975), Observation of Earthquake Response of Ground with Horizontal and Vertical Seismometer Arrays, *Proceedings of the Fourth Japan Earthquake Engineering Symposium-1975*, Architectural Inst. of Japan, Tokyo, Paper No. 118, pp. 137-144.

Tsuchida, H. and Kurata, E. (1976), Observed Earthquake Ground Displacements along a 2500 Meter Line, *Proceedings of US-Japan Seminar on Earthquake Engineering Research with Emphasis on Lifeline Systems*, pp. 29-42.

Tsuchida, H., Kurata, E. and Hayashi, S. (1977), Observation of Earthquake Response of Ground with Horizontal and Vertical Seismometer Arrays, *Proceedings, Sixth World Conference on Earthquake Engineering*, Sarita Prakashan, Meerut, India, Vol. I, pp. 509-515.

Tsuchida, H. and Iai, S. (1978), Observation of Earthquake Response of Ground with Horizontal and Vertical Seismometer Arrays (2nd report), *Proceedings of the Fifth Japan Earthquake Engineering Symposium-1978*, Architectural Inst. of Japan, Tokyo, Paper No. 22, Nov., pp. 169-176.

Tsujihara, O., Sawada, T. and Sugito, M. (1990), Identification of Subsurface Layers of the Ground by Using Vertical Array Records, *Fourth U.S. National Conference on Earthquake Engineering, Proceedings*, Earthquake Engineering Research Inst., El Cerrito, California, Vol. 1, pp. 395-404.

Tumarkin, A.G. and Archuleta, R.J. (1997), Recent Advances in Prediction and Processing of Strong Ground Motions, *Natural Hazards*, Vol. 15, No. 2-3, Special Issue, May, pp. 199-215.

Tumarkin, A.G. (1998), Site Response Analysis in 3D, *The Effects of Surface Geology on Seismic Motion: Recent Progress and New Horizon on ESG Study, Proceedings of the Second International Symposium*, A. A. Balkema, Rotterdam, Vol. 2, pp. 365-370.

Uang, C.M., Elgamal, A.W., Li, W.S. and Chou, C.C. (1999), *Ji-Ji, Taiwan Earthquake of September 21, 1999: A Brief Reconnaissance Report*, Department of Structural Engineering University of California, San Diego, La Jolla, CA, USA.

Ueshima, T. and Okano, H. (1996), Further Investigation on Seismic Response of Soil and Embedded Structure in Hualien LSST Program, *Proceedings of the Eleventh World Conference on Earthquake Engineering*, Pergamon, Elsevier Science Ltd., Oxford, England, Disc 4, Paper No. 1930.

Uetake, T. and Satoh, T. (1998), Recent array experiments in Japan, *The Effects of Surface Geology on Seismic Motion: Recent Progress and New Horizon on ESG Study, Proceedings of the Second International Symposium*, A.A. Balkema, Rotterdam, Vol. 1, pp. 51-70.

Vaid, Y.P. and Thomas, J. (1995), Liquefaction and Postliquefaction Behavior of Sand, *Journal of Geotechnical Engineering*, ASCE, Vol. 121, No. 2, February, pp. 163-173.

Vaid, Y.P. and Sivathayalan, S. (1999), *Proc. Intl. Workshop on the Physics and Mechanics of Soil Liquefaction*, Baltimore, Maryland, 10-11 Sept. 1998, Physics and Mechanics of Soil Liquefaction, Lade, P. V. and Yamamuro, J. A., eds., pp. 105-120.

Volant, P., Cotton, F. and Gariel, J.C. (1998), Estimation of Site Response Using the H/V Method: Applicability and Limits of This Technique on Garner Valley Downhole Array Dataset (California), *Proceedings of the Eleventh European Conference on Earthquake Engineering*, A. A. Balkema, Rotterdam.

Wang, S., Kutter, B.L., Chacko, M.J., Wilson, D.W., Boulanger, R.W. and Abghari, A. (1998), Nonlinear Seismic Soil-Pile-Structure Interaction, *Earthquake Spectra*, Earthquake Engineering Research Institute, May, pp. 377-396.

Wang, Z.L., Chang, C.Y. and Mok, C.M. (2001), Evaluation of Site Response Using Downhole Array Data from a Liquefied Site, *Procs. 4th International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, San Diego, California, March.

Wen, K.L. (1994), Non-Linear Soil Response in Ground Motions, *Earthquake Engineering and Structural Dynamics*, Vol. 23, pp. 599-608.

Wen, K.L., Beresnev, I.A. and Yeh, Y.T. (1994), Nonlinear Soil Amplification Inferred from Downhole Strong Seismic Motion Data, *Geoph. Res. Lett.*, Vol. 21, pp.2625-2628.

Wen, K.L., Fei, L.Y., Peng, H.Y., and Liu, C.C. (1995a), Site Effect Analysis from the Records of the Wuku Downhole Array, *Terrestrial, Atmospheric and Oceanic Sciences*, Vol. 6, No. 2, June, pp. 285-298.

Wen, K.L., Beresnev, I.A. and Yeh, Y.T. (1995b), Investigation of Non-Linear Site Amplification at Two Downhole Strong Ground Motion Arrays in Taiwan, *Earthquake Engineering Structural Dynamics*, Vol. 24, pp. 313-324.

Wen, K.L. and Peng, H.Y. (1998), Strong Motion Observations in the Taipei Basin, *The Effects of Surface Geology on Seismic Motion: Recent Progress and New Horizon on ESG Study: Proceedings of the Second International Symposium on the Effects of Surface Geology on Seismic Motion*, Yokohama, Japan, 1-3 December, edited by Kojiro Irikura, Kazuyoshi Kudo, Hiroshi Okada, and Tsutomu Sasatani, pp. 263-270.

Whitman, R.V. and Ting, N.H. (1994), Experimental Results For Tilting Wall With Saturated Backfill, *Intl. Conf. Verification of Num. Proc. for Analysis of Soil Liquefaction Problems*, Arulanandan, K. and Scott, R. F., Eds., Vol. 2, Davis, Balkema, pp.1515-1528.

Wilson, D.W. and Kutter, B.L. (1993), Experimental Results of Model No. 7, *Intl. Conf. on Verification of Num. Procedures for the Analysis of Soil Liquefaction Problems*, Arulanandan, K. and Scott, R. F., Eds., Vol. 1, Davis, CA, Balkema, pp. 809-816.

Wilson, D.W., Boulanger, R.W. and Kutter, B.L. (1997), Soil-Pile-Superstructure Interaction at Soft or Liquefiable Soils Sites-Centrifuge Data Report CSP3, *Report No. UCD/CGMDR-97/04*, Center for Geotech. Modeling, Dept. of Civil and Environ. Engineering, Univ. of California, Davis, February.

Wilson, D.W., Boulanger, R. W. and Kutter, B. L. (1998), Signal Processing for and Analyses of Dynamic Soil-Pile Interaction Experiments, Proceedings, Centrifuge 98. *Kumura, Kusakabe, and Takemura, Eds. Balkema, Rotterdam, pp. 135-140.*

Wilson, D.W., Boulanger, R.W. and Kutter, B.L. (2000), Observed Seismic Lateral Resistance of Liquefying Sand, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Oct., Vol. 126, pp.898-906.

Xie, L., Li, S. and Zhang, W. (1999), A Three Dimensional Array for Site Effects on Strong Ground Motion (in Chinese), *Earthquake Engineering and Engineering Vibration*, Vol. 19, No. 2, pp. 1-8.

Yahata, K., Sasaki, T., Niwa, M. and Tsugawa, T. (2000), Characteristics of Surface Motion on a Topographic Irregular Ground During Large Earthquakes, *Proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 1507.

Yamada, M. (1990), Seismic Pulses Repeated in Coda Part of Strong Seismic Waves (in Japanese), *Journal of Structural and Construction Engineering*, (Transactions of AIJ), Vol. 409, pp. 75-82.

Yamazaki, F., Ansary, M.A. and Towhata, I. (1995), Application of a Dynamic Effective Stress Model at a Reclaimed Site During the Great Hanshin Earthquake, 1995, *First International Conference on Earthquake Geotechnical Engineering*, A. A. Balkema, Rotterdam, Vol. 1, pp. 591-597.

Yanagisawa, E. and Kazama, M. (1996), Nonlinear Dynamic Behavior of the Ground Inferred from Strong Motion Array Records at Kobe Port Island During the 1995 Hyogo-ken Nanbu Earthquake, *Proceedings of the Eleventh World Conference on Earthquake Engineering*, Pergamon, Elsevier Science Ltd., Oxford, England, Disc 4, Paper No. 2152.

Yang, J. and Sato, T. (1999), Characteristics of Ground Motions at a Liquefiable Site, MCEER-99-0019, *Proceedings of the Seventh U.S.-Japan Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Soil Liquefaction*, MCEER, Buffalo, NY.

Yang, J. and Sato, T. (2000a), Identification of Soil Liquefaction Using Downhole Array Records, *Proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 0266.

Yang, J. and Sato, T. (2000b), Interpretation of Seismic Vertical Amplification Observed at An Array Site, *Bulletin of the Seismological Society of America*, Vol. 90, No. 2, April, pp. 275 –85.

Yang, J., Sato, T. and Li, X.S. (2000a), Seismic Amplification at a Soft Soil Site with Liquefiable Layer, *Journal of Earthquake Engineering*, Vol. 4, No. 1, Jan., pp. 1-23.

Yang, J., Sato, T., and Li, X.S. (2000b), Nonlinear Site Effects on Strong Ground Motion at a Reclaimed Island, *Canadian Geotechnical Journal*, Vol. 37, No 1, Feb. pp. 26-39.

Yang, Y.C., Huang, W.G., Liu, C.C., Cheng, S.N. and Yeh, Y.T. (1995a), Strong-Motion Earthquake Records on the 23 February, 1995, in LSST Array, Hualien, *Report IESER95-001*, Institute of Earth Sciences, Republic of China.

Yang, Y.C., Huang, W.G., Liu, C.C., Cheng, S.N. and Yeh, Y.T. (1995b), Strong-Motion Earthquake Records on the 1 May, 1995, in LSST Array, Hualien, *Report IESER95-002*, Institute of Earth Sciences, Republic of China.

Yang, Z., Parra, E. and Elgamal, A. (1999), Seismic Site Response and Liquefaction Induced Shear Deformation, *7th U.S. - Japan Workshop on E.Q. Resistant Design of Lifeline Facilities and Countermeasures Against Liquefaction.* August 15-17, Seattle, Washington.

Yang, Z. (2000), Numerical Modeling of Earthquake Site Response Including Dilation and Liquefaction, Ph.D. Dissertation, Dept. of Civil Engineering and Engineering Mechanics, Columbia University, New York, NY.

Yao, Y. (1999), Analysis of CNT Borehole Records: Seismic Response of Sedimentary Layers, *Individual Studies by Participants at the International Institute of Seismology and Earthquake Engineering*, Vol. 35, pp. 15-27.

Yoshida, N., *et al.* (1996), Nonlinear Behavior of Ground During the 1995 Hyogoken-Nanbu Earthquake, *Proceedings of the International Workshop on Site Response Subjected to Strong Earthquake Motions*, Yokosuka, Japan, January 16-17, Japan Port and Harbor Research Inst., Yokosuka, Japan, Vol. 2, pp. 374-389.

Yoshida, N. and Iai, S. (1998), Nonlinear Site Response and Its Evaluation and Prediction, *The Effects of Surface Geology on Seismic Motion: Recent Progress and New Horizon on ESG Study, Proceedings of the Second International Symposium*, A. A. Balkema, Rotterdam, Vol. 1, pp. 71-90.

Yoshida, N. (2000), Liquefaction of Improved Ground in Port Island and Its Effect on Vertical Array Record, *Proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 1509.

Youd, T.L. and Wieczorek, G.F. (1984), Liquefaction During 1981 and Previous Earthquakes Near Westmoreland California, U.S. Geological Survey Open-File *Report 84-680.*

Youd, T.L., Tang, T.K., Stepp, J.C., Holzer, T.L., and Jackson, G.O. (1989), A Wedging System for Downhole Accelerometers, *Earthquake Spectra*, Vol. 5, No. 4, Nov., pp. 813-818.

Youd, T.L. and Holzer, T.L. (1994), Piezometer Performance at Wildlife Liquefaction Site, California, *Journal of Geotechnical Engineering*, Vol. 120, No. 6, June 1994, pp. 975-995.

Youd, T.L., Hansen, C., and Bartlett, S. (1999), Revised MLR Equations for Predicting Lateral Spread Displacement, *7th U.S. - Japan Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Liquefaction*, August, Seattle, WA.

Zeghal, M. (1990), *System Identification of the Nonlinear Seismic Response of Earth Dams*, PhD thesis, Princeton University, New Jersey.

Zeghal, M. and Elgamal, A.W. (1993), Lotung Site: Downhole Seismic Data Analysis, *Report Submitted to EPRI*, Department of Civil Engineering Rensselaer Polytechnic Institute, Troy, New York.

Zeghal, M. and Elgamal, A.W. (1994), Analysis of Site Liquefaction Using Earthquake Records, *Journal of Geotechnical Engineering*, ASCE, Vol. 120, No. 6, Jun., pp. 996-1017.

Zeghal, M., Elgamal, A.W., Tang, H.T. and Stepp, J.C. (1995), Lotung Downhole Array II: Evaluation of Soil Nonlinear Properties, *Journal of Geotechnical Engineering*, ASCE, Vol. 121, Apr. pp. 363-378

Zeghal, M., Elgamal, A.W. and Parra, E. (1996a), Analyses of Site Liquefaction Using Downhole Array Seismic Records, *Proceedings of the Eleventh World Conference on Earthquake Engineering*, Pergamon, Elsevier Science Ltd., Oxford, England, Disc 1, Paper No. 371.

Zeghal, M., Elgamal, A.W. and Parra, E. (1996b), Identification and Modeling of Earthquake Ground Response -- II. Site liquefaction, *Soil Dynamics and Earthquake Engineering*, Vol. 15, No. 8, Dec., pp. 523-547.

Zeghal, M. and Elgamal, A.W. (2000), A Review of Site Seismic Response Using Vertical Arrays, *Proceedings of the 12th World Conference on Earthquake Engineering*, New Zealand Society for Earthquake Engineering, Upper Hutt, New Zealand, Paper No. 2175.

Zorapapel, G.T. and Vucetic, M. (1994), The Effect of Pore-Pressure on Ground Motion, *Earthquake Spectra*, Vol. 10, No. 2, pp. 403-438.